Network Rail

A Review of Earthworks Management

Prepared by a Task Force led by
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Executive Summary

Following the tragic train derailment at Carmont on 12th August 2020, Network Rail appointed our Task Force to undertake a Review of their Management of Earthworks. At the same time the Weather Advisory Task Force, chaired by Dame Julia Slingo, was also appointed. Emerging findings from investigations of the factors behind the Carmont derailment suggest that a significant contributing factor was heavy rainfall leading to material being washed onto the track. This Review does not cover the investigations into the Carmont incident but focuses on Network Rail's capability and methodology for the management of railway cuttings and embankments, particularly in the light of climate change.

Network Rail have inherited and manage 190,000 earthworks assets, comprising 70,000 soil cuttings, 20,000 rock cuttings and 100,000 embankments. The vast majority are over 100 years old and many are over 150 years old. The cut and embankment slopes continue to fail for a number of reasons. Historically, cuttings are overly steep and many have failed previously; embankments were uncompacted during their construction and their foundations were unprepared. The upper few metres of the slopes have often been weakened by weathering. Complex processes, known as progressive failure, operate in the high plasticity clays forming many of the troublesome cuttings and embankments. Drainage is often inadequate to ensure stability and historically was not designed to do so. Vegetation, which can have beneficial and detrimental effects on slope stability, has not been particularly well managed in the past. In addition, and of particular significance, weather patterns are changing, resulting in longer periods of prolonged rainfall, more intense rainfall and hotter, drier summers.

The combination of these factors is the challenge Network Rail face in managing their earthwork and drainage assets. This Review considers how this challenge is being met and whether improvements can be made by modifying the asset management policy, strategy, standards and procedures, as well as by implementing the latest methods of monitoring and surveillance.

Slope condition data is primarily derived by Network Rail through periodic earthwork examinations. These visual inspections rely heavily on data collected by examiners in the field that may be subjective, potentially encompass a degree of variability and may not be able to identify certain precursors to slope failure. Full condition monitoring and assessment of the extensive Network Rail earthwork asset base is challenging; slope stability cannot be determined on the basis of surface observations from examination alone. The rapid failure of cut slopes is especially difficult to predict, particularly when failures are triggered by locally intensive rainfall.

Recognising this Network Rail have put considerable resource into the development of a comprehensive asset management system for their earthworks and we commend the very substantial effort in achieving this. Nevertheless, some shortfalls in the earthwork examination and risk evaluation system need to be addressed, in particular reliance on algorithms and statistics as predictors of earthworks failure without verification by some site-specific engineering calculations. There are also limitations of mainly using pre-determined hazard categories to trigger earthwork evaluations and examination frequencies.

An overhaul of the Geotechnical and Drainage asset management systems is required to bring the existing data and decision support tools together in a common interface. This will provide the Network Rail engineering teams with the capability to properly evaluate and document the vulnerability of earthwork and drainage assets and accurately prioritise intervention activities required to safely manage the infrastructure.

An overriding message from this Review is that soil pore water pressure is a key parameter in determining the past and future stability of Network Rail's earthwork assets. Pore water pressure regimes have been modified by changing weather patterns and will continue to change. Rates and magnitudes of pore water pressure changes depend on the availability and ability of water to flow into the soil profile, while strong surface flows can also cause soil erosion and flooding in their own right. Hence surface and sub-surface water management is probably the single most important factor in determining if, when and where an earthwork failure will occur.

A holistic approach to water management, considering catchment to outfall and integrating all drainage systems, is needed to manage earthworks stability and track quality. The size, shape and location of all natural catchments draining towards Network Rail's railway should be established, in order that the water flow rates can be determined for the required design storm return periods, allowing for climate change. The effective control of water and proper understanding and maintenance of drainage assets is of fundamental underpinning importance to the safe operation of the railway network.

The process for the identification of localised water concentration features at the top of cutting crests and the likelihood of failure from washout or earthflow should be fundamentally reviewed to address the fact that many of the 2019/2020 failures occurred in slopes which had not been identified as vulnerable and most of the failures were still observed first by the train drivers. The aim should be to improve the prediction rate for rapid cutting slope failures, a feature of which there is often little or no indication of visible distress prior to failure. A forensic re-assessment of the significant number of previous washout and earthflows, together with the accompanying weather patterns, would be invaluable for calibration of the current examination and evaluation process and provide lessons learnt for future risk assessment.

We recommend that consideration is given to undertaking drainage inspections with sufficient and professionally qualified competent staff under the control of the RAM-Drainage, as is done for earthworks examinations, rather than the current arrangement where the NR Maintenance off-track team is often overloaded with inspections of drainage systems. More resource is needed for this vital activity. Consideration should also be given to having dedicated drainage maintenance teams across all Routes, rather than drainage being only one of the activities for which Off-Track Section Managers are responsible. Off-Track drainage maintenance should have its own budgets. There is a case for having Off-Track Maintenance Engineers with similar role and grading to the existing Track Maintenance Engineer posts.

Another area for significant investment is the updating of monitoring and surveillance methods. There have been recent advances, some of which have been explored by Network Rail. A notable example is the recently trialled wireless tiltmeter system; this is an extremely promising application of innovative sensor development to the management of earthworks assets. These sensor systems are capable of providing failure detection and reaction via alert alarm systems, as well as data on the performance and condition of a slope or embankment, and possible precursors to failure. Such monitoring systems should be more widely adopted on earthworks slopes and embankments that are judged to be potentially critical, along with pore water pressure measurement where appropriate; pore water pressures are critical but are not often measured.

More regular and frequent use should be made of surveillance technologies with helicopters and drones. There should be more widespread use of helicopter flights for inspections of earthworks, particularly after especially intense rainfall; they can serve as a key mitigation by providing warning or identification of an earthwork failure. Despite some existing limitations, particularly in respect of current regulations, drone technology is a rapidly expanding area and there is considerable potential for drones to significantly enhance Network Rail’s earthworks management; for example, by locating obstructions on the track before the train driver, identifying changes, and mapping features that lead to localisation. InSAR is a promising satellite technology which is also developing rapidly, with substantial developments in AI and machine learning, and should be given further attention. Routine analysis of track geometry data is a potentially valuable technique for the early detection of embankment instability; further development work is required to establish automatic data processing.

International experience indicates that the most promising surveillance technologies for slope and landslide management are LiDAR and photogrammetry (both aerial and land-based). Wireless sensors have been shown to be effective for monitoring of slope movements, provision of warning systems and detection of flexible barrier deformations. There is significant potential for these advanced surveillance and monitoring technologies; they need to be managed centrally, replacing several aspects of the well-established visual examination procedure but run in parallel with retained parts of that inspection.

With climate change, more intense rainfall and higher frequencies of extreme rainfall are likely. This will result in an increase in washout and earthflow slope failures, particularly in cuttings. The intense rainfall is associated with cyclonic storms that can occur at any time of year; however, they are particularly prevalent in the summer period. Shallow slope failures and washouts on cut slopes appear to predominate. Of the 252 reportable failures in 2019/2020, 190 were in cuttings and 62 in embankments. Localisation makes the prediction of precisely where they may occur almost impossible. Nevertheless, advances in monitoring technologies and surveillance techniques, in combination with data on past failures, can lead to identification of which geologies and geometries are especially vulnerable. In such cases a pragmatic approach would be to install instrumented barriers that will provide temporary restraint and notification of an instability event.

A key challenge for Network Rail's earthwork asset management is to focus on mitigating the effects of earthworks failures, as currently it is not reasonably practicable to detect nor prevent all earthwork failures. Mitigation measures are crucial to reduce the consequence of a failure should it occur.

Network Rail have carried out a comprehensive review of their vegetation management standards following the Varley Report on vegetation. Further work should be undertaken to develop vegetation management and bioengineering techniques to stabilise earthwork slopes as a cost-effective preventative and remedial intervention technique.

Vegetation management needs to balance the negative impacts of vegetation (blocked ditches and pipes, leaf fall, tree fall, desiccation adjacent to and beneath the track) against its positive impacts (reducing surface erosion, providing root reinforcement, avoiding channelling of flows, maintaining surface pore water suctions). The potential negative impacts of de-vegetation should be carefully considered. Vegetation should be treated as an asset and the railway system regarded as a wildlife corridor.

We recommend that Network Rail build on their comprehensive asset management system and progressively adopt a broader and more integrated approach to the management of Earthworks, Drainage and Vegetation, taking account of changing weather patterns. There is a need to breakdown the historic silos between these interdependent assets across the organisation to support the delivery of a safe, cost-effective and sustainable railway infrastructure into the future.

"A holistic approach to water management, considering catchment to outfall and integrating all drainage systems, is needed to manage earthworks stability and track quality. The size, shape and location of all natural catchments draining towards Network Rail's railway should be established, in order that the water flow rates can be determined for the required design storm return periods, allowing for climate change."

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Chapter 1

Introduction

1 On 12 August 2020, after a period of thunderstorms and heavy rain, a train derailed just north-east of Carmont in Aberdeenshire, fatally injuring the driver of the train, the train's conductor, and one passenger. Immediately following this tragedy our Task Force, chaired by Lord Robert Mair, was appointed by Network Rail (NR) to undertake a Review of their Management of Earthworks. At the same time the Weather Advisory Task Force (WATF), chaired by Dame Julia Slingo, was also appointed.

2 Emerging findings from investigations suggest that a significant contributing factor to the derailment at Carmont was heavy rainfall leading to material being washed onto the track (NR Interim Report to Secretary of State, 1 September 2020). This Review does not cover the investigations into the Carmont incident, but focuses on NR's capability and methodology for the management of railway cuttings and embankments. The aim of this Review is to equip NR with the expertise and competence in order that it can better manage earthworks in the future, particularly taking into account effects of climate change. The detailed Terms of Reference for the Earthworks Management Task Force are in Appendix A.

3 NR has also commissioned the Weather Advisory Task Force to review their capability to understand and manage the implications of rainfall, with the aim of equipping NR with the expertise and competence so that it can better manage rainfall in the future. For completeness, the Terms of Reference for the Weather Advisory Task Force are in Appendix B.

The Expert Panel and Task Force

4 The Earthworks Management Task Force comprises an Expert Panel and other members who have been consulted on various specific areas and contributed to some sections of our report, or reviewed drafts of our report. The Expert Panel, which has undertaken most of the drafting of the report, comprises Lord Robert Mair, Dr David Hight and Mr Brian McGinnity. A list of the members of the Task Force, together with summaries of their qualifications and expertise, is in Appendix C.

5 During the period September – November 2020 the Expert Panel has reviewed a large number of documents provided by NR, as well as relevant publications. Key documents and publications are given in the List of References. The Panel has heard evidence from 38 meetings with NR personnel, and with other individuals and organisations. A full list of the meetings, individuals and organisations is in Appendix D. Regular liaison meetings have also been held with the Weather Advisory Task Force.

6 The following railway organisations have been consulted:

+ Rail Accident Investigation Branch (RAIB)

The primary role of the RAIB is to investigate rail accidents and incidents. Since it was set up in 2005 it has undertaken 22 different investigations involving earthworks. Investigations in relation to the derailment at Carmont are in progress.

+ Office of Road and Railways (ORR)

The ORR, which has been in existence since 2006, oversees safety, reliability and economic performance and is responsible for assessing the funding submissions that NR make to government for each of the five-year Control Periods (CP). As the independent regulator, ORR ensures that results of investigations and investigations by the Rail Accident Investigation Board are acted upon, issuing improvement notices where necessary.

+ Rail Safety and Standards Board (RSSB)

Owned by the rail industry, the RSSB provides independent advice to the industry. It is responsible for standards and provides information and guidance; it collates and analyses data, manages research and development programmes, undertakes safety analysis, and develops safety risk models.

Acknowledgements

7 We are grateful to the staff of NR for answering our queries and providing a considerable amount of information that we have requested, particularly Simon Abbott and Mike Edwards who have been especially helpful. We also acknowledge the assistance given to us by Usman Ahmed and William Lever of NR in organising meetings, obtaining information and preparation of this report.

Methodology and Structure of the Report

8 To understand the problem that NR face in managing their earthworks we have examined first the available information on the excavation of railway cuttings and construction of railway embankments in Victorian times. We have then reviewed how these assets have performed since their construction and since being inherited by NR. Plainly they have not performed well; cuttings and embankments continue to fail, impacting on the safety and operation of the railway. This background is described in Chapter 2. To form an independent understanding of why these failures have taken place and whether they will continue in the future we have outlined in Chapter 3 the relevant principles of soil mechanics that could explain the mechanisms and triggers for the different forms of instability. There is no suggestion that NR have not been through the same exercise, undoubtedly in greater detail, and have not reached similar conclusions.

9 Changing weather and rainfall patterns have been identified as significant contributors to the ongoing failure of the earthworks assets; these are discussed in Chapter 4 in the context of climate change. With the background of Chapters 2, 3 and 4 we address in Chapter 5 the question of whether earthworks failures will continue in the future, which assets will be most vulnerable and what factors determine the vulnerability. We present these as independently derived check-lists; again there is no suggestion that they are not already being considered and acted upon by NR. Chapter 6 considers the likelihood of continuing failures in rock cuttings.

10 With this independent understanding of the past and likely future performance of NR's earthworks assets, and the reasons for them, we were then in a position to comment on how NR manage the vast number of their earthworks, drainage and vegetation assets. Chapters 7, 8 and 9 consider earthworks, drainage and vegetation asset management respectively in the light of the potential vulnerability of earthworks. Chapter 10 addresses key aspects of mitigation, covering monitoring, surveillance and interventions. Chapter 11 discusses what can be learned from other earthworks asset owners, including some relevant international experience. Finally, Chapter 12 makes some suggestions for future applied research.

11 Chapter 13 is a summary of our conclusions and recommendations.

Chapter 2

Background

History of Railway Construction

12 Skempton (1996) provides a very informative account of the construction of the main railway lines in England between 1834 and 1841. From a geotechnical perspective and as background to the subject of this Report, the following are relevant:

a. Where feasible, material excavated from cuttings was placed in adjacent embankments. An indication of the material in an embankment can be based, therefore, on the geology of the cutting from which it was taken.

b. Fill for embankments was generally placed by end-tipping to full height and so with no formal compaction and with little breakdown. The exception was adjacent to bridge abutments, where the fill was placed in layers and received some compaction.

c. The slopes to the embankments developed at the angles of repose of the material being placed and were trimmed to slopes of 1.5 or 2 (horizontal) to 1 (vertical).

d. As much of the fill was dug by pick and shovel, clay fill remained in the form of lumps within the embankments.

e. A failure of the foundation to an embankment during construction is described; other foundation failures are likely to have occurred.

f. No information is given on foundation preparation, in terms of drainage or removal of unsuitable material.

g. Slopes on embankments and in cuts were turfed or seeded with grass.

h. Failures/slips wholly within the embankments occurred during construction and at one or two years after construction. These were usually in uncompacted clay fills and the following clay units are referred to: Upper Lias, Oxford Clay, Weald Clay and London Clay (all high plasticity clays). The delayed failures are attributed to softening of the clay lumps as rainwater entered the bank.

i. Settlement of the uncompacted fill in the embankments occurred and was compensated for by placing additional ballast. Ash from coal-fired steam trains and power stations has also been used for this purpose.

j. At some locations borrow areas were dug immediately adjacent to the embankments that were under construction, a procedure referred to as side cutting. The presence of these pits was implicated in some of the embankment failures that occurred.

k. Cutting slopes in clay were generally constructed at 2 (horizontal) to 1 (vertical).

l. Quoting directly from Skempton (1996): *'Superficial slips were common in clay cuttings (and embankments) either in rainy seasons during construction or in the first or second winter afterwards. They usually required for their repair no more than trimming and a few shallow trench drains. In an altogether different category were deep slips which took place, almost without warning, several years after excavation. Three well documented cases are summarised in Table 4.'*

Table 4 from Skempton (1996): Delayed slips in clay cutting.

Line	Cutting	Effective Depth (m)	Slope	Material	Date of Slip	Time after Excavation
London & Croydon	New Cross	14.5	2:1	London Clay	2 Nov 1841	3 years
Great Western	Sonning	13	2:1	Reading Clay	24 Dec 1841	2.5 years
London & Birmingham	Bugbrooke	14	2:1	Upper Lias Clay	24 Sep 1842	4.5 years

In the table slopes are quoted as 2 (horizontal) to 1 (vertical).

m. *'The slopes were benched back in stages to an overall inclination of 4:1, and during these operations the polished nature of the slip surface and its shape were observed.'*

n. *'Cuttings with slopes steeper than 3.5:1 in London Clay or 2.5:1 in Upper Lias clay, for example, are prone to slip 10 to 50 years (or even longer) after excavation.'*

o. Counterforts[1] *'became practically a standard remedial measure on the railways and remained so for the next hundred years.'*

13 When trying to understand the cause of ongoing failures of NR's assets and when assessing the vulnerability of cut slopes and embankments to failures in the future, the following should be taken from Skempton's account, assuming it to be typical of construction between 1841 and 1900:

a. Embankments could have been formed from both cohesive and non-cohesive uncompacted material; cohesive fill will have been in lumps.

b. Previous failures have occurred in clay embankments and foundations to embankments; in plastic clays, low strength residual surfaces will have been formed within the embankment and foundation and movement on these surfaces can be reactivated.

c. Infilled borrow pits may be present alongside embankments and could affect the stability of the bank. It would be valuable to have a register of where these side/borrow pits have been excavated and have been identified.

d. Stiff plastic clays cut at slopes of 2:1 were stable in the short term but not in the long term. They fail at different times after construction and required to be reconstructed at much shallower slopes, in one case at 4:1.

e. Counterforts are a possible indicator of previous instability.

1 Counterforts are described in the section on Historical Interventions in Chapter 3. They consist of trenches dug into the slope below the slip surface and backfilled with gravel or rubble stone rammed in tight, Skempton (1996). They act as both an internal buttress and as a deep drain.

NR's Earthwork Assets

14 NR have inherited and manage 190,000 earthworks assets, comprising 70,000 soil cuttings, 20,000 rock cuttings and 100,000 embankments, the key features of which are illustrated in Figures 2.1 to 2.3, and the purposes of which are described as:

+ Soil cuttings – excavations that allow railway lines to pass at an acceptable level and gradient through the surrounding ground that is composed entirely or predominantly of soil

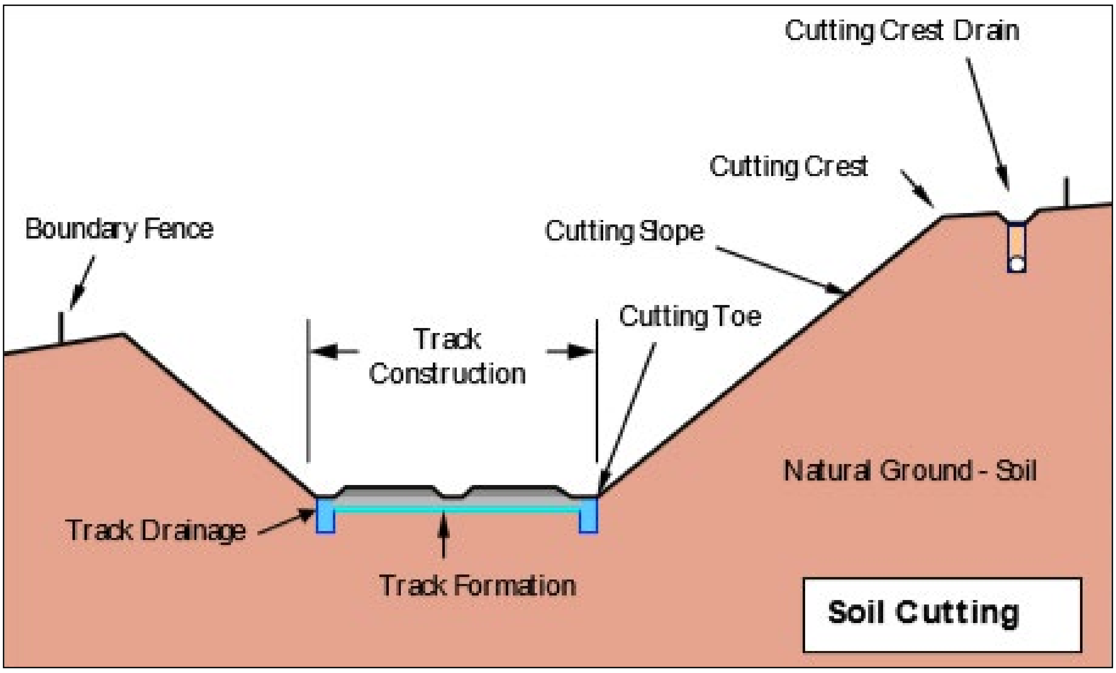


Figure 2.1: Soil Cutting Cross Section (Taken from NR Earthworks Policy NR (2018c))

+ Rock cuttings – excavations that allow railway lines to pass at an acceptable level and gradient through the surrounding ground that is composed entirely or predominantly of rock. Generally, rock cutting slopes are steeper than soil cutting slopes

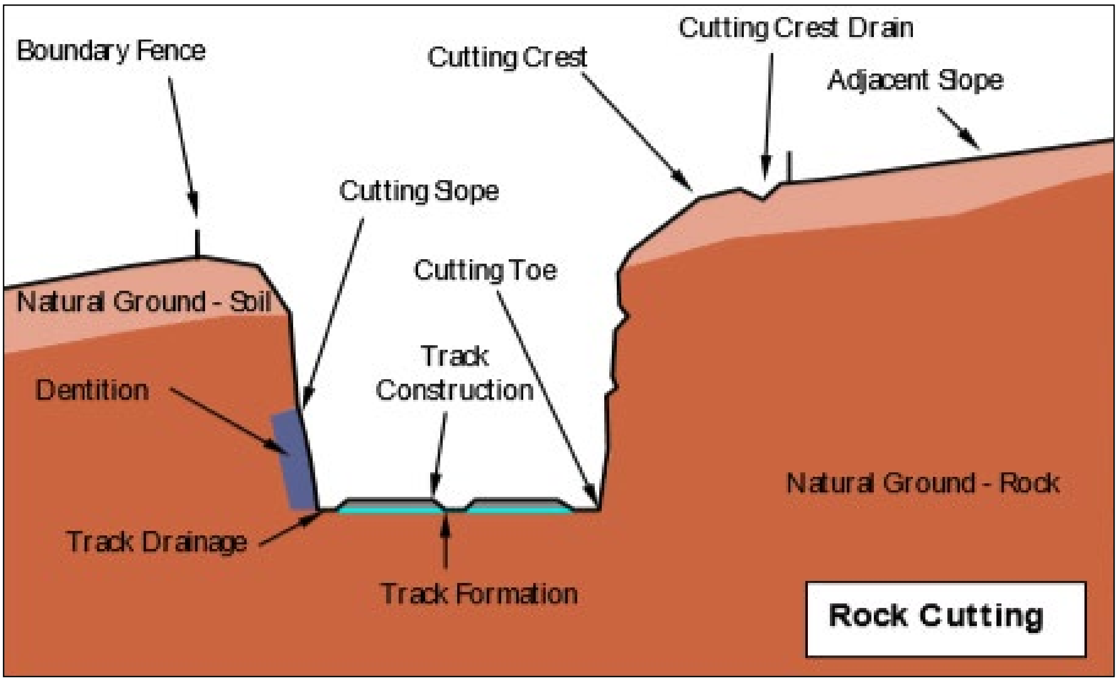


Figure 2.2: Rock Cutting Cross Section (Taken from NR Earthworks Policy NR (2018c))

+ Embankments – constructions that allow railway lines to pass at an acceptable level and gradient over low lying ground

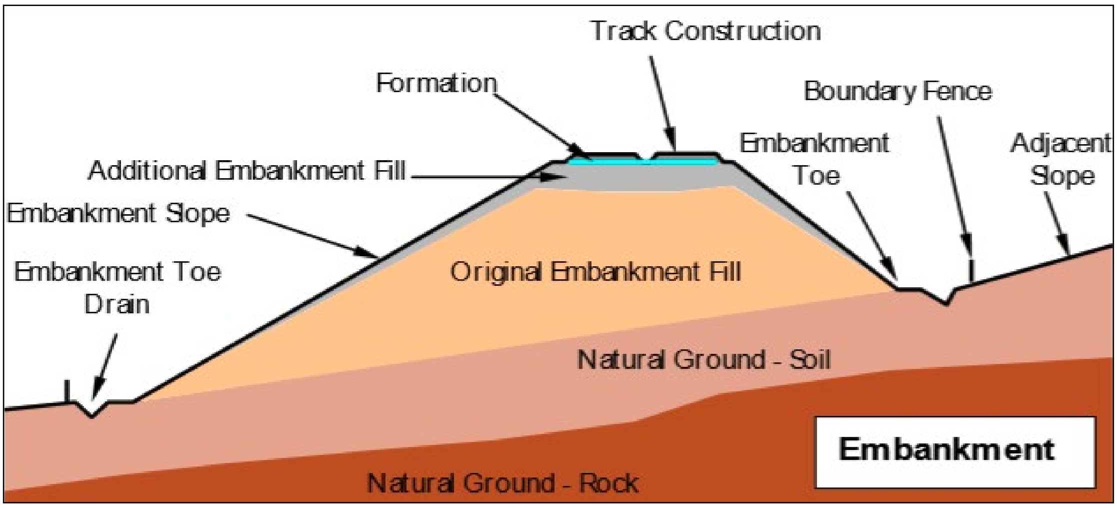


Figure 2.3: Embankment Cross Section. (Taken from NR Earthworks Policy NR (2018c))

15 Being largely uncompacted the embankments have undergone both creep settlements and collapse settlements when the loose unsaturated soils have wetted up. In the past, embankment levels have been maintained by capping the uncompacted fill with ballast or coal ash, a procedure which presents its own problems.

16 The estimated years in which the tracks on these assets were opened to traffic are shown in Figure 2.4, taken from NR's Earthworks Policy (2018) and based on work by Cobb (2015). Figure 2.4 and other data provided to us illustrate that the vast majority of the assets are over 100 years old and many are over 150 years old.

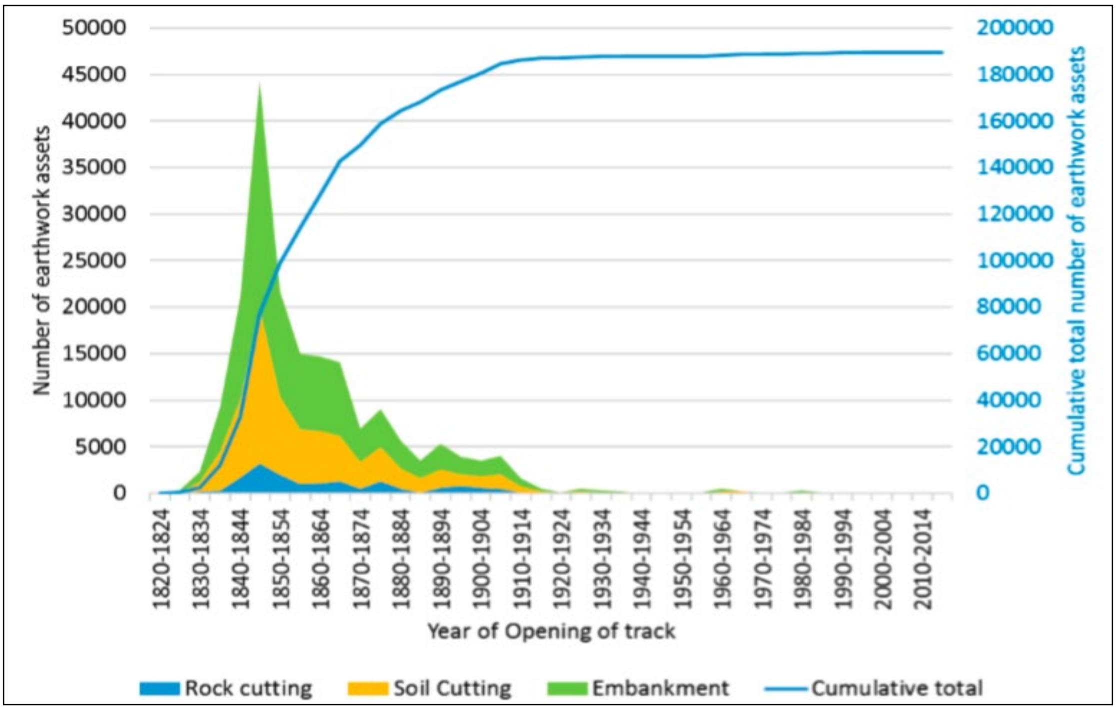


Figure 2.4: Assessed age of earthworks based on year of opening (largely derived from Cobb, 2015.) (Taken from NR Earthwork Policy NR (2018c))

17 Formal asset management of the NR earthwork assets began in the 1990s, and standardised collection of earthwork inventory and condition information has been undertaken electronically since 2005, with the data held in an online database and an associated field data-collection tool (GISmo).

18 **Earthworks assets owned by NR comprise cuttings and embankments many of which were built over 150 years ago. Cuttings were excavated at angles which were stable in the short term, but, particularly in plastic clays, would not necessarily be stable in the long term. Embankments were formed by end tipping of soil from adjacent cuttings and so can comprise granular or cohesive soil, sometimes mixed, and not subject to formal compaction. The preparation of the foundation to the embankment is not known in terms of benching, under-drainage and extent of removal of unsuitable materials. Embankment assets are associated, therefore, with major uncertainties and, as with cuttings, a high risk of instability.**[2]

2 Throughout this report Conclusions are in bold and Recommendations in bold and italics. All these are presented in Chapter 13.

NR's Drainage System

19 The railway drainage system (Figure 2.5) includes all components designed to collect surface and groundwater which runs towards, falls onto or issues from the railway asset, and deliver it to a suitable outfall, whether that be a river or stream, a public sewer or a soakaway.

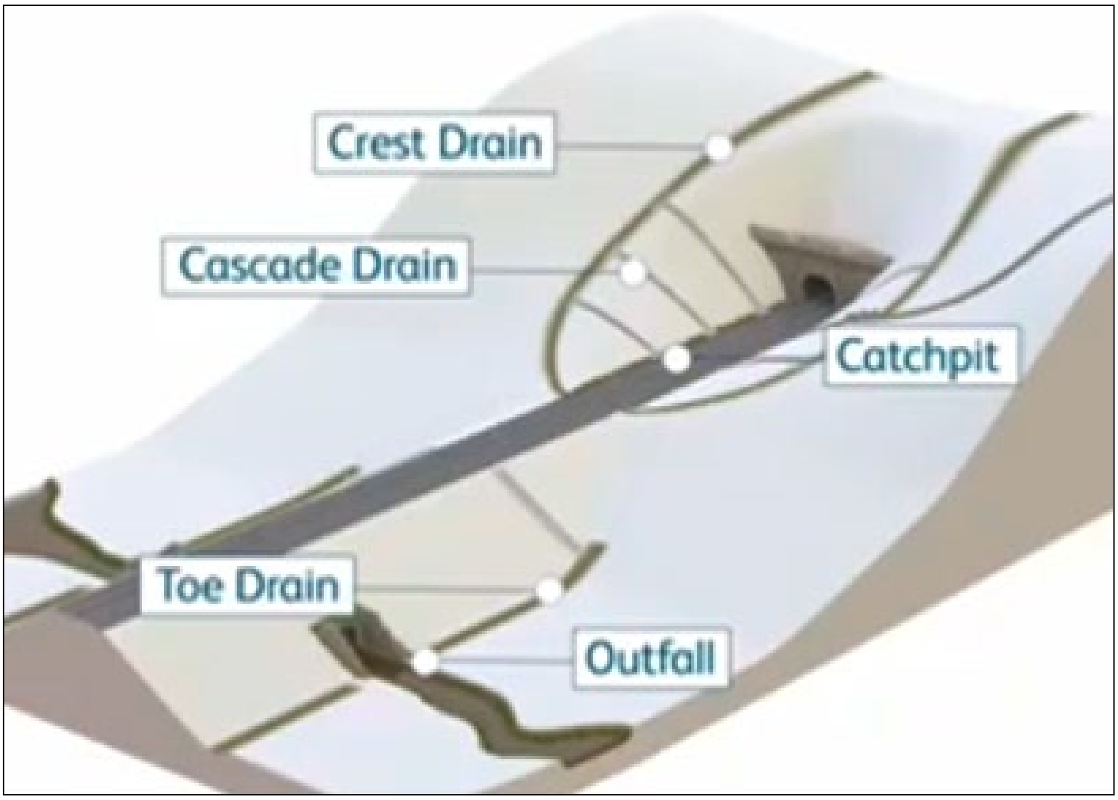


Figure 2.5: NR Drainage System that collects surface and groundwater running towards, falling onto or issuing from the railway, delivering water to a suitable outfall. (after NR Drainage Asset Policy NR (2017c))

20 The drainage assets are defined in the Railway Drainage Systems Manual: Part 1 (Network Rail, 2018) which includes the following, see Figures 2.5 to 2.7:

+ Earthworks drainage (of both surface and groundwater)
+ Track drainage (of both surface and groundwater)
+ Structures drainage in relation to tunnels, culverts etc

The NR Drainage asset groups are listed in Appendix F3. These are defined by NR in a classification that is compatible with CIRIA (2014). Assets of various types within each group have a similar form and function, and similar mechanisms of degradation.

21 The purpose of track drainage assets is to remove water from the track support system (see typical cross section in Figure 2.6). Track drainage is not required where the infiltration capacity of the support system exceeds the rate of infiltration from all sources of water. For much of the railway network, track drainage relies on infiltration of rainwater into the underlying ground and so infiltration is an important component of track drainage.

22 NR differentiate between track drainage assets and off-track drainage assets (Figure 2.6). Earthwork drainage forms the majority of off-track drainage assets (Figure 2.7).

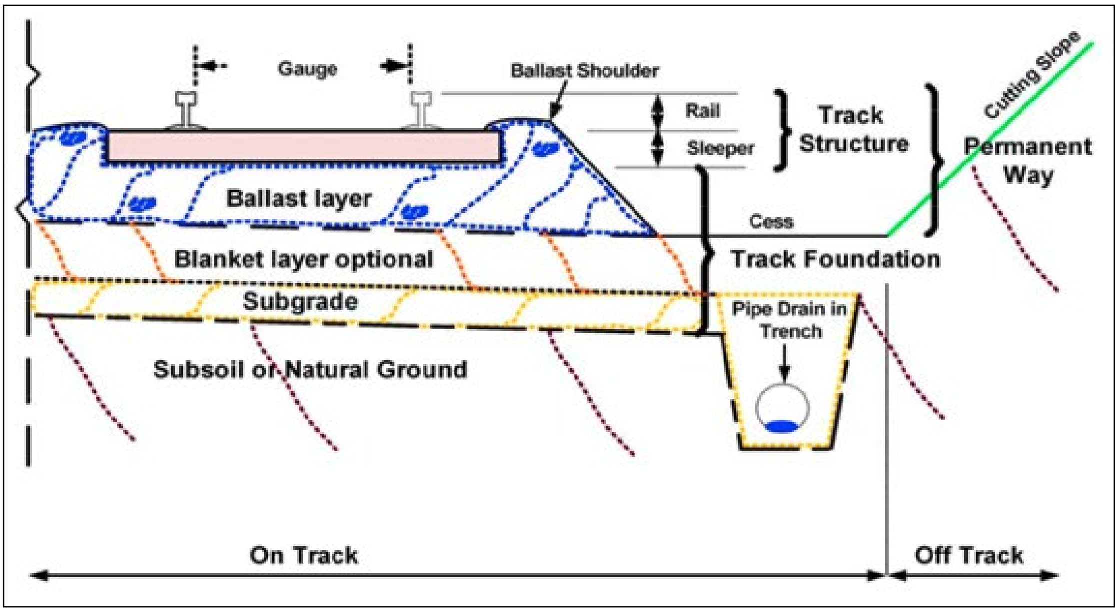


Figure 2.6: Typical track drainage cross section illustrating the boundary between track and off-track drainage. (Taken from NR Drainage Asset Policy NR (2017c))

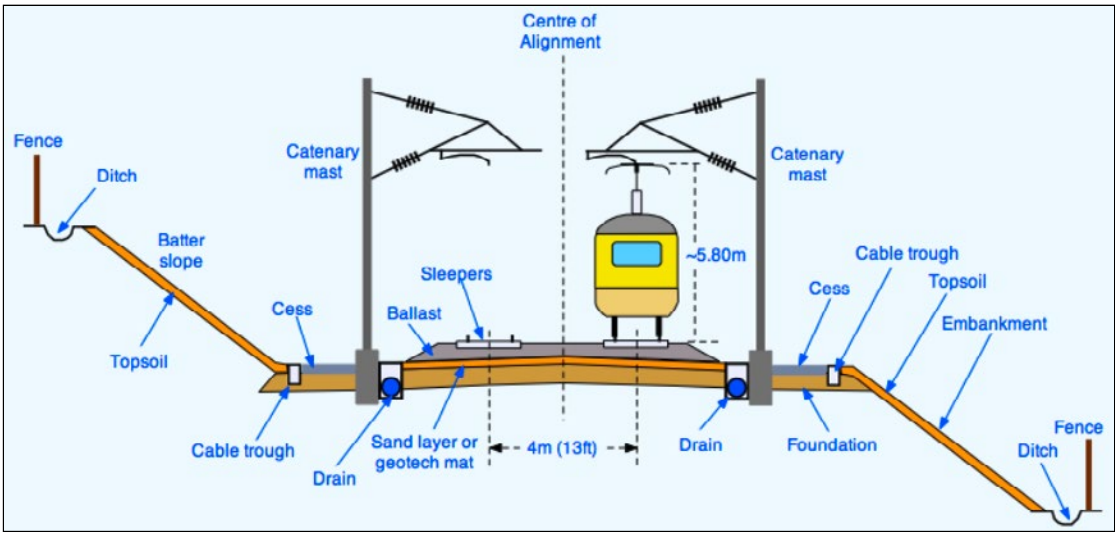


Figure 2.7: Earthwork (Off-Track) and Track Drainage cross section (after The Railway Technical website http://www.railway-technical.com/infrastructure/)

23 The main sources of water that have to be dealt with by off-track earthwork drainage include:

+ Precipitation on the earthworks
+ Groundwater within the earthworks
+ Run-off from areas adjacent to the earthworks including catchments external to the NR boundary

24 **The stability of the cut slopes and embankments is dependent to a large part on the drainage system, which is also often over 150 years old and was installed to a pre-set 'design', which did not take account of catchment areas, run-off and water flow. The drainage system was also not "designed" as a slope stabilisation measure. Replacement over the years has generally been on a like-for-like basis, so the drainage system has not been enhanced.**

Failures of NR's Earthworks Assets

Statistics on failures

25 Failures of railway cuttings and embankments continue to this day and much analysis and statistical evaluation of these failures has been carried out by NR. We have been provided with a failure database in an Excel spreadsheet that covers the period 1/04/03 to 01/12/20. Plots produced from this database for us by NR are presented in Figures 2.8 to 2.10 and comprise:

a. The distribution of the historical failures (2003-2020) along the NR network (Figure 2.8).

b. The distribution of the historical failures (2003-2020) along the NR network, distinguished in terms of soil cutting, rock cutting and embankment failures (Figure 2.9).

c. The distribution of the historical failures (2003-2020), distinguished in terms of failure categories adopted for soil slopes and embankments by NR in their failure database, namely: deep/rotational, shallow/translational, earthflow, debris flow, washout, burrowing, natural slope/boulder fall, natural slope/debris flow, rock/planar, rock/ravelling, rock/toppling, rock/wedge, (Figure 2.10).

Figure 2.8: Distribution of earthworks failures 1/04/03-1/12/20

26 Figure 2.8 shows that in the 2003/2020 period there have been 1900 reportable[3] failures at the locations shown. Of the reportable failures 944 were in soil cuttings, 543 in embankments and 346 in rock cuttings. The distribution of the soil cutting and embankment failures across the network in Figure 2.9 shows them to be more-or-less equally spread.

3 Reportable geotechnical failures are defined in Standard NR/L3/CIV/185. A failure is reportable if it has a potential to affect safety.

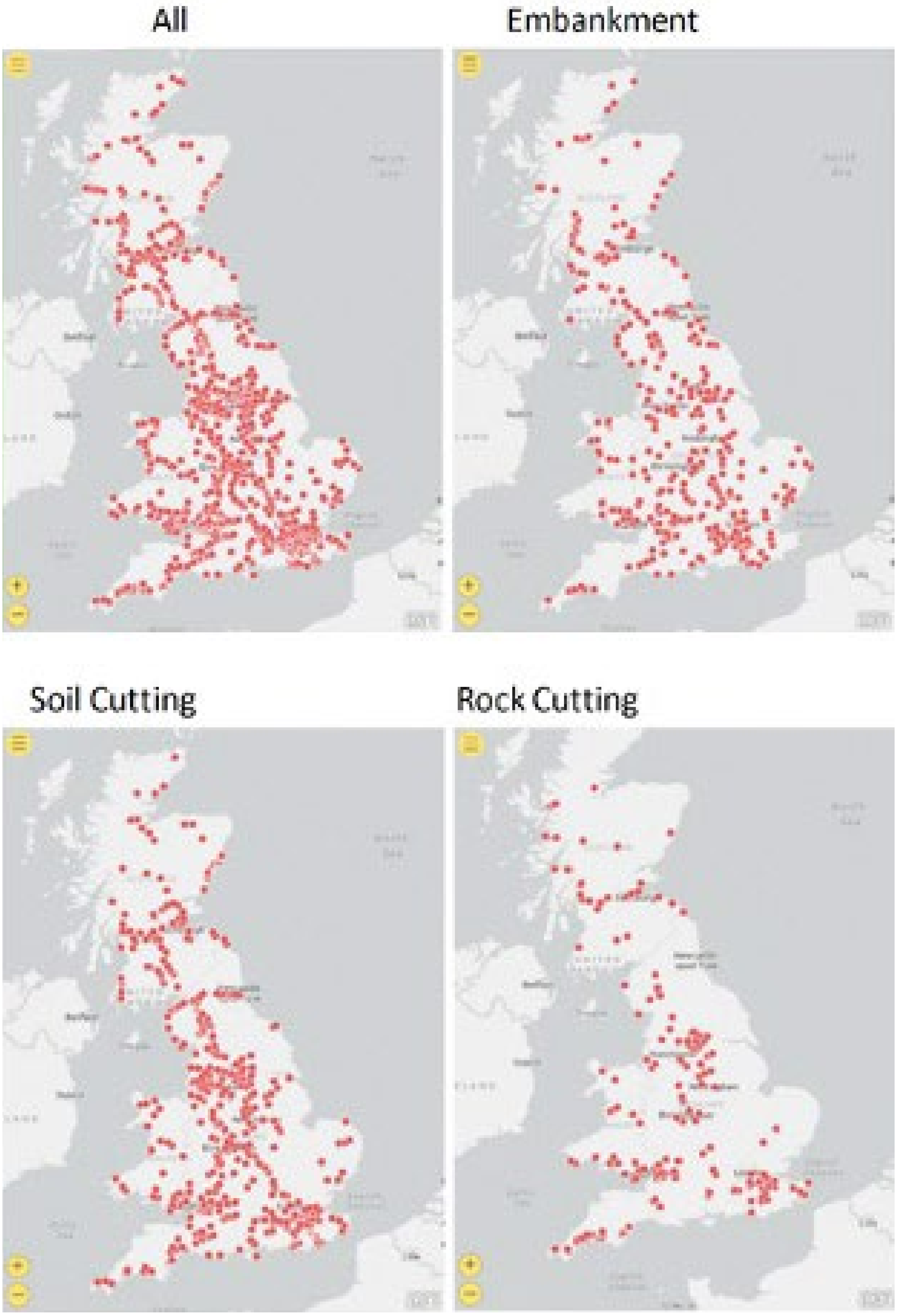


Figure 2.9: Distribution of earthworks failures in embankments, soil cuttings and rock cuttings 1/04/03-1/12/20

27 Since recording of failure type only became mandatory in 2015, the map of unspecified modes in Figure 2.10 is the most populated. It appears from Figure 2.10 that rotational failures are concentrated in the South and Midlands, whereas the shallow translational failures are spread throughout the network. Debris flows are largely confined to Scotland and the North of England; these are discussed further in Chapter 6.

28 **In the 1/04/03-1/12/20 period, 1.73% of the rock cuttings failed, 1.34% of the soil cuttings failed and 0.54% of the embankments failed; some of the same cuttings and embankments may have failed more than once. Deep rotational failures occurred largely in the heavily overconsolidated plastic clays in the South and Midlands. Shallow translational failures and washouts were spread across the network.**

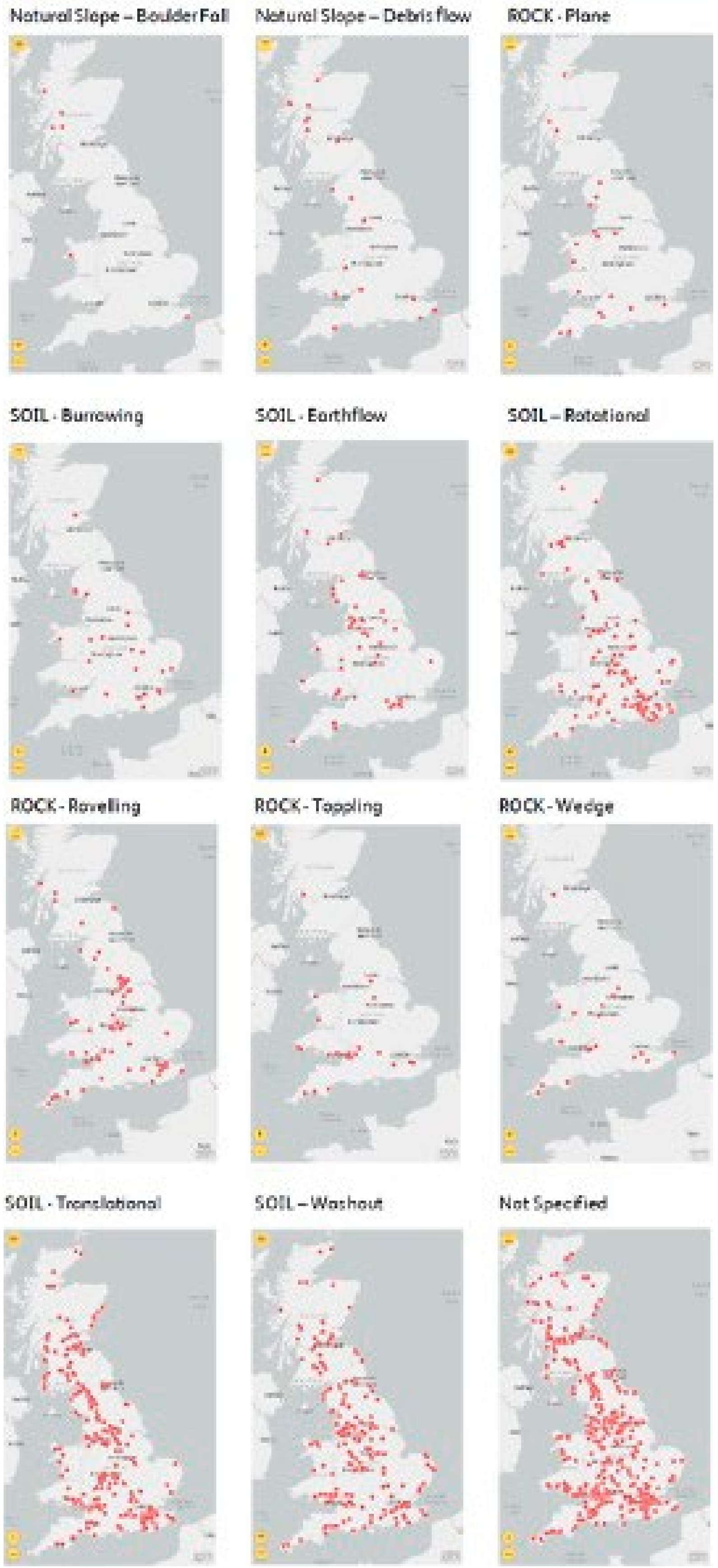


Figure 2.10: Distribution of rock and soil failure types 1/04/03-1/12/20

29 The failure data for the 2019/2020 period, from 1/4/19 to 31/3/20, has been analysed for us by NR, refer to Figures 2.11 to 2.13. Of the 252 reportable failures in that period, 190 were in cuttings and 62 in embankments. Of the 48 failures in rock cuttings, 30 were classified as ravelling, 10 as planar failures, 5 as wedge failures and 3 as toppling. Of the 130 failures in soil cuttings, 73 were shallow translational failures, 37 were washouts, 14 were rotational, 4 were earthflows and 2 were put down to the effects of animal burrowing. Five of the cuttings failures involved debris flows from natural slopes and 3 were boulder falls from natural slopes. Of the embankment failures, 21 were rotational, 12 translational, 14 washouts, 7 earthflows and 1 ascribed to animal burrowing. Four of the embankment failures were related to events on natural slopes, 2 debris flows and 2 boulder falls. The modes for seven of the failures were unclassified.

Figure 2.11: Distribution of earthworks failures 1/04/19 - 31/3/20

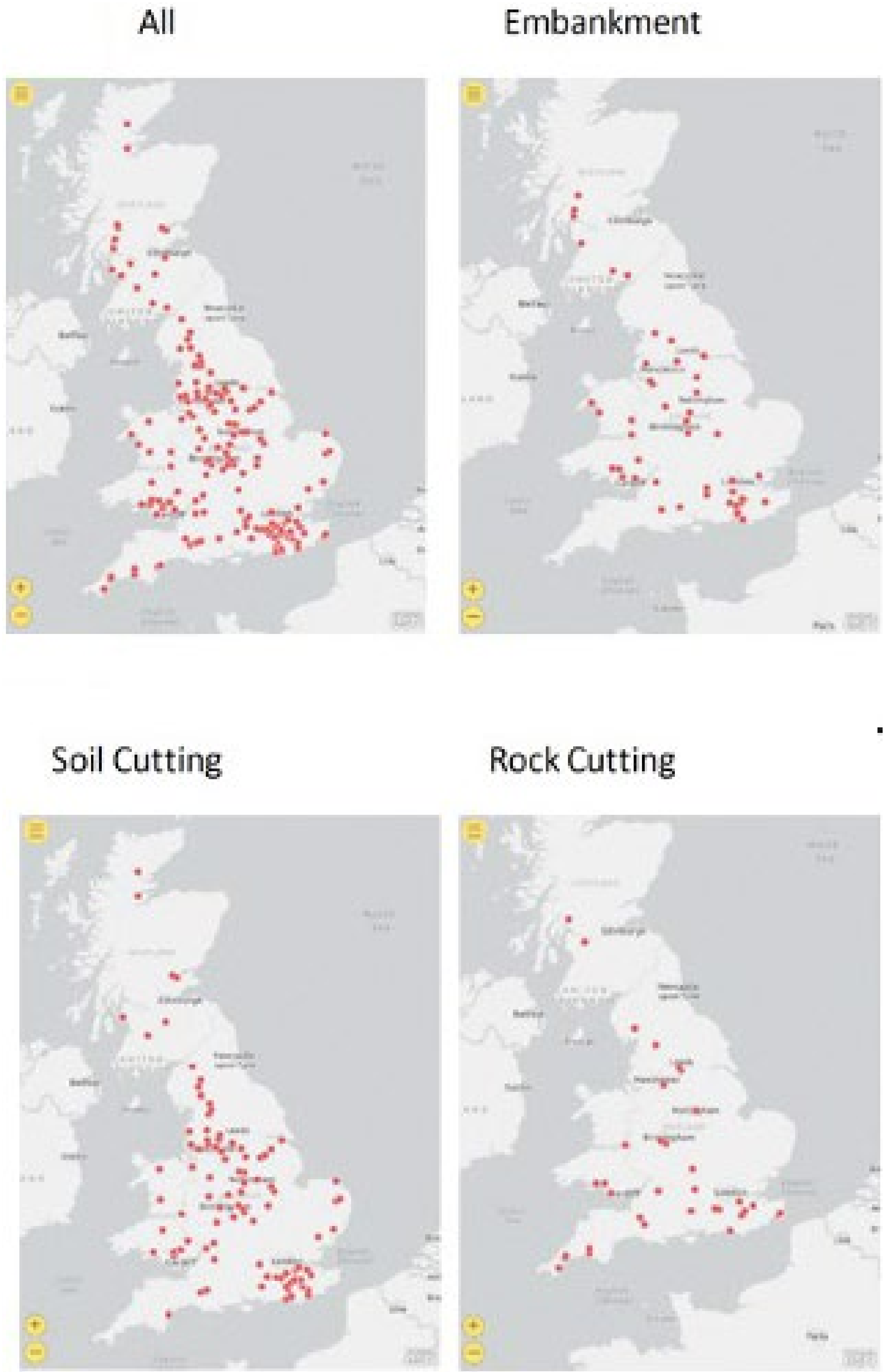


Figure 2.12: Distribution of earthworks failures in embankments, soil cuttings and rock cuttings 1/04/19 - 31/3/20

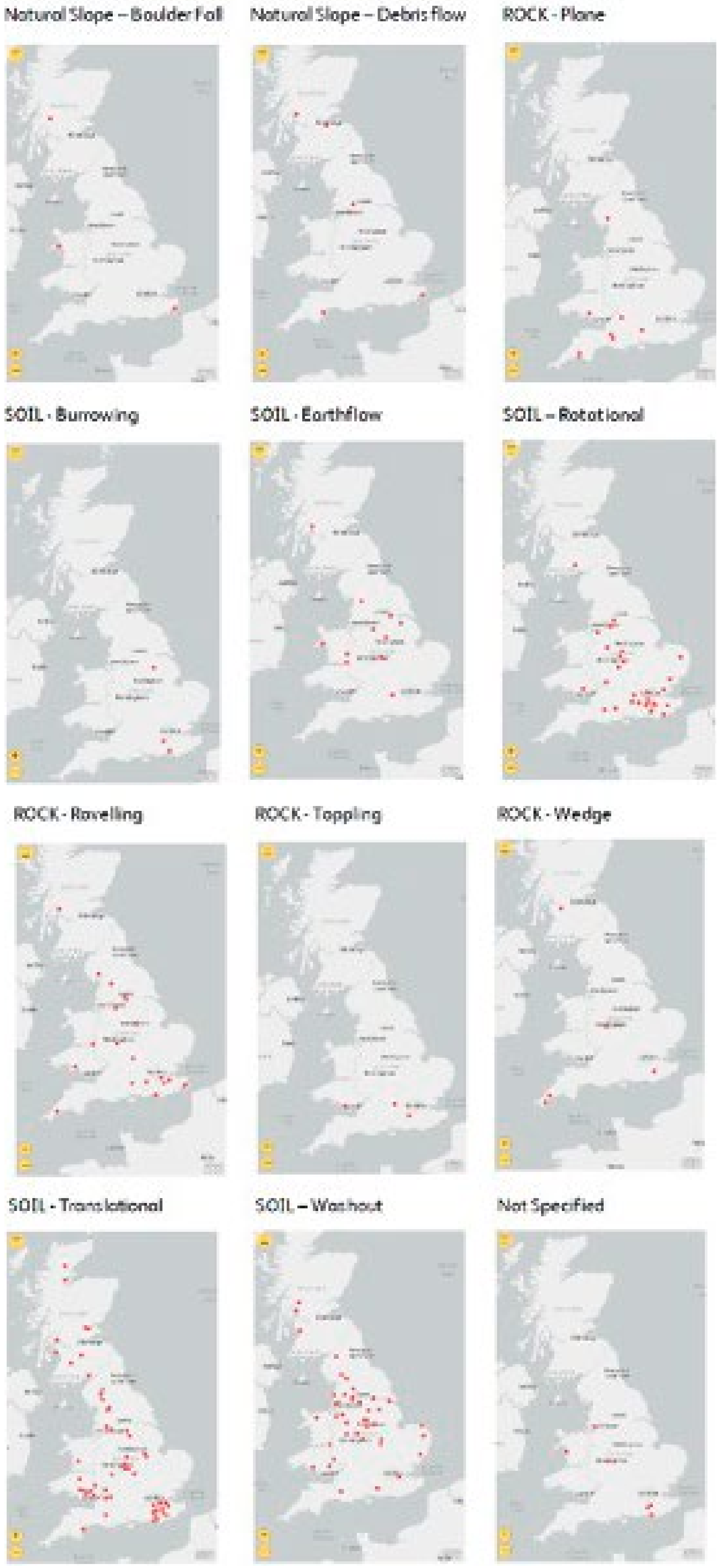


Figure 2.13: Distribution of rock and soil failure types 1/04/19 - 31/3/20

30 **In the one-year period 1/04/19 - 31/3/20, 0.24% of the rock cuttings failed, 0.27% of the soil cuttings failed and 0.06% of the embankments failed. Comparing these percentages with the average values over the 17.5-year period of 1/04/03-1/12/20, then more than three times the average number of soil cuttings failed in 2019/2020, twice as many embankments failed and about two and a half more rock cuttings failed. It is evident that in 2019/2020, shallow translational failures and washouts dominate in soil cuttings, while ravelling (and hence weathering) is the dominant factor in rock cuttings.**

Links between earthworks failures and rainfall

31 **The correlation between earthworks failures and rainfall over the 2003-2020 period is very strong and the total number of earthworks failures per month appears to be increasing.** As shown in Figure 2.14 each spike in the rainfall total is accompanied by a spike in the earthworks failures, as in January 2013, 2014, 2016 and February 2020. Figures 2.14 and 2.15 show the total number of earthworks failures increasing to be consistent with a trend for increasing winter rainfall, but the number of derailments is decreasing (Figure 2.14).

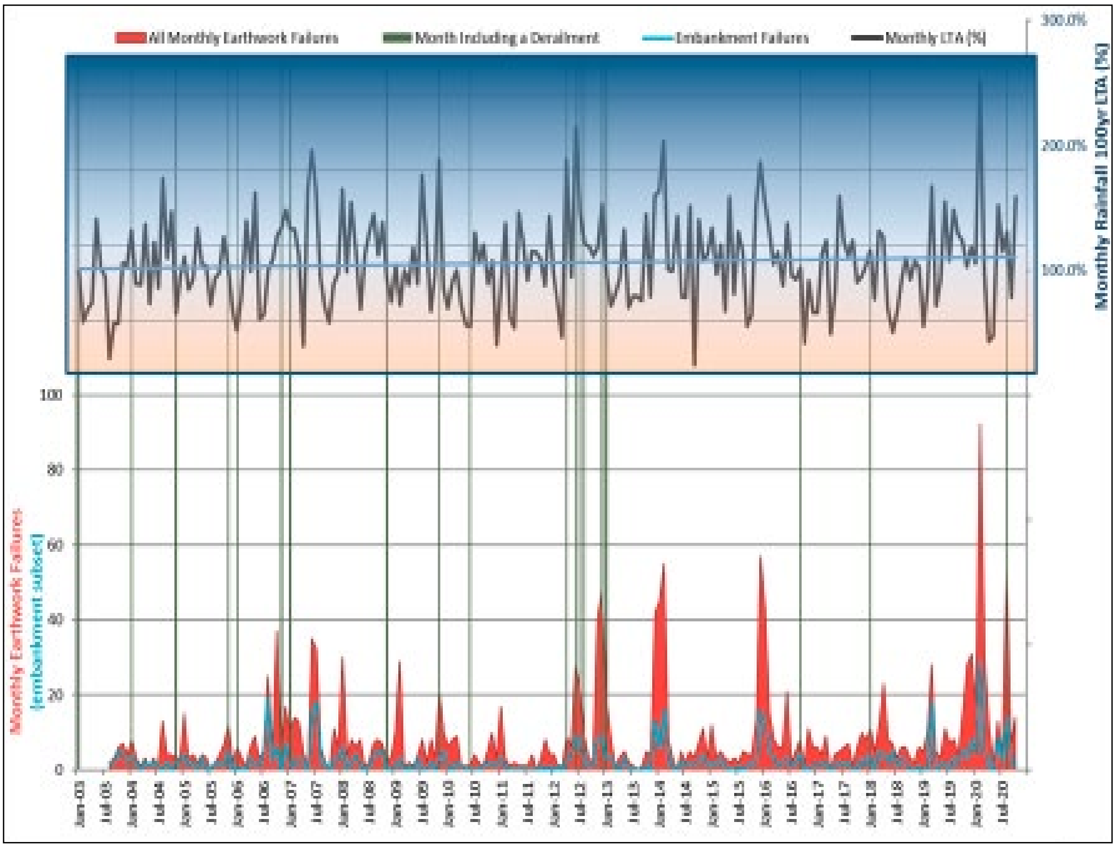


Figure 2.14: Comparison between earthworks failures and rainfall patterns (LTA=Long term average)

32 NR point out that the reporting of failures has improved over the recent past, and this needs to be taken into account in making the comparisons referred to in paragraph 30 and in Figures 2.14 and 2.15.

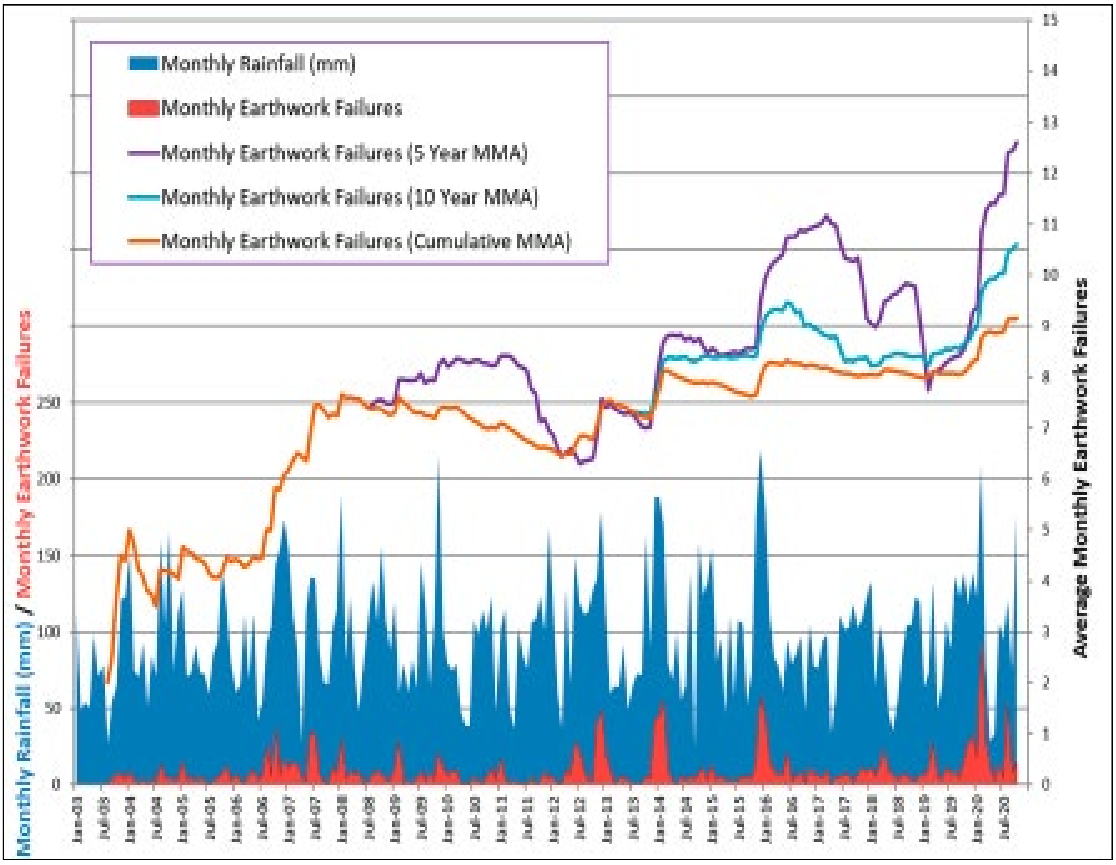


Figure 2.15: Trend for increasing monthly earthworks failures

Links between earthworks failures and geology

33 To assist in developing an understanding of the link between earthworks failures and geology, we have produced a series of maps of the UK showing the solid geology and NR's track network, on which we have superimposed the information regarding failures reported in the period 1/04/03 to 01/12/20, distinguishing between embankments (E) and cuttings (C).

A legend for these maps can be found at http://mapapps.bgs.ac.uk/geologyofbritain/home.html

Network Rail have inherited and manage 190,000 earthworks assets, comprising 70,000 soil cuttings, 20,000 rock cuttings and 100,000 embankments. The vast majority are over 100 years old and many are over 150 years old. The cut and embankment slopes continue to fail for a number of reasons. Historically, cuttings are overly steep and many have failed previously; embankments were uncompacted during their construction and their foundations were unprepared.

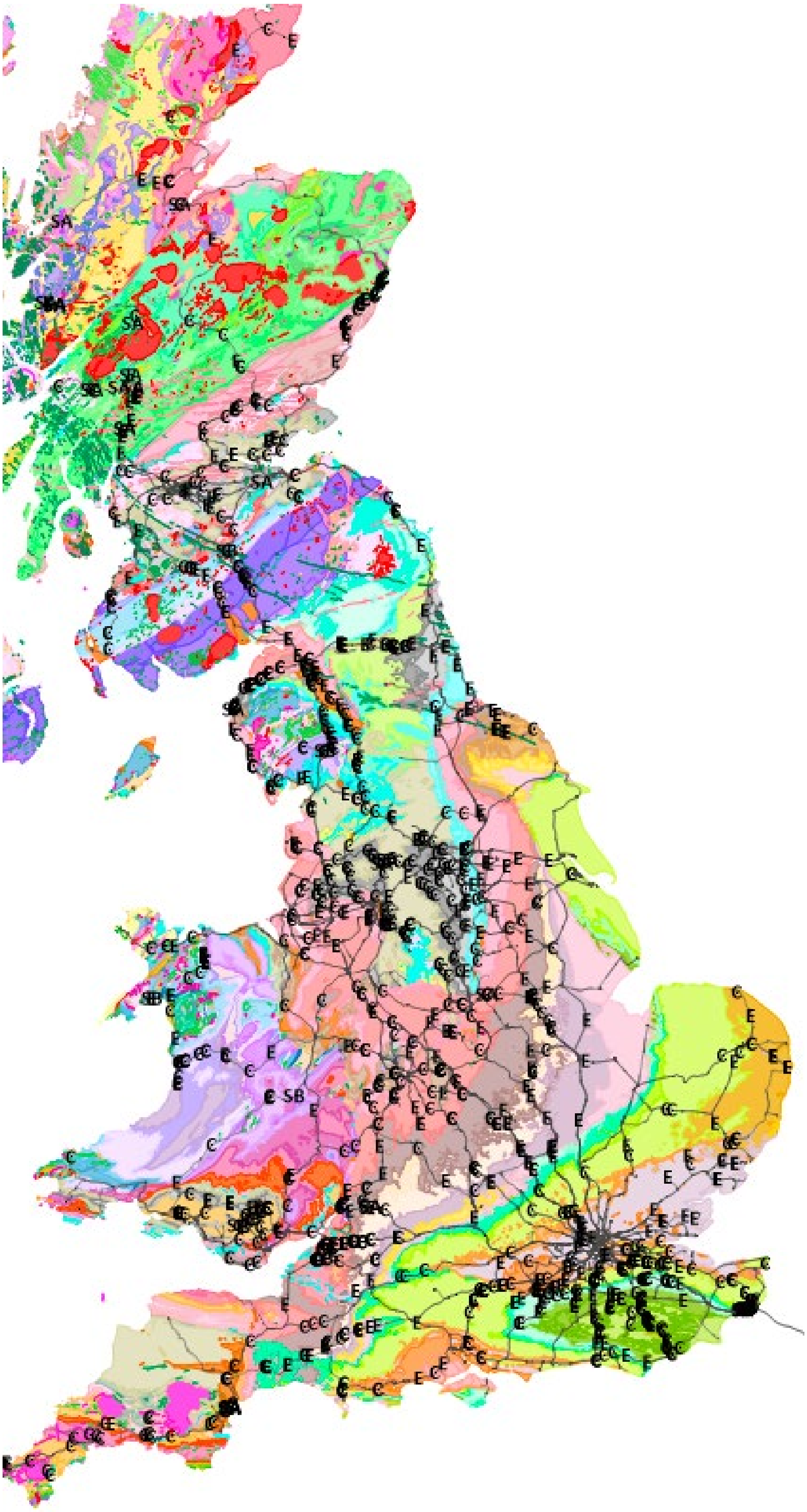


Figure 2.16: All earthworks failures in the period 1/04/03 to 01/12/20

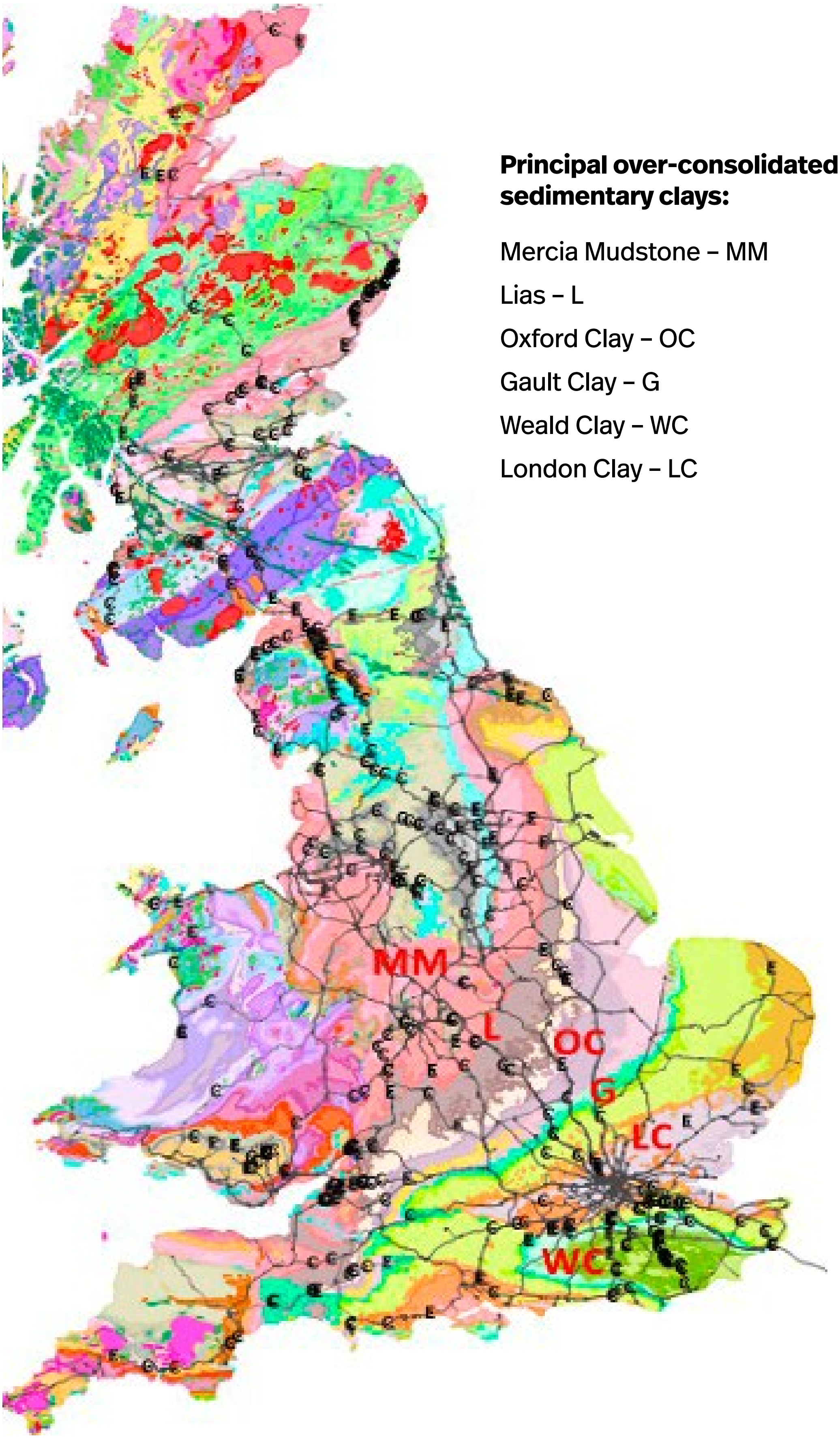
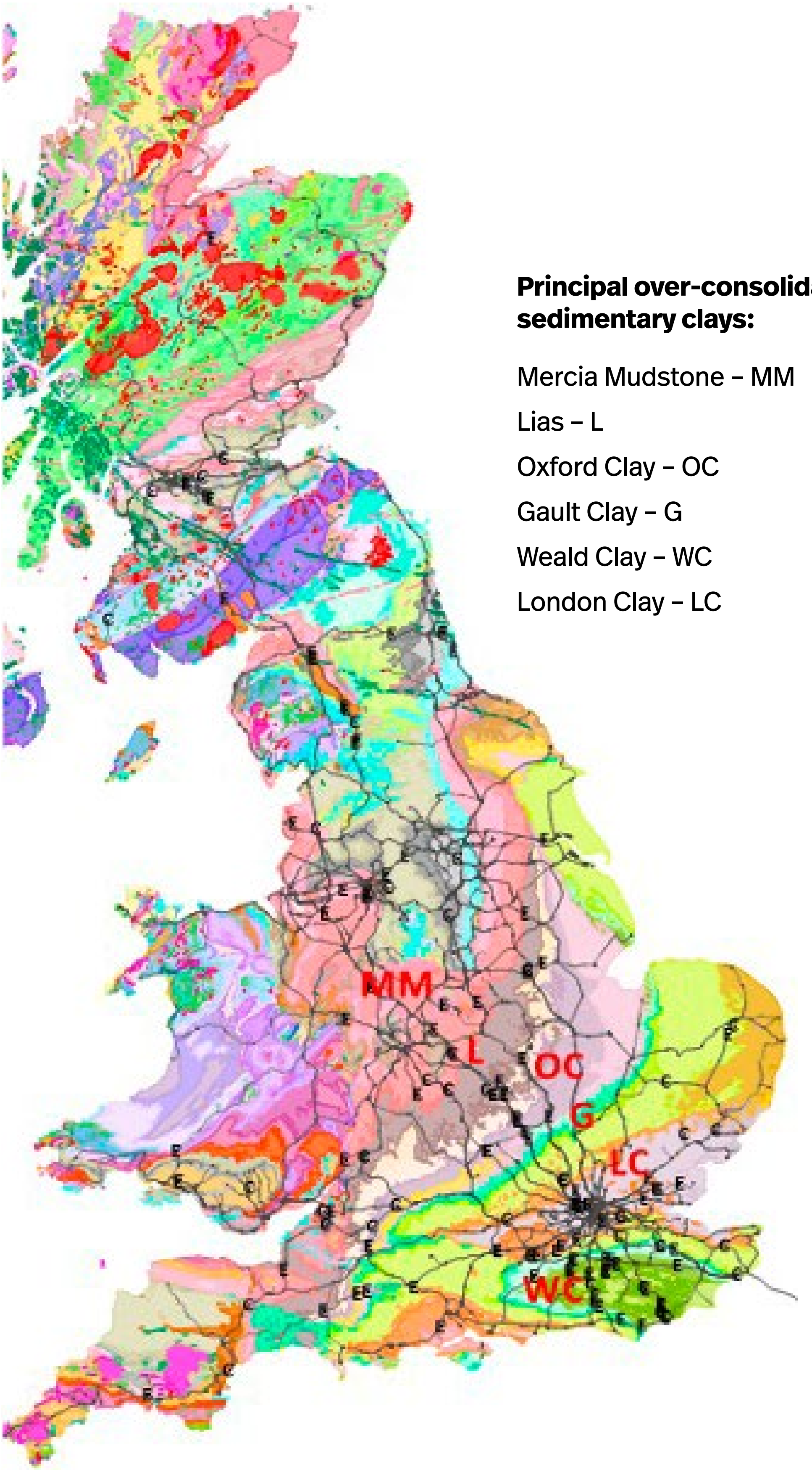


Figure 2.17: All shallow translational failures in the period 1/04/03 to 01/12/20



Principal over-consolidated sedimentary clays:

Mercia Mudstone – MM

Lias – L

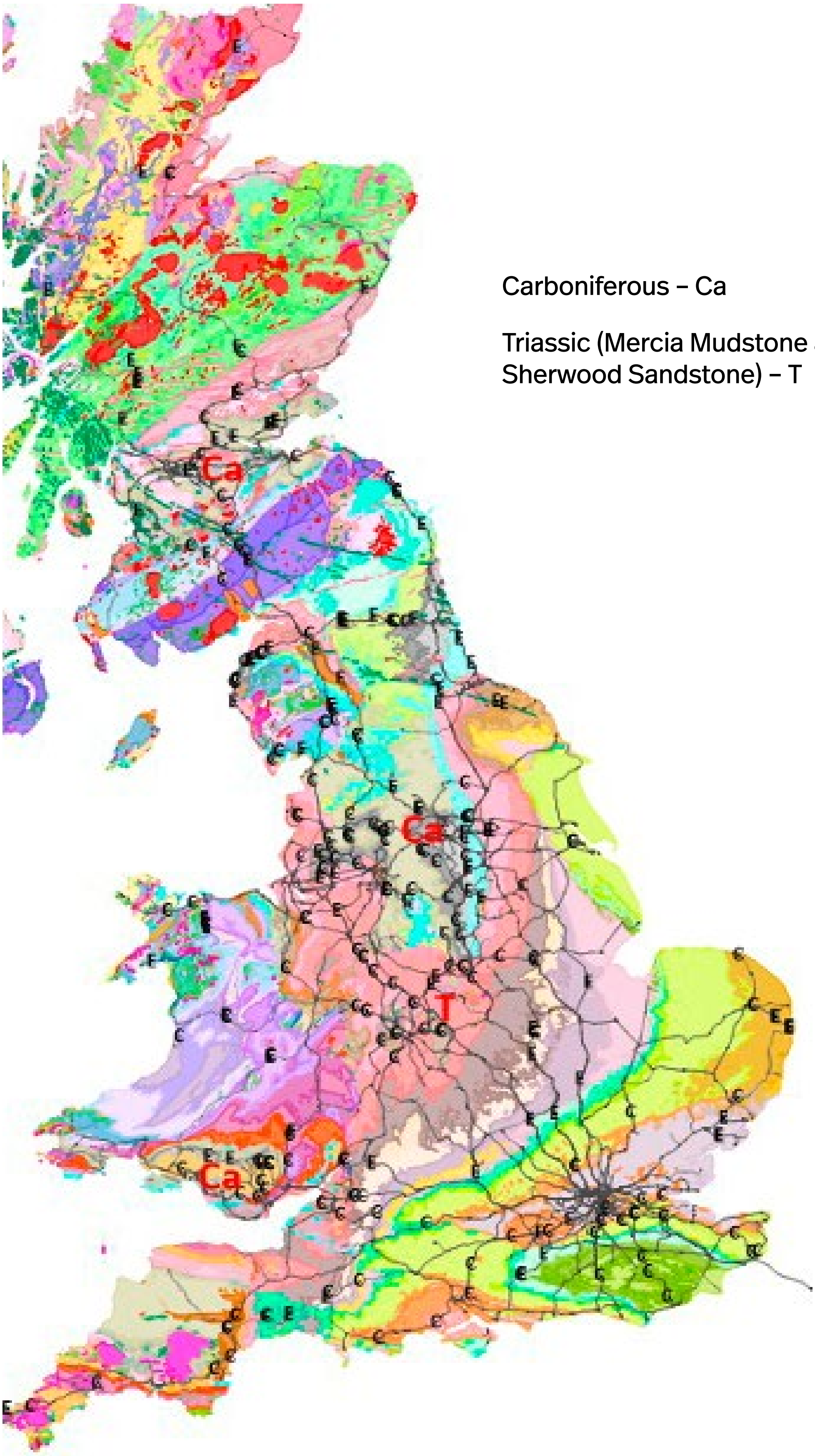
Oxford Clay – OC

Gault Clay – G

Weald Clay – WC

London Clay – LC

Figure 2.18: All deep rotational failures in the period 1/04/03 to 01/12/20



Carboniferous – Ca

Triassic (Mercia Mudstone and Sherwood Sandstone) – T

Figure 2.19: All washouts in the period 1/04/03 to 01/12/20

Figure 2.20: All earthflows in the period 1/04/03 to 01/12/20

34 The maps illustrate the following points:

a. Shallow translational failures dominate in cuttings.

b. Deep rotational failures dominate in embankments constructed with Weald, Oxford and Lias clays.

c. Deep rotational failures have been reported in cuttings in Oxford, Lias, Weald and London clays. Whether these are first-time failures or reactivations of old failures is not reported.

d. The Wealden geology is particularly vulnerable to both embankment and cutting failures.

e. Washouts are mainly associated with cuttings in the Triassic and Upper Carboniferous (Coal Measures).

f. Earthflows are reported in both cuttings and embankments, with only a small number in the clay geologies.

35 NR have helpfully produced Table 2.1 below, showing the relative occurrence of different geotechnical groupings across each Region, the occurrence of failures within each grouping across each Region, and the occurrence of failures within each grouping. The geotechnical groupings are based primarily on the GSRA work, with rock cuttings added, through the Rock Cutting Hazard Index (RCHI) examinations.

Ref	GSRA Group	% Occurrence in All Assets						% Occurrence in all Failed Assets						Relative Occurrence (% Failed Assets/ % All Assets)					
		Eastern	North West & Central	Scotland	Southern	Wales & Western	Grand Total	Eastern	North West & Central	Scotland	Southern	Wales & Western	Grand Total	Eastern	North West & Central	Scotland	Southern	Wales & Western	Grand Total
Organic Soil	GSRA_P_bin	1.6%	0.3%	1.0%	0.1%	0.2%	0.8%	0.3%	0.0%	0.1%	0.0%	0.0%	0.1%	0.2	0.0	0.1	0.0	0.0	0.1
High plasticity cohesive soil	GSRA_D4-S4_bin	11.5%	5.8%	0.4%	30.2%	9.5%	10.6%	14.6%	3.8%	0.5%	22.3%	9.4%	10.9%	1.3	0.7	1.2	0.7	1.0	1.0
High/ Medium plasticity cohesive soil	GSRA_D3-S3_bin	10.4%	6.4%	2.9%	5.3%	6.8%	6.9%	7.2%	8.4%	1.2%	1.4%	8.0%	5.4%	0.7	1.3	0.4	0.3	1.2	0.8
Medium plasticity cohesive soil	GSRA_D1-S1_bin	23.5%	39.7%	37.0%	1.5%	18.4%	25.2%	25.6%	35.9%	36.4%	1.2%	13.9%	21.0%	1.1	0.9	1.0	0.8	0.8	0.8
Low plasticity cohesive soil	GSRA_D0-S5_bin	8.6%	2.8%	4.2%	7.6%	6.6%	6.2%	8.1%	2.7%	1.9%	3.5%	3.4%	4.0%	0.9	0.9	0.5	0.5	0.5	0.6
Unknown plasticity cohesive soil	GSRA_D#-S#_bin	2.6%	0.7%	1.7%	0.3%	0.6%	1.4%	2.0%	1.6%	1.2%	0.5%	1.0%	1.2%	0.8	2.5	0.7	1.8	1.6	0.9
Granular soil	GSRA_S6_bin	13.4%	14.9%	16.0%	24.6%	9.6%	15.1%	10.0%	8.8%	10.9%	19.6%	3.7%	10.7%	0.7	0.6	0.7	0.8	0.4	0.7
Chalk	GSRA_C1_bin + RCHI-C1	4.5%	2.8%	0.0%	26.2%	2.1%	6.0%	3.5%	1.3%	0.0%	29.3%	0.8%	7.8%	0.8	0.5	NA	1.1	0.4	1.3
Soft rock	GSRA_R_bin + RCHI-SR	1.6%	1.2%	1.9%	0.5%	13.3%	3.4%	1.8%	2.5%	3.2%	4.7%	12.7%	5.3%	1.1	2.1	1.7	9.1	1.0	1.5
Mixed Rock	RCHI-MR	3.8%	0.7%	0.9%	0.6%	1.0%	1.7%	4.2%	2.7%	2.7%	6.2%	2.0%	3.8%	1.1	4.0	2.8	10.5	2.7	2.2
Hard rock	GSRA_X_bin + RCHI-HR	18.4%	24.5%	33.3%	3.2%	31.0%	22.3%	22.7%	32.0%	40.7%	11.4%	38.8%	28.3%	1.2	1.3	1.2	3.6	1.3	1.3
Unknown rock	RCHI-UR	0.1%	0.1%	0.7%	0.0%	1.0%	0.3%	0.0%	0.2%	1.2%	0.0%	5.7%	1.5%	0.0	2.6	1.8	0.0	5.7	4.6

Table 2.1: The relative occurrence of failures in different geotechnical groupings across each NR region (GSRA = Global Stability and Resilience Appraisal)

36 The information in Table 2.1 and Figures 2.16 to 2.20 merits more detailed study, but the following points are noted:

a. For the soil mechanics reasons explained in Chapter 3, we would expect stiff and hard plastic clay geologies to be more prone to previous deep-seated failures, reactivation of previous failures, and to experience shallow translational failures and earthflows. This is borne out by the geological maps and Table 2.1. 30.2% of the earthworks assets in the Southern Region fall into the GSRA category, NR (2017d) of 'high plasticity cohesive soil' and 22.3% of their failures occur in these soils. In the Eastern Region 45.4% of their assets are in the high, high/medium, medium plasticity groupings and 47.4% of their failures occur within these clays. The evident link between earthworks failures and plastic clays is consistent with deep rotational failures being concentrated in the South and Midlands, where plastic clays are present.

b. In the Eastern, North West and Central, and Scotland Regions, clays of medium plasticity are widespread, comprising 23.5%, 39.7% and 37.0% of the earthworks assets, and accounting for 25.6%, 35.9% and 34.6% of their failures. We assume these clays are matrix-dominated glacial clays and the precise form of their failures needs to be examined more closely.

c. Shallow translational failures are more uniformly spread than deep rotational failures because all soil types are subject to weathering.

A partial review of failures in soil cuttings and embankments

37 To obtain a better understanding of NR's problem of failing earthworks assets, we have reviewed some typical examples, as recorded, photographed and investigated by NR and/or RAIB. In addition to RAIB reports, we have relied on an excellent lecture given by Simon Abbott of NR in Zagreb (Abbott, 2018) and a very informative report by Mike Edwards of NR (Edwards, 2020) on nine earthworks failures that occurred in the Southern Region in the winter of 2019/2020. The results of this review are presented in a series of photographs and accompanying notes included as Appendix H. Our review does not cover all failure types; we recommend that the exercise should be extended to examine all historical failures and to relate these to the relevant weather patterns. However, from the limited review we have undertaken we note the following (referring to Appendix H):

a. Failures occur in cut slopes (H1 to H14) and in embankments (H15 to H19).

b. Failures in cuts are more likely to cause derailments because they can lead to obstructions on the track (H1 to H13). Failures in embankments tend to cause a loss of track support (H16-H19) which can sometimes be identified in track quality measurements.

c. The size of obstruction that can lead to derailment is relatively small (H3 and H10).

d. Failures in cuttings occur in summer and winter (H1 and H7). Failures of embankments predominate in winter. Localised undermining of tracks on embankments can occur in summer (H19).

e. Failures generally occur after prolonged periods of rainfall in winter and after intense rainfall in summer.

f. There is sometimes a delay between the cessation of rainfall and the failure, depending in part on the time taken for infiltration and for sub-surface flow.

g. Deep-seated failures in cut slopes are described as 'rotational' (H4 and H5). The majority of these deep-seated failures are in plastic clays; they can be triggered by loading outside the NR boundary (H5). Deep-seated failures in glacial tills are associated with the heterogeneity in the soil, especially the presence of more permeable zones (H11).

h. Shallow failures in cut slopes often occur in the softened/weathered zone and bring down vegetation cover –they are described as 'translational' (H1, H2 and H7). Shallow failures are often linked to third party run-off (H2), absence of crest drain (H8), blockage or damage to crest drain (H6, H7, H10), land drains issuing into the slope (H12). Shallow failures can develop in a range of soil types (H2, H6, H7). They often only involve ground local to the toe of the slope (H9). Layering of permeable and impermeable soft rocks can be associated with failures in unexceptional weather (H10).

i. Cut slopes comprising rock with a shallow soil cover over part of the slope length can be vulnerable to translational failure of the superficial soil during or after prolonged rainfall (H3 and H8).

j. Embankment failures can occur in both predominantly cohesive fill and in predominantly granular fill. Failures in cohesive fill embankments appear to be more deep-seated and can involve the development of residual shear surfaces (H15, H17 and H18). Failures in granular fill involve movement by spreading and by internal and external erosion. Deep-seated embankment failures tend to follow prolonged winter rainfall.

k. Embankment failures are more likely to be associated with their original construction being on sidelong ground.

l. Embankment failures can develop in stages (H16), be triggered by the weight of passing trains and by rainfall (H18), and, in the case of clay fills, be caused by softening of the clay when the embankment is surrounded by flood water.

m. The composition and plasticity of the fill does not appear to be recorded routinely.

n. Shallow failures in embankment slopes also occur in the softened/ weathered zone and bring down vegetation cover; they are also described as 'translational'.

o. Burrowing by rabbits and badgers (H20) can contribute to embankment failures by weakening and allowing water entry (H17).

p. Washouts, which are defined herein as uncontrolled surface water flow eroding and scouring the ground over which it flows (H28), tend to be an immediate response to intense rainfall. There are no precursors to washout failures and little time to react because of their rapid rate of movement.

q. Washouts can develop into debris flows. Debris flows can be triggered by rainfall and melting snow on natural ground uphill of the asset (H25), or by intense summer rainfall (H26 and H27).

r. Earthflows, which are defined herein as the downslope movement of a mass of softened soil, often comprising the weathered zone with its vegetation, move more slowly than washouts and debris flows. Shallow translational failures can develop into an earthflow (H12). Mudflows are earthflows in which the soil has reached an extremely low undrained strength as a result of remoulding or entrapment of water during downslope movement (H1, Rosyth).

s. Tunnel portals appear to be particularly vulnerable to erosion/washout failures because of the inevitable ground shape and topographic water concentration features. Examples are provided in: H21, Clarborough Tunnel, where there was an ineffective crest drain on the neighbouring land; H22, Watford Tunnel North Portal, where crest drains at the top of the chalk cutting were blocked or missing; H23, St Catherine's Tunnel and Wallers Ash.

t. Special drainage measures and slope shaping and protection should be provided at tunnel portals. An example of the measures taken by the Japanese Railways at portals is shown in H24.

u. Shallow failures in cut slopes can occur sometime after widespread vegetation removal in soil cuttings (H13) and in rock cuttings (H14).

v. The necessity for vegetation clearance, bearing in mind its cost and potential negative impact on slope stability, needs careful consideration on an asset specific basis.

w. Crest drains are critical to collecting third party water entering NR property but are sometimes absent, blocked, inadequate, or damaged by burrowing animals. Future attention to crest drains, their installation, protection and maintenance is critical.

x. Failures can occur when the existing piped drainage is overwhelmed or blocked or when water is fed into the slope area from unidentified drains (H12 and H22). Drainage capacity needs to be upgraded and mapping and maintenance of drainage assets are essential.

y. Failures can be triggered by construction work adjacent to (Bradwell Abbey – over-excavation at slope toe, H29) or over the track (Gerrards Cross) or beneath the track (pipe jacking), and during planned stabilising works. Careful sequencing and supervision of all construction works over, under or adjacent to the tracks is essential.

z. Failures can be related to mining subsidence.

aa. Failures can occur at different times at the same or adjacent locations, e.g. tunnel portals (H22 and H23) or adjacent to previous failures (H7, H8 and H15). Failures adjacent to an earlier and/or repaired slip can be related to the disturbance of the ground adjacent to the previous failure.

bb. Categorisation of failure mechanisms is not straightforward and not always reliable.

cc. Earthworks failures are probably increasing in frequency, with more failures being in the form of washouts, earthflows and debris flows, but further work is required to confirm this.

dd. Most obstructions are observed first by the train driver.

Mike Edwards's report on nine earthworks failures that occurred in the Southern Region in the winter of 2019/2020.

38 In his report, Edwards (2020) notes that the 2019/20 winter was the fifth wettest on record with the wettest February on record (5th wettest month ever). In the South/South East of England the rainfall as a percentage of long-term average (LTA) since 1862 was, over part of this period, 131% in September, 144% in October, 129% in November and 154% in December. Importantly he also notes that 'there were specific circumstances which further concentrated water at the locations that failed:

a. *At Templecombe* (H13)*, the surface topography is such that a large area of farmland drains towards the railway cutting into a complex drainage system. This conveys water eastwards along the railway corridor towards the River Cale at Templecombe itself.*

b. *At St Catherine's Tunnel* (H23)*, rainfall radar recorded 191% of local 1981-2010 December average rainfall. This likely entered the slope face directly through voids opened by long-term weathering/root-jacking, animal burrowing, and more recent removal of overhanging, undermined trees.*

c. *At Cuxton* (H2)*, a car wash on an otherwise residential road along the crest of the cutting prevented infiltration of rainwater and allowed it to run off the hardstanding to overtop the cutting crest. The car wash itself constituted a source of water, and leaking pipes were observed on site.*

d. *At Edenbridge, the River Eden reached a peak level some two metres above its eight-year average the day before failure. Debris observed on site supports a hypothesis that the toe of the embankment was submerged, as does toe softening of the adjacent segment. A complex drainage system is present, with some unusual features, and prior to flooding this may not have been functioning as intended.*

e. *At Robertsbridge* (H6), *degradation of the unlined crest drain coupled with near-crest burrowing into it created a flow path for water.*

f. *At Epsom* (H17), *Wivelsfield, Cookspond* (H15) *and Ockley* (H15) *the embankments were already in an advanced state of deterioration. Rainfall alone is likely to have activated rotational failure in the over-consolidated clays at these locations after decades of progressive, irrecoverable plastic strain.'*

39 Observations of earthworks failures that occurred in the Southern Region in the winter of 2019/2020 highlight the importance of localisation of failures, the difficulty of predicting where failure might occur, and a reason why failures continue to occur. The statistics on earthworks failures in the 2019/2020 period also strongly support the link between these failures and rainfall.

Chapter 3

Soil Mechanics of Earthworks

Introduction

40 NR has 190,000 earthworks assets, comprising 70,000 soil cuttings, 20,000 rock cuttings and 100,000 embankments. NR's assets cover the whole of the UK and involve a vast range of different solid and drift geologies. Figure 3.1, taken from Mott Macdonald's (Mott's) study for NR, entitled Global Stability and Resilience Appraisal and dated August 2017, NR (2017d), lists the geologies encountered along the different routes and provides information on the liquid limit and clay-size fraction[3] of the different soils associated with each geology. This highlights the large range of soil types involved.

3 We are unable to find data on plasticity index of the soils in Mott's report. There are useful correlations between plasticity index and soil behaviour to which we refer in this Section.

41 The majority of the cutting and embankment assets are more than 150 years old yet continue to fail in the form of deep-seated and shallow slips and are prone to erosion (washout). The observations regarding the ongoing failure of the earthworks assets, described in Chapter 2, raise the following questions:

+ Why are both the cuttings and embankments in a range of geologies continuing to fail
+ Why have slopes that have been assessed as 'over-steep' by Motts in their GSRA Report, NR (2017d), based on modern design codes, not failed
+ What are the mechanisms and triggers for the different forms of failure that have been observed
+ Is the frequency of the different forms of failure changing and, if so, why
+ Will failures continue to occur
+ Which assets are the most vulnerable to future failures

The answers to these questions influence the way in which the earthworks assets should be managed.

42 The number of assets that NR have to manage is huge, as is the number of asset examinations, reports, investigations, standards, and procedures needed to deal with their basic problem – namely that they have inherited plastic clay cuttings that were excavated at angles that were too steep to ensure long term stability, and embankments that were formed with fills that were not compacted. Of necessity NR have to deal with a huge number of statistics related to the state (condition) of these assets and their past, current and future stability. Algorithms have been developed to handle the data, to draw conclusions from the data and to assist in making decisions on mitigation. Often the soil mechanics principles are buried within these algorithms.

43 In the time available for our Review it would not have been possible to do justice to the excellent work done by the Technical Authority[4] and Regional Geotechnical Engineers in managing the huge portfolio of assets, by delving into the algorithms and their background. Instead, in an attempt to see the wood for the trees, we have stood back and considered in this Chapter a number of established soil mechanics principles that may assist in addressing the questions in para. 41.

4 The Technical Authority team includes the Professional Head of Geotechnics with responsibility for Earthworks.

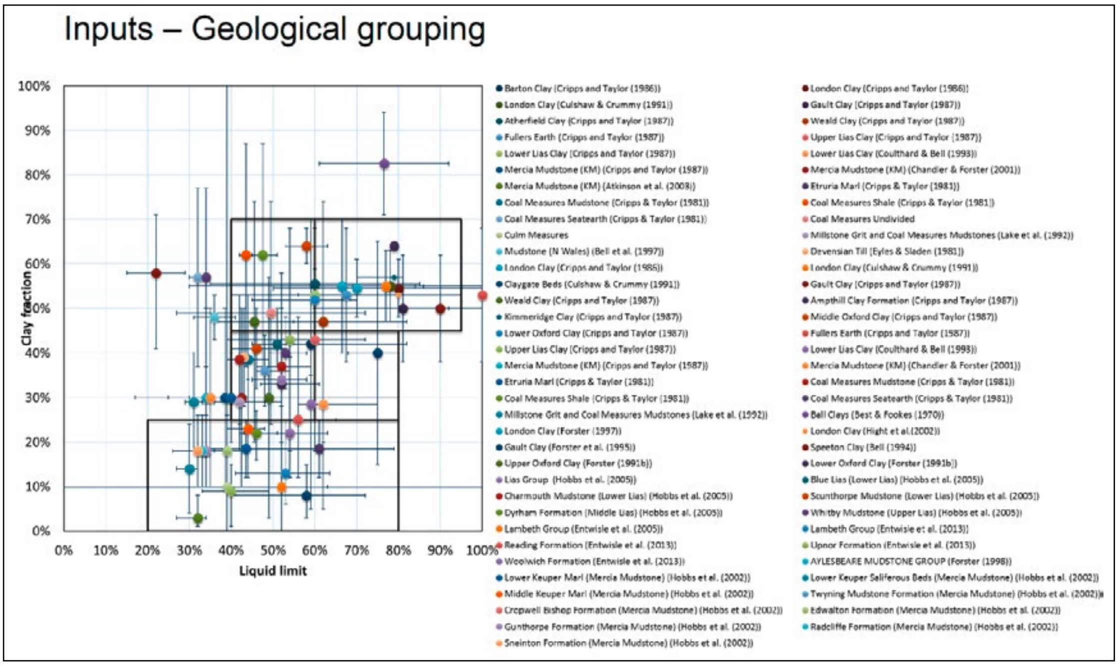


Figure 3.1: Geological groupings adopted by Mott MacDonald (after NR, 2017d)

Soil composition, plasticity and key features of behaviour

44 In the simplest terms, and for the purpose of this Section of our review, the soils encountered can be considered in three categories: clays of low plasticity; clays of high plasticity; and non-plastic soils such as sand, silt and gravel. Clays of low plasticity have relatively low contents of clay-size material and relatively high contents of sand (they are often referred to as sandy clays). Clays of high plasticity have high contents of clay-size material. The permeability of both clay types is low. Clay-size fractions in most UK clays have relatively low activity and a useful dividing line between the two types of clay for our purposes is a plasticity index of approximately 25%. Non-plastic soils are of higher permeability and can be erodible and so prone to instabilities caused by both surface and internal erosion.

45 Composition and plasticity of the soil determine peak and residual angles of shearing resistance, and the difference between them, i.e. the potential brittleness of the soil. Low plasticity clays have similar peak and residual angles of shearing resistance and are ductile (non-brittle), refer to Figure 3.2 (a). As soil plasticity increases, peak angles of shearing resistance reduce and above a plasticity index of about 25% in UK clays, residual angles fall well below the peak angles (Figure 3.2 (a)). The stress-strain-displacement behaviour of a brittle soil is illustrated in Figure 3.2 (b), distinguishing the peak, post-rupture and residual strengths; the ductile behaviour of a low plasticity clay is shown for comparison. The low residual strength, reached at large displacements in the plastic clay, is the result of orientation of the clay along sliding surfaces.

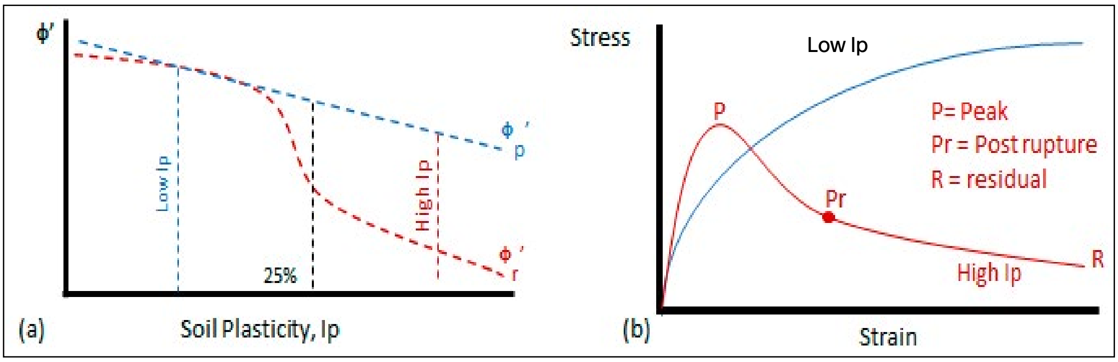


Figure 3.2: Dependence of angle of shearing resistance and soil brittleness on soil plasticity

46 Composition and soil plasticity also determine the compressibility and expansibility (shrink-swell potential) of the clays. Clays of low plasticity have low compressibility and expansibility, so do not undergo significant shrinkage and swelling during drying and wetting; they are not significantly affected by seasonal changes in pore water pressure that take place close to the slope surface of cuts and embankments. Clays of high plasticity are more compressible and expansible and undergo important changes in volume during shrink-swell, including the formation of desiccation cracks. Of particular significance in stiff high plasticity clays is the fact that swelling, and so increases in water content, accelerate when effective stresses fall below a threshold value (Figure 3.3). This characteristic means that swelling and increases in water content are highest close to the slope surface and this contributes to the development of a softened/weakened zone of clay within 2 to 3m of the slope surface.

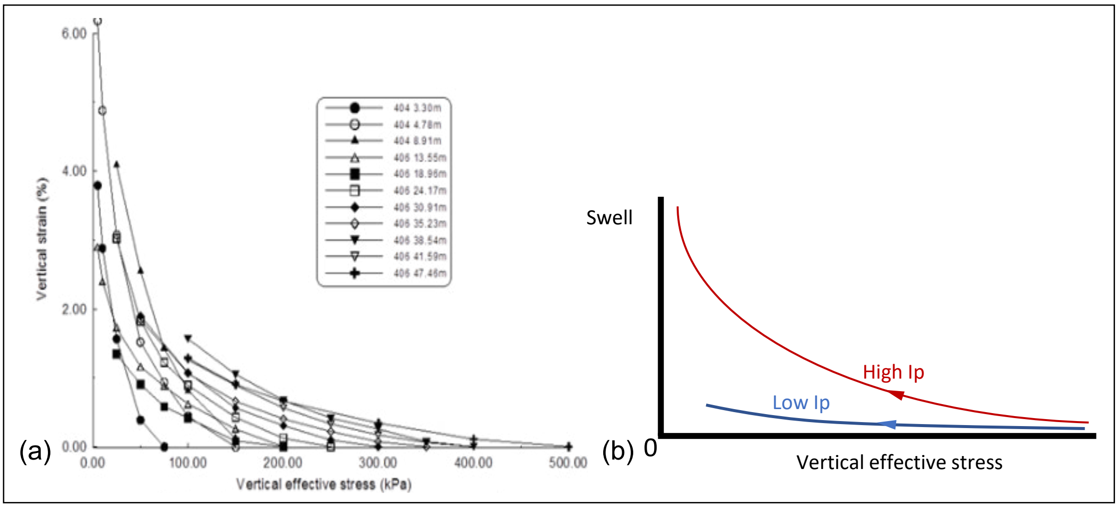


Figure 3.3: Dependence of swelling potential on soil plasticity (a) Oedometer swelling of rotary cored London Clay samples from Heathrow Terminal 5 (b) Swelling of high vs low plasticity (Ip) clays

47 For simplicity we will regard the sedimented clays in the Midlands and Southern England to be high plasticity clays. These are stiff to hard, heavily overconsolidated, and include macro-fabric features, such as joints and fissures, that can have an important impact on mass drained and undrained strengths and permeability. These clays include London Clay, Gault Clay, Weald Clay, Upper and Lower Lias Clays, Oxford Clay, Mercia Mudstone, and the various subdivisions of each (refer to Figure 3.1 for a fuller list).

48 We will regard most of the Devensian glacial tills, the distribution of which is shown in Figure 3.4, to be low plasticity clays and to be dense in the case of lodgement tills. The behaviour of the tills is determined by composition and whether they are matrix or clast dominated.[5] Being of glacial origin they can be heterogeneous, containing water-bearing seams and lenses of more permeable sands and gravels which affected the development of suctions during excavation, shortened drainage paths, and resulted in a relatively quick equilibration of pore water pressures with time following excavation. Any ongoing deep-seated failures in glacial till cut slopes are not the result of delayed failure due to pore water pressure equilibration following excavation.

49 In summary, the term plastic clay is used herein to mean a clay having a plasticity index greater than 25%, which is brittle in shear, develops low strength polished surfaces after large displacements, and is expansible, particularly when swelling to low effective stresses. These features make these clays particularly troublesome in cuts and embankments, not least because they can fail abruptly.

50 The term low plasticity or sandy clay is used herein to mean a clay with a plasticity index less than 25%, which does not develop low strength shear surfaces and has low compressibility and expansibility. These clays are more benign and failures are usually not abrupt.

5 Clast dominated tills are those in which the sand, gravel and boulder content interact and determine response to loading.

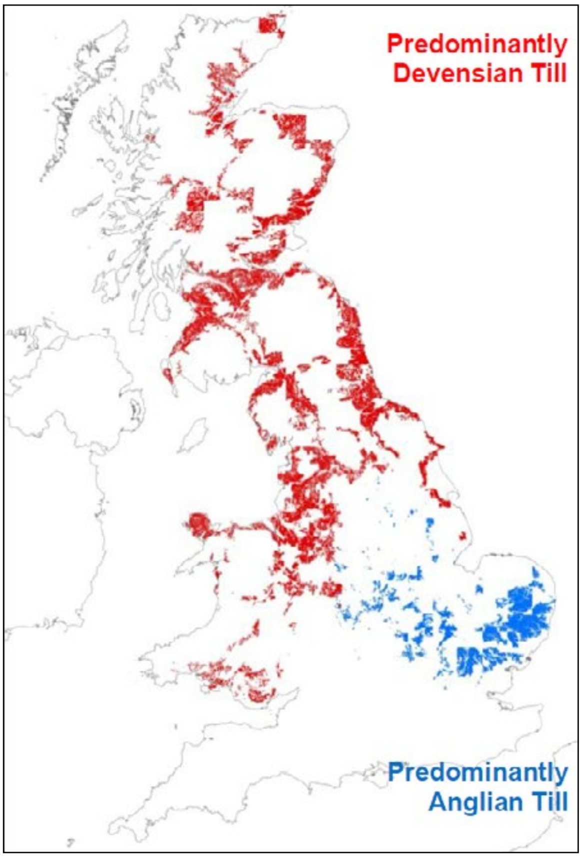


Figure 3.4: Glacial till distributions from CIRIA Report C504 (CIRIA, 2009).

Water content and soil moisture deficit

51 In soil mechanics, water content or soil moisture content is the mass of water that can be removed from the soil by oven drying at 105°C to constant mass, expressed as a percentage of the dry mass of the soil. In clay soils water content is expressed relative to plastic and liquid limits of the clay; this is liquidity index and provides information on undrained remoulded strength. At a particular packing of soil particles, water content determines the percentage of void volume that is occupied by water – this is referred to as degree of saturation.

52 For soil at a particular density, degree of saturation, and so water content, determine the suction in the soil. This link can be expressed in a soil water characteristic curve (SWCC) or soil retention curve (SRC). Suction is a measure of the stress required to move moisture in a soil that lies above the natural water table, measured as negative pore water pressure. Suctions are critical to the stability of unsaturated soils.

53 Soil moisture deficit (SMD) is a measure of the amount of water required for a soil to reach saturation (or field capacity). Its calculation requires information on rainfall, evaporation, wind speed, soil type and type of vegetation, and run-off; SMD reflects antecedent rainfall. At the location where SMD=0 the soil is saturated and has no suction. Soil moisture index (SMI) appears to be a similar measure of closeness to saturation but is either measured indirectly, involving radar penetration to only 0.5m depth, or is predicted using models. Both SMD and SMI appear to be poor indicators of what is happening at depth but may be of value for warning when shallow failures could occur.

54 The WATF Final Report, Slingo et al (2021), Section 8 'Earthwork management and assessing risks of failure due to weather events', discusses SMI and SMD, as well as Soil Water Index (SWI) derived from satellite measurements. It concludes that there is no index for soil moisture that does not have serious uncertainties and the use of a single index (e.g. SMI) within a risk assessment is fraught with difficulties.

55 In a presentation to NR, the WATF Team drew attention to the potential use of the G2G hydrological model that runs on a 1x1km grid at a 15-min time step and provides information on hydrological sensitivity to further rainfall. In the model the hydrology of soil types is based on permeability and run-off characteristics. Its use in the prediction of earthworks failures should be investigated.

Delayed failure of clay cuttings and embankments

Changes in stability of cuttings with time after excavation

56 In general terms, soil cuttings in both high and low plasticity clays reduce in stability with time after excavation, as negative excess pore water pressures generated by unloading dissipate towards their new equilibrium values. This was elucidated in the classic paper by Bishop and Bjerrum (1960), from which Figure 3.5 has been re-drafted. The figure shows an initial situation of horizontal ground, with groundwater level at a shallow depth. A cut slope is excavated rapidly under undrained conditions and pore water pressures reduce. Two cases are shown, one for a normally consolidated clay, labelled as A=1, and one for an overconsolidated clay, labelled as A=0. The reduction in pore water pressure is greater in the overconsolidated soil because of the negative excess pore water pressures generated by shear, which are additional to the negative pore water pressure generated by the reduction

in mean stress. In the normally consolidated soil, the shear induced excess pore water pressures are positive, reducing the overall negative excess pore water pressure.

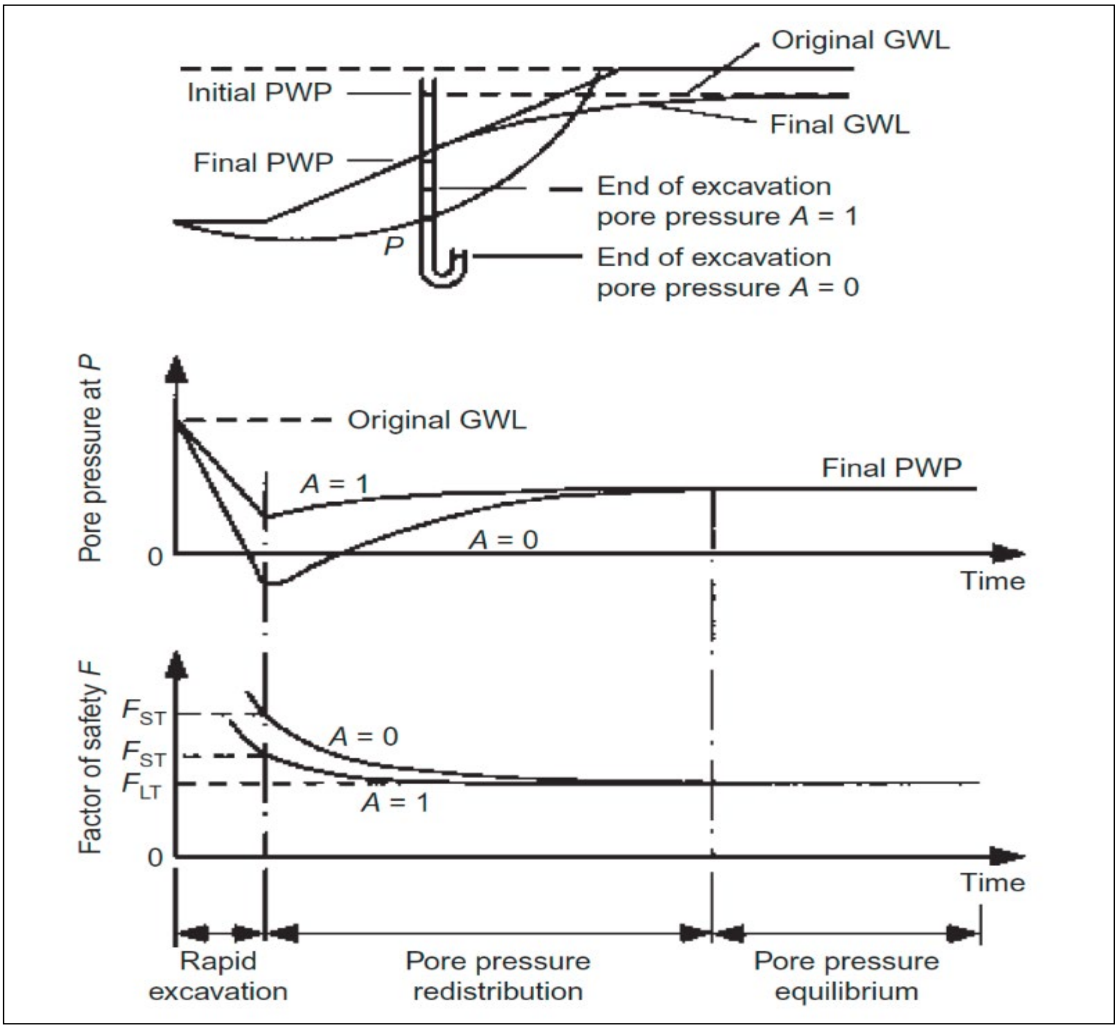


Figure 3.5: Changes in pore pressure and factor of safety during an excavation of a cut in clay (after Bishop & Bjerrum, 1960) (Figure from Leroueil, 2001)

57 Following excavation pore water pressures then dissipate with time towards their equilibrium conditions, which are shown in the upper diagram as drawdown towards the slope face; no toe drain is assumed in this hypothetical situation. As the negative excess pore water pressures dissipate and effective stresses reduce, the factor of safety reduces to its long term value.

58 The rate at which the pore water pressures dissipate, and the rate at which the factor of safety reduces, is determined by: clay permeability and its variation with depth; boundary conditions, including average suction values at the slope surface and the availability of water for the swelling process from both within and outside the slope; degree of overconsolidation, brittleness and the stored energy in the clay; and the slope geometry (slope angle and height of cut).

59 Whether or not failure occurs as pore water pressures dissipate and the factor of safety reduces depends on the slope geometry, the pore water pressures in potential shear zones and the strengths that can be mobilised along potential shear surfaces. The equilibrium values of pore water pressure, and so the long term factor of safety, depend in part on whether or not drainage is installed and operational.

Delayed failure in London Clay railway cuttings

60 The cases quoted by Skempton (1996) and referred to in Chapter 2 illustrate that the stability of railway cuttings did reduce with time in London Clay and other stiff overconsolidated plastic clays. A more complete picture for London Clay is presented in Figure 3.6 which shows by observation and prediction that failure of cut slopes in London Clay can occur up to 80 to 100 years after their formation. The picture is greatly enhanced by the fact that pore water pressure measurements were made in some of the slopes and these measurements showed that the slopes failed well before the pore water pressures had reached their predicted equilibrium values.

61 **The fact that railway cutting slopes failed at increasing times after excavation before pore water pressures had fully dissipated, demonstrates that the initial slopes were too steep and that delayed first-time failure is a relevant mechanism to consider.** Extrapolation of the data in Figure 3.6 suggests that equilibrium pore water pressures should have been reached in London Clay cut slopes no more than 100 years after their formation, i.e. about 50 years ago in most cases. Delayed first-time failure due to the reduction in strength of the clay caused by dissipation of excess negative pore water pressures generated by excavation seems unlikely, therefore, to be an explanation for the ongoing deep seated 'rotational' failures reported by NR in London Clay. This needs to be confirmed by answering the following additional questions:

+ Are the reported deep-seated 'rotational' failures in London Clay all the result of reactivation of previous failures in which residual shear surfaces are present and on which pore water pressures have risen?

+ Is London Clay typical of the behaviour of the other plastic clays in terms of the period over which delayed failures can occur?

+ Can there be slopes over 150 years old in which average pore water pressures are still increasing towards their equilibrium value? Very long equilibration times, over 1,000 years, have been suggested for large thicknesses of London Clay, over 44m, by Leroueil (2001). Pore pressure measurements in cuttings in the different geologies would provide insight into whether there is a remaining risk of delayed failure following original excavation. In-situ measurements of mass permeability in the Lias at Cheltenham show it to be much higher than in London Clay, indicating that delayed failure is not likely to be a problem in Lias with limestone or siltstone horizons

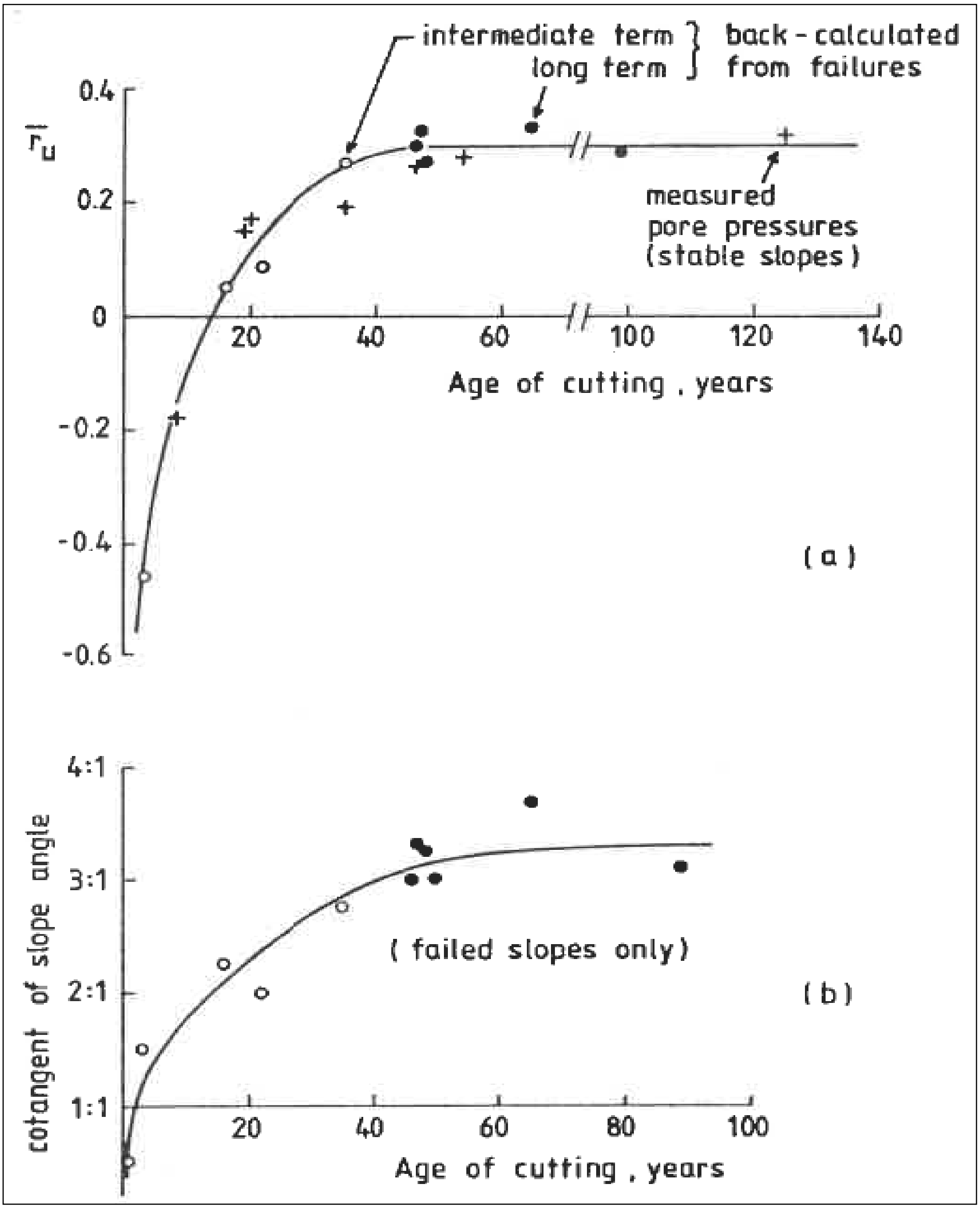


Figure 3.6: First-time slides in London Clay. (a) pore water pressure versus time, (b) slope inclination versus time (Chandler, 1984)

Changes in stability of embankments with time

62 In compacted overconsolidated plastic clay fill in embankments, stability reduces with time because distortion of the lumps of overconsolidated clay during compaction generate negative excess pore water pressures that are superimposed on suctions due to excavation; these excess pore water pressures dissipate with time but slowly because of the low permeability of the compacted clay. Reducing stability with time is also likely to be the

case for uncompacted overconsolidated plastic clay fills (lumpy clay fills). In these, suctions will be present due to removal of stress around the much larger lumps, but suctions will not be increased much by distortion. The open structure of the uncompacted lumps means that mass permeability is high and water can both enter and leave the embankment relatively quickly. Lumps will soften where water is available for the swelling process and this may not be the case in the core of the embankments, above any water table that may have developed in the embankment. Where lumps soften, they coalesce and reduce bulk permeability.

63 In compacted sandy clay fills of low plasticity (glacial tills), embankment stability generally increases with time, because of the breakdown of the soil during compaction to a tilth and the generation of positive excess pore water pressures during compaction of this 'new' material, which then dissipate with time. This is unlikely to be the case in uncompacted sandy clay fills in which the breakdown does not occur and suctions in the lumps, generated by excavation, will dissipate with time, clay lumps will soften, and stability will reduce as in uncompacted plastic clays.

64 In uncompacted granular fills, low densities will introduce a potential for collapse settlement on wetting and increase risks of both internal and surface erosion of the open structure.

Changes in stability of embankment foundations with time

65 Again, in general terms, foundations to embankments increase in stability with time as positive excess pore water pressures generated by loading dissipate. Foundation failures could be triggered by excavation, erosion, or animal burrowing close to the toe of the embankment, or events which might lead to a rise in pore water pressures in the foundation. An inventory of embankment foundation failures and their causes would be valuable.

Weathering and development of softened zone

66 After and during excavation of a cut and formation of an end-tipped embankment, water will have been available for swelling from rainfall on the slopes, beyond the slope crest in a cutting, and on the top surface of the embankment, so that swelling would have proceeded inwards from these surfaces. Water entry into the slopes can be influenced by the formation of shrinkage cracks, by the presence of animal burrows, by the type of vegetation and its removal. Water entry into embankments will have been much faster than into cut slopes.

67 The slope surfaces, being exposed to the atmosphere, will have been subject to chemical and mechanical weathering. Chemical weathering includes the effect of leaching, oxidation and the removal of cementing agents, potentially leading to a reduction in cohesive components of strength. Mechanical weathering includes the effects of shrink-swell and freeze-thaw which can reduce strength by the introduction of additional discontinuities in plastic clays, leading to a reduction in both the cohesive and frictional components of strength, c' and phi', and a possible increase in permeability. Evidence for reductions in strength in some of the soils being considered, due to weathering, is available from Table 3.1 below.

	Fresh:		Weathered:	
	ϕ': degrees	c': kPa	ϕ': degrees	c': kPa
London Clay	20–29	31–252	17–23	1–18
Bearpaw shale	25–30	10–152	20–28	0–41
Lower Oxford clay	23–40	10–216	21–28	0–20
Upper Lias clay	24	27	18–25	1–17
Keuper Marl	>40	>30	25–42	2–80
Coal Measures Mudrock	46	131	26–39	0–25

After Taylor & Cripps (1987)

Table 3.1: Strength characteristics of selected fresh and weathered mudrocks and overconsolidated clays (Leroueil, 2001)

68 A zone of weathered and weakened soil develops over time on the slopes. Evidence from observations of the Newbury cutting in London Clay (Smethurst et al, 2006) indicates that the weathered zone develops rapidly. Vegetation roots can be influential in this zone through their reinforcing effect, their effect on increasing permeability and the effect of evapotranspiration on suctions.

69 The weathered zone is subject to seasonal cycles of pore water pressure change, the very cycles which have contributed to its development. The amplitude of these cycles is determined by the weather pattern and vegetation. The depth of influence of these fluctuations depends on the amplitude of the cycles and the depth of the vegetation roots, particularly trees, as well as the soil properties. Measurements of pore water pressures in and below the weathered zone of a compacted embankment of Gault Clay by Crabb, West and O'Reilly (1987) (Figure 3.7) demonstrate that the fluctuations at 0.5m below the slope are large but they rapidly reduce with increasing depth. The limited depth of influence of the seasonal pore water pressure changes is confirmed by measurements of pore water pressures and suctions made in clays below grass covered slope surfaces in the UK (Vaughan, 1994; Walbancke, 1976), refer to Figure 3.8. The limited depth of influence of these near surface effects indicates that the body of the slope undergoes monotonic swelling.

70 Accompanying these seasonal changes in pore water pressure and water content in the weathered zone, are seasonal changes in undrained strength. In stiff plastic clays these changes can be of the order of those shown in Figure 3.9. In winter, undrained strengths at the slope surface can be as low

as 20kPa. Even if a slope or embankment failure is initiated as a drained event, and so determined by drained strengths and by pore water pressures, movements following the failure initiation, i.e. the post-failure behaviour, are determined by the undrained strength. Some triggering events can occur under undrained conditions so that undrained strengths are again relevant.

71 The impact of weathering will vary with geology and soil type. The process is quite different to that of progressive failure, but progressive failure plays a part in determining when and how shallow failures can develop in the weathered zone of plastic clays, as described below.

72 **Many of the shallow 'translational' failures reported by NR involve movement of a shallow weathered zone, so involving slides of 1m to 2m depth. The weathered zone has developed on slopes which are already 'over-steep' in many cases.** ***It is recommended that some measurements are made of the undrained strengths of the typical weathered zones in summer and winter.***

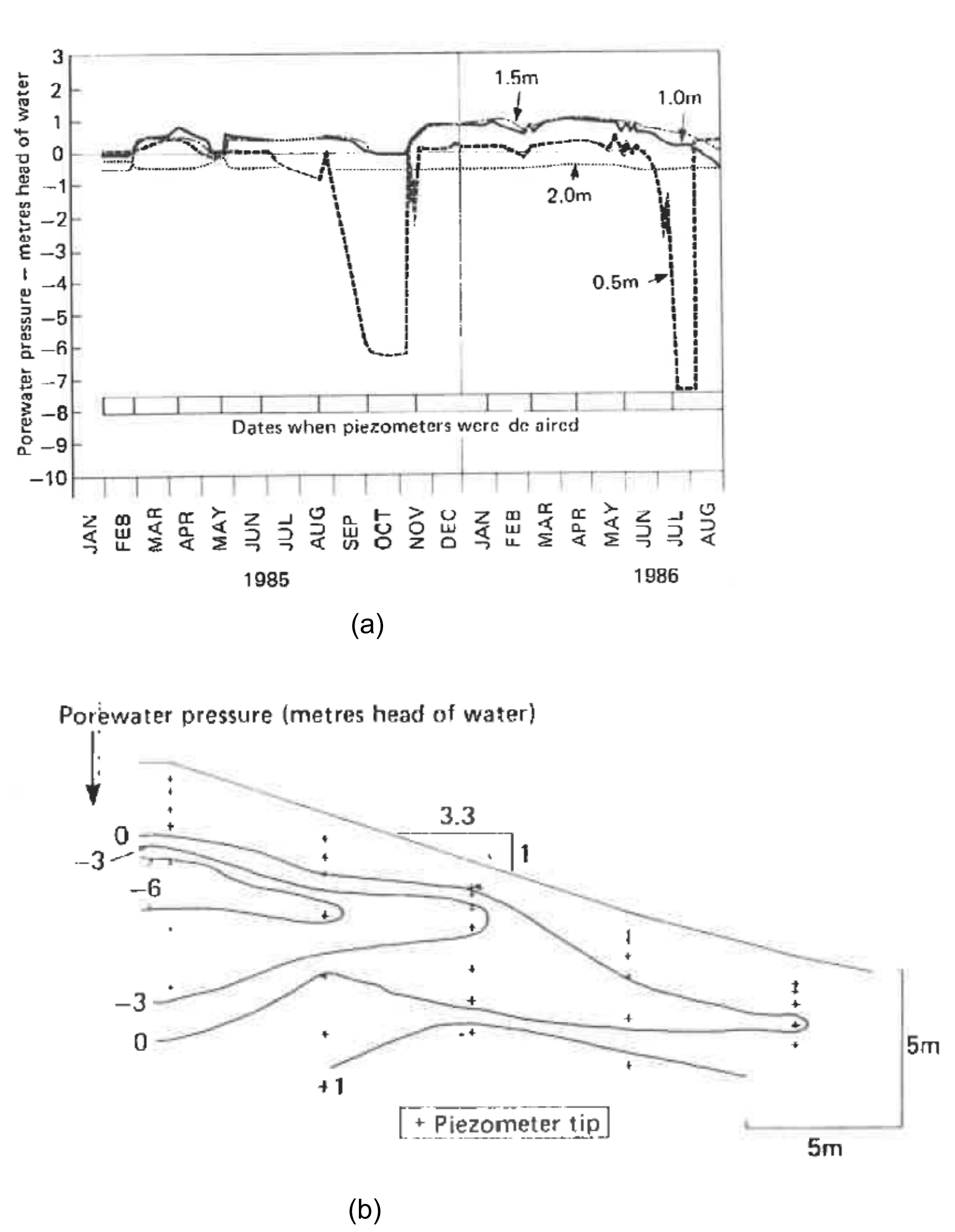


Figure 3.7: Compacted Gault Clay embankment at Wrotham
(a) Pore water pressures measured at four different depths
(b) Pore water pressure distribution in January 1986.
(Figures from Crabb, West and O'Reilly, 1987)

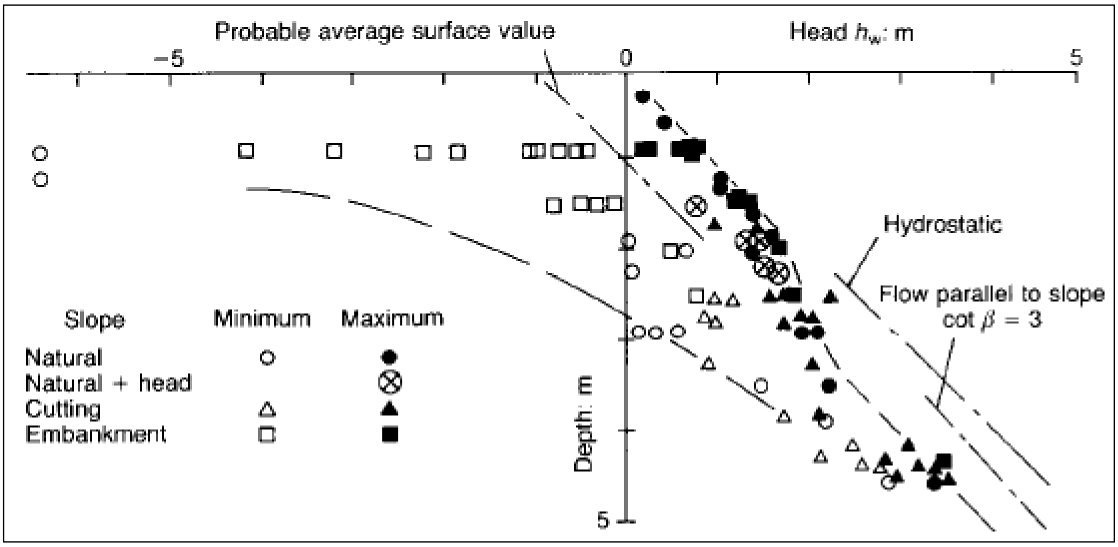


Figure 3.8: Pore pressures near the surface of the ground: slopes in clay in the UK (Walbancke, 1976; Potts, Kovacevic and Vaughan, 1994; Vaughan, 1994)

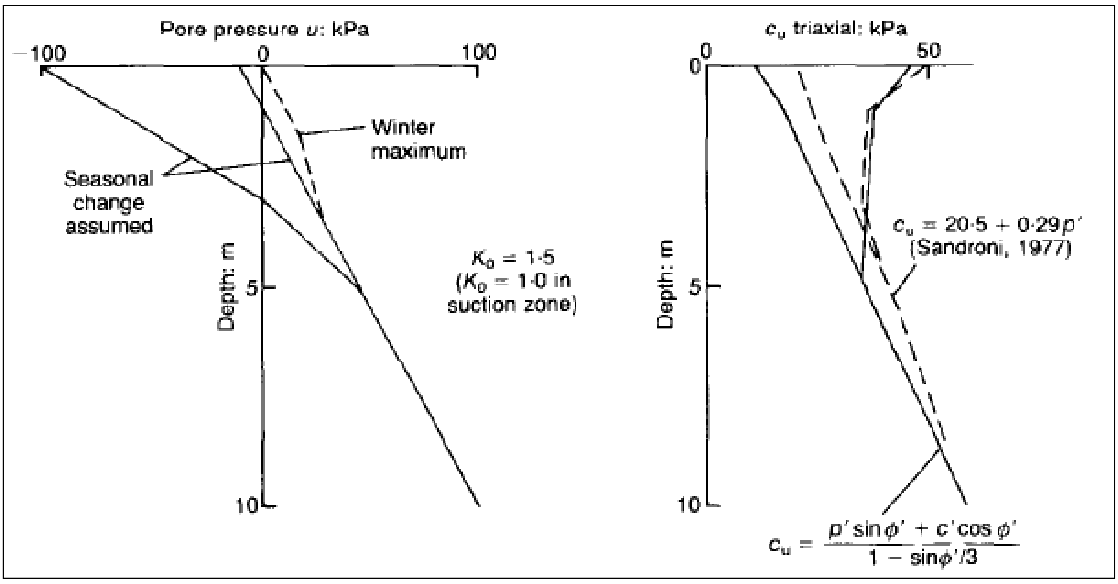


Figure 3.9: Changes in undrained strength of stiff plastic clay due to changes in pore pressure near the surface of the ground (Vaughan, 1994)

Progressive failure

73 Strains within a slope caused by its excavation are non-uniform. These non-uniformities in strain increase as the clay swells differentially. Strengths can be mobilised locally, where the shear strains are sufficiently high. This is not a major problem in ductile low plasticity clays since drained strength, phi', does not reduce with increasing strain and the slope only fails when the strength has been mobilised along the full length of the slip surface. The failure is ductile. Progressive failure is not a key consideration in low plasticity clays.

74 This is not the case in plastic clays which are brittle/strain softening (Figure 3.2). The process of progressive failure has been observed in the field in Oxford Clay, at Saxon Pit (Burland et al, 1977), in Gault Clay at Selborne (Cooper et al, 1998), and has been modelled in sophisticated finite element analyses of typical London Clay cut slopes (Potts, Kovacevic and Vaughan, 1997).

Progressive failure in deep-seated failures in plastic clay slopes due to monotonic swelling

75 Potts, Kovacevic and Vaughan (1997) carried out analyses of a 10m high, 3 (horizontal) to 1 (vertical) slope cut in London Clay in which the brittle characteristics of the heavily overconsolidated plastic clay were modelled. Permeability was assumed to reduce with depth and a suction of 10kPa was maintained at the surface of the slope. The results are discussed by Vaughan (1994). They show that a stage is reached in the swelling process when the shear strains are sufficient to mobilise the peak strength of the clay in a zone which extends inwards from the toe of the slope (Figure 3.10); this prediction matches the observations at Saxon Pit. As swelling strains continue to increase, this zone extends, and within the zone mobilised strengths drop rapidly to post-rupture values and then drop more slowly towards residual values; stress transfer takes place from this zone to zones where the peak strength has not been fully mobilised. The process of swelling and stress transfer continues until a point is reached at which no further transfer of stress is possible and the slope fails abruptly. As the slope moves, strength on the shear surface drops towards its residual value, and movement only stops when the geometry of the slope is such that the new driving force can be resisted by strengths along the shear surface.

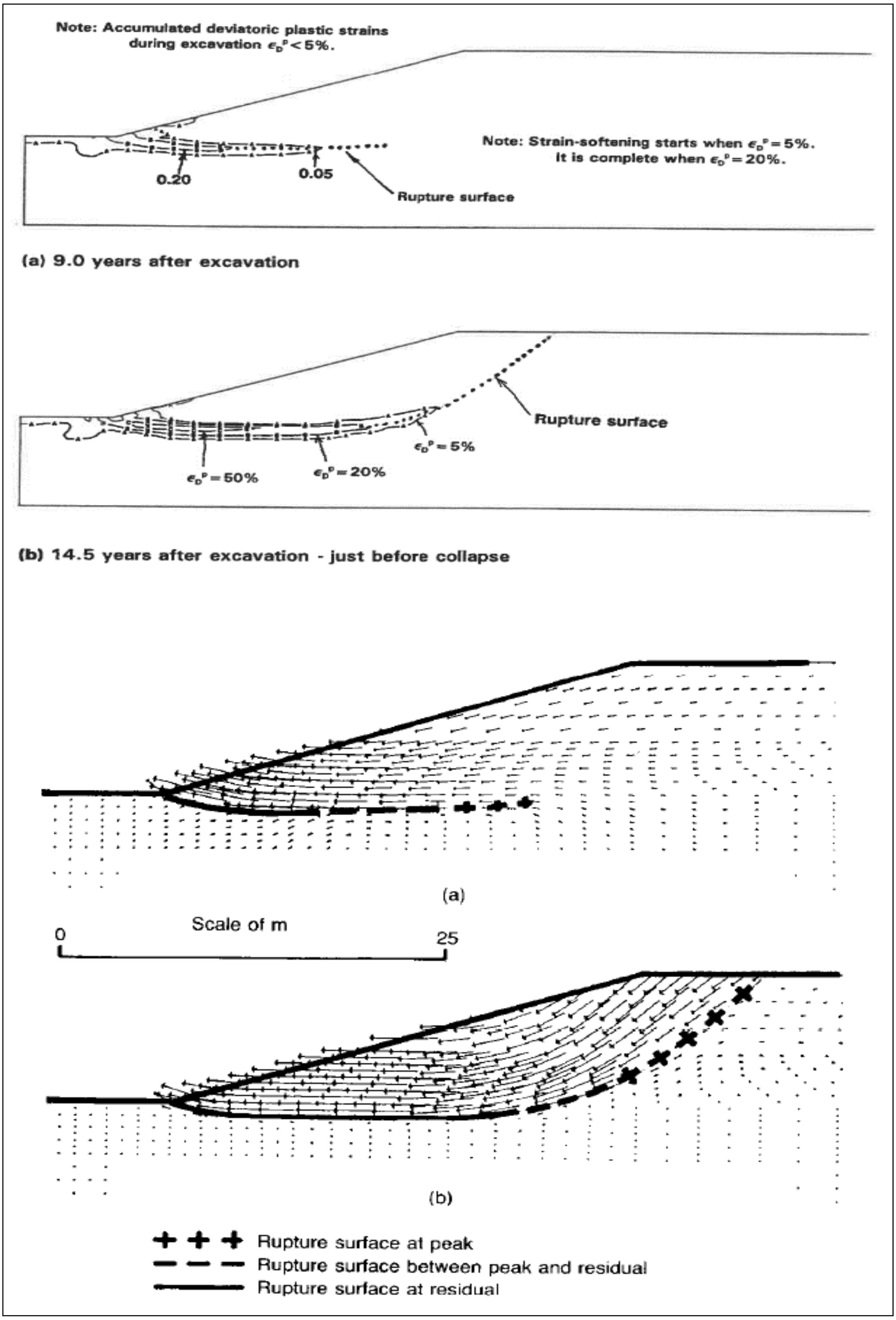


Figure 3.10: Results of finite element analyses of 3:1 cutting slope 10m high in stiff plastic clay. Ko=1.5, surface suction=10kPa. Contours of accumulated plastic strain (top) and vectors showing current direction of movement (bottom). (a) 9 years after excavation, (b) 14.5 years after excavation, just before collapse.

76 **Parametric studies by Potts et al (1997) show that:**

a. Slopes fail with average pore water pressures well below their long-term equilibrium values; a finding consistent with the observations presented in Figure 3.6.

b. The pore water pressures at collapse increase with decreasing slope angle.

c. Management of vegetation, i.e. increasing the average surface suctions from 10kPa, typically observed for grass slopes, to 20kPa by growing selected bushes and/or low trees can increase the safe slope angle.

d. The initial value of Ko[6] in the clay below the level ground influences the shape of the predicted rupture surface and the time to its full development.

e. The operational or average strength at the point of first-time failure is between peak and residual strengths, depending on slope geometry and Ko. The effect is that the average strengths available to ensure stability may be less than conventionally assumed.

f. To avoid deep-seated failures in the long term, and for the assumptions made in the analyses, such as uniform slope, no underdrainage or layering, and surface suction of 10kPa, slopes need to be flatter than 4.5 to 1. This finding is consistent with the tabulated data below, taken from Crabb and Atkinson (1991), in which it can be seen that of the stiff plastic clay slopes investigated, only the slope with an inclination of 14 degrees and height of 8.3m was stable.

Location	Soil	Geometry		Stable/ Failed (S/F)	Depth of Slip, Z (m)	Pore water pressure at 1.5m depth (m head of water)	Ip(%)
		Slope (°)	Height (m)				
Cambridge - A45	Gault Clay	27	7.8	F	1.5	-0.5 - 0.0	42
M26-Dunton Green	Gault Clay	14	8.3	S	NA	~ 0.8 max in spring	42
M26-Wrotham (Nepicar)	Gault Clay	17	6.7	F	1.3	0.0 - 1.0 (see Fig 2)	43
M1 Junction 13	Oxford Clay	25	7.3	F	1.5	Not measured	28
M4 Reading	London Clay	29	6.5	F	0.5	"	27
M11 Junction 8	Reading Beds Clay	19	7.5	F	2.0	"	32
M4 Junction 16	Kimmeridge Clay	24	8.1	F	1.0	"	27
M23 Surrey	Weald Clay	24	6.7	F	1.5	"	23

Table 3.2: Summary of slope geometries and soil parameters for some high plasticity clays (data from Crabb and Atkinson, 1991)

6 Ko is the ratio of the horizontal effective stress to the vertical effective stress, under conditions of no lateral strain.

77 The data in Table 3.2 indicates that progressive failure of the form predicted for the London Clay slopes also applies to other brittle stiff plastic clays in which NR have cuttings.

78 **Shear surfaces at or close to residual strength can be present in the cut slopes in brittle plastic clays before there is overall failure of the slope. After there has been failure, a continuous shear surface at or near residual strength will be present.**

Progressive failure in shallow zones of weathered plastic clays due to monotonic swelling

79 Cut slopes formed in London Clay often fail at the interface between the brown (weathered) and blue (unweathered) clay, where there are changes in permeability, stiffness and strength. Analyses described by Vaughan (1994) demonstrated that when allowance is made for the presence of a weathered layer with higher permeability on the slope of a strain-softening clay, monotonic swelling can introduce progressive failure at the boundary between the weathered and unweathered clay, where a discontinuity in pore water pressures and strains is predicted. The predicted progression of failure with time in a 1m thick weathered zone, having a permeability ten times higher than the underlying clay, is illustrated in Figure 3.11.

80 **The key mechanism of progressive failure in a slope with a shallow weathered zone involves a rupture surface with reducing strength propagating upwards from the toe of the slope, along the interface between the weathered and unweathered soil; this is a mechanism that may well contribute to the shallow failures occurring on NR's cut slopes in plastic clays, failures which sometimes involve only the lower part of the slope.**

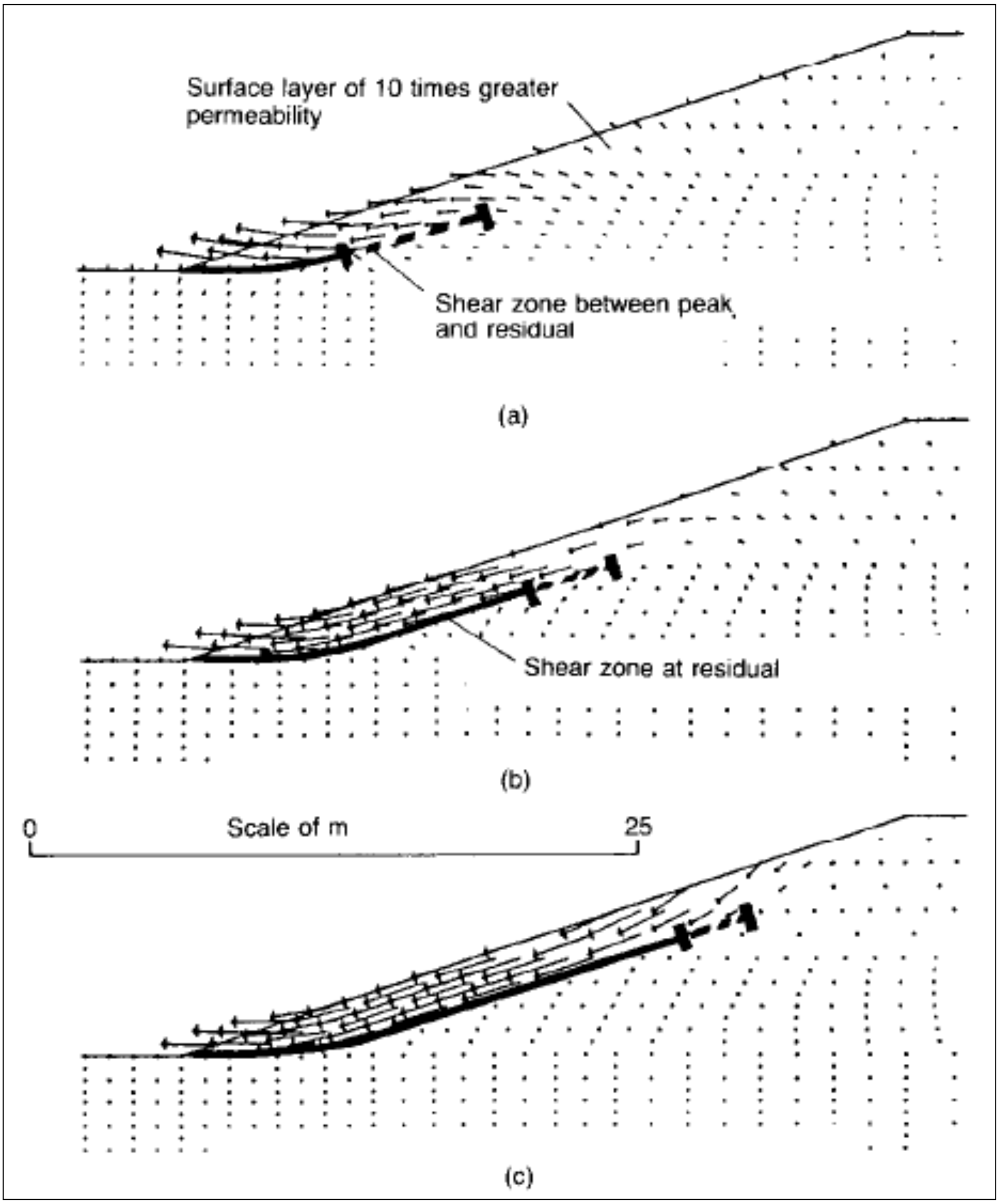


Figure 3.11: Results of finite element analyses of 3:1 cutting slope 10m high in plastic clay with shallow surface zone of higher permeability, Ko=1.0, surface suction= 0. Vectors showing current direction of movement. (a) 1 year after excavation, (b) 1.5 years after excavation, (c) 1 year 7 months after excavation, just before collapse. From Vaughan (1994)

81 The predicted times for the failure are particularly short, possibly because monotonic swelling with a zero pore water pressure boundary at the slope surface was assumed. Vaughan (1994) noted the following: *'Delayed failure of superficial slides may be more dependent on the occurrence of climatic extremes than on the age of the slopes.'* Superficial slides referred to by Vaughan are the same as the shallow transitional failures identified by NR and discussed herein.

Progressive failure and downslope movements (ratchetting) in cuts and embankments due to cyclic pore water pressure changes

82 Observations have shown that old London Underground (LU) embankments, comprising dumped and uncompacted London Clay fill with a cover of coal ash, showed movements as superficial pore water pressures changed seasonally (drying in summer and wetting in winter). Relatively deep slips in the LU embankments, affecting the tracks, occurred and coincided with long wet winter periods in which the surface pore water pressures increased, and swelling was encouraged by the presence of tension tracks established during dry summers. Similar observations have been made in similarly constructed embankments among NR's assets.

83 Kovacevic et al (2001) analysed the embankment geometry in Figure 3.12 and subjected the embankment of London Clay and ash fill slope to cycles of drying and wetting. The seasonal cyclic stress changes caused net outward movements of the slope due to non-recoverable plastic strains and reductions in strength, which, in the strain-softening fill, eventually led to collapse through progressive failure starting from the embankment toe. This mechanism is referred to as ratchetting. The displacements predicted for the last cycle prior to failure of the embankment are shown in Figure 3.13, (a) being the shrinkage phase when the ground moves into the slope, (b) being the swelling phase, when the ground heaves out of the slope, and (c) being incipient failure with horizontal movement over the lower part of the slope, very similar to a number of the shallow failures referred to in Chapter 2.

84 The number of cycles required to cause failure was found to depend on the amplitude of the pore water pressure cycles and the value of suction assumed to apply at the surface during the winter swelling period. Horizontal displacements prior to collapse were small, less than 20mm at the crest and less than 40mm at mid-slope; collapse was abrupt. In the analyses it was assumed in each cycle that there was full dissipation of excess pore water pressures, i.e. shrinkage was complete before complete swelling took place. In reality neither shrinkage nor swelling will necessarily be complete and the number of cycles to failure will be higher than predicted. Defects in the slope, such as tension cracks and pre-existing shear surfaces, are also likely to play a role in determining the processes of progressive failure.

85 Although the analyses were of an uncompacted London Clay embankment, it is reasonable to draw the conclusion that the seasonal cycles of pore water pressure change which develop in response to wetting and drying at the surface of a cut slope surface and in response to different levels of evapotranspiration by the vegetation, can themselves lead to progressive failure of plastic clay slopes in cuts which have otherwise reached equilibrium following excavation. This conclusion is particularly reasonable when considering the predictions for monotonic swelling shown in Figure 3.11.

Indeed the ratcheting mechanism has been observed in centrifuge tests on clay slopes (Take and Bolton, 2011) and has been modelled by Postill et al (2020).

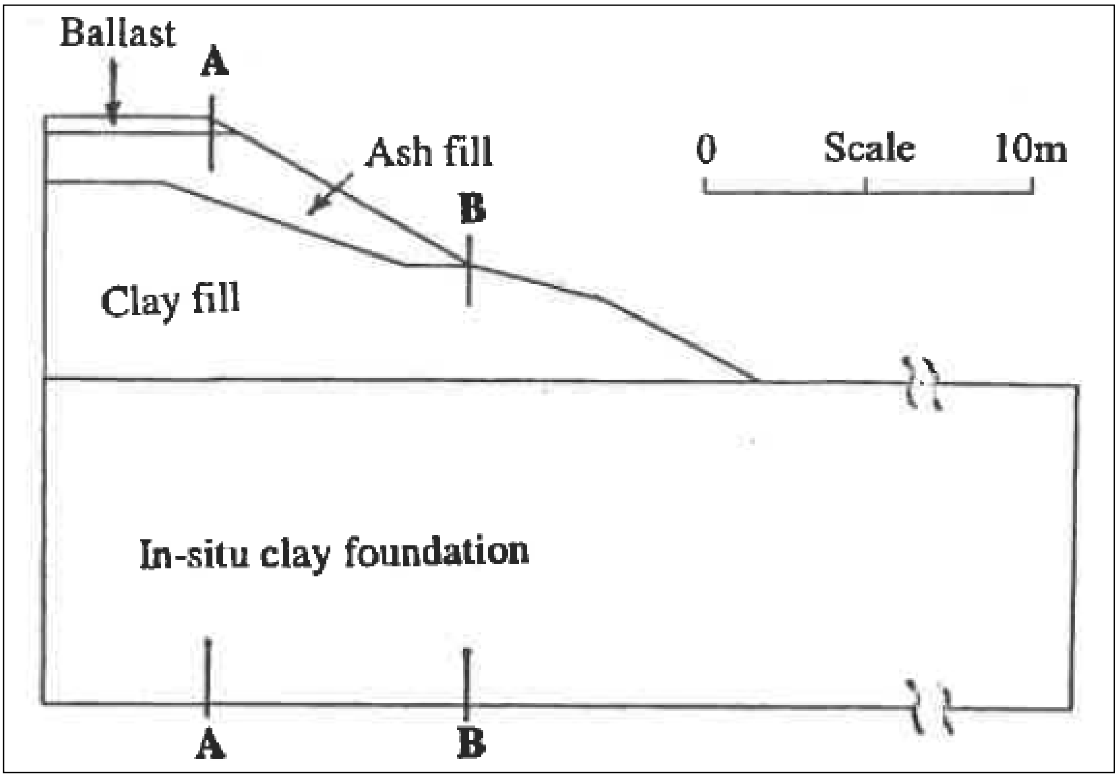


Figure 3.12: Modelled ratchetting mechanism in plastic clay embankment due to seasonal pore pressure changes and progressive failure. Typical cross section of LUL embankment. (Kovacevic et al. 2001)

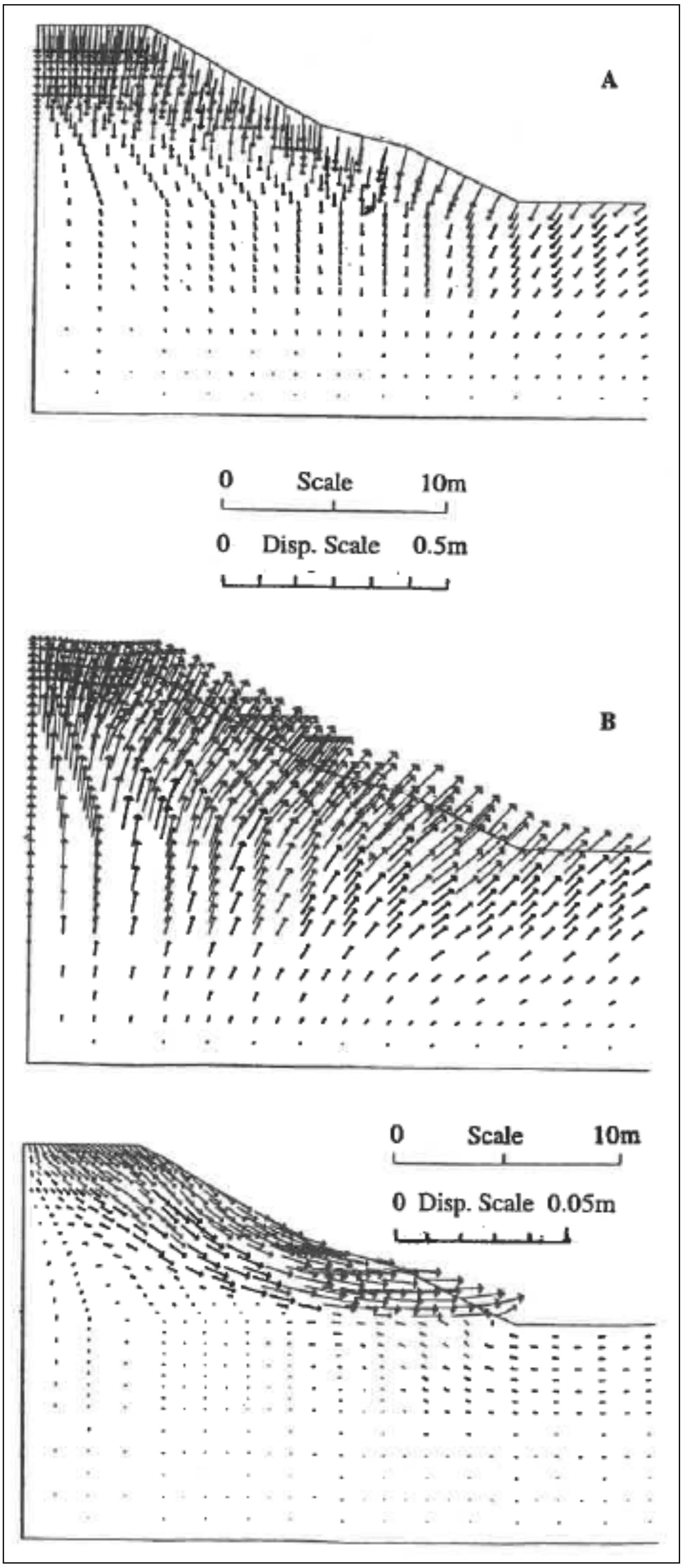


Figure 3.13: Modelled ratchetting mechanism in plastic clay embankment due to seasonal pore pressure changes and progressive failure. Displacement vectors during the cycle before collapse (a) shrinkage phase, (b) swelling phase, (c) the whole cycle. (Kovacevic et al., 2001)

Stable slope angles

Stiff plastic clay cuttings

86 By observations (Table 3.2), confirmed by analysis, 8-10m high slopes in stiff plastic clays such as London Clay, Gault Clay, Oxford Clay, Weald Clay and Kimmeridge Clay need to be cut at angles less than 14 degrees to avoid failures involving progressive failure; for engineering purposes 14 degrees can be considered to be a stable slope angle. From Chapter 2 it appears that all railway cut slopes in the stiff plastic clays were excavated at the considerably steeper angle of 26 degrees (2 horizontal to 1 vertical). We also know that slopes cut at these steeper angles continued to undergo first-time failure up to an age of 100 years (Figure 3.6). This leads to the following questions:

+ Have all NR cut slopes in stiff plastic clays undergone first-time failure and so are likely to contain low strength residual shear surfaces, and if not, why are some still stable
+ What are the post-failure angles of the current slopes and how do they compare with the as-constructed slope angles
+ What interventions/stabilising measures have been carried out in the past? Are these measures maintained and how are their presence allowed for in the assessment of current stability

87 The danger of reactivating slip movements on low strength residual shear surfaces in NR plastic clay cut slopes that have previously failed is highlighted elsewhere. A second danger is if there are slopes in brittle clays which have not previously failed, perhaps because of localisation or having been excavated more recently, but in which progressive failure and a low strength residual shear surface are likely to have developed to some extent (see Figure 3.10). The continuing stability of such slopes is likely to depend critically on the pore water pressures in the body of the slope being depressed, either naturally or by installed drainage. This could explain 'why slopes that have been assessed as 'over-steep' by Motts, NR (2017d) have not failed'.

88 If these depressed pore water pressures rise sufficiently, because of rising groundwater levels or deteriorating drain function, the failures will be abrupt and involve large displacements. Investigation of pore water pressures and ground movements in examples of over-steep slopes in plastic clays are essential and are discussed in Chapter 12.

Sandy clay cuttings

89 Having plasticity indices of less than 25%, sandy clays are non-brittle and not subject to reductions in operational strength due to progressive failure. The lower plasticity sandy clays are, however, erodible. Vaughan (1994) has noted that natural glacial till slopes in the North East of England are stable at angles between 33 and 36 degrees at heights between 10m and 35m. Steeper slopes up to 45 degrees are actively eroded and have no vegetation cover. Slope angles between 33 and 36 degrees can be considered as stable slope angles in these soils. This leads to the following questions:

+ At what angles were the railway cuttings in glacial tills excavated and how do they compare with current slope angles
+ Have they undergone first-time failures
+ Does NR experience match that of Vaughan (1994) in these soils, in that there are no deep-seated failures in slopes flatter than 36 degrees, but slope problems are related to erosion and washout failures if vegetation protection is insufficient

Embankments

90 Safe slope angles cannot be defined for uncompacted clay fill embankments. End tipping will have produced angle of repose slopes relevant to the excavated lumps but, as noted in Chapter 2, these slopes were trimmed back to 2 or 1.5 (horizontal) to 1 (vertical). Softening of the clay lumps and slope failures will have led to flattening of these trimmed slopes. This leads to the following questions:

+ What are the current slopes of the NR embankments and how have they changed over time
+ What is known about the base drainage conditions below embankments, the importance of which has been identified in the study of LUL embankments by Briggs et al (2013)

Historical interventions

Cuttings

91 Chapter 2 refers to the cut slopes in clay failing at different times after their excavation. The usual method of stabilising a cutting slope failure on the early railways was to flatten the slope, either by trimming or benching back, or in extreme cases by removing the slip mass. Slope flattening often required the removal of considerable volumes of clay. 25,000 cu. yd of material was removed to stabilise a landslip at Wotton Bassett Cutting (a 42 ft (14 m) deep cutting at a 2 (horizontal) to 1 (vertical) slope in the Oxford Clay) in 1841 on the Great Western Railway (I.K. Brunel, 1842).

92 However, Gregory (1844) stated that the construction of counterforts "*was a far less expensive method, than removing the slip and trimming back the slope, and avoided the necessity of so many obstructions to the traffic of the railway, which would have occurred in removing the spoil along the main line*". They consist of trenches, typically 6 ft wide at 24 ft centres, dug into the slope to a depth of 2 or 3 ft below the slip surface and backfilled with gravel or rubble stone rammed in tight (Skempton, 1996). They act both as an internal buttress and as a deep drain. Gregory (1844) presented the first published description of counterforts (Figure 3.14), though by that time they were quite well known, as clearly emerges from the extensive discussion on his paper to the Institution of Civil Engineers. They became practically a standard remedial measure on the railway system, and remained so until very recently. Counterfort drains are still installed where required as part of NR earthwork stabilisation works. Figure 3.15 is a photograph of the counterfort and drainage installations after a cutting failure in London Clay at Northolt, described by De Lory (1957).

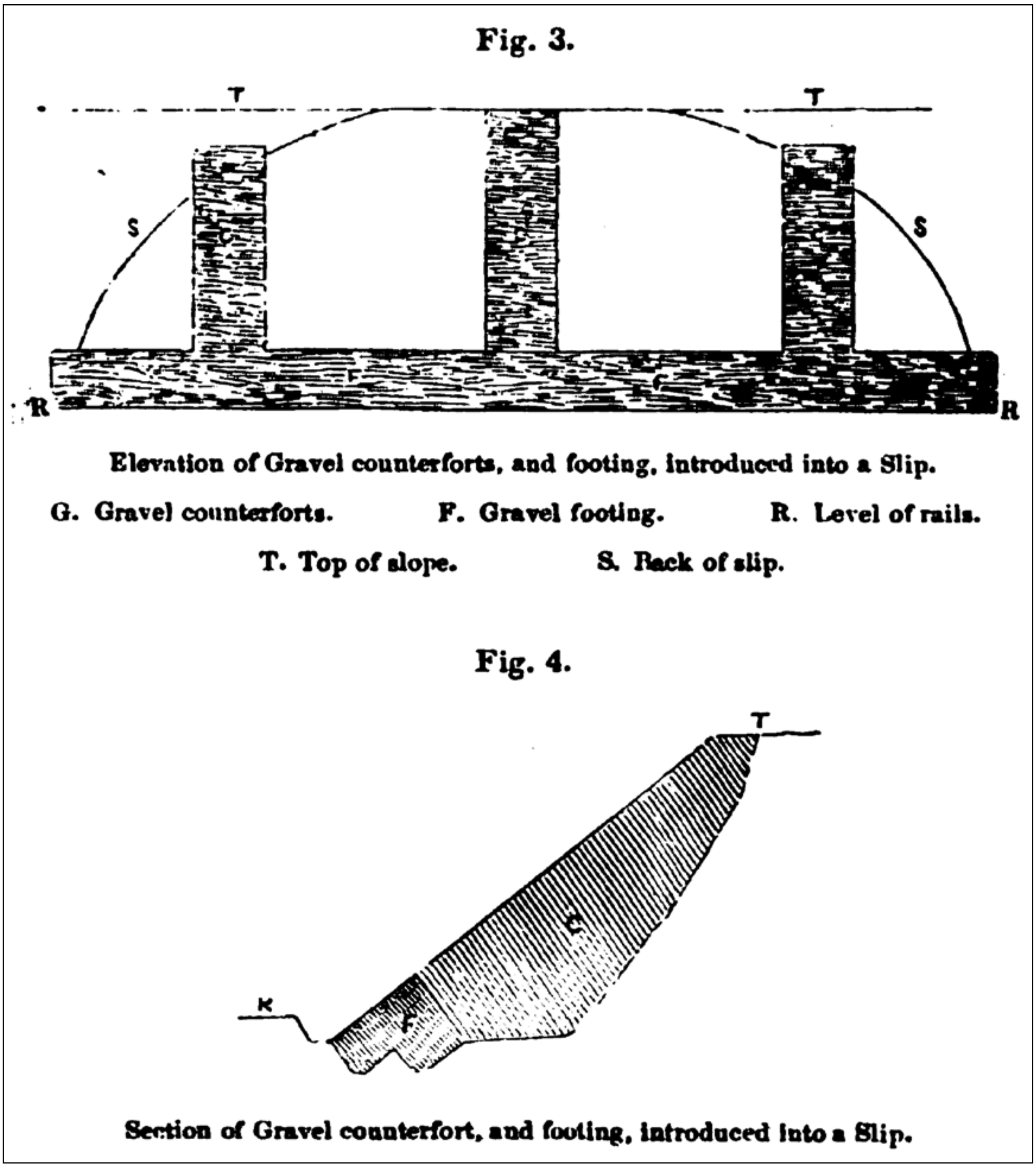
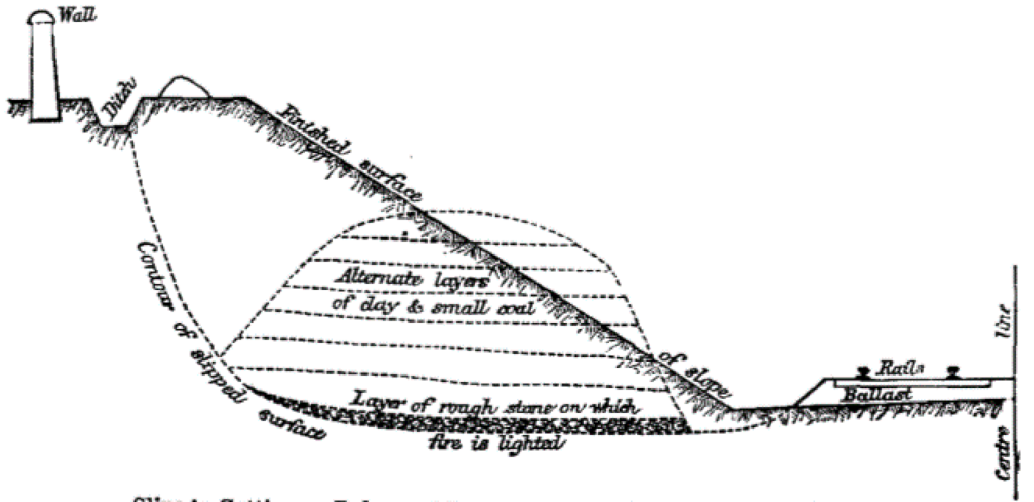


Figure 3.14: Gravel Counterfort and Footing – after Gregory (1844)

Figure 3.15: Counterforts and Slope Drainage installed for slope stabilisation in Northolt Cutting (1956) (after De Lory, 1957)

93 Laws (1881) described the burning of clay in-situ, which was another common slope stabilisation technique on the early railways. "*On a decided slip occurring the first thing done was to clear away a space of 15 to 20 feet in the line of the cutting, until the solid clay was reached both downwards and sideways. A good fire was then lighted on the solid ground, using plenty of broken wood and coal, and allowed to burn up well; on to this the clay was cast from both sides, in layers varying from 12 to 30 inches, small coal being spread between, until the heap was from 8 to 12 feet high. This was allowed to burn out on the one side and continually extended on the other, as in firing a clamp of bricks. The burnt material from the cool side was then cast back as soon as possible into the void in the slope, and trimmed to shape*". (Figure 3.16)

FIG. 2.



Slips in Cuttings. Byker and Percy Main branch, North Eastern Railway.

Figure 3.16: Burning of clay in situ to stabilise landslips on Byker and Percy Main branch, North Eastern Railway after Laws (1881)

94 It is quite common to find burnt clay which has the appearance of crushed bricks in present-day railway cutting slopes during intrusive investigations.

95 A 1970's visual inspection of all the NR London Clay cuttings out of Kings Cross and Euston to the M25 indicated that all had some form of historical intervention, mostly counterforts and toe retaining walls (Professor Peter Vaughan, 1994, pers. com). However, there may be other historical interventions e.g. clay burning, that are not always apparent from a visual surface inspection, since the slopes are often overgrown with vegetation.

96 **On the basis of observations it is likely that the majority of NR's plastic clay cuttings will have failed in the past (at least over part of their length), because they were built over-steep, typically at a gradient of 2 (horizontal) to 1 (vertical)**.

Embankments

97 As noted in Chapter 2 NR's embankments predominantly consist of end or side tipped clay fills, overlain by variable thicknesses of ash. This has resulted in the characteristic railway embankment shape in cross-section, with steeper sides in the ash capping and a break in slope to the less steep side slopes in the underlying clay fill. As described above, these embankments have undergone seasonal cycles of pore pressure change which have led to ratchetting and to failures within the embankments. Observations by Vaughan et al (2004) indicate that most embankments over 6-7 m high, formed of London Clay fill overlain by ash, exhibit some evidence of this form of failure.

98 A variety of techniques were employed to stabilise the landslips and restore the track alignment, including in-situ burning of the clay fill (Laws, 1881), but most common was the addition of low-density ash, initially from steam trains and subsequently from coal burning power stations. Failures, which were not fully excavated and replaced, will have left a weakened shear surface in the embankment fill just above the foundation or in the foundation itself.

99 Grouting was used to stabilise embankment slips by the British Rail Soil Mechanics Section from the 1950's to the 1980's. The "British Railways embankment grouting system" (Ayres, 1985) was used to grout over 600 embankments, mostly on the Great Western between Paddington and Bristol. The grouting system was based on forming a strong, thick (50-150mm), continuous seam of cementitious grout along slip surfaces, tension cracks and "imminent tension cracks" by means of hydrofracture displacement grouting, followed by penetration grouting into the overlying ash/ballast to expel water and stabilise the ash/ballast fill.

100 Unlike the reported experience of British Rail (Ayres, 1994), the effect of the embankment grouting operations undertaken over 28 lineside km in the 1970's by London Underground does not appear to have produced as great or sustained an improvement as originally expected. Investigations have revealed very little grout in the embankment clay fill. The grout was mainly found in the ash or at the ash boundary with clay or ballast. As the grout did not significantly penetrate into the clay fill or fully permeate the ash capping, grouting did not resolve the overall problem of poor embankment performance (McGinnity et al, 1998).

Potential reasons for ongoing failures of cuttings and embankments

Increasing destabilising forces

101 Slopes which have reached assumed equilibrium after initial formation, and whether or not they have failed, can continue to fail because either destabilising forces are increasing or resisting forces, i.e. soil strengths, are reducing. Increases in destabilising forces can result from additional loading at the head of the slope or unloading at the toe of the slope. Additional loading at the head can result from third party influences or, for example, reactivation of solifluction[7] slides at and beyond the crest, themselves caused by pore

7 Solifluction slides developed during periglacial times and involved the downslope movement of thawing ground which, in plastic clays, created low strength residual shear surfaces. Movement can be reactivated by pore pressures rising on these shear surfaces or by excavation at the toe of the slide or lobe.

water pressure rises. Unloading at the toe of potential deep-seated failures can be by shallow slides in the weathered zone, of which there are many, by planned excavation, or by scour, or animal burrowing.

102 There is an example in Chapter 2 of a failure being triggered by the passage of a freight train, so the potential impact of train loading, particularly if it has been, or is due to be, increased can provide an increased destabilising force. This topic has been reviewed by Mott MacDonald (2011). Train loading was a significant issue on LU ash/clay embankments in the summer where the dynamic forces from train loading, particularly if the track quality was poor, resulted in significant downslope movement of the "dry" ash from the embankment crest, undermining the track.

Reducing resisting forces

103 In effective stress terms, the ability of the soil to resist shear is determined by cohesion, c', the effective angle of shearing resistance, phi', and the pore water pressure, u, and normal total stress, σ_n, acting on the potential or actual shear surface. Various angles of shearing resistance need to be considered: phi' at peak, post-rupture and at residual; mass phi' in which the effects of all discontinuities are included; mobilised phi', the value applying at different points along the rupture surface; operational phi', the average value calculated to be applying at the point of failure.

104 Reductions in c' and mass phi' can occur as a result of destructuring by swelling and the introduction of fissures due to undrained stress relief. Reductions in c' and mass phi' can occur in the relatively shallow weathered zone below the slope surface as a result of chemical and physical weathering; this is referred to above. Physical weathering in plastic clays is dominated by shrink-swell which can introduce additional discontinuities in the form of desiccation cracks.

105 Vegetation is regarded as effectively contributing to c' through the benefits of root reinforcement in the shallow weathered zone. Removal of vegetation removes this contribution to c'; this can take time as roots decay. See also Para 541 to Para 543.

106 Weathering and the effects of shallow pore water pressure cycles do not penetrate into the main body of the slope and are not the cause of any deterioration at depth. Apparent reductions in c' and peak phi' at greater depths are found when calculating average strengths mobilised in plastic clays which have undergone first-time failure or in which progressive failure is developing as a result of increasing strains. Mobilised angles of phi' can reduce along developing shear surfaces if displacements continue. At shallow depths, increasing plastic strains accompany the cycles of pore water pressure and downslope movements. At greater depths, strains may continue because of differential creep along the developing shear surface, where different phi' values are mobilised.

107 **There are a number of reasons why strength parameters may reduce in a slope and these could well play a part in the ongoing slope failures. In our opinion, by far the most important parameter which leads to strength reductions are increases in pore water pressure above equilibrium values previously reached after a long period following completion of construction. Pore water pressures can increase above these previous equilibrium values (a) if groundwater levels rise as a result of prolonged rainfall and changing weather patterns; (b) if drains are missing, blocked or of insufficient capacity and/or depth; (c) if vegetation is removed.**

108 Reductions in resisting forces can also result from deterioration of the stabilising measures that may have been installed in the past, as described above.

Importance of rainfall patterns

109 Two features of rainfall patterns that are relevant to identifying triggers for earthworks failures and the form of failure are antecedent or cumulative rainfall (mm/day or/week) and rainfall intensity (mm/minute or /hour). Prolonged antecedent rainfall can result in:

a. Reduced suctions and increased degrees of saturation in the weathered zone.

b. The development of perched water tables within the weathered zone.

c. A general rise in groundwater levels in the body of the cut slopes and in the embankments as a result of infiltration over time.

Both a) and b) can trigger shallow failures. The triggering of deep-seated landslides generally requires rainfall of long duration and so c). As changes in pore pressure at depth are delayed, compared with changes in pore pressure close to boundaries, deep failures are generally delayed in comparison with rainfall.

110 Figure 3.17(a) illustrates how average rainfall intensity R_1 divides into run-off, R_2, sub-surface flow, R_3, infiltration into the body of the slope, R_4 and the flow held in the unsaturated zone, R_5. For a given average rainfall intensity and slope angle, α, run-off increases as cumulative rainfall increases (Figure 3.17(b)). Rainfall intensity is, therefore, a factor in determining run-off volumes, run-off rates and erosive power, in combination with the permeability and suction (degree of saturation) profiles in the surficial layer. In winter, because of antecedent rainfall, near-surface suctions are low, degrees of saturation high and run-off rather than infiltration is encouraged, particularly on steep slopes. In summer, infiltration through surface cracks dominates initially until the advance of the wetting front is impeded by the low permeability of the uncracked, unsaturated soil below, following which run-off dominates.

Hydrostatic pore pressures can develop in the newly saturated and cracked zone. Intense rainfall over a short period of time can, therefore, trigger shallow slides or slumps in summer and washouts in both summer and winter.

111 Bombardment by intense rainfall on the surface of a saturated zone which is unprotected by adequate vegetation can initiate surface erosion (Figure 3.17 (d)). Antecedent rainfall provides the softening blows, by leading to a minimum undrained strength, Cu_{min}, and intense rainfall provides the knockout.

112 Figure 3.18 illustrates some of these points using data presented by Johnson & Sitar (1990) and discussed by Leroueil (2001). The pressure heads measured in one nest of piezometers/tensiometers are shown, together with the cumulative rainfall and the hourly rainfall intensity. The conditions before the 24 November 1985 event were considered as `dry', with suctions of about 60 kPa (Figure 3.18(a)). The pore pressure response to the storm was very rapid at the shallowest depth and gradually propagated with some delay (12-24 hours) at larger depths. The conditions before 14 February 1986 were considered to be `wet', with initial suction values generally smaller than 5 kPa (50 cm of water, Figure 3.18(b)). This study illustrates how pore pressure response varies with the pattern of antecedent rainfall and the current state of the near-surface ground. Inevitably the response will vary from site to site, adding to the list of factors determining localisation of any failure.

113 Both cumulative rainfall and rainfall intensity are increasing with climate change, as discussed in Chapter 4; the first by longer periods of prolonged rainfall, the second in terms of intensity, frequency and localisation.

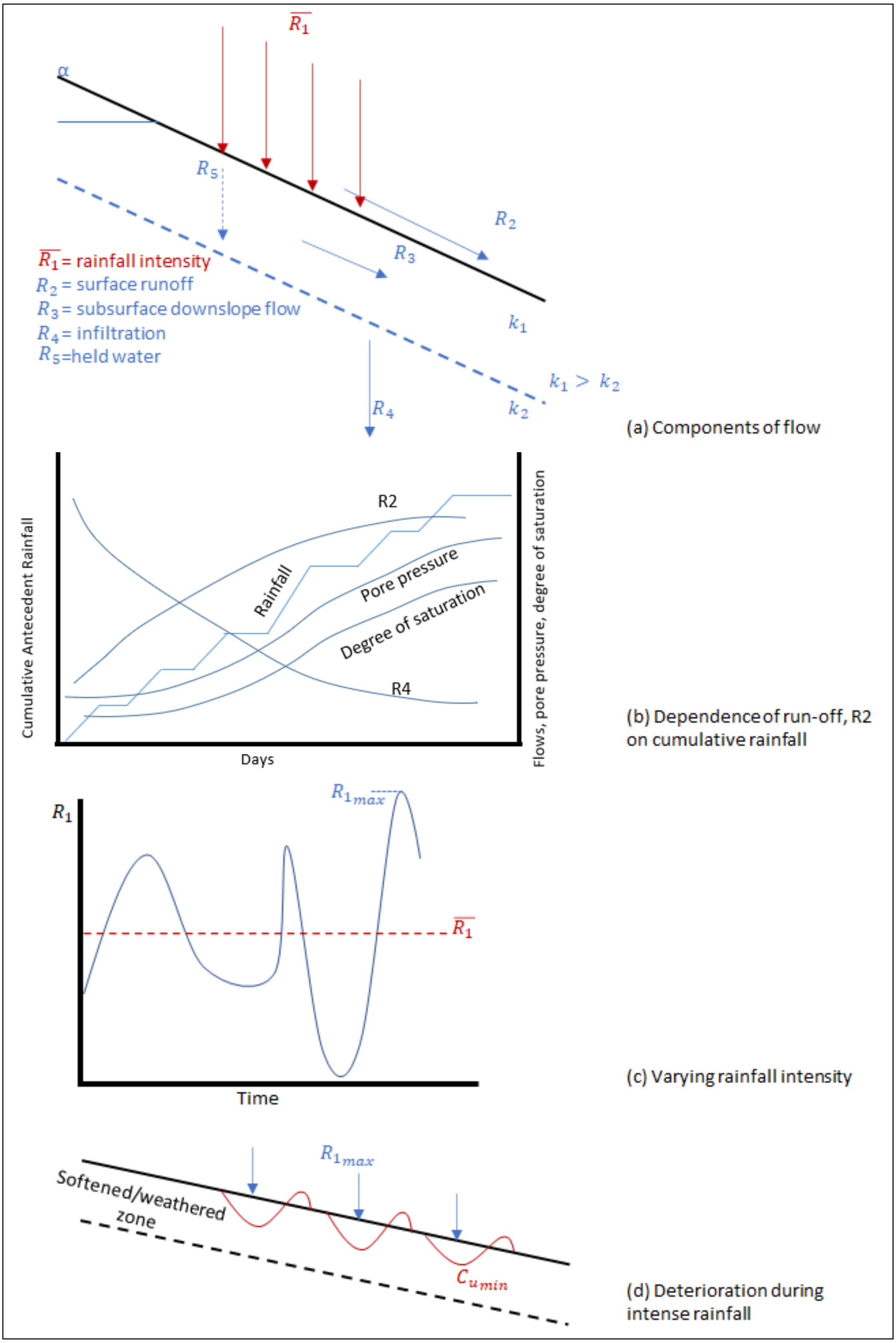


Figure 3.17: Impacts of cumulative rainfall and rainfall intensity

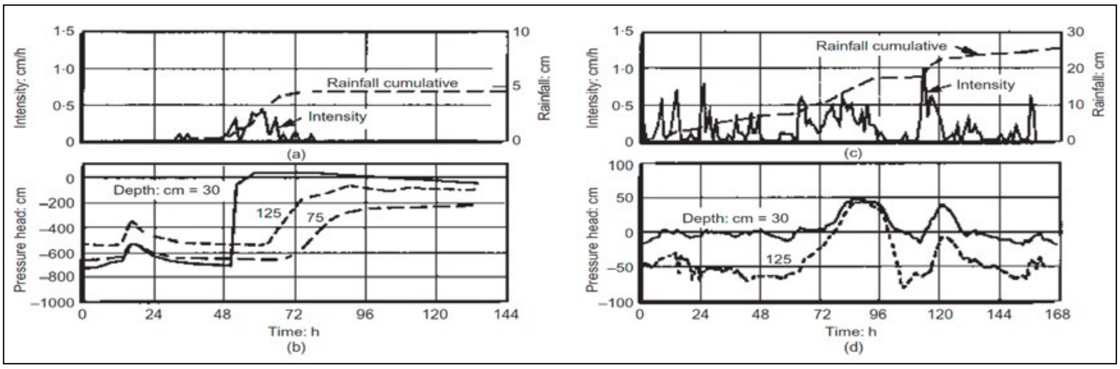


Figure 3.18: Rainfall characteristics and pore pressure response at the Briones Hills field site (piezometer nest 4): (a), (b) storm of November 1985; (c), and (d) storms of 12-20 February 1986 (after Johnson & Sitar, 1990) (Figure from Leroueil, 2001)

Importance of vegetation

114 Together with rainfall patterns and permeability profiles in the cuts and embankments, vegetation plays a key part in determining pore water pressure regimes through evapotranspiration, and through its influence on infiltration and surface run-off. Evapotranspiration generates suctions in the soils which vary seasonally and penetrate to depths related to the type of vegetation. The cyclic suction changes caused by trees have a larger amplitude and penetrate deeper than grass, leading to a higher potential for progressive failure in plastic clays. The associated cyclic shrinking and swelling can be detrimental to track levels and ride-quality, as discussed above.

115 The analyses of progressive failure described earlier have demonstrated the importance of the magnitude of the sustained suction at the surface of slopes during winter; this can be influenced by vegetation type. As noted elsewhere, vegetation roots also have a reinforcing effect and contribute to soil strength at shallow depths. Vegetation and their roots can also disrupt or block drains or reduce their capacity.

116 Vegetation management should make use of these beneficial effects of vegetation, while appreciating its drawbacks. An example of using vegetation management to improve stability at the Thameslink Resilience Project was provided to us, see Figure 3.19. See also Chapter 9 Vegetation Asset Management.

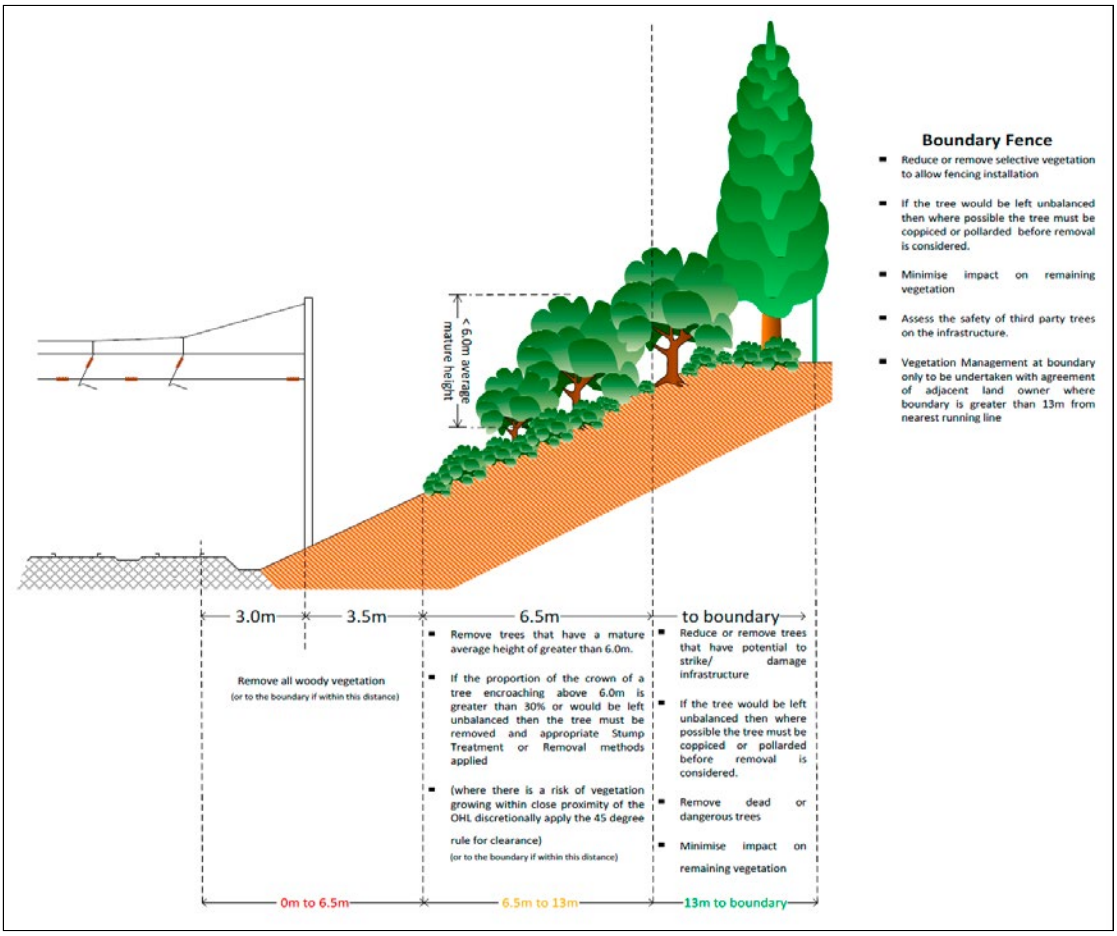


Figure 3.19: Thameslink Resilience Project – an example of planned vegetation management. From 'Valuing nature – a railway for people and wildlife. The Network Rail Vegetation Management Review'. Varley (2018)

Importance of animal burrowing

117 The importance of animal burrowing was demonstrated in the presentation by Ian Payne, RAM for the Anglian region. The burrows can increase permeability and introduce a mechanism for local collapse (see also Para 660). Animals are reported to have reduced the capacity of crest drains (see also Para 514).

Summary

118 Potential reasons for ongoing failures of cut slopes and embankments can be summarised as follows:

+ Increased destabilising forces as a result of
  - increased loading at the head of a cut slope, or increased train loading on an embankment
  - unloading at the toe of a cut slope caused by shallow failures in the weathered zone, or unloading at the toe of an embankment by erosion or excavation
+ Reduced resisting forces as a result of:
  - reductions in strength parameters due to weathering and stress relief (weakening)
  - reductions in strength because of increases in pore pressure resulting from equilibration following excavation, removal of vegetation particularly trees, changes in rainfall patterns involving increased periods of prolonged rainfall and increased rainfall intensity, and resulting from deficiencies in management of surface and sub-surface water, including from third party sources
  - reductions in strength following vegetation removal resulting in the loss of mechanical reinforcement from roots
  - initiation or resumption of progressive failure in plastic clays because of increasing strains resulting from:
    - creep
    - cyclic changes in near-surface pore pressures (ratchetting)
    - cyclic changes in shear stress (fatigue)
  - deterioration of installed stabilising measures, including drainage.

Complex processes, known as progressive failure, operate in the high plasticity clays forming many of the troublesome cuttings and embankments. Drainage is often inadequate to ensure stability and historically was not designed to do so.

Mechanisms and triggers for ongoing failures

119 This sub-section addresses the question: 'what are the mechanisms and triggers for the different forms of failure that have been observed?' It takes as read that loading at the head of the slope and unloading at the toe can be powerful triggers for over-steep slopes and uncompacted embankments.

120 We consider the mechanisms of failure and their triggers that would be consistent with the observed deep-seated 'rotational' and shallow 'translational' failures in cuttings and embankments, earthflows, washouts and debris flows.

Deep-seated 'rotational' failures in cuts

121 **Prior to becoming NR's responsibility and during the dissipation of negative excess pore pressures following excavation, first-time failures in the railway cut slopes are known to have occurred, resulting in the presence of low strength residual shear surfaces within plastic clay slopes. It is essential to be aware of the potential presence of these surfaces and to have an inventory of these historical failures, and the interventions that were carried out, from literature and library reviews.**

122 Reactivation of sliding on low strength residual shear surfaces, formed by these earlier failures, can be triggered by pore water pressures rising above previous maximum and critical values on the surfaces, as a result of prolonged rainfall leading to a rise in groundwater levels or as a result of a deterioration of drain function (Figure 3.20). Surfaces at residual strength may also be present in stiff plastic clay slopes as a result of tectonism, solifluction and previous landslides.

123 This is the mechanism (reactivation of old slides) and these are the triggers (increased pore water pressures) for most of the deep-seated rotational failures that are reported in plastic clays and are the cause of continuing displacements.

124 As discussed above, it seems unlikely that any of the deep-seated rotational failures recorded by NR are first-time failures resulting from pore water pressures generated by the original excavation finally reaching equilibrium values. However, it must be recognised that slopes that have been assessed as over-steep are at risk of deep-seated first-time failure triggered by a rise in groundwater levels above maximum previous values, and in plastic clays by ongoing strains related to creep, cyclic pore pressure changes and cyclic shear stress changes.

125 Properly maintained and designed drainage of sufficient capacity is essential to keep groundwater below required levels in the body of the slope to avoid both first-time failures and reactivation of previous failures.

126 Some cut slope failures recorded as being deep 'rotational' may only be shallow failures which, have been able to drag off some of the underlying soil, particularly when it is relatively permeable.

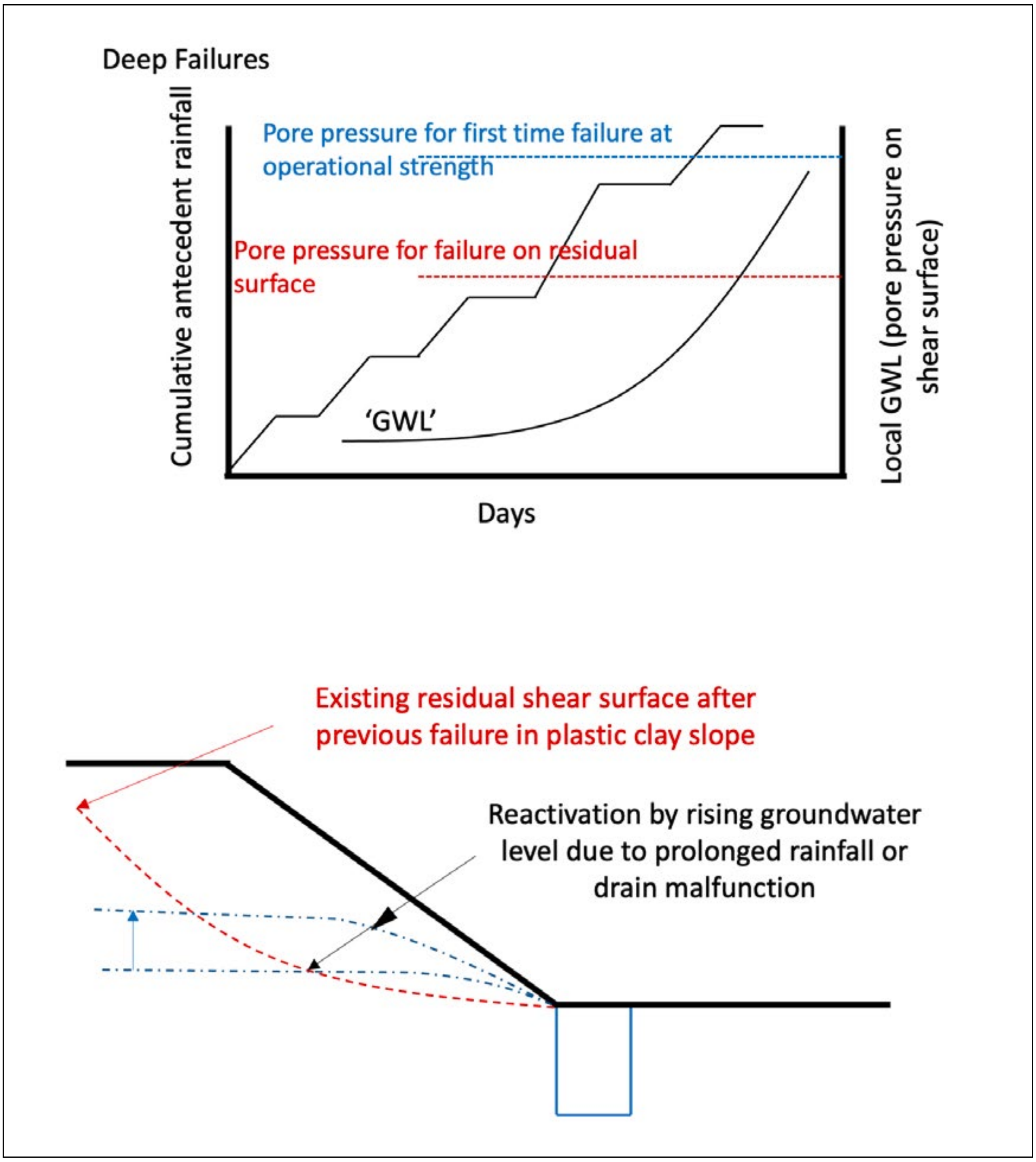


Figure 3.20: Rising groundwater level due to cumulative antecedent rainfall, increasing pore pressures that may reactivate previous failures or trigger first-time failures

Shallow 'translational' failures in cuts

127 One of the mechanisms for the reported shallow 'translational' failures in cuts appears to be sliding of the weathered clay zone at the interface with the unweathered clay or underlying rock (Figure 3.21(a)). Along part of the rupture surface in plastic clay, this may involve sliding on a residual shear surface, developed as a result of differential swelling or cyclic pore water pressure changes that led to ratchetting.

128 A number of triggers that initiate the failure can be envisaged, each of which results from prolonged antecedent rainfall or the absence or reduced efficiency of toe drains:

+ Development of a perched water table in the weathered zone (Figure 3.21(b))
+ A general rise in groundwater levels, increasing pore water pressures at the weathered/unweathered interface (Figure 3.21(c))
+ Downslope flow of water in the weathered zone (Figure 3.21(d)). (An analogy with infinite slope calculations applies.)
+ Water entry into the slope through tension cracks at different locations (Figure 3.21 (e)) which determine the length of the failed mass

129 The shallow failure develops as result of pore water pressures increasing under drained conditions, and so swelling, under an approximately constant shear stress (Figure 3.22). The failure is initiated when the stress path reaches the failure envelope for the clay, and so whether a shear surface is present or not. On reaching the failure envelope, subsequent movement depends on the current undrained strength in the weathered zone. In winter, the strength is low enough for there to be 'flow' as a block, which may be referred to as an earthflow (Figure 3.23). In extreme conditions and if undrained strengths are very low or if water is entrained in the moving mass, the earthflow may degenerate into a mudflow or mudslide. Run-out distances are likely to be greater in winter.

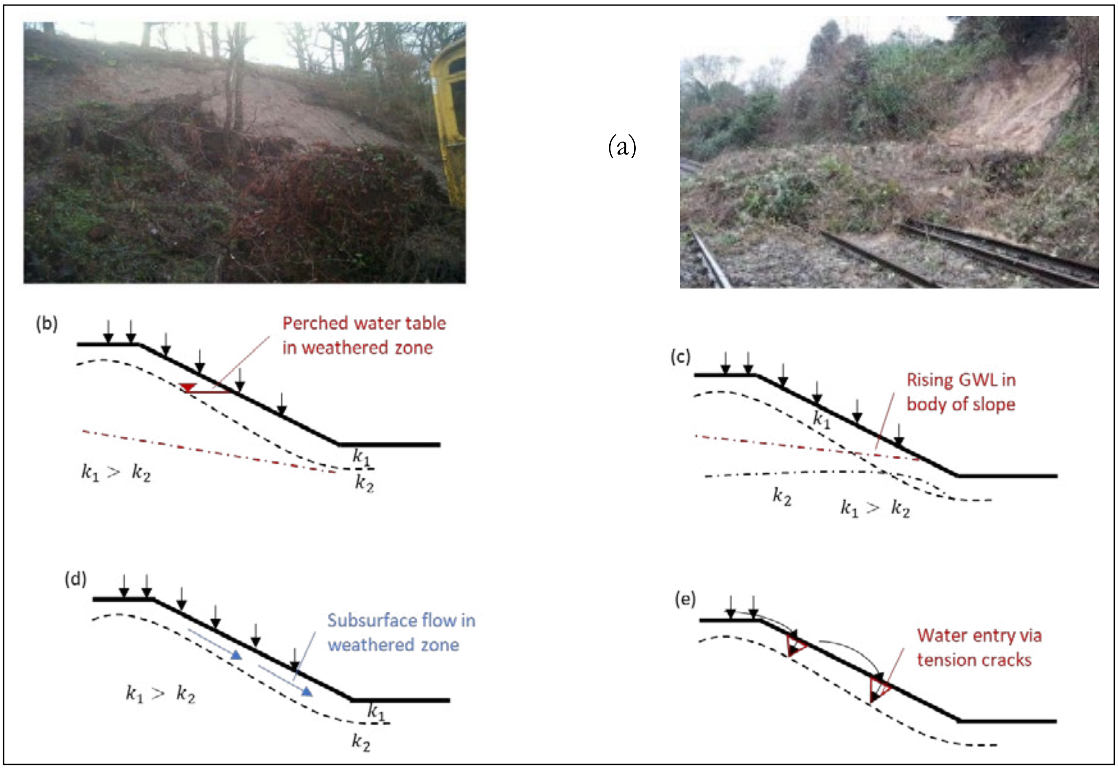


Figure 3.21: Triggers for shallow failures involving sliding in the vicinity of the base of the weathered zone

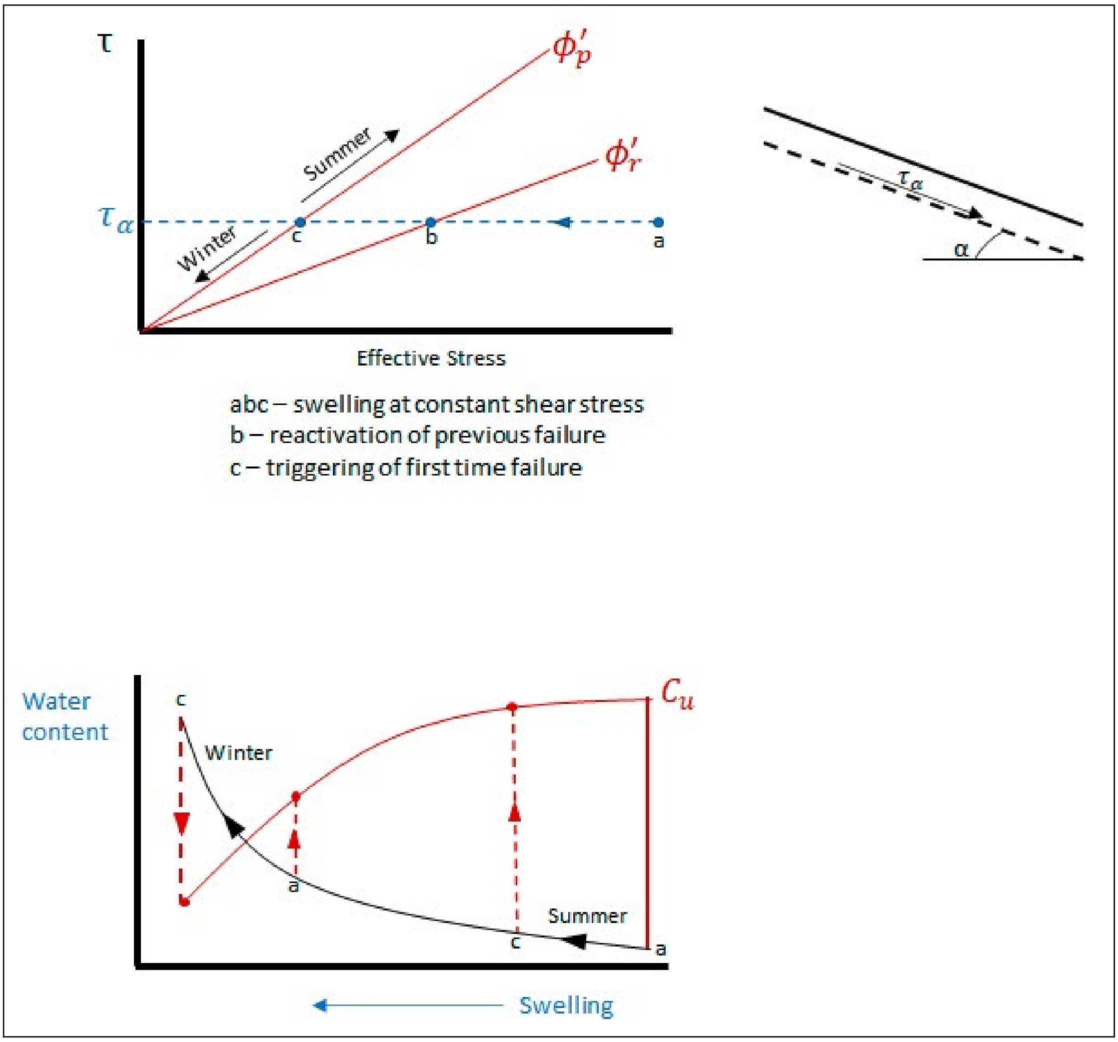


Figure 3.22: Shallow failures involving swelling under constant shear stress

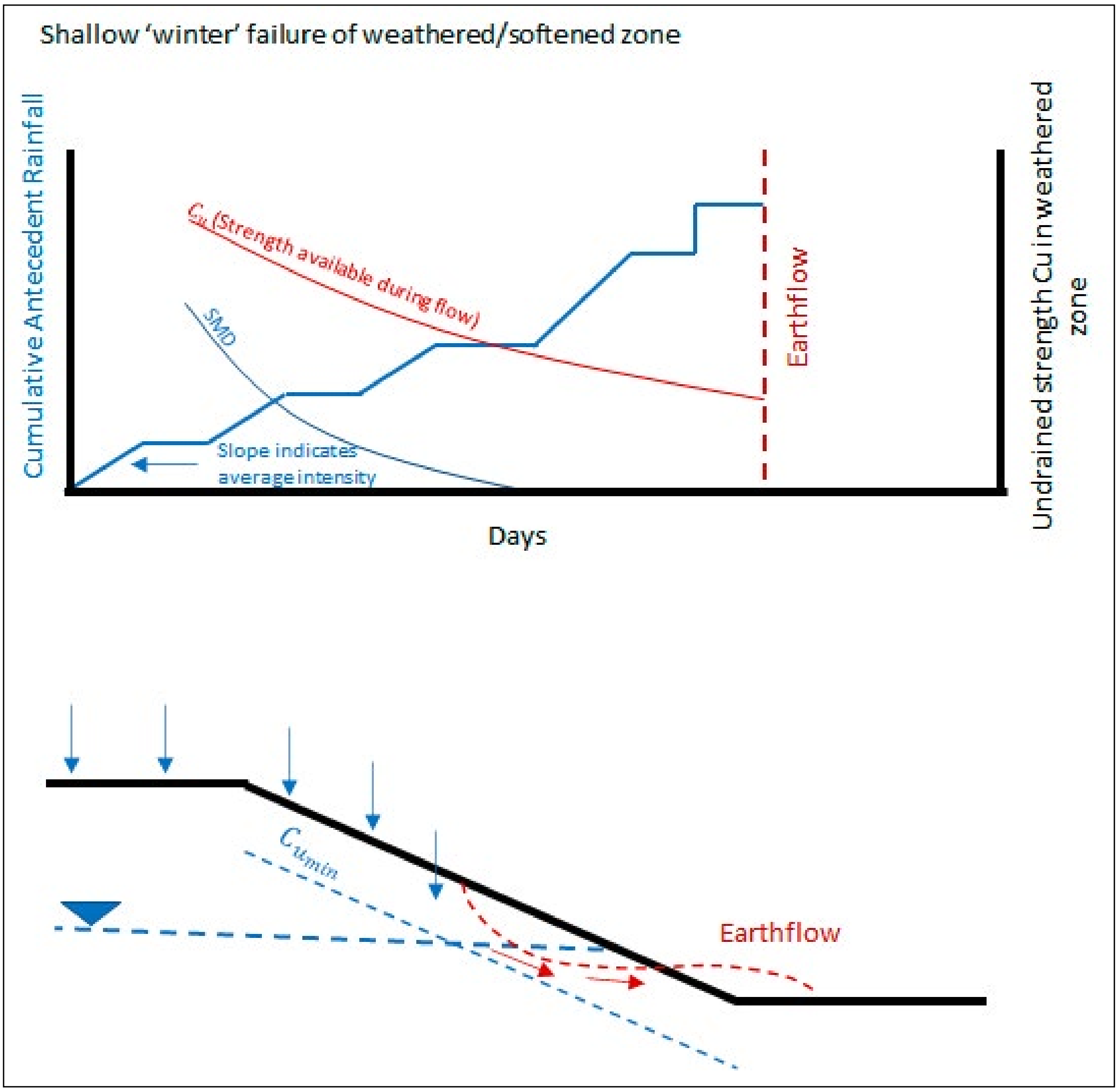


Figure 3.23: Shallow winter failure of weathered/softened zone, developing into an earthflow

130 In summer or autumn, a different mechanism and trigger is envisaged. Pore water pressures are less likely to build up to critical levels and the undrained strength will be such that flow will not occur. Instead it is suggested that where desiccation cracks have developed in a drought these can be infilled during subsequent intense rainfall so that hydraulic forces act on the blocks between the cracks and a shallow slump develops (Figure 3.24). 1976 is a good example of a year in which this type of shallow slope failure occurred when there were a significant number following severe thunderstorms in September and October 1976 which brought the 1975–1976 drought to an end.

131 Shallow failures in permeable soils are likely to be caused by groundwater flowing out of the slope surface, causing internal erosion and/or undercutting of the slope above.

132 Installation of any drainage system at the toe of the slope as a mitigation measure will be difficult because of lack of access space. The use of horizontal directional drilling may provide an option. Where drainage installation is not feasible, and since these local failures will be inevitable, flexible barriers should be installed to provide short term restraint over significant lengths.

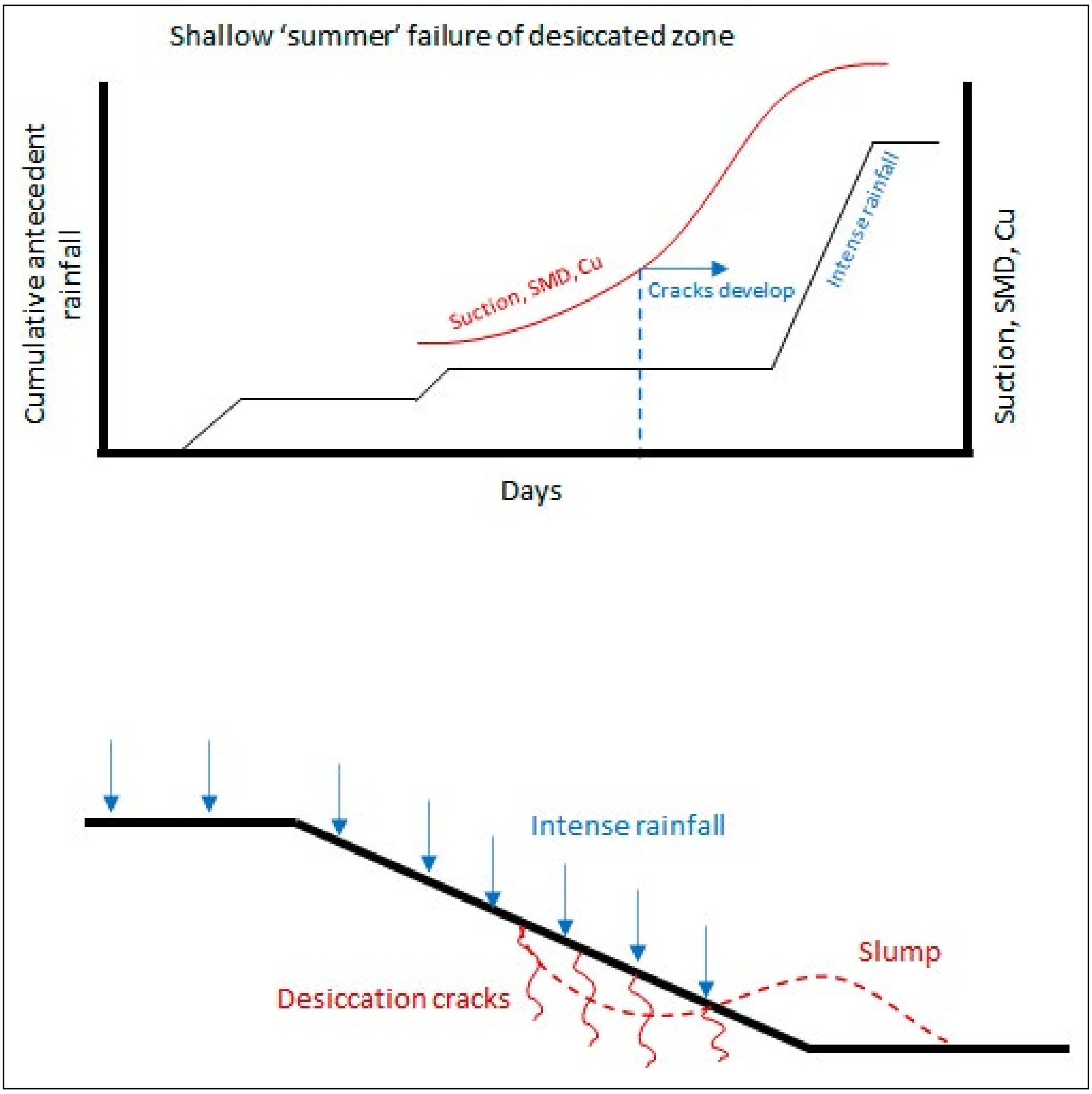


Figure 3.24: Shallow summer failure of the desiccated zone developing into a slump.

Washouts

133 Our understanding of the mechanism for a washout is that of erosion by concentrated over-ground water flows, as illustrated in Figure 3.25 for a cut or natural slope. The erosive power of the water stream increases downslope as entrainment of eroded material increases.

134 Washouts develop during and immediately after intense rainfall over the catchment and slope, especially when the ground is saturated or close to saturation. The importance of antecedent rainfall, which leads to saturated conditions prior to the intense rainfall, is explained by the sketches in Figures 3.17.

135 Any increases in the occurrence or reporting of washouts are likely to be the result of changing weather patterns with increasing durations of prolonged rainfall and increased intensity of rainfall.

136 **Mitigation of washouts requires the provision and maintenance on cut slopes of crest drains of sufficient capacity to deal with third party flows, and channelling features need to be identified, catered for or eliminated. Absence of such mitigation has been the cause of a number of the reported washouts. Crest drains should be provided, regardless of whether they are present on neighbouring land. There is need for a more reliable distinction between washouts, earthflows and mudflows when reporting on failures.**

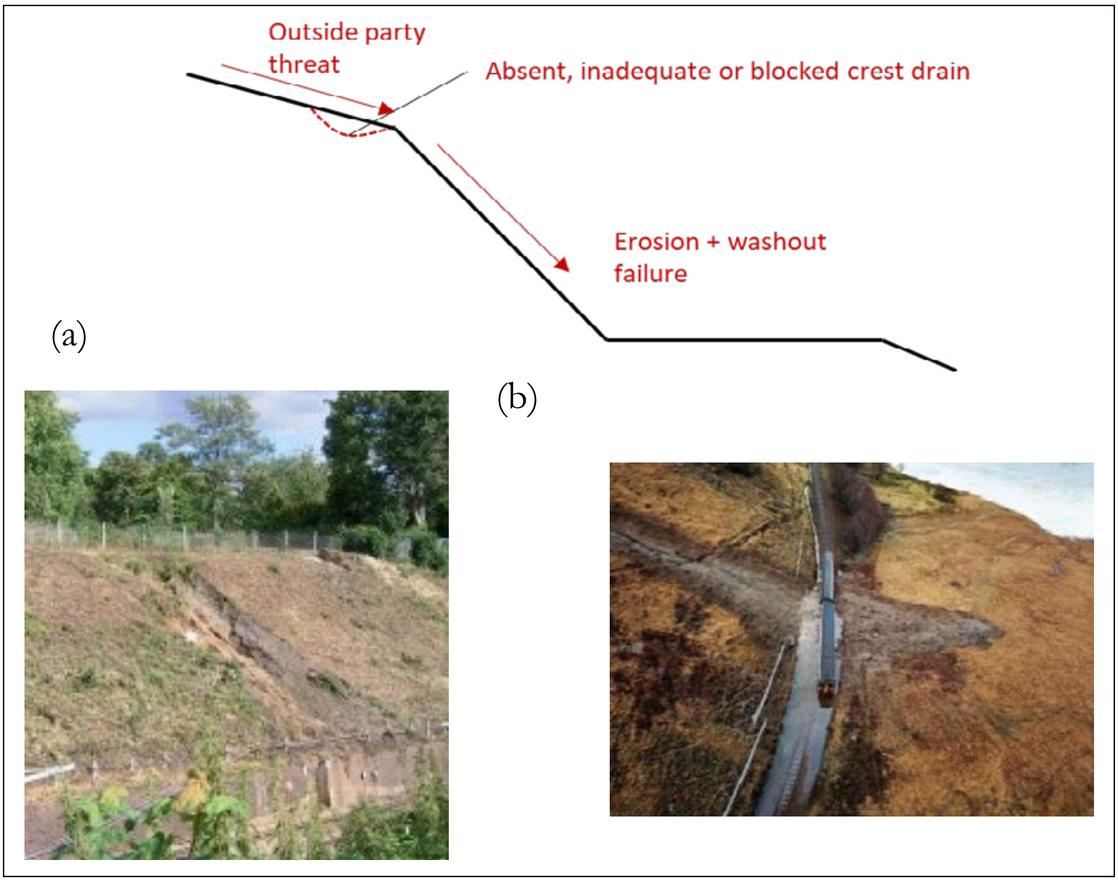


Figure 3.25: (a) Erosion and (b) washout/debris flow

Debris flows

137 Debris flows would appear to be the rapid movement of a mix of vegetation, soil and other objects, associated with intense rainfall and concentrated surface flows. The soil may be derived from surface erosion or from earthflows, initiated as described above. Debris flows may develop from washouts. Further discussion on debris flows is provided in Chapter 6.

Embankments

138 It is not clear if the process of softening of the uncompacted lumps in predominantly clay fill is complete throughout the embankment. The process will be complete in the lower part of the embankment, below standing water, and may have led to first-time failures of the bank in the past. These previous failures are likely to have been reactivated by rises in groundwater levels within the embankment.

139 Creep will be a much larger component of movements in the embankments than in the cuts and has contributed to progressive failure in the plastic clay embankments.

140 Weathered zones will have developed beneath the surface of the embankment slopes in the same way as beneath the surface of the cut slopes. The zones may be deeper because of the higher permeability of the uncompacted fill. As in the cut slopes, these zones will be subject to seasonal cycles of pore water pressure and to ratchetting in the plastic clays, and prone to the development of perched water tables or downward flow of water in the zones. The same failure mechanisms and triggers as in shallow transitional failures in cut slopes are envisaged to have applied.

141 Uncompacted and loose granular fills will be particularly erodible and prone to surface erosion, especially to concentrated flows. The situation shown in Figure 3.26 of an embankment on sidelong ground can be critical with water entering the embankment and, in granular fills, leading to internal erosion and interpretation as washouts.

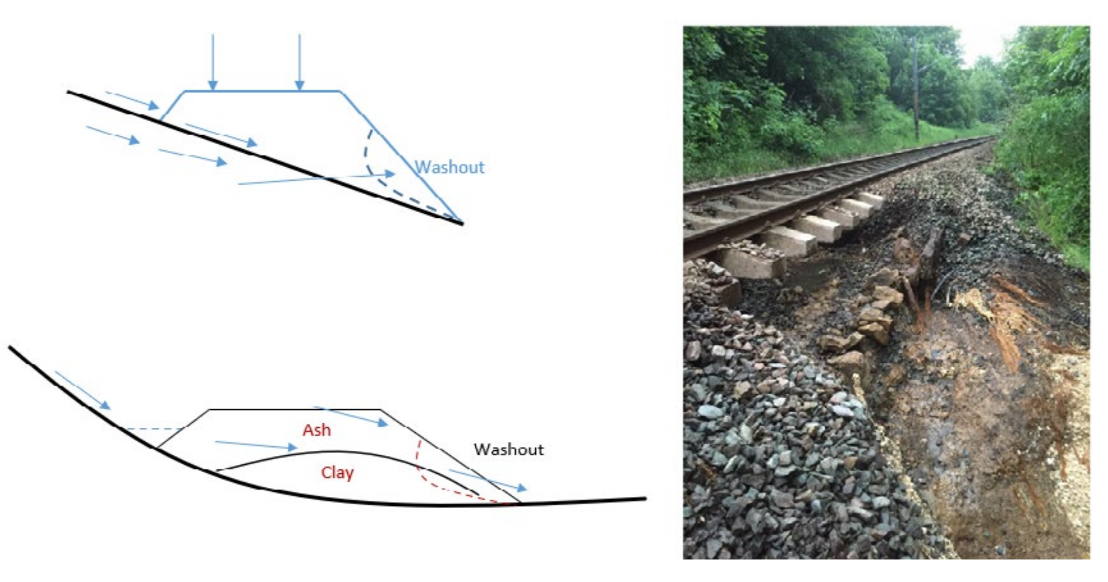


Figure 3.26: Washout failures in embankments on sidelong ground

142 An open structure in uncompacted and loose fills which are predominantly granular can be retained by suctions. When these suctions are lost by inundation, the fill undergoes collapse settlement, and potentially flow for embankments on sidelong ground (for example, Aberfan, Bishop, 1973). The large ballast thicknesses and the use of ash as a make-up fill could be an indication that these collapse settlements have occurred in the past, but equally could be an indication of creep and lateral spreading of the embankment. It is not clear whether the loose open structures still exist and whether their collapse can be put forward as a mechanism to explain some of the distress in embankments. If the loose open structures are still present, they provide a threat to future stability if groundwater levels within the embankment rise above highest previous levels.

Summary

143 **Addressing the question of 'why are both the cuttings and embankments in a range of geologies continuing to fail', observations show that stability of the assets is strongly related to weather patterns, in particular to antecedent rainfall and rainfall intensity. It follows that, while reductions in drained strength parameters over time and changes in vegetation may play a part, the dominant reason for continuing failures is the exposure of over-steep and previously failed slopes, including their weathered zones, to rainfall patterns and pore water pressure values not previously experienced at particular locations.**

Embankment movements

Clay fill embankments

144 Movements of cutting and embankment slopes are important as pre-cursors of potential failures and affect ancillary equipment placed on the slopes. Movements of embankments and their slopes can also be critical to track support and track ride quality, and can lead to restrictions on train operations being imposed. In plastic clay fills the movements are the result of shrinkage in dry summers and swelling in wet winters. O'Brien (2013) notes that climate and vegetation-induced seasonal shrink–swell can either cause excessive track deformation or deep-seated delayed failure, depending on the type and spatial distribution of the vegetation and the prevailing weather patterns. He noted that during dry summers, very high water demand trees caused desiccation of high plasticity clay fills and excessive track deformation.

145 O'Brien (2013) summarises some relatively recent monitoring of NR embankments, one composed of Gault Clay fill, and the other composed of London Clay fill. During the 2-year monitoring period there was a net outward movement of between 10mm and 15mm per annum. The greatest displacements were at the slope surface and were less than 5mm at depths greater than about 4m.

146 In the uncompacted embankments, movements can build up relatively slowly and be relatively large before a complete rupture surface develops. O'Brien (2013) reported that of ninety-five NR embankment failures that developed, about half were classified as deep-seated, with failure through the embankment crest. The rest of the failures were classified as local crest instability, unravelling of over steepened ash/ballast at the shoulder (typically most prevalent during the summer), or shallow translational failures.

Ash-covered clay fill embankments

147 Standing et al (2020) instrumented two London Underground embankments formed of ash and dumped London Clay fill to investigate the mechanisms and causes of movement. The Roding Valley embankment was constructed in 1903 by the Great Eastern Railway with ownership being transferred in 1948 to London Underground. It is an unusually high embankment, which had slipped during construction on clayey alluvium. Up to about 4m of ash has been placed to maintain track alignment, with crest slopes in ash as steep as 1.5 (horizontal) to 1 (vertical). The ash typically is vesicular in nature, well graded, with particle sizes ranging from fine sand to coarse gravel (roughly 40% sand to 60% gravel size by mass), and has an in-situ dry density of about 1 ± 0·2 t/m^3.

148 The monitoring revealed that during drier periods of the year, the ash becomes mobile and the maximum movement occurs at this time. As the track and ballast lie directly on the ash, this leads to track level deterioration. Although not intuitive, shrinking of the underlying clay fill also leads to embankment spreading, but to a lesser degree. During wetter periods, the ash is more stable but the clay fill swells, again leading to lateral movement within the embankments, especially near the slope surfaces, and consequent settlements of the crest and track. The displacements that occur in both periods are mostly irreversible. Very good correlations between soil moisture deficit (SMD), displacements and pore water suctions are evident from the data presented.

Chapter 4

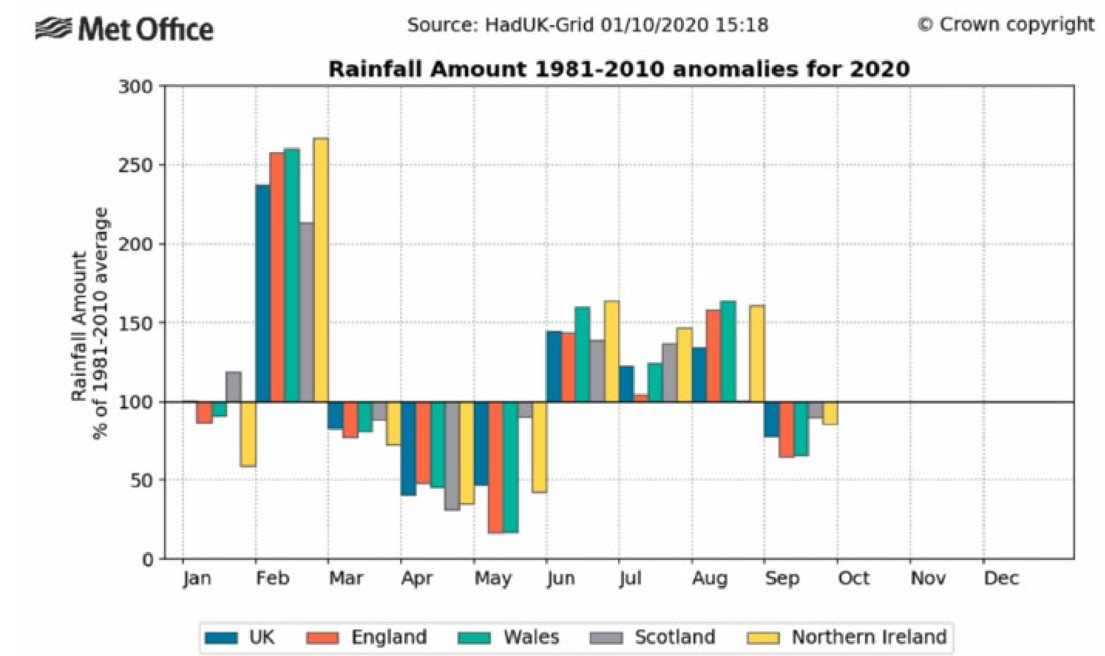
Changing weather patterns and loading

149 The general correlation between earthworks failures and rainfall has been demonstrated in Chapter 2 (Figure 2.14) and is to be expected. The trend of increasing numbers of earthworks failures (Figure 2.15) would be consistent with changing rainfall patterns, involving longer periods of prolonged rainfall in winter. A view has been expressed in discussions with NR, RAIB and ORR that the number of washout failures has increased over the last few years; this would be consistent with increasing rainfall intensities, probably following extended periods of prolonged rainfall. Increasing winter rainfall volumes and increasing rainfall intensity are features of the changing weather patterns associated with climate change, discussed in the WATF Report, Slingo et al (2021).

150 ***A link between earthwork failure type and rainfall pattern is apparent and it is recommended that this link be explored using recent and historical data.*** A preliminary investigation into this link is described in a report by Robbins (2020) and referred to by the WATF Team.

151 Rainfall and rainfall patterns, together with surface and sub-surface drainage, influence groundwater levels and groundwater flows and so influence pore pressures at deep and shallow depths. As discussed in Chapter 3, pore pressures are critical to stability and increases in pore pressures and reductions in suctions will reduce stability.

152 Changes in rainfall patterns have been influencing earthworks failure events and timings over the last several years. There have been four extreme winters in the last 20 years. In 2019/2020 there were four consecutive months of above long-term average rainfall; in February 2020 the monthly rainfall in England and Wales was 2.5 times the 1981-2010 average for that month (Figure 4.1).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UK	100	237	82	40	47	144	122	135	77			
England	86	258	77	48	17	143	104	158	65			
Wales	91	260	81	46	17	160	124	163	65			
Scotland	119	213	88	31	90	139	137	100	90			
Northern Ireland	59	267	72	35	42	163	147	161	85			

https://www.metoffice.gov.uk/research/climate/maps-and-data/summaries/index

Figure 4.1: Time sequence of monthly rainfall anomalies for the UK nations for 2020

153 We understand from discussions with the WATF Team that:

a. Weather patterns and their sequencing will continue to change in the future. This must be taken into account in predictions and assessment of vulnerability.

b. Rainfall totals will increase in a warming climate; Figure 4.2 illustrates the trend of increasing surface temperatures in the UK.

c. Periods of prolonged rainfall in winter will increase, eliminating near surface suctions that, with vegetation, contribute to the stability of near surface layers. Groundwater levels will rise in winter, increasing the risk of reactivation of previous deep-seated slips in plastic clays (containing low strength residual shear surfaces) and increasing the risk of new deep-seated failures. 80% of NR failures follow prolonged rainfall, i.e. rainfall over several consecutive days

d. Periods of prolonged drought and cycles of wetting-drying will increase, accelerating the mechanical weathering of soils and rocks, and contributing to continuing downslope ratchetting by increasing the amplitude of cyclic pore pressure changes. Prolonged drying will increase the depths to which desiccation cracks penetrate, increasing permeability and allowing rainwater to penetrate to greater depths.

e. Rainfall intensities will increase in cyclonic storms, particularly in summer. Run-off (surface flows) and sub-surface flows will increase, particularly after periods of prolonged rainfall, increasing the risk of erosion in erodible soils and wash-out, especially where flows are localised or funnelled, as at tunnel portals. 20% of NR failures occur during or after intense rainfall. 40% of those involve erosion and are classified as washouts.

f. Stronger and more prolonged high winds are likely, increasing the risk of tree falls on to the track.

Although not discussed, changing rainfall patterns will affect preferred vegetation types and the impact of vegetation on stability.

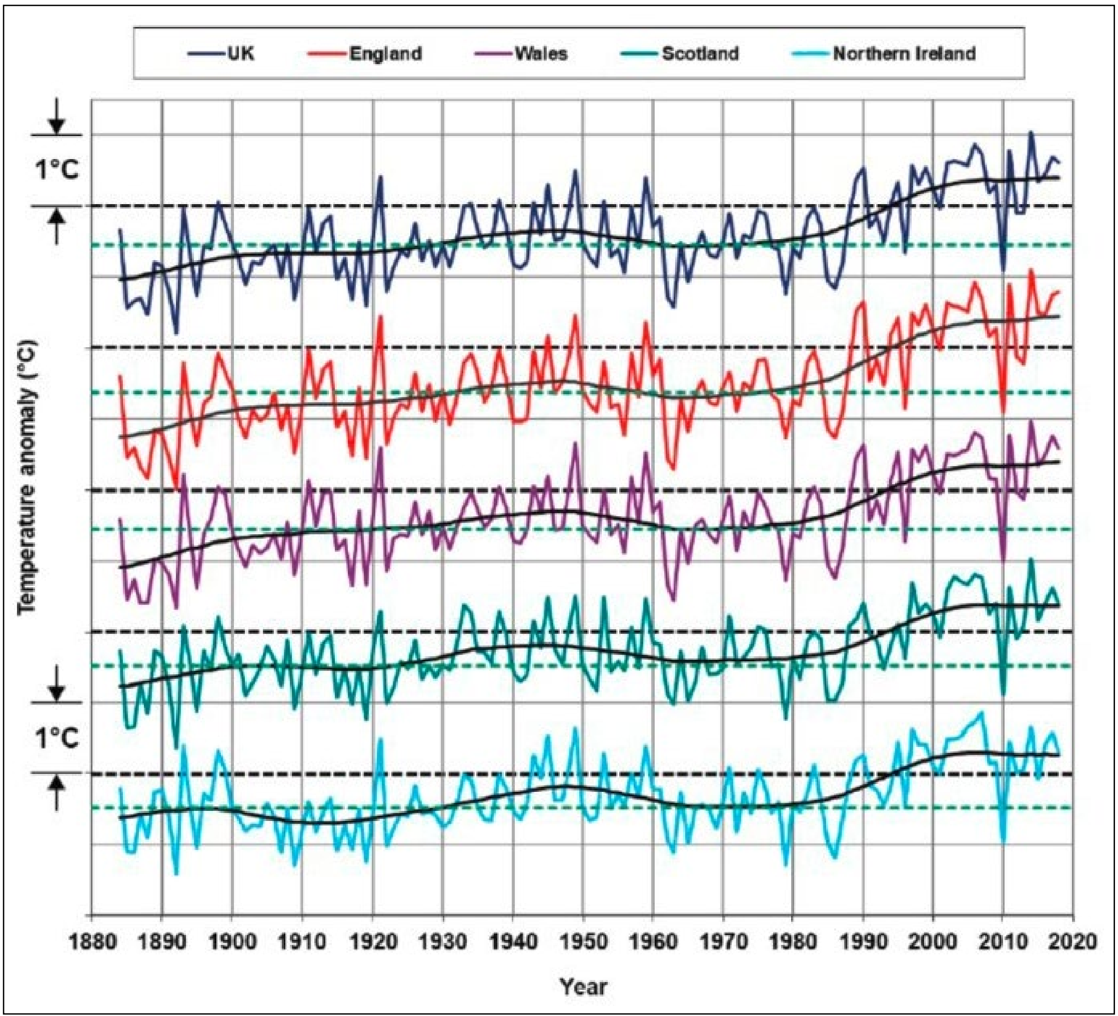


Figure 4.2: Annual mean surface temperature for the UK and countries, 1884-2018, expressed as anomalies relative to the 1981-2010 average (dashed black line). The lower dashed green line is the 1961-1990 long-term average. Light grey grid-lines represent anomalies of +/- 1oC. From Kendon (M.) et al. 2020)

"Rainfall patterns and rainfall intensity are important contributors to the localisation of earthworks failures since both show major spatial and temporal variations. These variations may well increase with climate change."

154 Rainfall patterns and rainfall intensity are important contributors to the localisation of earthworks failures since both show major spatial and temporal variations. These variations may well increase with climate change. The WATF Report (Slingo et al, 2021) refers to the challenges of observing rainfall and rainfall intensity accurately at a location and forecasting the exact locations of the most extreme downpours because of this local variability (i.e. what areas will be bombarded with what rainfall). Localisation means that care must be exercised in using parameters such as Soil Moisture Index which are average values applying to a relatively large area.

155 The WATF Report (Slingo et al, 2021) considers the link between rainfall and hydrology impacts. The link between rainfall and geotechnical impacts involves consideration of antecedent/cumulative rainfall and rainfall intensity, hydrogeomorphology, infiltration, run-off, localisation, and installed stabilisation measures, including drainage. Interaction of these factors makes it difficult to define thresholds for rainfall and rainfall intensity. An approach to combining the effects of rainfall duration and rainfall intensity in setting thresholds for shallow slides and debris flows was described by Caine (1980), from whom Figure 4.3 has been taken. The value of this approach should be checked in the recommended review of the link between rainfall patterns and earthworks failures.

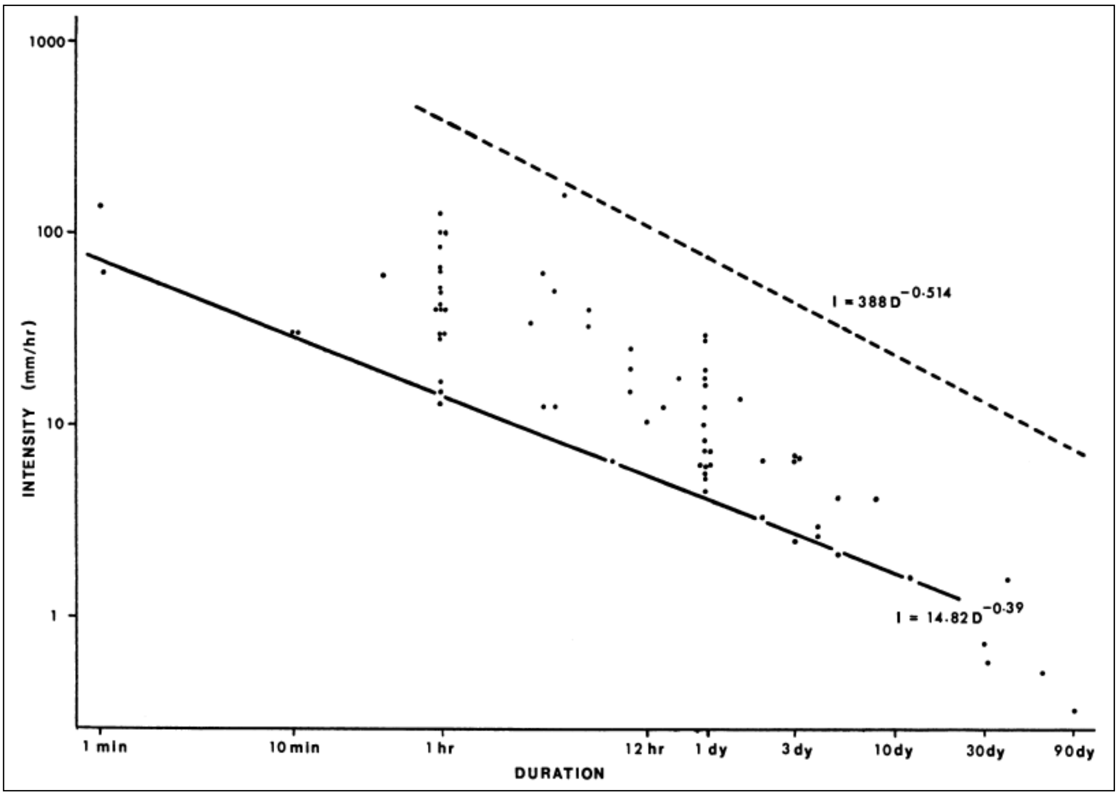


Figure 4.3: Rainfall Intensities and Durations Associated with Slope Failures. I = rainfall intensity (mm/hr) and D = rainfall duration (hr). (From Caine 1980).

156 The threats posed by climate change may be summarised as:

a. **Longer periods of prolonged rainfall in winter months leading to rising groundwater levels and higher pore pressures in earthwork slopes which could trigger first-time slides and reactivation of previous slides in late winter.**

b. **More frequent periods of more intense rainfall which could trigger washouts and debris flows.**

c. **Hotter and drier summers that will increase serviceability problems on clay embankments and will increase the amplitude of cyclic pore pressure changes experienced on the slopes, promoting additional ratchetting failures. Intense rainfall falling on a desiccated cracked slope will result in a rapid increase in pore water pressure and the risk of shallow slope failures of the form described in Chapter 3.**

d. **Increased demand on drainage capacity and the risk of it being overwhelmed.**

157 The impacts of these threats are already being realised in the increasing numbers of earthworks failures. Changing rainfall patterns associated with climate change are, therefore, part of the answer to the question: why are both the cuttings and embankments in a range of geologies continuing to fail?

Chapter 5

Vulnerability of earthworks assets in the future

158 In order to predict whether NR's earthworks assets would continue to fail in the future, with the added burden of climate change, and to assess their level of vulnerability, we set out to answer the following questions.

Why are both the cuttings and embankments in a range of geologies continuing to fail?

159 Soil cutting and embankment slope failures and slope and track movements are continuing to occur for the following key reasons:

a. Cut slopes in plastic clays were excavated at angles which were too steep for them to be stable in the long term. We assume that the majority have failed in the past, and movements on their residual shear surfaces can be reactivated by increases in pore water pressures. Most over-steep slopes have yet to reach their equilibrium geometry.

b. Embankments were constructed by end-tipping on to unprepared ground and the fill received no formal compaction, making it prone to collapse settlements when inundated and to creep settlements. Permeability is much higher than in compacted fill so the embankments are susceptible to both internal and surface erosion.

c. The necessary drainage to deal with these particular challenges has not always been installed or maintained. The need for drainage to control pore pressures and stability was not foreseen at the time of original construction.

d. Weathering has created a zone of weaker and higher permeability soil on slopes, which, in the cuts, are often over-steep, making the weathered zone vulnerable to slips when pore water pressures rise due to prolonged rainfall.

e. After the end of steam locomotion, vegetation developed on the slopes, largely unmanaged. Removal from slopes of vegetation for inspection or remediation purposes has sometimes been a trigger for failures.

f. The slopes are subject to seasonal pore pressure cycles which can lead to increasing downslope movements and failure by ratchetting in plastic clays.

g. Weather patterns have changed. Longer periods of prolonged rainfall in winter have resulted in more infiltration and higher pore pressures that provide the trigger for new deep and shallow slides, and reactivation of old slides. Increasing rainfall intensity has led to more run-off and increasing numbers of washouts and debris flows. Hotter drier summers have led to increased depths of desiccation cracking.

h. Slope failures occur locally where local adverse conditions coincide with local triggering events. This is localisation and is key to understanding why failures can continue. The process is discussed below.

i. Previously installed stabilising measures and drainage have deteriorated.

j. Slopes are undergoing strains due to creep and cyclic changes in pore pressure and shear stress; these strains can promote progressive failure.

k. Changes have taken place in land use and drainage beyond NR's boundaries.

The potential mechanisms and triggers for earthworks failures are discussed in Chapter 3.

Localisation

160 Generally, long lengths of an ostensibly similar slope do not fail as one, but failures are localised and may occur at different times. The location and triggering of many failures are the result of a series of local factors that coincide at a particular point, including:

a. over-steepening

b. channelling of run-off because of topography or vegetation

c. infiltration from neighbouring land drains

d. blocking, failure or absence of crest or toe drains

e. intensity of rainfall

f. variations in soil properties and soil profile

g. impact of rainfall pattern on pore pressure regime

h. presence of permeable seams or lenses

i. reduced resistance because of the presence of unfavourably oriented discontinuities or faults, or of intense weathering

j. vegetation type and density of coverage

k. activities beyond NR's boundaries.

Localisation of failures means that predicting exactly where failures will occur is like looking for a needle in a haystack. In the case of the railway slopes the practical approach is to search for the haystacks, i.e. the vulnerable lengths of slope. The fact that a localised failure has occurred is a strong indication that the remainder of the similar slope is vulnerable to future failures. *Having identified the lengths of slope that are vulnerable to shallow failures, we recommend that consideration be given to the installation of instrumented barriers of the form described in Chapter 10.*

Will failures continue to occur?

161 **Rainfall patterns are predicted to continue to change: periods of prolonged rainfall will increase, resulting in more infiltration and rising pore water pressures; rainfall intensity will increase, resulting in more surface water run-off. Drainage and other stabilising measures will continue to deteriorate. It follows that soil cutting and embankment failures and slope movements will continue, taking the form of deep-seated and shallow slips, earthflows, washouts and debris flows. These are the challenges facing NR when trying (a) to minimise the risk of failures; (b) to identify failure locations immediately; and (c) to mitigate the effects of failures by the use of restraining measures.**

Rainfall patterns are predicted to continue to change: periods of prolonged rainfall will increase, resulting in more infiltration and rising pore water pressures; rainfall intensity will increase, resulting in more surface water run-off. Drainage and other stabilising measures will continue to deteriorate. It follows that soil cutting and embankment failures and slope movements will continue, taking the form of deep-seated and shallow slips, earthflows, washouts and debris flows.

Which assets are the most vulnerable to future failures?

162 With an understanding of the potential failure modes and triggers based on soil mechanics principles, the confirmed links between failures, rainfall and soil type, and using the lessons learnt from our partial review of the historical failures, it is possible to identify the key factors determining the vulnerability of the cut slopes and embankments to failures in the future, and so determine priorities for surveillance, monitoring, mitigation and intervention. The lists below are offered as checklists to ensure that none are missed from NR's future methods of assessment.

Vulnerability of cut slopes to failures in the future

163 The following factors determine the vulnerability of cut slopes to failure in the future:

a. Age of the cut slope.

b. Setting of the cutting within the landscape, including orientation/aspect, location within existing landslides. The setting will determine potential catchment areas and third party threats, and can influence the run-out distance of the failing mass, determining whether or not it reaches the track.

c. Geometry of the cut in terms of slope angle, height, bench dimensions; geometry in relation to the safe slope angle for the particular soil type and cut height; safe slope angles based on observation depend on whether or not drainage is present; in stiff plastic clays safe slope angles appear to be around 14 degrees, in sandy clays (glacial tills) between 33 and 36 degrees; NR's failure database should enable these values to be refined.

d. Geology: soil or rock; soil type – composition, plasticity (whether ductile or brittle), stress history, heterogeneity, macro- and micro-fabric, microstructure, water content, relative density, discontinuities, erodibility, resistance to weathering; rock type – material strength, discontinuities, mass strength, resistance to weathering.

e. Mass permeability and its spatial variation; ease of water ingress and egress.

f. Hydrogeomorphology – scope for channelling of run-off.

g. Past, current and future weather patterns (antecedent and cumulative rainfall and rainfall intensity, droughts).

h. Past, current and future pore water pressure regimes in the slope – maximum values and cyclic amplitude.

i. Natural and installed drainage, including its location, state and level of maintenance.

j. The presence, state and remaining life of other historical stabilising works.

k. Vegetation type and permanence; vegetation can provide protection against erosion and increase suction levels in the near surface zone, as well as adding root reinforcement; de-vegetation eliminates these effects.

l. Past and current stability, especially in plastic clays:

   - the presence of low strength residual shear surfaces resulting from previous failures, and

   - the presence of slopes in which progressive failure had previously been initiated but failure had not occurred because of depressed pore water pressures or limited slope height. The continuing stability of these slopes depends critically on the pore water pressures in the body of the slope remaining at low levels. If these pore water pressures rise sufficiently, the failures will be abrupt and involve large displacements.

m. Trends in the rate and magnitude of slope movements.

n. The presence, depth, range of undrained strength and permeability of a surficial weathered zone.

o. The threat posed by burrowing animals.

Vulnerability of embankments to failures in the future

164 The following factors determine the vulnerability of embankment slopes to failure in the future:

a. Geometry in terms of embankment height and slope angles. As noted in Chapter 3, safe slope angles cannot be defined for the uncompacted fill embankments.

b. Composition and plasticity of the soils within the embankment.

c. Current state of the fill in terms of density, lump strength, groundwater level. Together with composition these determine the form of failure (collapse settlement on inundation, spreading, erosion, washout, etc), and the risk and rate of failure.

d. Foundation condition, including whether the embankment is under-drained or not.

e. History of previous failures and of groundwater levels within the embankment.

f. Age and state of stabilising works, including drainage.

g. Setting of the embankment within the landscape and relative to existing landslides, in particular its position on sidelong ground, and proximity to water courses with their risk of flooding and causing toe erosion.

h. Train loading, particularly dynamic loading resulting from reducing track support.

i. Threat posed by burrowing animals.

j. History of mining.

Inventories

165 Assessing the level of vulnerability to future slope failures and slope movements is dependent on having up-to-date and comprehensive inventories containing the following information:

a. Cut slope and embankment geometries: as-constructed and current, identifying slopes which are over-steep and have not failed; date excavated or constructed; setting in the landscape.

b. Predominant soil behaviour type of each cut, based on geology and on soil composition and plasticity.

c. Current state of the embankment fill, in terms of profiles of composition, plasticity, density, water content, undrained strength and permeability; records of previous ground investigations, including any cone penetration test (CPT) profiles; details of foundation.

d. Groundwater levels and typical pore pressure regimes.

e. History of previous deep-seated failures and movements along the length of the cutting or embankment, and whether low strength residual surfaces are present.

f. History of previous stabilising measures in failed and unfailed slopes, when installed and their current state.

g. The type, size, installed depth, state, current capacity of installed drainage (earthwork and track).

h. The presence, type, density and state of vegetation.

i. Third party threats.

166 We are aware that inventories of drainage assets and vegetation have not yet been completed. We understand that asset geometries are being revised on the basis of LiDAR surveys. We are not aware of inventories of historical failures and interventions, pre-2003, but we understand that this information, where it exists, will reside in the National Records Group in York. We are also not aware of any results of intrusive investigations of embankments.

Pore pressures and soil moisture

167 **There is insufficient information on pore water pressures and suctions in slopes and embankments and on their response to different rainfall and weather patterns.** ***We recommend that consideration be given to more widely monitoring pore water pressures in earthworks to obtain a more detailed understanding of the behaviour and stability of a particular slope or embankment that is judged to be critical.***

168 **Currently use is being made of Soil Moisture Index, SMI, in some of NR's analyses. We and the WATF Team have reservations about this parameter.** ***We recommend that, instead of SMI, use is continued to be made of Soil Moisture Deficit, SMD, but in combination with and with much greater emphasis on cumulative antecedent rainfall and rainfall intensity.***

Post-failure investigations

169 **We note that neither NR nor RAIB tend to carry out post-failure intrusive ground investigations for forensic purposes; in the case of NR this is driven by the priority to re-open the track as quickly as possible and to obtain information for the design of remedial works.** ***Investigations of earthworks failures should provide information on: the extent of the catchment; the rainfall pattern that has been experienced, in terms of antecedent/cumulative rainfall and rainfall intensity; the vegetation in place at and in the vicinity of the failure; soil and rock properties (to be considered on a site-by-site basis based on complexity and size of failure)***

– as a minimum bulk samples should be taken of the material involved for measurement of composition and plasticity; geometry of the slope and failure, including run-out distance; state of the adjacent ground, including depth and strength of the weathered layer; potential contributors to localisation and trigger, including evidence for concentration of flows, local weaknesses, infiltration versus run-off, water seepages; the drainage that is in place – its state, capacity and prior maintenance.

Summary

170 The risk of future deep-seated cut slope failures is likely to be highest in cuts in stiff plastic clays:

- **which are over-steep and have not failed previously**
- **which have failed previously, are still over-steep, and rely on deep drainage and other stabilising measures for safety against reactivation**

The main threat is a rise in groundwater levels, and so rise in pore water pressures, associated with climate change or with a deterioration in drainage function, or both.

171 The risk of shallow translational failures in cuts is likely to be highest:

- **in stiff plastic clays on which a softened weathered zone has formed on an over-steep slope which has undergone downslope ratchetting movements that will continue with larger amplitudes of cyclic pore pressure changes**
- **In more permeable soils in which groundwater rises to such an extent that water enters the overlying weathered and vegetated layer**

172 The risk of washouts is likely to increase because of increasing rainfall intensities and rates of over-ground flows. Erodible soils in cuts and embankments will be most at risk. Debris flows remain a threat. The lack of prior warning for washouts and debris flows and the speed at which they develop are a major problem for NR.

173 **The risk of failures of embankments is likely to be highest:**

- **in embankments comprising uncompacted clay fill in which standing water levels can exceed previous maxima; Briggs et al (2013a) provide information on the importance of the relative permeabilities of the embankment and its foundation**
- **in embankments comprising permeable soils through which increased rainfall can pass through, causing erosion**
- **in embankments on sidelong ground**

174 **A key factor in determining future stability is the provision and maintenance of drainage of sufficient capacity to cater for the increased demands arising from climate change and changes in neighbouring land use.**

Chapter 6

Rock cuttings and vulnerability in the future

Introduction

175 Rock cuttings are defined here as those that are assessed using NR's modified version of the Rock Slope Hazard Index developed by the Transport Research Laboratory (TRL) for highway rock slopes in Scotland. The application of this is discussed in detail in Chapter 7. The rock slopes covered by this assessment tool are those where the stability is essentially controlled by the character and orientation of naturally occurring joints or fractures (discontinuities). As well as cuttings, rock slopes below the railway in sidelong ground are covered by this assessment tool.

176 Rock cutting slopes tend to be steep and in general terms stable at the scale of the whole cutting slope. Failures in rock cuttings take the form of falls of individual blocks or localised groups of blocks rather than failures of the cutting. These failures can be classified according to the orientations of the discontinuities bounding the failure:

+ Planar failures are those where a block slides out on a single discontinuity
+ Wedge failures are those where a block slides out of a groove formed by a pair of discontinuities

- Toppling failures are those where blocks rotate out of a slope
- Ravelling failures. In this context ravelling failures are those that involve a loss of blocks caused by a surface loosening of the cutting slope. This loosening could be created by weathering, root growth or erosion

177 In the UK most existing natural large scale inland rock slope failures occurred in prehistory and were caused by combinations of initial glacial oversteepening followed by post-glacial stress and climate change. Stress changes occurred on a local and regional scale. Examples of local stress changes would be de-buttressing of steep slopes by ice loss and by local stress relief possibly inducing additional jointing. Wider scale stress relief effects would include neo-tectonic and seismic events related to ice loading and unloading. Distant echoes of these stress changes are still felt in the UK today.

178 Climate-based changes led to physical weathering (freeze-thaw), enhanced erosion, enhanced dissolution of soluble rocks in colder temperatures and variations in vegetation cover.

179 All these types of stress, climate or weather-related effects on rock slope stability apply to a lesser degree in today's more stable climatic conditions. It is worth noting that some of the UK interglacial temperatures were considerably warmer than today's temperatures and that prior to man-made climate change there has been substantial climatic variation over than last 10,000 years.

180 The reason large non-coastal natural rock slope failures are relatively rare in the UK is that the existing natural rock slopes have already experienced a great deal more external change than is being experienced now.

181 This does not apply to relatively new man-made rock slopes such as those found alongside railway infrastructure. Hence the question here is how do these relatively 'new' slopes degrade with age and which aspects of this could be affected by the changing weather patterns referred to in Chapter 4 and described in the WATF Report, Slingo et al (2021).

Rockfall triggers

182 Discounting man-made causes of instability (loading, excavation, and blasting), the immediate triggers for rock falls from steep slopes can be classified into two groups:

(a) those not affected by increases in the frequency of extreme weather events:

+ Seismicity
+ Stress relief
+ Freeze-thaw
+ Dissolution of intact rock
+ Physical and chemical weathering leading to strength changes
+ Disturbance by animals or birds

(b) those that are potentially affected:

+ Increased water pressures in discontinuities
+ Erosion or dissolution of discontinuity infill
+ Erosion by surface water
+ Disturbance by vegetation

183 The timescales considered in this Review in relation to changing weather patterns and to NR‘s processes are relatively short term (i.e. decades) in relation to the first group of instability triggers, so these are not considered any further. Many of these could occur regardless of any medium-term weather changes related to global warming and climate change.

184 The second group of triggers do have the potential to become more frequent immediate causes of rock falls. These are discussed in general terms below and then in relation to different types of rocks found in NR cuttings.

Geological background

185 In general terms the following statements can be made about surface geology in the UK:

+ Younger sedimentary rocks are weaker than older sedimentary rocks
+ Coarser grained and generally more permeable sedimentary rocks tend to have larger joint (discontinuity) spacings than finer grained sedimentary rocks
+ The youngest rocks are largely found in the south east of the country and the oldest in the north
+ Distortion of rocks (folding and faulting) in the UK is greatest in hilly or mountainous areas of Britain where railways are relatively rare. These areas tend to be associated with stronger rocks. In England steeply dipping strata are far from the norm in low relief areas where railway track is mostly found
+ The bedrock in a strip from the Bristol Channel to Lincolnshire through the English Midlands is dominated by mudrocks, materials that often tend to behave in a soil-like fashion rather than a discontinuity-controlled rock-like fashion
+ Geologically speaking, much of the lowland UK's bedrock is covered by glacial deposits north of a line from mid-Wales to south Essex and that most exposed rocks south of this line would have experienced sustained periods of permafrost and near surface freeze-thaw cycles during glacial cold spells. There are fewer rock exposures in these areas

All these statements can be explained in terms of the UK's overall geological history.

186 There are many exceptions to these broad-brush statements but despite this they remain useful when considering the expected and actual distribution of rockfalls in railway cuttings.

187 Combining these statements, rock cuttings might be expected to be more frequent in weaker rocks with smaller discontinuity spacings, with the greatest frequency of rock falls in those areas where weaker rocks dominate the railway environment; a high proportion of these incidents would involve ravelling types of failures (release of low volumes of small blocks).

188 This is borne out in practice, as can be seen in Figure 6.1, which shows the distribution of rockfall events in cuttings since 2003 overlain on a geological bedrock map of the UK. The failures tend to cluster in the weaker rocks of the south east (especially the Chalk) and the Carboniferous rocks of South Wales, the Pennines and the central belt of Scotland. The clusters of failures in the south west are split between the Devonian sedimentary rocks and the granites that are intruded into them. It should be noted that the distribution of failures is also affected by the density of railway track and by the hilliness of the terrain.

Those failures marked with an R are ravelling type failures.

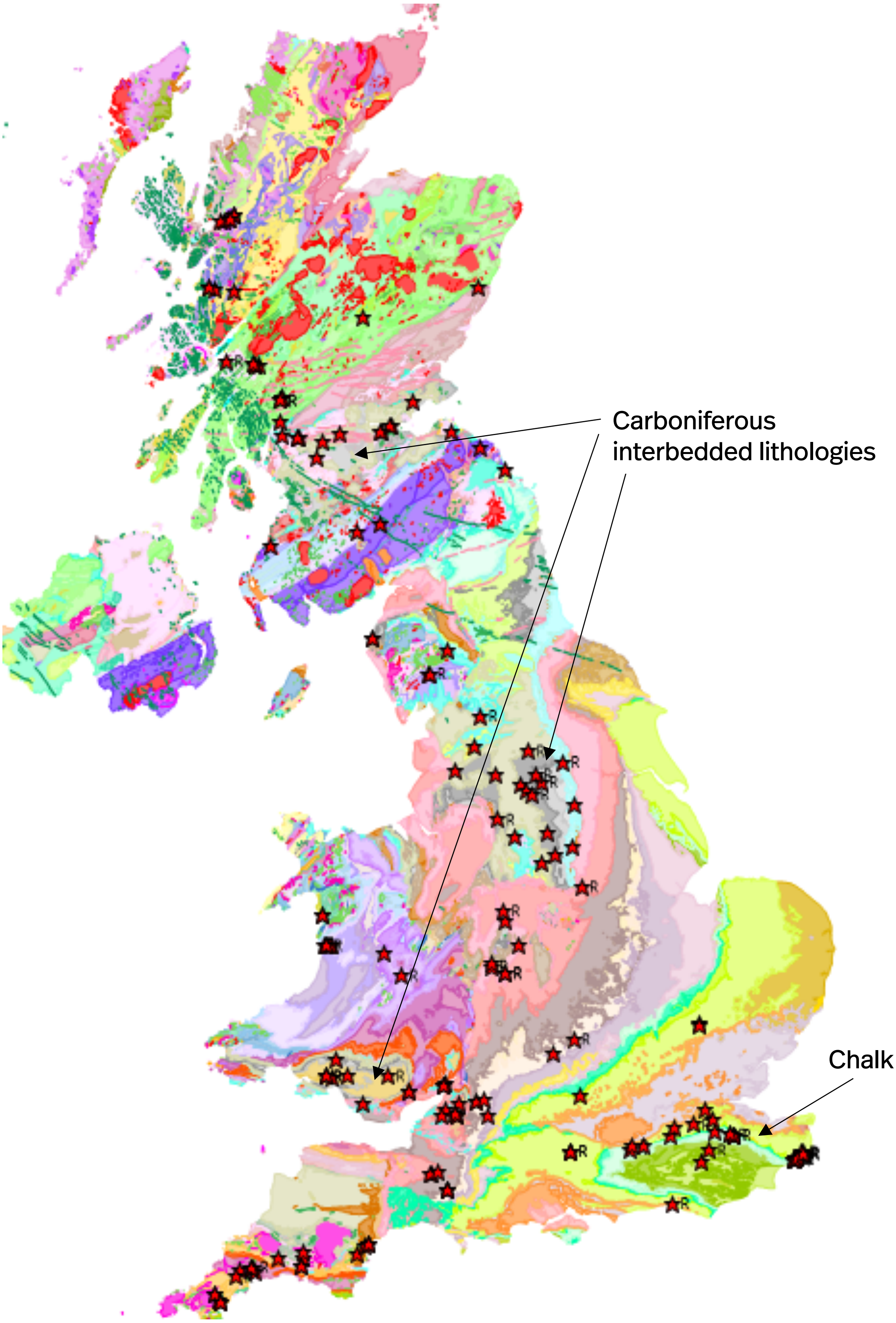


Figure 6.1: Rock failures in cuttings 2003 to 2020 overlain on the BGS 1:625000 solid geology map. 'R' denotes a ravelling failure. A legend for this map can be found at http://mapapps.bgs.ac.uk/geologyofbritain/home.html

189 Rockfalls related to discontinuity orientations (planar, wedge and toppling failures) conversely tend to be found in older, stronger rocks, where rock joint orientations may not be orthogonal and may be without a near horizontal component. These failures are rarer, but they have the potential to have a greater disruptive impact. This lower occurrence is likely to be related to a lower density of railway track and rock cuttings (partly because of the presence of glacial materials masking the bedrock) and the presence of stronger rocks. The greater severity is related to the potential for stronger and larger volume blocks falling on to the track.

190 The rockfalls in the western Highlands of Scotland are all located in mountainous regions where designing and constructing the Victorian railway was extremely challenging. There are alignment arrangements there that probably would not be considered if these routes were being designed today.

191 Rock types found in cuttings are broadly classified into four groups as they relate to the potential weather-related rockfall triggers listed above. These are set out in Table 6.1.

	Typical lithologies in an NR cutting	Examples of named strata in NR cuttings	Typical characteristics relating to cutting stability
Igneous and metamorphic rocks	Dolerites, granitic rocks, schists etc.	Relatively rare in an NR setting. Mostly found in or close to upland settings	Very strong rocks, well defined often non-orthogonal joint sets, often widely spaced. Intact rock permeabilities very low, fracture permeability can be low or high. Not normally easily erodible.
Single sedimentary lithologies with large joint spacings	Sandstones and some limestones (excluding Chalk)	Sherwood Sandstone (Liverpool Lime Street Station approaches). Carboniferous limestones (Settle-Carlisle)	Weak to strong rocks, intact rock permeabilities low to moderate, fracture permeabilities can be high. Not normally easily erodible.

	Typical lithologies in an NR cutting	Examples of named strata in NR cuttings	Typical characteristics relating to cutting stability
Single sedimentary lithologies with small joint spacings	Chalk	Chalk, excluding the lower Chalk which has soil-like characteristics. (Cuttings through the North Downs south of London).	A weak rock, intact rock permeabilities low, fracture permeability high. Not normally easily erodible.
	Mudstones	Mudstone cuttings are not usually classed as rock cuttings by NR. Mudstones in rock cuttings tend to be found with other lithologies as set out in the row below.	

	Typical lithologies in an NR cutting	Examples of named strata in NR cuttings	Typical characteristics relating to cutting stability
Sedimentary rocks with mixed interbedded lithologies	Repeating sandstone, siltstone, mudstone and sometimes limestone sequences.	Carboniferous, Permian and Devonian sandstone, siltstone, mudstone sequences. As found in parts of the South West, South Wales, the Pennines and the central belt of Scotland	Mixed weak to strong rocks. Intact rock permeabilities can vary significantly from lithology to lithology creating a strong bedding parallel anisotropy in bulk permeability. Fracture permeabilities are lithology dependant but can be high in stronger lithologies. This could facilitate groundwater flow out of cutting surfaces. Potentially susceptible to differential erosion between interbeds. If folded it is possible bedding parallel reduced shear strength horizons exist in the weaker beds due to interlayer slip during folding.

Table 6.1: A simple classification of cutting rock types

"Rock cutting slopes tend to be steep and in general terms stable at the scale of the whole cutting slope. Failures in rock cuttings take the form of falls of individual blocks or localised groups of blocks rather than failures of the cutting."

Qualitative risk assessment

192 The implications of increasingly adverse weather on the weather-related rock fall triggers set out above are briefly described below; Table 6.2 contains a qualitative view of increased stormy weather risk for each of the rock type classes .

Increased water pressures in discontinuities during storm events

193 These could be caused by temporary increases in groundwater levels (including groundwater flooding), external surface water flooding or surface water infiltration from above. Each of these sources of water potentially arrive in the discontinuities at the cutting face from different directions and could potentially impose additional water pressures.

194 The consequence of this occurrence is potentially reduced shear strengths on discontinuities which, if they are unfavourably orientated, could lead to blocks falling from a cutting face.

Erosion or dissolution of discontinuity infill during storm events

195 This is similar to the previous point except failure would be triggered by water flowing through the cutting material, eroding discontinuity infill from within, leading to loosening of blocks. In practice distinguishing this failure mode from the increased water pressure mode could be difficult.

Erosion by surface water during storm events

196 This refers to the direct physical removal or undermining of blocks by flowing water.

Disturbance by vegetation during storm events

197 As well as the normal potential for root systems to lever blocks out of cutting faces, in very windy conditions shrubs and trees could additionally lever blocks out of rock cutting slopes without themselves becoming dislodged.

198 All except the last of these mechanisms could also provide delayed triggers for block falls in the event of a storm that involved heavy snowfall followed by a rapid thaw.

	Increased water pressures in discontinuities	Erosion or dissolution of discontinuity infill	Erosion by surface water	Disturbance by vegetation
Igneous and metamorphic rocks	Moderate	Low	Low	Low
Single sedimentary lithologies with large joint spacings	Low	Low	Low	Low
Single sedimentary lithologies with small joint spacings	High	High	High	High
Sedimentary rocks with mixed interbedded lithologies	High	High	High	High

Table 6.2: Risk of increased frequency of block fall incidents with increased storm frequency

199 **Quantification of the potentially increased risks for rock cuttings would require enhanced geological and hydrogeological knowledge of the ground below, behind and above cutting faces.** Much of this information is likely to be obtainable via desk-based studies carried out by suitably experienced engineering geologists. ***It is recommended that NR give consideration to incorporating an enhanced classification of rock cuttings that incorporates a desk-based view of the geological and hydrogeological conditions below, behind and above cutting faces into any future revisions of its processes.***

Upland Slopes And Debris Flow Vulnerability In The Future

200 This section deals with the potential for future increased risk of debris flows, like those currently affecting the A83 Rest and Be Thankful road (RabT) in Argyll. For NR this is specifically a Scottish issue though it is possible some upland slopes above NR tracks in Wales and in the Pennines could become susceptible in the future.

201 In a geotechnical sense these types of failure involve soils but are included in this Chapter because they occur in materials that sit on large steep (circa 30°) upland rock slopes. The material involved in these failures also often contain large boulders of strong rock (see also paragraph 37 in Chapter 2).

202 Debris flows in an upland UK context can be characterised in the following ways (adapted from Milne, 2015):

+ They involve the rapid downslope movement of well-graded (clay to boulder sized) hillslope material
+ They initiate as shallow translational landslides (e.g. shallow rafts of soil) that rapidly become mass flow movements
+ They occur either on open upland slopes or within existing gullies or channels on those slopes. They often transition from the latter to the former
+ They tend to initiate on upper slope inclinations of 30° or more where they are concavities or gullies passing though rocky crags
+ Upland debris flows are unique in an NR context in that:
    - It is highly likely they will always initiate on land owned by outside parties
    - Physical inspection of extensive upland slopes above NR track is impracticable, particularly in poor weather
    - Failures tend to move from initiation to full failure very rapidly

203 Evidence of pre-historic debris flows on Scottish mountainsides is common and probably arose from extreme weather and climate variation since the end of the last ice age. This type of slope instability has come to public prominence over the last decade or so because it has begun to affect some important Highland roads. The A83 at RabT mentioned above is regularly closed by debris flows triggered by heavy rainfall. Active consideration is being given to significantly re-routing this road as the civil engineering mitigations (catchpits, box culverts and fences) that have been put into place have been breached several times and the economic impacts of road closure are judged to be severe.

204 In August 2004 two separate debris flows crossed the A85 road in Glen Ogle trapping 20 vehicles and 57 people between them. One vehicle was swept off the road. August 2004 was an exceptionally wet month in the Highlands and contained several intense storms, one of which triggered the Glen Ogle flows. Several other debris flows affected Scottish roads in August 2004.

205 In recent years NR has suffered two upland debris flows that caused derailments. In 2012 a debris flow crossed the line between Corrour and Tulloch at Loch Treig causing a freight train to later derail (see H26 in Appendix H). This location has a steep 700m high slope above the track, it lacks any road access and is so remote the locomotive (which ended up on the slope below the track) had to be cut up on site to be removed. The steep slope below the tracks continues down into the artificial Loch Treig some 30m below the track. The slope failure was preceded by particularly intense rainfall.

206 In January 2018 a debris flow crossed the track of the Fort William to Mallaig line at Loch Eilt (see H25 in Appendix H). The flow destroyed a modern boulder catch fence. The debris on the track subsequently derailed a two-car diesel passenger train see Figure 7.7. The weather earlier in January 2018 had been very wet followed by a very cold spell with snowfall. It is likely the ground surface was frozen at this time and just prior to the slope failure a rapid thaw had begun. All these factors were identified as having a role in the initiation of the debris flow. The overall arrangement of the slope at Loch Eilt is less extreme than at Loch Treig, there was no significant slope or deep water below the track and the slope above the track was less steep and approximately 200m high. Once again there was no road access to the site.

207 The increasing frequency of debris flow events at the RabT since the 1990’s (Wong and Winter, 2018) and the events of August 2004 prompted Transport Scotland to commission research into debris flows in relation to their highways network. This research has produced a great deal of useful experience and information. This is discussed further in the Transport Scotland part of Chapter 11.

208 Transport Scotland's experiences and the results of this research indicate the increasing weather-related risk of rapid debris flow failures in upland areas. The ongoing experiences at RabT indicate the difficulties debris flows can present in prediction and mitigation terms. This increasing weather-related debris flow risk is likely to apply to some upland slopes containing NR track.

209 Of note is a largely desk and GIS based quantitative debris flow risk assessment study published by Transport Scotland (Winter, McGregor and Shackman, 2009). This identified 66 potential debris flow sites that present a high or very high hazard rating to the road network. This study was carried out without the benefit of airborne LiDAR data. Had this data been available at the time at an appropriate density, a detailed desk based geomorphological mapping assessment of higher risk slopes could have also been undertaken.

210 Many of the railway corridors in the Highlands were developed long before the modern road network and are often distant from roads for considerable distances. For example, there is a twenty-nine-mile section of track from just north of Bridge of Orchy to Fersit, where the route only passes the dead ends of one public road and one private road. This section contains the Loch Treig failure described above.

211 There are other examples where NR track in a glen is separated from a road by large unbridged rivers or lochs. In some cases, as at Loch Treig, there are steep slopes and/or large bodies of water below the track. These factors significantly increase difficulties of rescue and recovery and increase the risks to life in the event of derailment, especially if multiple Glen Ogle type flows occur that isolate remote sections of track in poor weather.

212 **It is expected that the assessment of the consequence of a natural slope failure for NR track in upland areas (in accordance with NR/L2/CIV/086 Geohazard Assessment) ensures that the difficulty of rescue and recovery at those locations is considered alongside an assessment of any additional factors that might increase the risk of death or injury in the event of a derailment.**

213 Physical or remote monitoring of large outside party slopes for rapid debris flow development is not likely to be practicable in an upland railway setting unless there was already an active stability issue on a slope, as at RabT. This is discussed further in the Transport Scotland part of Chapter 11.

214 The likely locations of high debris flow hazard slopes adjacent to NR track and the difficulties experienced in successfully applying civil engineering mitigations at RabT suggest an approach focused on debris flow warning systems could be usefully explored and be relatively simple to deploy in these remote upland locations.

215 For instance, the anchored boulder catch fences of the type that were destroyed at Loch Eilt could be instrumented with strain sensors linked to warning signals. It is unlikely these fences would hold a large debris flow, but their use as warning triggers could prevent a Loch Eilt type derailment where the train hit the debris in poor visibility.

216 The lines where such a system might be deployed typically carry very few trains a day, so the risk of a derailment could reduce to that of a train being in a similar location as a debris flow as it occurs. This risk could potentially be further mitigated by using local weather monitoring and rainfall radar techniques to control the passage of trains and to allow visual checks, either in person or by remote cameras.

217 There is a Scottish precedent for physical warning systems: 'Anderson's Piano', a system of tensioned wires linked to signals, was installed over a 6km length of track between the Pass of Brander and Dalmally in the late 19th century. Its purpose was to warn of rockfall; it is effective and still in use.

218 ***It is recommended that the feasibility of using instrumented anchored catch fences linked to warning signals be researched for use in remote upland areas with a high hazard potential for debris flows.***

Chapter 7

Earthworks Asset Management

Introduction

219 Asset management is a specialist field in its own right, and this Chapter does not attempt to cover it in detail other than to highlight some of the principal considerations of asset management where they relate to Network Rail (NR) earthworks. Further details of NR's Earthworks Asset Management system are given in Appendix E.

220 Organisations have been managing assets, including geotechnical assets such as transportation earthworks, for centuries. However, it is only in more recent times that asset management has become recognized as a distinct set of activities that can be carried out within a set framework or system. In the UK, the management of physical assets was aided by the publication of the Publicly Available Specification document PAS55 in 2004, British Standards Institute (2004). This was followed by the International Standard ISO 55000, developed under the leadership of the Institute of Asset Management, and first published in 2014, British Standards Institute (2014).

221 Key aspects of Asset Management best practice from ISO 55000 include:

- Clear line-of-sight from organisational strategy to activity "on the ground"
- Whole-organisation alignment with asset management
- Active and visible sponsorship from senior executives
- Defining the levels of performance provided by the assets to customers
- Recognising the lifecycle and associated risks of the assets
- Turning data into useful information
- Understanding the true costs of ownership
- Understanding the implications of deferred interventions
- Evidence-based decision making

222 Asset Management creates a holistic focus and provides the basis for a coordinated and coherent approach. In the case of NR, the holistic focus ensures essential infrastructure receives appropriate investment and attention, and has the appropriate resilience to meet business requirements. Asset management best practice requires that NR align the way they manage their assets with their corporate objectives. The principal objective is the delivery of a better railway, in a safe, reliable and sustainable way for the lowest whole-life, whole system cost.

223 NR's Asset Management System, considered in the next section, operates in the context of their regulatory, contractual and legislative commitments. It is underpinned by the NR safety management system, and the key principle is that NR will reduce passenger, public and workforce safety risk so far as is reasonably practicable. Safety is integral to everything NR do. It goes hand in hand with good performance and, while NR have made significant progress in the past 10 years, they recognise that they still have much more to do to make the railway even safer for the public, passengers, and the railway workforce.

224 Asset management comprises all systems, procedures and tools to maximise asset availability for a minimum whole-life cost and risk. NR decision making considers whole system and lifecycle costs and is subject to continual refinement from their experience. **NR have put considerable resource into the development of a comprehensive asset management system for their earthworks and we commend the very substantial effort in achieving this.**

225 Asset management covers an asset's entire lifecycle, from design, construction and operation through to renewal and disposal, and the consequences of each activity. With more than 190,000 individual earthwork assets, 20,000 miles of track, 30,000 bridges and tunnels, 2,500 stations

and a vast range of equipment installed around each, NR are one of the largest asset management organisations in the UK. The history of the earthwork assets NR have inherited and manage is outlined in Appendix E1, Para 912 to Para 930.

226 NR are one of the safest railways in Europe (ORR, 2020a). However, with increasingly frequent severe weather conditions due to climate change, maintaining this high level of safety performance is a constant challenge. This is particularly true for managing earthworks and drainage infrastructure. NR were the lead convener for the 2017 conference on Ground Related Risks to Transportation Infrastructure (Power et al. (2019), which drew nearly 200 delegates from around the world. At this conference the development of an integrated set of policies, procedures, standards and tools to allow NR to plan for the maintenance and renewal of their earthworks were indicated to be world leading.

227 There are no commonly agreed standards that specifically relate to the asset management of geotechnical assets including earthworks. The Construction Industry Research and Information Association (CIRIA) has however published guidance on the management, condition appraisal and repair of infrastructure cuttings and embankments, CIRIA (2003a) and CIRIA (2003b). This guidance is based on a detailed literature review, infrastructure owners' procedures, consultation with experts and practitioners in the field and case studies demonstrating good practice.

228 UK asset-owning organisations such as Highways England, London Underground, Environment Agency and NR have developed their own policies, strategies, plans, and standards that relate to the management of their earthwork assets. Chapter 11 outlines how other UK asset owning organisations manage earthwork risks and what NR might learn from them.

NR Asset Management System

229 NR have adopted the definition of asset management, NR (2018a), as included in the international suite of standards, BS ISO 55000 series, British Standards Institute (2014). "*The coordinated activity of an organisation to realise value from physical assets"*

230 The framework NR use to define the scope of their asset management activities follows BS ISO 55000 guidance and is shown in Figure 7.1.

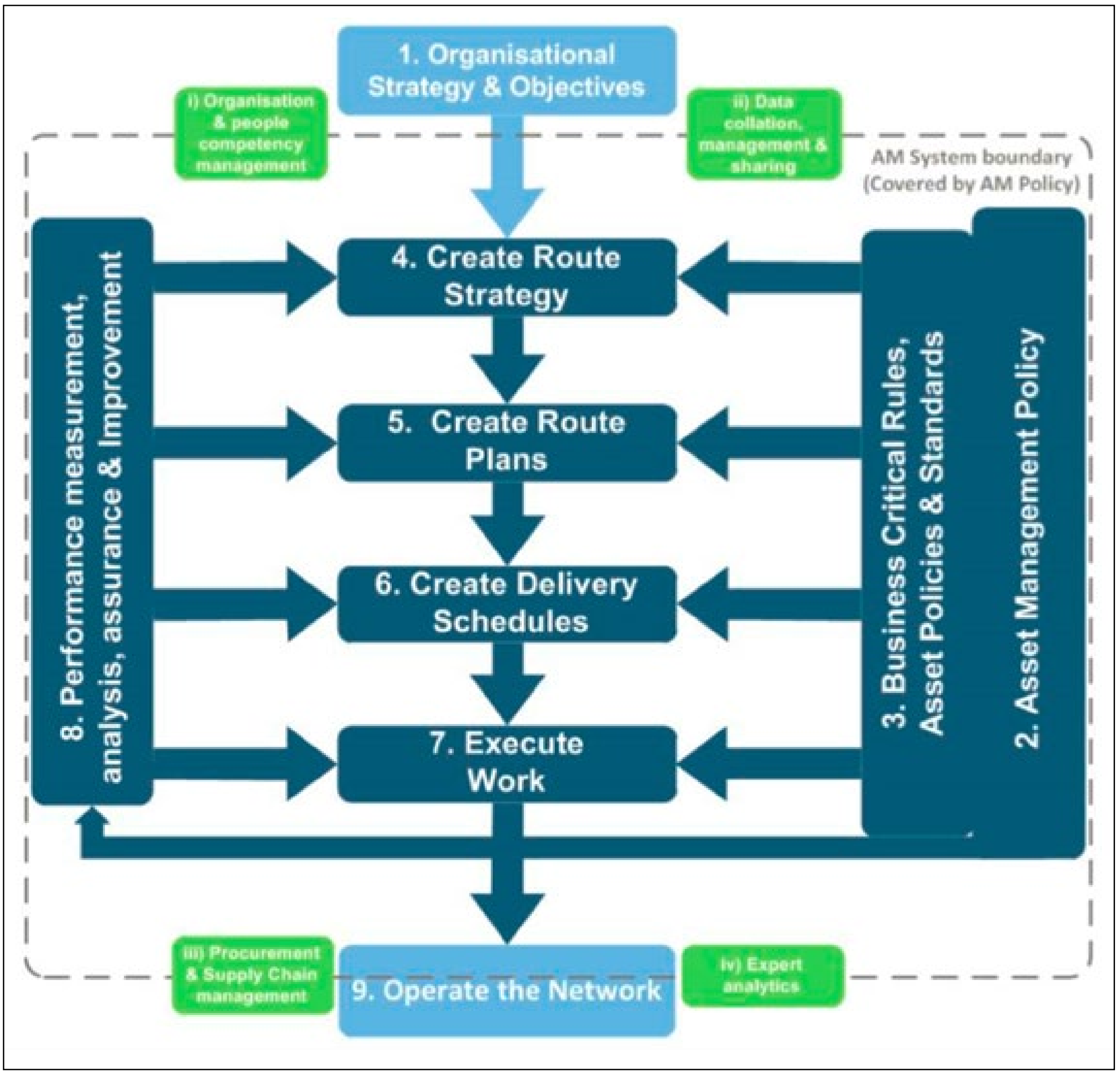


Figure 7.1: NR's Asset Management Framework. (Taken from Asset Management Policy, NR (2018a)

NR Asset Management Policy

231 The Asset Management Policy, NR (2018a), defines the key principles and requirements which NR apply to the assets. The policy plays a key role in creating an overall 'Line of Sight' between NR asset interventions and the overall NR objectives. Specifically, it provides the Asset Management Framework (Figure 7.1) and the document hierarchy used to disseminate NR's overall output and funding specification into both an asset management plan, and the associated interventions required for the assets. Interventions typically include maintenance, refurbishment and renewal works.

232 NR's overall asset management system is described in their Asset Management Policy, NR, (2018a) and Asset Management Capability – Short Form Strategy, NR (2018b).

NR Asset Management Strategy

233 The NR Asset Management Strategy NR (2018b) has two main purposes:

+ It summarises the high-level objectives and targets for the infrastructure for the current Control Period (CP)[8] and the baseline assumptions for the next
+ Secondly, it defines what needs to be done to improve NR asset management capability both to deliver these requirements and to achieve a level of asset management maturity that is at least as good as the best comparable organisations in the UK

234 The NR Asset Management Strategy recognises that in order to deliver reliable services to customers NR need to be proficient in asset management. The NR strategy seeks to develop their asset management capabilities, specifically: aligning decision making in planning and delivery of all enhancement, maintenance, and renewal works in a whole life cycle cost efficient way. This requires improvements in NR people, process, tools and information capabilities to more consistently apply best practice, continuously improve and embrace opportunities created by new technology. This strategy represents the key areas of improvement necessary to support excellence in Asset Management and thereby deliver enhanced safety, reliability, resilience, growth and value-for-money in NR railway infrastructure, maximising the availability of the network for the use of customers.

NR Organisational Structure

235 NR are currently completing a significant re-organisation, "Putting Passengers First". NR's asset management operations are based on a devolved structure, with five geographic Regions (Eastern, North West & Central, Scotland's Railway, Southern and Wales & Western) and 14 underlying Routes responsible for operations, maintenance and renewals, including the day-to-day delivery of train performance and the relationship with their local train operating companies (Figure 7.2).

8 Control Periods are the 5-year timespans into which NR uses for financial and planning purposes. The current CP6 began on 1 April 2019 and ends on 31 March 2024

Figure 7.2: NR Routes and Regions 2020

236 A Route Asset Manager (RAM) (Geotechnical) is responsible for the development and management of the Earthworks Route asset management plans. In some Regions, the RAM (Geotechnical) is also responsible for Drainage and Off-Track e.g., Southern Region. Other Regions e.g., North West and Central Region have separate responsibilities with a RAM (Geotechnical) and RAM (Drainage and Off-Track).

237 The Regions and Routes are supported by a centralised Network Technical Authority group[9] , which ensures consistency in the approach to running the railway across Routes and Regions. The Technical Authority group, which includes the Professional Head of Geotechnics with responsibility for Earthworks, is accountable for policies, standards, technical strategy, sharing best practice, competency definition and assessment, and company-wide engineering & safety assurance.

238 Regions own their Technical and Asset Strategies and manage application of Technical & Safety policies. Region safety and engineering teams are empowered to make local decisions, challenge and support the Network Technical Authority, develop good practice and innovation and act as an intelligent client for the delivery of services. The Route engineering teams are empowered to make local decisions, in recognition of unique differences in asset condition, deterioration rates, environment and/or performance requirements across different geographies.

239 Working with the Regions' safety and engineering capability, the Technical Authority is required to take a holistic approach to the development of policies and standards, balancing safety, train performance, finance and deliverability.

Office of Rail and Road (ORR) Regulation

240 NR are externally regulated by the Office of Rail and Road (ORR), an independent non-ministerial government department, which oversees safety, reliability and economic performance and is responsible for assessing the funding submissions that NR make to government for each of the five-year CP's. As part of this funding mechanism, NR must demonstrate to the ORR that they have robust asset management frameworks in place (including asset specific policies) and that the regulatory requirement for outcomes within each CP can be met. ORR hold NR to account for delivering what it promised, at the cost it agreed to do it for. ORR do this by enforcing compliance with NR's licences and by conducting five-yearly reviews that set the funding and what NR must achieve within the relevant control period. ORR inspectors normally enforce health and safety standards by giving advice to NR on how to comply with the law. Sometimes, ORR require NR to make improvements by issuing a notice (an Improvement Notice), which allows time for the recipient to comply.

9 The Technical Authority group was formed in 2020 from the former Safety, Technical & Engineering (STE) team as part of the NR Putting Passengers First re-organisation

241 Following a number of earthwork failures in 2012, ORR issued NR with an Improvement Notice. ORR served another Improvement Notice in 2015 as NR had not demonstrated effective management of risks arising from drainage systems. More details of these ORR Improvement Notices are included in Appendix E1, Para 925 to Para 928.

Earthworks Asset Management Framework

242 In accordance with the overarching NR asset management framework, all earthworks should be managed by an appropriate asset management system to ensure that that earthwork assets function as required to fulfil NR's role to operate a safe and reliable railway.

243 Effective asset management allocates sufficient resources, within budgetary constraints, for efficient performance. Until fairly recently in NR, a reactive approach to earthwork management has frequently prevailed but this is disruptive, inefficient and uneconomic, and inconsistent with long-term asset management objectives. Earthwork asset safety and performance has consequently suffered as a result. More recently in NR there has been an increasing trend to adopt a more proactive asset management approach. This requires the implementation of a reliable system of condition appraisal, maintenance and repair or renewal, so that existing earthworks can be kept in a condition commensurate with an acceptable level of safety risk, avoiding service loss and minimising expensive unplanned works.

244 NR's Earthworks Asset Management Policy and Strategy is owned and administered by the Technical Authority geotechnical team headed by the Professional Head for Geotechnics who sets out the approach to management of NR's earthworks asset that is to be followed by the Regions and Routes.

Earthworks Asset Management Policy

245 In 2012, NR published an asset specific Earthworks Policy, NR (2012) for the first time. At that time, NR noted that their Earthworks Policy was new and largely untried in practice. As part of their continuous improvement activity, NR issued an updated Earthworks Asset Policy, NR (2014c), which was used by the Routes as a basis for planning and developing their earthwork workbank

for CP5 (2015-2019). The current Earthworks Asset Policy (2018c) was an update to reflect further CP6 (2019-2024) policy developments and was used to develop the CP6 workbank. It also sets out the key objectives of how NR should manage its earthwork assets. The Earthworks Asset Policy can be seen as an overarching guidance document, which is supported by NR standards. It is in essence a vision and strategy document that sets out the overall approach for the management of the earthwork asset base to fulfil NR's role to operate a safe and reliable railway.

246 The Earthworks Asset Policy summarises NR's overall approach and describes how organisational objectives and network strategies will be supported by asset management. It is based on seven Earthworks Policy statements aligned to corporate objectives that reflect the NR role, purpose and vision, and sets out 11 core asset management principles on which the NR asset management approach is based. The Policy therefore plays a key role in creating the Line of Sight between earthwork interventions and the overall NR asset management objectives.

247 The key objectives of the Earthworks Asset Policy are to:

+ Prevent portfolio level condition degradation or risk growth
+ Prioritise sites with highest safety risk
+ Optimise the number of assets improved in condition for a given level of funding
+ Adopt a lowest whole life cost approach balancing operational and capital investment
+ Focus primarily on assets that pose the greatest likelihood of derailment, targeting works on rock cuttings over soil cuttings and soil cuttings over embankments
+ Adopt a proactive approach to intervene prior to reduction in level of service

248 Through satisfying the above objectives, NR aspire to maintain and incrementally improve the earthwork asset resistance to the threat from adverse and extreme weather.

249 Whole life cost models are used to forecast and inform work volumes, outputs and expenditure at portfolio level. Whilst forecasting and uncertainty go hand in hand NR continue to update degradation modelling from asset inventory data to best inform whole life cost modelling rules.

250 Currently NR Route (Region) businesses produce the specification of physical interventions utilising tactical decision support tools (DSTs) and with refinement these requirements are consolidated into Route and Region asset management plans. Management plans within the Routes consist of a range of intervention types: renewal, refurbishment and maintenance on embankments, rock cuttings and soil cuttings. The Earthworks Asset Policy provides guidance on the type of capital investment that would be applicable to the relative risk within the portfolio. Strategic whole life cost models are used to provide guidance on activity levels to deliver the policy objectives.

251 In June 2020, NR commissioned AECOM to undertake a review into the effectiveness of their current Earthworks Asset Policy (2018c). AECOM (2020) made a number of observations to highlight areas in which NR demonstrate industry leading practice or where improvements can be made. Related to these observations are recommendations made by AECOM to address perceived gaps in the current policy approach. We are generally in agreement with the conclusions and recommendations made by AECOM.

252 AECOM recognised that it is common for organisations to find it difficult to write succinct, clear and well organised strategies/policies. This is improving, with more businesses using BS ISO 55000 (British Standards Institute, 2014). to guide their asset management documentation.

253 Some RAMs have commented that their Route/Region earthwork workbanks did not always align with the guidance on the appropriate type of intervention taken from the intervention matrices for each earthwork type from the Earthworks Asset Policy. Some NR Earthwork managers also question the long-term effectiveness of the Refurbish option in the Policy and Standards and whether it represents good value for money. This suggests that there may not be a consistent understanding of the Earthworks Policy guidance, as, given the inherent variability of the earthworks asset base, it is unlikely that workbanks will fully align to the Earthworks Policy intervention matrix. As the Earthworks Asset Policy is updated, a clear cascade and engagement with the Regions and Routes will help improve alignment and consistent understanding of the requirements across the business.

254 **The Earthworks Asset Policy NR (2018c) is not well integrated with the equivalent Policy documents for Drainage and Vegetation. There are also some key omissions from the Earthworks Policy e.g. Roles and Responsibilities, Competence, Assurance etc. The content structure of the Earthworks Policy document can be improved by addressing the omissions and, in line with best practice and relevant standards (BS ISO 55000), to be more concise, succinct, clear and better organised. We understand that NR are transitioning to an ISO accredited Asset Management System, which is likely to help address these issues.**

255 ***We recommend that the Earthworks Asset Policy, NR (2018c), is updated to address the current identified deficiencies in content and structure. These revisions should be clearly communicated to the Regions and Routes to improve alignment and consistent understanding of the requirements across the business.***

Earthworks Standards and Procedures

256 Standards are a set of documents produced to define the way NR works. They give NR a consistent, safe and coherent set of requirements across the whole company. Further details are given in Appendix E2, Para 931 to Para 939.

257 The Professional Head of Geotechnics in the Technical Authority team has the responsibility for owning, developing and maintaining the Earthworks suite of standards across NR. The Earthworks standards provide details on specific roles and responsibilities and dictate which procedures are mandatory (i.e. no variations permitted), which procedures may be varied subject to approved risk analysis and mitigation, and which procedures are provided as guidance (i.e. they are to be used unless alternative solutions are followed). As a result, the Regions/Routes have authority to deviate from some of the procedures set out in the Policy, as allowed for in the standards. It is understood that this is a necessary provision to enable the RAMs to use their detailed local knowledge of their assets and region-specific constraints, pressures and opportunities to effectively manage their earthworks assets. We agree with this approach, particularly in view of the local geology and climate having a major influence on the earthwork assets.

258 The NR Earthworks Standards suite has been continuously developed since the 1990's, the key standards having generally evolved over a number of iterations and we recognise that they are comprehensive and technically sound.

259 A Standards Challenge process is available for all NR company standards, for organisations to challenge NR standards where they believe that requirements are onerous, drive unnecessary cost or both.

260 **All the earthwork standards have been updated since 2017. Inevitably there are still some key omissions e.g. the absence of any reference to emerging earthwork decision support tools such as GSRA (Global Stability Resilience Appraisal). There are also a number of references to the Civils Strategic Asset Management Solution (CSAMS) which has not yet been delivered. We anticipate that the Earthworks Standards will be kept updated to address key omissions and as a commitment to continuous improvement in earthwork asset management.**

Earthworks Technical Strategy

261 In June 2018 NR published its Earthworks Technical Strategy, NR (2018d), to articulate priorities and key activities to enable continued long-term improvements in safety performance.

262 We welcome the Technical Strategy, NR (2018d) aspiration, to see an infrastructure that is free from service-affecting earthwork failures, and one where the directly interfacing drainage and vegetation assets are sustainably managed. We recognise that this is a long-term vision that can only be delivered over multiple control periods.

263 Specifically, the short- and long-term Technical Vision (Figure 7.3) for the earthwork asset includes:

+ Maintaining and improving the current levels of safety and performance
+ Providing people in the NR engineering and asset management communities with the opportunity to do what they are best at every day, enabling them to add the most value in the available time
+ Coherently articulating the vulnerability from legacy design and how the capability/resilience of the earthwork asset should be compared against modern infrastructure design codes
+ Improving earthwork asset capability through progressive strengthening from commitments in funding, to improve the resilience and reliability of the asset base to perform in a changing and evolving climate
+ Standardising and increasing the deployment of condition monitoring, failure detection alarms and the process for analysing data to implement mitigation controls
+ Planning for automation from available technologies to improve the quality, efficiency, repeatability and reproducibility of asset inspections and evaluations

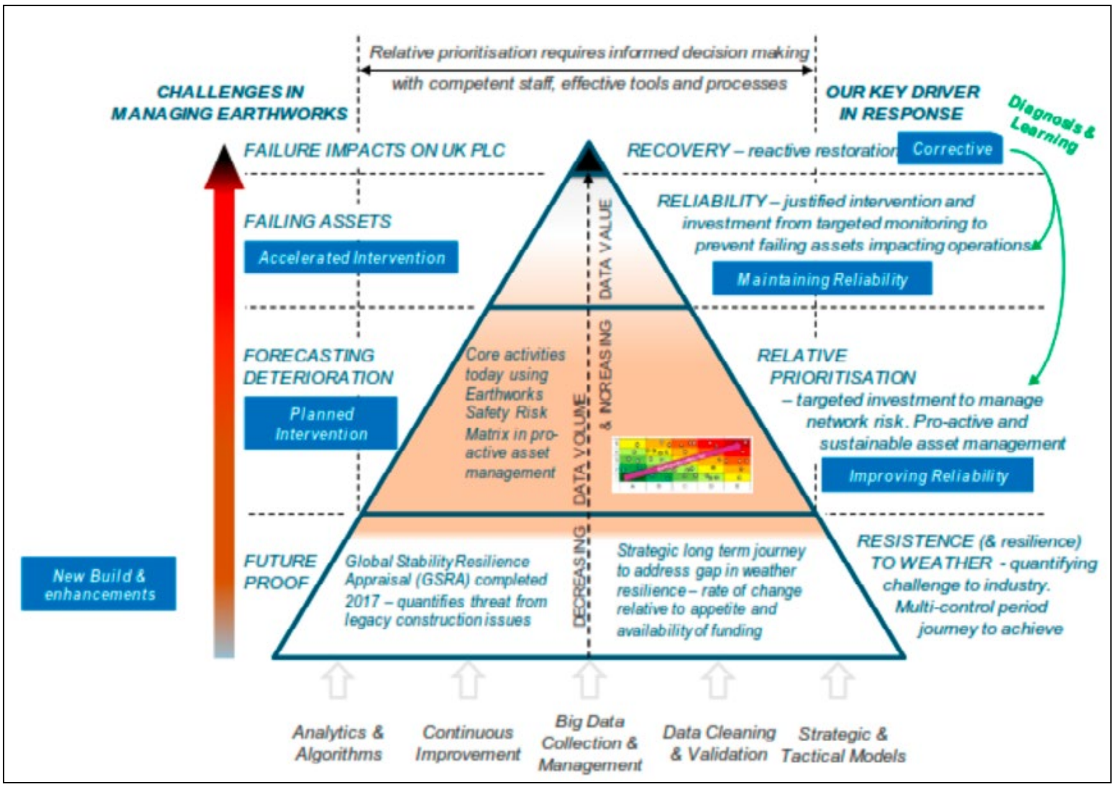


Figure 7.3: Technical Vision for Earthworks

264 The NR earthwork asset management activities, funding and operational responses primarily focus on the threat of failures from their own infrastructure. But more recently NR have also started to consider threats beyond the boundary fence, particularly from steep-sided natural terrain which exists alongside hundreds of km of the railway. Changing weather patterns, with more periods of intense rainfall, are already increasing the likelihood of landslip events from such areas and will continue to do so. To address this, NR have been working in conjunction with the British Geological Survey and engaging with Transport Scotland to learn from previous comparable trunk road studies how they can best manage this threat. The potential impact of these risks has become clearer in recent years, so NR are working hard to understand it better. NR have already undertaken some initial risk assessment of outside party natural slopes (see Para 301 Outside Party Slopes) adjacent to the NR boundary and are now progressing plans for more detailed assessments.

265 The Technical Strategy outlines the strategic initiatives and key activities to enable long term improvements in Earthwork safety performance and in particular the topics of focus in research and development.

266 **The Drainage (Water Management) Technical Strategy has not yet been developed and the Earthworks Technical Strategy does not consider Drainage (Water management) or Vegetation management in any meaningful way.**

267 **The Earthworks Technical Strategy, NR (2018d), would benefit from a well-defined articulation of the vision and stepping stones to world class earthworks asset management through harnessing knowledge, continuous improvement and the exploitation of emerging technologies.** ***We recommend that the Earthworks Technical Strategy, NR (2018d), is kept regularly updated, particularly to reflect the technical developments NR are proposing for the management of the drainage and vegetation assets associated with earthworks*.**

Earthwork Examination and Classification System

268 An understanding of earthwork condition, performance and behaviour is a fundamental requirement for effective asset management. Earthwork examination comprises a regular visual inspection of condition by walkover to identify and record evidence for ongoing and incipient instability in a standardised and repeatable manner. The development of the NR Earthworks Examination and Classification system from the 1990's is described in Appendices E3 and E4. The current Earthwork Examination Process (Para 278 to Para 285), helps to identify earthworks potentially at risk of failure and facilitates the prioritisation for further detailed assessment at sites that have the potential to impact the rail network.

269 Slope condition data is primarily derived through periodic earthwork examinations. These visual inspections rely heavily on data collected by examiners in the field that may be subjective, potentially encompass a degree of variability and may not be able to identify certain precursors to slope failure. A level of uncertainty in the output of these inspections is to be expected; NR are aware of the uncertainty and have attempted to calibrate their examination process against historical failures to reduce this.

270 Full details of the earthwork classification systems developed by NR are given in Appendix E4, Para 946 to Para 962.

271 For each 100 m earthwork asset a hazard score is derived using an algorithm by applying a weighting to each observed parameter; the value of the weighting factor is derived by statistical analysis of the importance of each parameter as a precursor indicator of slope instability. Parameters more prevalent in the pre-failure examination of failed earthworks than the whole population of earthworks were given a positive weighting in an algorithm. Those more prevalent in the whole population are negatively weighted. The parameter weightings are then summed and the resultant scores segmented into five Earthwork Hazard Categories (EHCs), ranging from A (lowest Hazard Indices, lowest likelihood of failure) to E (highest Hazard Indices, highest likelihood of failure). The process for arriving at a particular EHC is illustrated in Figure 7.4.

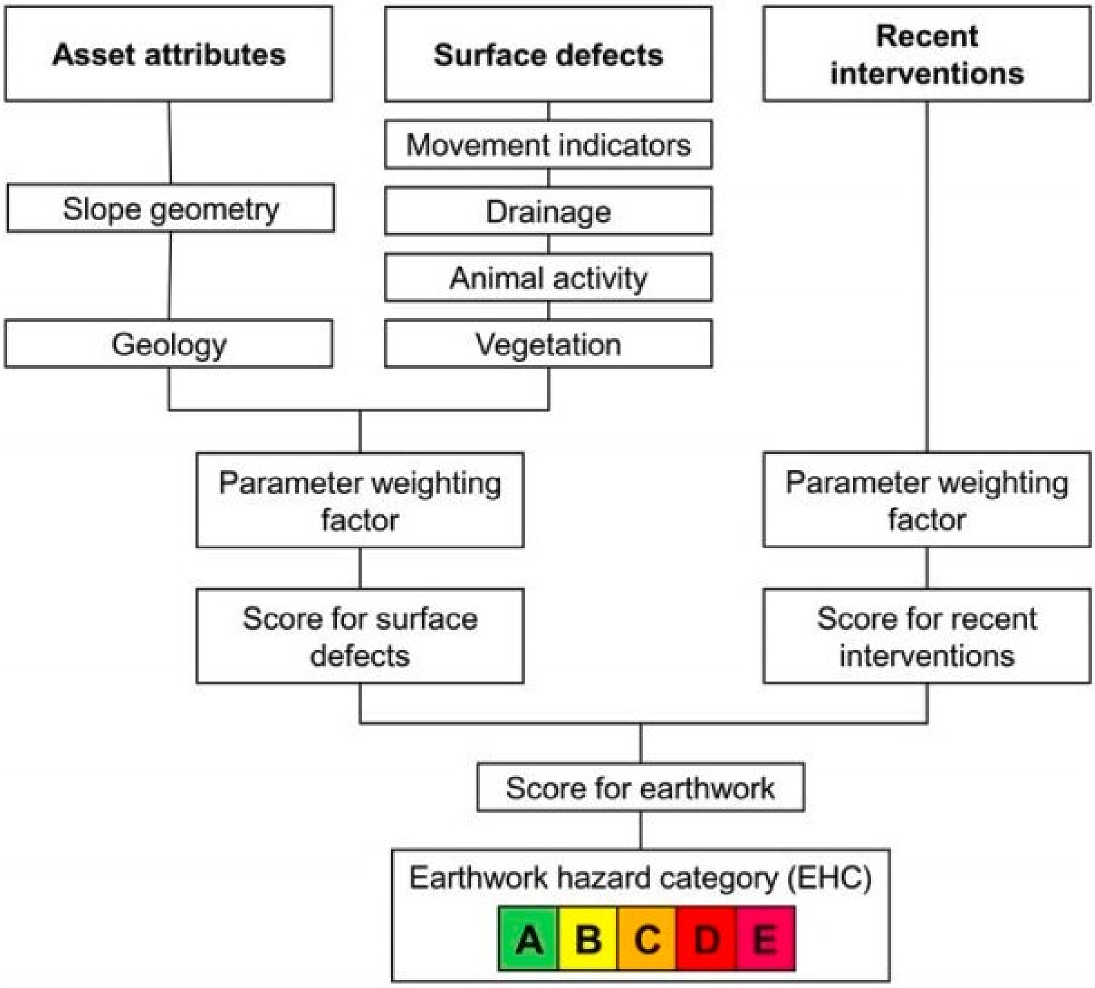
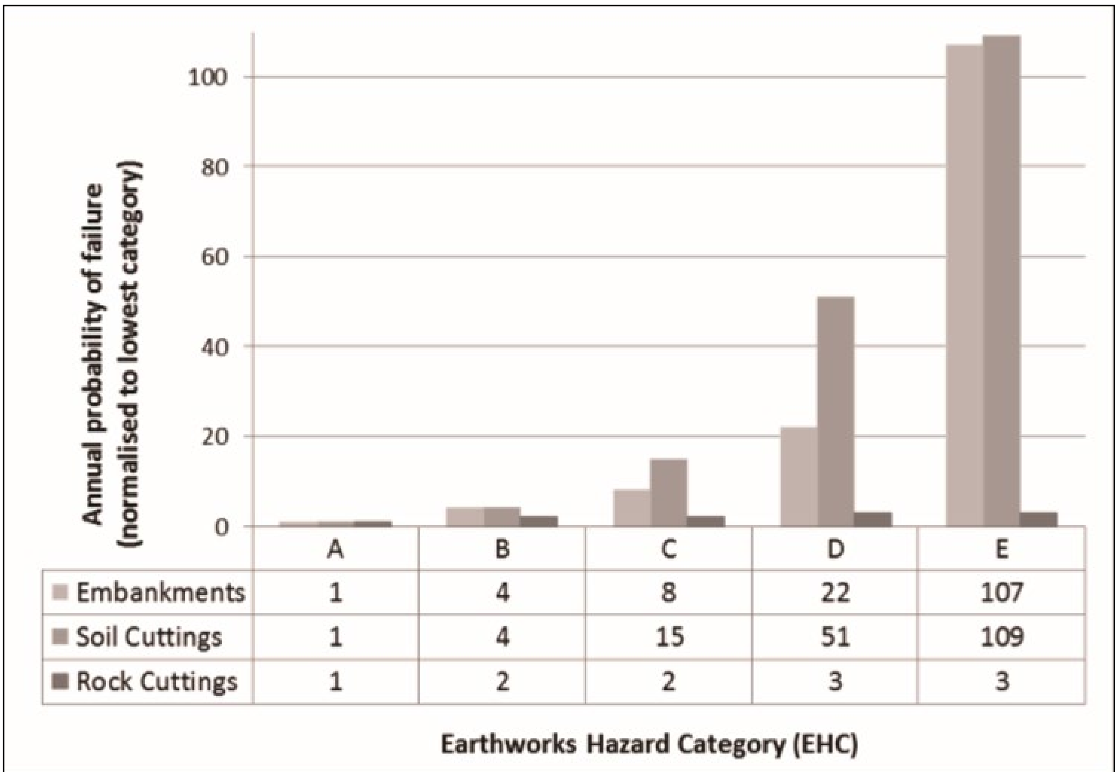


Figure 7.4: Derivation of the Earthwork Hazard Category (EHC), after Spink (2020)

272 Because the number of assets in each EHC is known, and the number of failed earthworks in each category is also known, a comparison of the statistical likelihood of failure of an asset in each category has been undertaken, Power et al (2016) – see Figure 7.5.



	A	B	C	D	E
Embankments	1	4	8	22	107
Soil Cuttings	1	4	15	51	109
Rock Cuttings	1	2	2	3	3

Figure 7.5: Annual probability of failure (normalised to the lowest EHC category) for each EHC and each earthwork asset type), after Power et al (2016)

273 In Figure 7.5, the annual probability of failure in each EHC has been normalised to the value in EHC A. With the previous NR Earthwork Hazard Indices (Appendix E4), an embankment or soil cutting in the worst condition category was 10 to 20 times more likely to fail than one in the best condition category. It can be seen in Figure 7.5 that this multiplier was improved by the current algorithms to over 100 for embankments and soil cuttings, an order of magnitude improvement in the ability to predict earthworks failure.

274 The five EHCs A to E are shown in the Earthworks Safety Risk Matrix Figure 7.6 plotted against Earthworks Asset Criticality Band (EACB).

275 We recognise that further work is in progress to refine the Earthwork Hazard Category (EHC) scoring algorithm from the examination process to enhance its ability to predict of the likelihood of earthworks failure (see Appendix E7 Para 981 to Para 983).

276 The EACB is a criticality measure and is a combination of two components:

- The probability of an earthwork, having failed, causing a train derailment. This is based on a number of factors including the likely size and hardness of the failed material, but also factors such as the distance of the slope from the rails
- The potential safety consequences of a train derailment at a given location derived through the NR Common Consequence Tool (CCT). It takes into account factors such as the maximum speed of trains on the line, whether a derailing train is likely to hit an oncoming train or a hard structure at the side of the track

277 The EACB is segmented into five bands, from lowest to highest safety consequence designated 1, 2, 3, 4 and 5. Full details of the EACB are given in Appendix E5, Para 963 to Para 968.

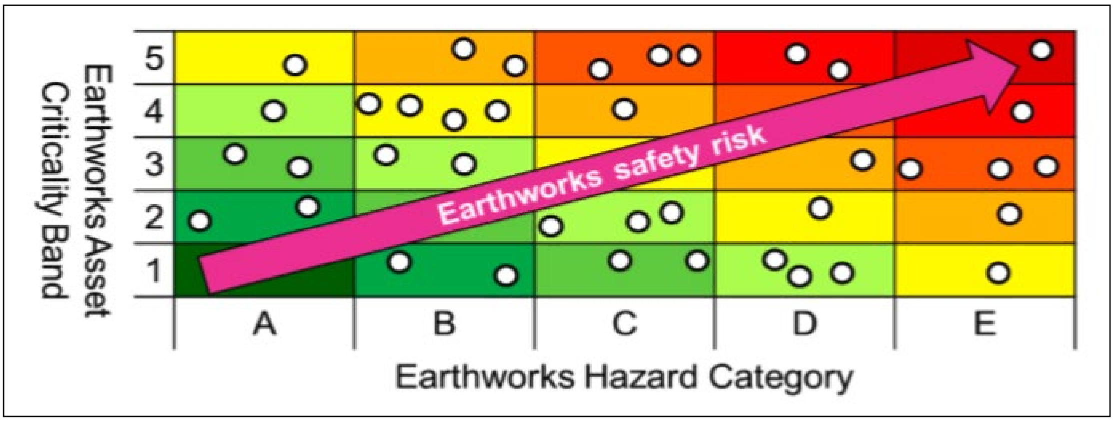


Figure 7.6: Earthworks Safety Risk Matrix. (Taken from NR Earthworks Asset Policy (2018c))

Current Earthwork Examination Process

278 The examination of NR earthworks assets is currently undertaken in accordance with Examination of Earthworks Manual, NR (2017a) – 'the 065 standard'. Full details are given in Appendix E6, Para 969 to Para 980.

279 Large numbers of earthwork examinations are required each year e.g. nationally 51,802 examinations were planned to be undertaken in the 2019/20 examination season. In the Scotland Region 9,500-10,000 exams are typically required per year. An inspector typically completes 15 earthwork asset examinations per day, looking for an observable change from the previous inspection e.g. visual signs of ground movement.

280 In the earthwork failure investigations carried out by the RAIB, standing water, water flows and drainage issues were often highlighted as key contributing features. These deficiencies may not always be fully identified within the current earthworks examination process where typically only 30 minutes is allowed for the inspection of a 5-chain (100m) earthwork asset. Despite the examinations being undertaken during the winter period, it is likely that water or drainage issues are not present or visible to the examiner because inspections are rarely undertaken during or shortly after heavy rainfall. Deficiencies in drainage systems can result in cutting instability, particularly following significant rainfall events (see Para 37, A partial review of failures in soil cuttings and embankments). **The examination process should be improved by giving more consideration to drainage condition and water management associated with earthwork slopes. We consider that for those earthworks vulnerable to washout and earthflow failure mechanisms, examinations during or shortly after heavy rainfall are essential. The use of drone and/or helicopter surveys should be considered for these examinations.** See Para 605 to Para 611, Helicopter surveillance and Drone surveillance.

281 Earthwork examiners informed us of the following key issues regarding drainage defect reporting in earthwork examinations.

+ They often come across crest drainage that is choked with vegetation
+ Many crest drains have been affected badly by fly tipping or householder encroachment
+ Earthwork examinations often cannot tell whether drainage pipes are blocked

Earthwork examiners observe drainage assets and record defects but this is only incidental to their earthwork inspections. They are also limited in the inspection of hidden or buried drainage assets. Consideration should be given to better integrating earthworks and drainage examinations.

282 The periodic nature of the earthworks examinations introduces an additional degree of uncertainty in the asset condition data. This is particularly acute if earthworks are exposed to threats such as adverse / extreme weather or third-party activity which may trigger deterioration of the asset in the intervening period between examinations.

283 Earthwork examiners are trained by NR to collect information about earthwork slopes within and outside the railway boundary by standing on the side of the track and, providing it is safe to do so, by walking up and down slopes within the railway boundary. **Examiners are not expected to go outside the railway boundary, and safety considerations (e.g. very steep slopes) sometimes prevent examiners reaching the boundary. These constraints mean that collection of information about slope instability features outside the railway boundary may be restricted. In particular the identification of**

deficient or inadequate water management from catchments beyond the boundary fence is likely to be limited, especially if the examinations are not undertaken during or following heavy rainfall.

284 The Earthworks examination season typically runs from the end of October to the beginning of April, approximately a 22-23-week season with Christmas and New Year in the middle bringing this down to nearer a 20-week season. Feedback from examiners suggested it is not appropriate to start the examination season any earlier in October due to the presence of vegetation potentially concealing slope features. However, April is considered a very useable month in terms of examinations, with better weather, longer days and spring vegetation growth having not yet had the opportunity to conceal slope features. ***We recommend that consideration be given to formally including April in the Earthworks Examination season.***

285 Examinations are often incomplete because the slopes are covered in dense vegetation. At any one time the number of unfinished examinations due to vegetation varies from approximately 250 to 1400. Earthwork Examiners consider that the "standard devegetation" undertaken to facilitate earthwork examinations is often not sufficient to allow accurate identification of all slope defects. The problem is particularly acute if re-examining is undertaken in the summer months. **The examination process could be improved by earthworks examiners formally advising the slope de-vegetation requirements to facilitate the next examination**.

286 The Risk Evaluation Matrix (REM) (see Appendix E4, Para 953) is used to carry out a subjective assessment of the risk posed to the safe operation of the railway from earthworks subject to examinations, in accordance with NR (2017a). However, the REM does not feed into the algorithm derived EHC, but allows engineering judgement to be recorded by examiners.

287 **We recognise that full condition inspection and assessment of the extensive NR earthwork asset base is challenging. However, we consider that slope stability cannot be determined on the basis of surface observations from examination alone. The inherent factor of safety against slope failure of the earthwork is not included in the algorithm derived EHC condition grading system which is largely based on surface-visible precursor indicators of failure from examination and does not take account of two key parameters in any slope stability assessment: shear strength and pore water pressures. The rapid failure of cutting slopes is especially difficult to predict by the EHC condition grading system, particularly when failures are triggered by intensive local rainfall.**

288 There appears to be reliance in the EHC condition grading process on the use of statistics, data analytics and algorithms, without parallel verification by deterministic methods, based on engineering judgement, soil and rock mechanics.

289 Forward predictions using retrospective observations from examination can be problematical when controlling factors are changing – climate change, weathering, failure modes.

290 Examination should be used for identifying changes rather than pre-dicting failure events which depend on a combination of factors, not all of which are represented in the EHC algorithm.

291 ***We recommend that shortfalls in the earthwork examination and risk assessment system need to be addressed, in particular reliance on algorithms largely based on surface-visible features and defects, slope geometry and material type as predictors of earthworks failure with limited consideration of inherent slope stability and generally without verification by engineering calculations.***

Examination Frequencies and the Trigger for Slope Evaluations

292 If the examination algorithm classifies a slope in EHC categories A, B and C, NR processes generally require no further action until the next examination i.e.

+ after 2 years for "B" and "C" rock cuttings
+ after 5 years for "A" rock cuttings
+ after 3 years for "B" and "C" soil cuttings
+ after 10 years for "A" soil cuttings
+ after 5 years for "B" and "C" embankments
+ after 10 years for "A" embankments

293 Examination reports for a slope in EHC categories A, B and C are only reviewed by the NR Geotechnical RAM team if the need for a Slope Evaluation, NR (2017b) is triggered by special circumstances such as:

+ the REM indicates a high-risk earthwork or it is subject to rapid deterioration
+ a proposed change of land use which could affect the slope
+ track maintenance engineers report exceptional changes in the track geometry
+ works on or around the earthwork that might affect the stability, condition or performance

294 **Reliance on mainly using the algorithm derived EHC to determine whether the RAM team review examination reports in an Earthwork Evaluation, NR (2017b) means that NR can be unaware of important slope characteristics or defects if these have limited or no effect on the scoring in the examination algorithm**.

295 NR's examination frequencies are determined based on asset failure likelihood (via EHC scoring), with the assets considered most likely to fail subject to the most frequent examinations and vice versa. **The frequency of examination is not generally linked to consequence or risk (EACB), although the prescribed examination frequencies for rock slopes (which typically pose a higher consequence of failure) are higher than those for soil cutting slopes, which are in turn higher than those for embankment slopes.**

296 ***We recommend that the limitations of mainly using the EHC category to trigger Earthwork Evaluations and Examination frequencies are addressed.***

Risks developing between examinations

297 The EHC is used to define the maximum planned interval between successive cyclical examinations of an earthwork, and the tolerance on that interval that is allowed, see Table 7.1 below and NR (2017a). All of the earthwork assets within an earthwork inspection 5 chain (100m) asset are required to be examined at the same time at an interval determined by the component earthwork asset with the shortest interval**. A 5 chain (100m) soil cutting or embankment in EHC "A" will receive a "partial" (depending on access, weather, vegetation etc) visual examination, typically undertaken in 30 minutes every 10 years and the results will not looked at by a competent NR Geotechnical Engineer unless something is specifically highlighted. In 2019/20 there were 36 slope failures (14% of the yearly total) in earthworks classified (pre-failure) in EHC "A".** See also Para 413, Earthwork Failures.

Earthwork type	Earthworks Hazard Category (EHC)	Planned examination interval (years)	Permitted examination tolerance (months)
Soil Cutting	A	10	12
	B, C	3	3
	D, E	1	3
Rock Cutting	A	5	6
	B, C	2	3
	D, E	1	3
Embankment	A	10	12
	B, C	5	6
	D, E	1	3

Table 7.1: Maximum interval between examinations and the tolerance on that interval. (Taken from Network Rail 2017a. NR/L3/CIV/065. Examination of Earthworks Manual. Issue 6. September 2017.)

298 Changes both inside and outside the boundary fence can result in risk to the railway developing from earthworks instability between examinations. Under UK safety law, the Health and Safety at Work etc Act (1974) NR are required to take reasonably practicable measures to recognise and manage these risks. A process is required to recognise, and report to RAM Geotechnical and/or Drainage Engineers, significant changes which occur between examinations and which could adversely affect earthwork stability. Changes of this type can occur outside and within the railway boundary. They include man-made and natural deterioration processes which result in additional loadings at the top of slopes, excavation at the bottom of slopes and changes in the way water flows onto and through railway property. They are changes which would be generally apparent to a non-specialist observer given appropriate training.

299 However, NR cannot overly rely on routine patrolling by track staff to report any significant changes in earthwork asset condition between examinations. There is little evidence that track patrollers ever effectively identified "failing" earthworks adjacent to the track[10] and most earthwork defects are not observable from a track patrol anyway. Much of the visual track patrolling activity is also being replaced by PLPR (plain line pattern recognition), which is a form of train-borne monitoring focused on the ballast, sleepers, pads, clips and rails. One of the earthwork competencies in the framework, GEO-OM-I Informed Earthwork Person, is targeted at people routinely on track such as track and operations staff. This is still to be rolled out as it is very much dependent on the development of supporting training materials, as well as a need to keep the number of competencies these roles hold manageable.

300 ***We recommend that NR should review and improve its processes (in the absence of routine track patrolling) for identifying, and responding appropriately, to changes outside and within the railway boundary which could adversely affect earthwork stability between routine examinations. We have also recommended (Para 605 to Para 611) that consideration be given to more widespread use of helicopter flights and drone technology for inspections of earthworks including the identification of any changes in condition between formal examinations.***

Outside Party Slopes

301 An outside party slope is defined as a cutting, embankment or natural slope lying outside the NR boundary that is owned and/or managed by an outside party being a person or organisation other than NR. The term outside party includes Highway Authorities, Roads Authorities, Passenger Transport Executives, public or private land owners or developers, and Train Operating Companies.

302 The way outside party land is managed outside the railway boundary also has an impact during adverse weather. Even small blockages upstream or downstream in otherwise innocuous ditches, burns or streams and changes in land use can alter flow paths and concentrate water in areas detrimental to railway infrastructure. Between 2012 and 2018 there were four significant landslips in the Scottish Highlands originating from natural hillsides in land outside the ownership of Scotland's Railway that had the potential to adversely impact on the safe performance of the railway e.g., Loch Eilt January 2018 – a failure of an outside party slope resulted in the derailment of a passenger train, (Figure 7.7) and discussed in Chapter 6.

10 certainly since active lineside vegetation management was abandoned following the demise of steam locomotives in the 1950's – see also Para 535 Vegetation Asset Management.

Figure 7.7: Aerial view of the Loch Eilt landslip January 2018, RAIB (2018).

303 Where the outside party is unable to provide a satisfactory management policy for the slope, or demonstrate by other means that it is being managed in a satisfactory manner, the slope will, so far as is lawful, be subject to a cyclical examination in accordance with NR (2017a). If the slope cannot be examined, then the Geohazard Assessment NR (2017c) process is followed. A Geohazard Assessment relates to:

+ Identification of hazards from natural slopes
+ Assessment of the consequence of a natural slope failure

304 A decision support tool (Classification of Hazards on Outside Party Slopes (CHOPS)) has been developed for NR by the British Geological Survey (BGS) to quantify hazard susceptibility from natural slopes starting within 50m of the NR boundary (BGS, 2017). Geographic Information System (GIS) processes and a digital terrain model (DTM) were used to compile geohazard maps for the following types of slope failure, with each geohazard classified by severity and/or presence:

+ Translational and rotational landslides
+ Debris flows of saturated loose superficial deposits either on open, steep hillsides or focussed along stream channels and gullies
+ Earthflow (or washout failure) of slopes in glacial till deposits
+ Rockfalls of hard or strong rocks
+ Recorded landslides in a national database, assessed for proximity to the railway
+ Outside party failures, recorded in the NR Examination database (although their number is small)
+ Mapped areas of mass movement which may be historic failures in bedrock, superficial deposits or made ground

305 The limit of the geohazard map buffer is a distance of 500m from the centre line of the railway. The CHOPS model determines the maximum hazard of the outside party natural slope in the buffer, adjacent to each Earthwork 100m (5 chain) length asset. The hazard is recorded on a scale of A to E, where A is least likely for the slope to be susceptible to failure, and E is most likely. There is no equivalence between the CHOPS A to E classification and the Earthworks Hazard Category (EHC) A to E category in terms of quantitative likelihood of failure. The outputs are combined in a series of matrices with NR consequence of failure criticality banding assessments.

306 The CHOPS model is a desk-top tool to aid site prioritisation for the next phase of evaluation and assessment. It is not a risk map and should not be used as such. A high hazard score within the model does not necessarily translate to a high risk; there is no interpretation of likelihood, preventative construction or hazard management schemes in place.

307 The CHOPS study (BGS, 2017) indicates that 42% of the total buffered railway has a combined hazard rating of C or above; 20% of the network is classified as having a hazard rating of D or above and 13% of the network is classified as category E.

308 The CHOPS study identified many areas of the NR network susceptible to localised potential landslides from adjacent natural slopes; however, the spread of the hazard is variable across the NR Regions.

309 The evolution of understanding from the CHOPS study regarding geohazards beyond the land owned by NR is a significant step forward. However, this baseline assessment requires further validation, review and consideration to ascertain the best way of proportionally incorporating potential threats from natural slopes into the already challenging area of geotechnical asset management. NR (2017c) details the process to prepare for and carry out a Geohazard assessment to outside party natural slopes adjacent to the railway and report the results into NR's earthworks database. A geohazard assessment is carried out:

+ when the evaluation of an earthworks examination identifies there is a risk of failure from earthworks and outside party natural slopes which warrants further investigation and analysis; or
+ where the railway has been identified to be at risk from a natural slope

A Geohazard assessment aims to either provide confirmation of the hazard rating obtained by the CHOPS or to find specific site information which may indicate that the CHOPS poses a low risk to the railway (with justifications).

310 NR processes currently do not provide a robust means of identifying activities on neighbouring land which could increase railway risk between routine examinations (see our Recommendation in Para 300).

311 ***Given the need to detect, where reasonably practicable, precursors of slope failure and emerging problems on outside party land, with the potential to exploit new technology, we recommend that NR review their methods of identifying and managing geohazards on outside party land that have the potential to adversely impact on the safe performance of the railway.***

Washout and Earthflow Risk Mapping (WERM) methodology

312 Washout failures are caused by water flow eroding surface material from the surface of a slope. This failure type commonly occurs where adjacent ground falls towards a vulnerable cutting and the local conditions provide little obstruction to surface water, allowing it to concentrate at a specific point. The slope surface materials must also be susceptible to erosion e.g. Watford Cutting failure in 2016, (RAIB 2017) where intense rainfall led to a washout failure on the cutting slope adjacent to a tunnel portal. The local topography

created a water concentration feature, and the resulting flow over the edge of the cutting (there was no crest drainage or sub-surface drainage) caused a washout failure of the cutting slope (Figure 7.8).

Figure 7.8: Watford Cutting Washout Slope Failure 2016 (RAIB 2017)

313 An earthflow is a downslope viscous flow of fine-grained materials that have been saturated with water e.g. Oubeck (near Lancaster) Cutting failure in 2005 (RAIB, 2006a). A field drain at the top of the cutting was draining water from adjacent land and feeding it onto a cutting slope of glacial till underlying a layer of topsoil. The heavy rainfall immediately prior to the failure saturated the topsoil layer on the cutting slope surface. The resulting weight increase caused the upper 300 to 500 mm soil layer to slide down the cutting slope (a translational failure). The loss of confinement on the underlying heavily saturated glacial till allowed it to flow down the cutting slope onto the track resulting in the derailment of a train that ran into the debris (Figure 7.9).

Figure 7.9: Oubeck Cutting Earthflow Slope Failure 2005 (RAIB, 2006a)

314 The WERM (Washout and Earthflow Risk Mapping) is a decision support tool to identify and assess cuttings at risk from the concentration of surface water runoff towards the railway that has the potential to adversely affect slope condition and cause serious safety incidents e.g. Oubeck 2005 (RAIB, 2006), Watford 2016 (RAIB, 2017). Further details are given in Appendix E8 and NR (2016a).

315 The WERM methodology is used to locate water concentration features at the crest of soil cuttings in the NR earthwork examination database. A digital terrain model has been created 100m either side of the railway using LiDAR data and photogrammetry. Analysis of this digital terrain model has identified low points that can channel water towards the railway. A concentration feature risk score from 1 to 12 is assigned to each 5 chain (100m) earthworks section, with 12 presenting the highest risk.

316 The WERM tool was initially calibrated against the history of earthworks failures in the London North West Route. 47 cutting slope failures were evaluated and showed a broad trend of higher-than-average concentration feature risk score, confirming the significance of this feature as a precursor to failure. The study is described in further detail in Mott MacDonald (2012).

317 A review of the initial WERM1 methodology, NR (2014b) made recommendations for improvements to the means by which water concentration features are identified, namely:

+ To improve the consideration of up-slope topography, by assessment of catchment areas away from the railway through the use of a digital terrain model
+ To enhance the means by which the permeability of the ground in the catchment of potential water concentration features is assessed

318 These recommendations were addressed in the development of WERM2 described in Appendix E8, Para 989 to Para 998.

319 Following the Watford cutting failure in 2016, RAIB (2017) made the following recommendation: *"NR should review, and if necessary, improve its process for identification of localised water concentration features which can channel significant amounts of water onto the railway with the consequent risk of slope failure."* This recommendation was addressed in the development of WERM3 described in Appendix E and NR (2018d)

320 The analysis of the WERM3 data in NR (2018n). shows that nationally only 1 in 5 historic examination database cutting failures occurred at a WERM3 water concentration feature location; therefore, at best, the WERM3 algorithm can predict no more than 20% of failures of any type. For washouts recorded in the examination database the percentage is even lower at 13%. We conclude, therefore, that the WERM3 tool is not fit for purpose and is actually effectively misleading because it is giving a false sense of objectivity when none exists.

321 ***We recommend the process for the identification of localised water concentration features at the top of cutting crests and the likelihood of failure from washout or earthflow is fundamentally reviewed. The aim is to improve the prediction rate for rapid cutting slope failures, with little or no indication of visible distress prior to failure. A forensic re-assessment of the significant number of previous washout and earthflows would be invaluable for calibration of the current examination and evaluation process and provide lessons learnt for future risk assessment.***

Earthwork Evaluations

322 Earthwork Evaluations, NR (2017b), are carried out when there is a need to appraise the stability or condition of a slope and determine the actions required. For those earthworks identified as presenting a higher risk from the examination and classification process (see Para 292 to Para 296), an evaluation is carried out to determine whether the current level of safety risk is acceptable and the earthwork can continue to be managed through cyclical examination, or whether some intervention is required to reduce the likelihood of the earthwork failing. If intervention works are not possible, practical or economic, or the risk needs to be managed until the intervention can be carried out, then mitigation measures will be considered.

323 Evaluations are undertaken by the Route/Region Earthworks Manager when, following examination, there is a need to appraise the stability or condition of earthworks and determine the actions required.

324 The mandatory and non-mandatory drivers for the Earthworks Manager undertaking an Earthworks Evaluation are given in Appendix E9, Paras 1005 – 1006. In the 2019/20 examination season 30% of the Earthwork Evaluations were undertaken as additional management actions. These were over and above the mandatory requirements of the NR (2017b) standard.

325 RAM's reported to us that the Regions /Routes carried out Evaluations in accordance with NR (2017b), with the focus on new EHC D and Es or worsening EHC D and Es, plus some other situations like 10 yearly repeat evaluations on EHC Ds and Es. In 2019/20 the larger Routes/Regions were required to undertake between 400 (London North East and East Midlands) and 751 (Western) evaluations. Although a site visit by the RAM team is not mandatory from NR (2017b), the standard advises that most Evaluations will include a site visit. This is highly demanding of RAM staff time considering that it can be a 3 to 4hr drive from the Region Headquarters office to the extremities of the Routes.

326 It has been reported to us that the Evaluation process is often restricted to a desk top review of examination reports, particularly as a site visit is not mandatory but advisory according to the Earthworks Evaluations standard, NR (2017b). **Earthwork Evaluations should not be considered just as an examination report sign off**.

327 ***We recommend that more resources be made available to enhance the RAM teams and enable thorough Earthworks Evaluations to be undertaken, including site visits which in our view should be mandatory.***

328 The Earthwork Evaluations standard NR (2017b) lacks any reference to the use of existing NR geotechnical support tools e.g. WERM, GSRA, CHOPS etc. **We anticipate that at the next revision the Earthwork Evaluations standard, NR (2017b), will include the requirements and guidance for the use of existing NR geotechnical support tools e.g. WERM, GSRA, CHOPS etc.**

329 A limited record of the Earthwork Evaluation findings is available (but not the supporting data) as only the output decision is recorded in the Earthwork Examination database. We consider it essential that the Earthwork Evaluation decisions (including the data supporting the evaluation recommendations and actions) are traceable and accessible. It is recognised that development of CSAMS in the Intelligent Infrastructure II Programme, to bring the existing data and decision support tools together in a common interface, will address this requirement (see Para 852).

Geomorphological mapping

330 Geomorphological mapping may be undertaken as part of Earthworks Assessment, NR (2018o), and Geohazard Assessment, NR (2017b). We understand that the output of the walkover survey for earthworks assessment is routinely documented through geomorphological maps even if the standard, NR (2018o) does not explicitly use the term. In Geohazard Assessment, NR (2017b), the application of geomorphological mapping is only applicable to outside party natural slopes.

331 An example of geomorphological field mapping for railway earthworks is given by Phipps and McGinnity (2001), who condition assessed 20 km of chalk cuttings on the London Underground Metropolitan Line to form the basis of a risk classification scheme.

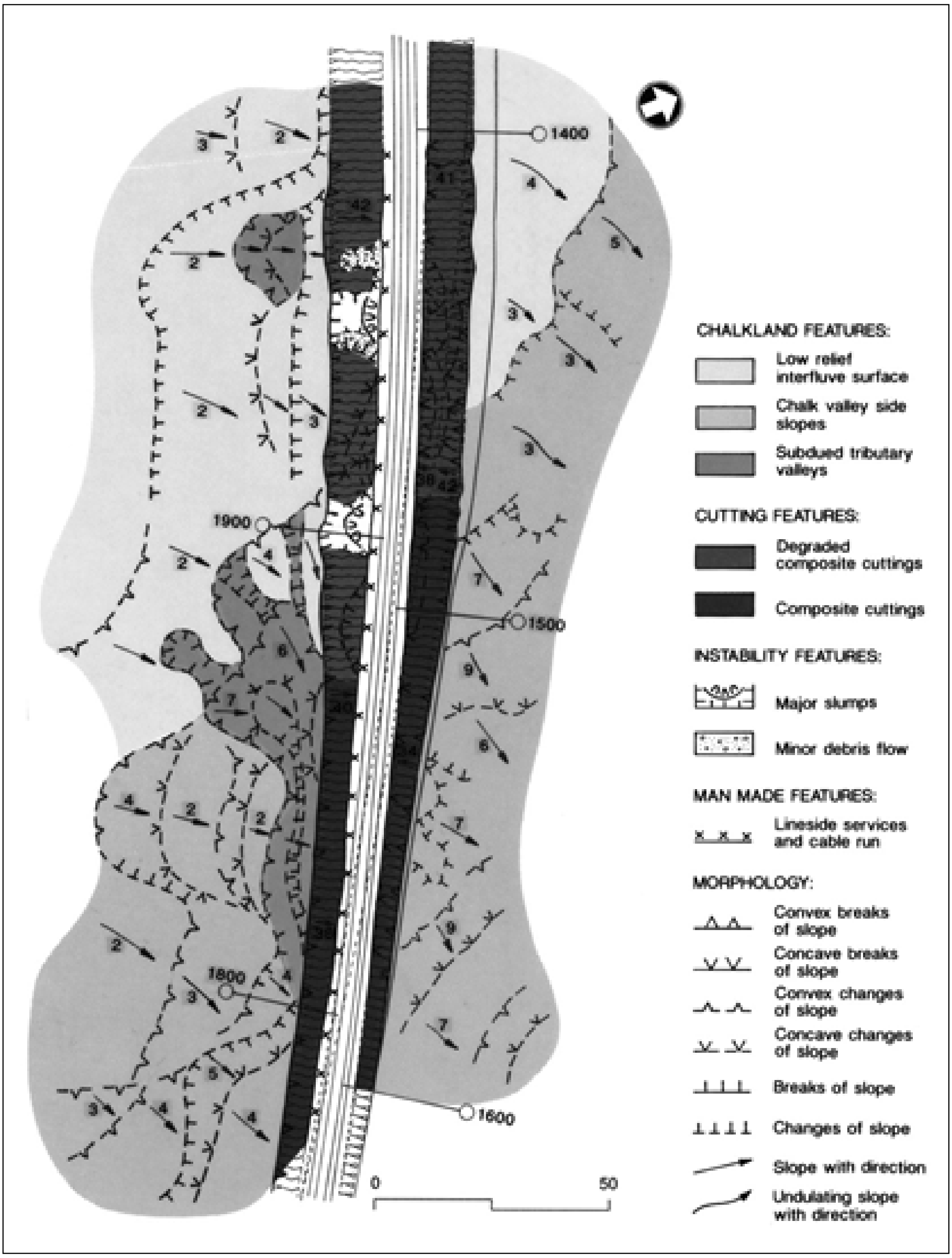


Figure 7.10: Geomorphological Map of a Metropolitan Line Chalk Cutting, after Phipps and McGinnity (2001)

332 NR suggested to us that the examination process creates a rudimentary geomorphological map since many of the pertinent slope movement indicators are geolocated. When these are viewed in the NR GIS viewer Geo-RINM (GRV), with the right combination of layers, a result can be obtained that is not too dissimilar to the geomorphological map in Figure 7.10 .

333 The requirements for the desk study to include geological, engineering geological and hydrological mapping are explicitly noted in EN 1997-2, Eurocode 7 (CEN 2007). Geomorphology has been acknowledged in the authoritative publication Soil and Rock Description in Engineering Practice (Norbury 2020), in which it is stated (following Hutchinson, 2001): '*A large majority of site failures are marked by a failure to carry out all stages of the site appraisal thoroughly such as desk study, appreciation of the geomorphology, mapping and appropriate forms of investigation*'.

334 The assessment of landform, slope materials and geomorphological processes from high resolution aerial photographs and topographic models, coupled with targeted field validation to provide the formulation of earthwork specific hazard models to evaluate risk, would allow NR to prioritise earthwork slopes for further assessment and in some case mitigation works.

335 **It is considered that NR should include significantly more comprehensive guidance and description of the techniques and value of engineering geomorphology mapping in their earthwork asset management processes**.

336 ***We recommend that there would be significant benefits in formally incorporating and encouraging the use of relatively low-cost engineering geomorphological mapping within the overall earthworks risk assessment framework***.

Global Stability and Resilience Appraisal (GSRA)

337 Given the large scale of the Earthworks asset population, a challenge for NR has been to prioritise slopes for detailed evaluation and appraisal following evidence of instability arising from the examination process. The size of the asset base means that it is not generally feasible to undertake detailed, site specific ground investigations and analytical slope stability assessments on a rolling programme, as is done by London Underground. The Global Stability and Resilience Appraisal (GSRA) process was therefore developed to allow the vulnerability of an earthwork to be assessed with respect to several slope instability mechanisms. GSRA considers the fundamental stability of an earthwork rather than an assessment of observed defects. It therefore provides an alternative way of considering a sub-set of the earthwork asset population (e.g. GSRA is not applicable to rock cuttings where discontinuities control stability) compared to the existing examination EHC process.

338 Stability charts based on earthworks slope height and angle were developed, NR (2017d), following analysis of geological formations, geotechnical parameters, vegetation and pore water pressure. Modes of slope failure that were considered include deep seated rotational stability, shallow translational stability, ravelling of chalk and other weak rock. The results are presented for soil cuttings and embankments in the GSRA visualisation tool.

339 The tool was designed for a rapid high-level assessment of the network and not as a replacement for more detailed stability assessments where needed. However, the influence of general vegetation and drainage conditions is included in the GSRA, and in part defines the vulnerability zones applied to earthwork assets. For embankments, geological map information, combined with an assessment of embankment foundation geology, is used to estimate underdrainage conditions at specific embankment locations.

340 The use of automatically processed, network-wide LiDAR surveys were shown as providing a better measurement of slope geometry compared to estimation during earthwork examinations (CIV065), see Figure 7.11. Compared to the LiDAR survey data, the geometry recorded during the earthwork examination generally overestimated slope gradient, whilst there was a large scatter for height comparison. It was concluded GSRA should use the LiDAR data in preference to the earthwork examination (CIV065) slope geometries.

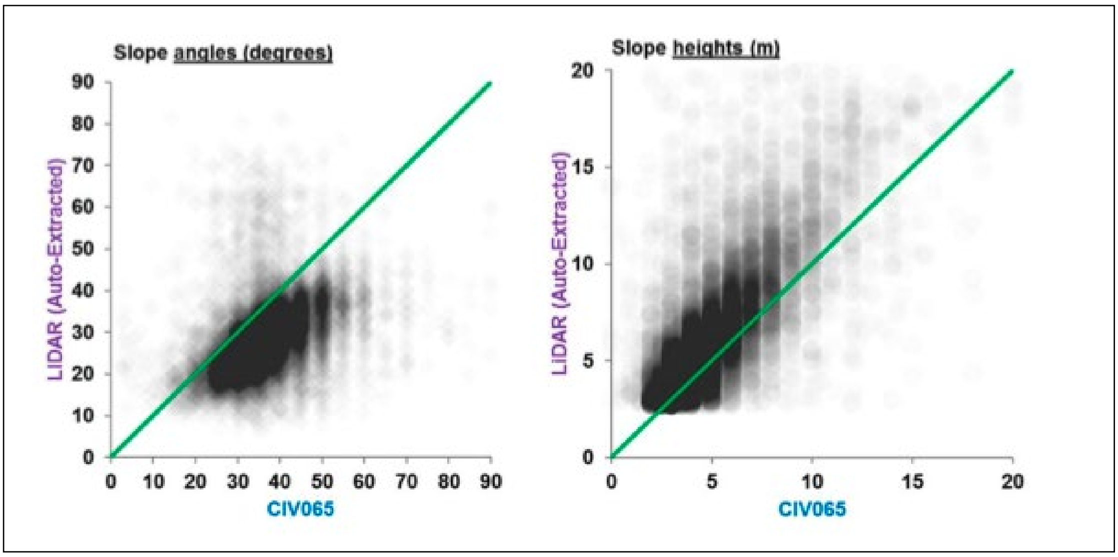


Figure 7.11: Comparison of CIV065 Examination and LiDAR Slope Geometries. (Taken from NR 2017d. CP6 Earthworks Asset Policy Development Task 36 – Global Stability and Resilience Appraisal Interim Report August 2017.)

341 Geological formations were grouped by similar engineering performance and mode of failure to provide the widest possible network coverage, rather than needing individual appraisal (Figure 7.12).

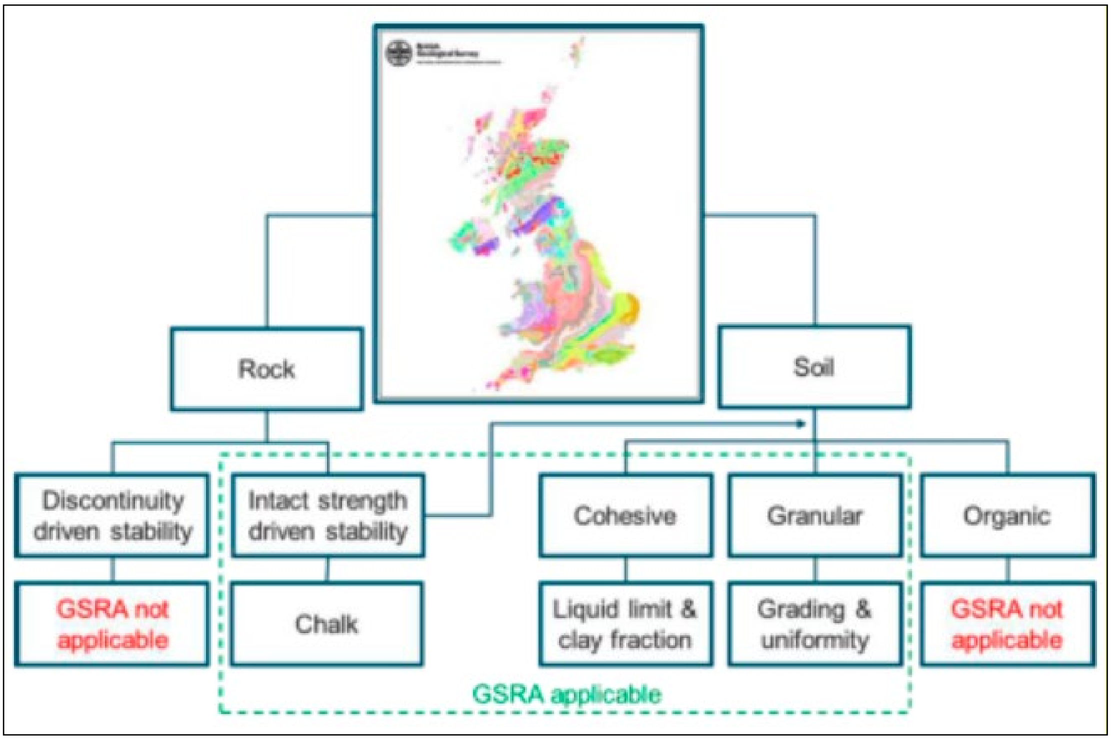


Figure 7.12: Geology based GSRA groupings (Taken from NR (2017d). CP6 Earthworks Asset Policy Development Task 36 – Global Stability and Resilience Appraisal Interim Report August 2017.)

342 Stability charts were constructed by carrying out a large number of analyses for each material group, considering different failure mechanisms (such as shallow translational failure or deep-seated circular progressive failure), and different porewater pressure regimes. An exemplar stability chart for high plasticity clay cuttings with a high porewater pressure regime and deep-seated failures is shown below in Figure 7.13

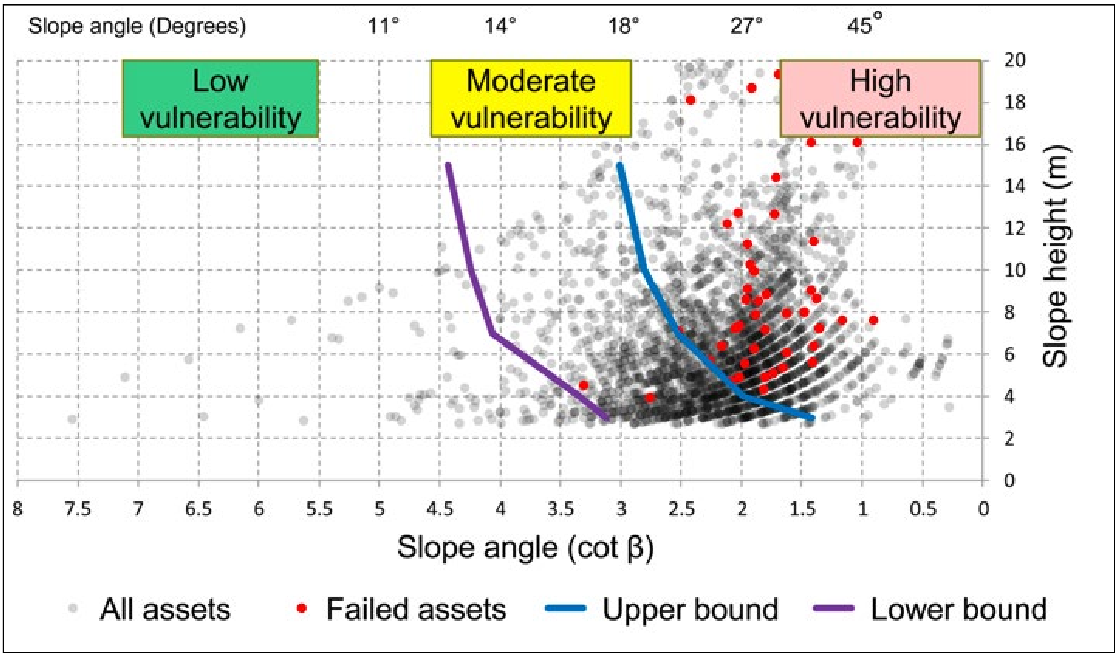


Figure 7.13: Global Stability chart for high plasticity clay cuttings with a high porewater pressure regime and deep-seated failures, (after Spink (2020).

343 The axes of Figure 7.13 are slope height (m) against slope angle (expressed as the cotangent of the slope angle, i.e., cot 2 is approximately 27°). Every earthwork in the material group is plotted on the chart, which is divided into three zones of low, moderate and high vulnerability. The high vulnerability zone defines the highest and/or steepest slopes that would have a factor of safety less than 1.0, even with the "best-case" input assumptions on material strength and porewater conditions. Conversely, the low vulnerability zone is defined by the lowest and/or shallowest slopes that would have a factor of safety greater than 1.0, even with the "worst-case" assumptions on material strength and porewater conditions. The shape and position of the vulnerability boundary lines changes with geology, failure mode and porewater pressure conditions. The majority of the recorded failures plot in the high vulnerability zone. This approach has allowed the identification of earthworks across the whole NR portfolio that are likely to have the lowest factors of safety and, hence, the highest vulnerability to failure from triggering events.

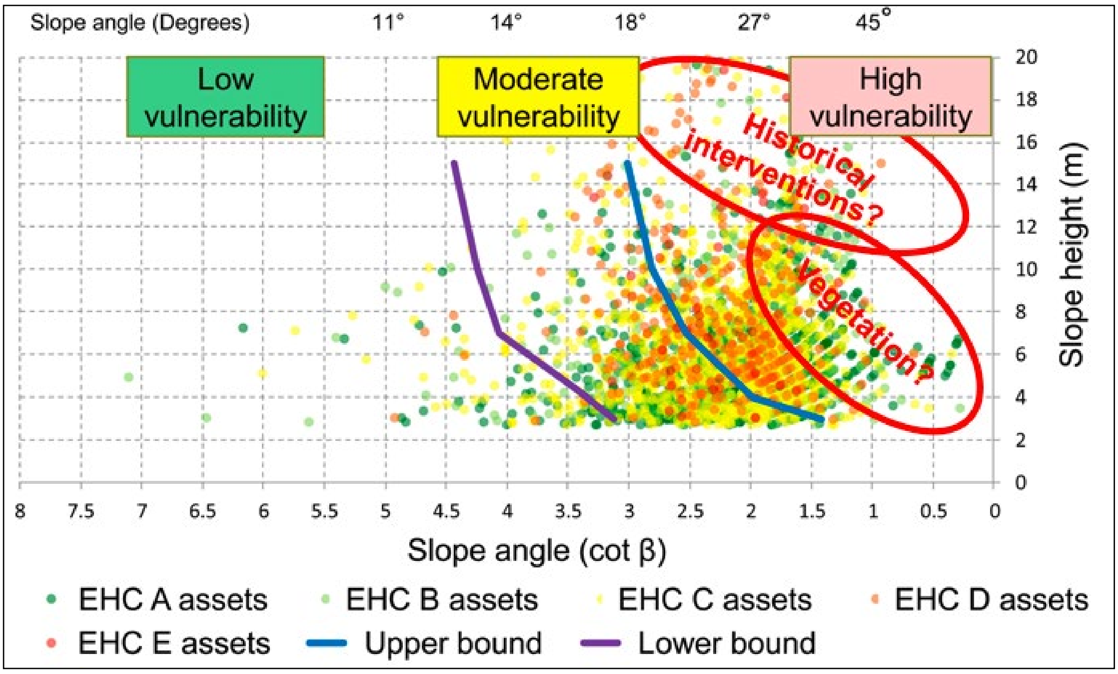


Figure 7.14: Global Stability chart for high plasticity clay cuttings with a high porewater pressure regime and deep-seated failures with EHC (Earthworks Hazard Category), after Spink (2020).

344 Figure 7.14 above shows the same stability chart as Figure 7.13, but with the individual earthworks colour-coded by EHC, Spink (2020). It can be seen that whilst there is some tendency for the poorer-condition assets in EHCs D and E to plot towards the right, there is not a good correlation between EHC and the vulnerability zones. This should be anticipated from the inherent differences in the approaches. The vulnerability zones are defined by the inherent below-ground factor of safety of the slope, whilst EHC is derived using an algorithm by applying a weighting to surface-visible precursor indicators of failure. It should also be noted that the interval between visual examinations from which EHC is determined may be up to 10 years and, therefore, the most recent EHC may not reflect the degraded state of the earthwork today. Extreme weather events can rapidly accelerate the rate of deterioration or change the porewater regime and, hence, the factor of safety of the slope.

345 **In the global stability assessment high vulnerability zone (Figure 7.14), there are a significant number of earthworks standing at heights and/or angles that should not be feasible for the particular geology and the "best case" assumed pore water pressure conditions in the GSRA analysis. A high proportion of these earthworks appear to be in good condition with EHCs of A or B, Spink (2020).**

346 **The GSRA analyses, based on assumed parameters, frequently show that earthwork stability is more sensitive to pore pressure conditions than to variations in the geological material properties. However, NR have very limited knowledge of the distribution of pore water pressures in its earthwork slopes. The full effect of vegetation, particularly large trees, on**

stabilising a slope through porewater reduction and root reinforcement has also not been included in the global stability appraisal, and this may account for the apparent stability of some of the lower, steeper slopes.

347 Some of these discrepancies may also be due to unknown historical interventions, such as slope counterfort drains, in-situ clay burning or grouting that are now barely visible without intrusive investigation. Earthwork slopes that have previously been remediated, in which the geometry profile may not have changed (e.g. soil nailing), also need to be discounted from the GSRA plots.

348 Analysis by Spink (2020) of the GSRA output confirms that appropriate vegetation and drainage management are key elements in sustaining earthwork slope stability.

349 At a strategic level the outputs of GSRA will enable long term tracking of resilience against the rate of earthworks strengthening that takes place. Achieving weather resilience for the NR earthworks portfolio is a long-term journey that will require investment over multiple control periods. GSRA allows the magnitude of this challenge to be understood.

350 GSRA is one of several geotechnical support tools awaiting full integration into the NR earthworks asset management system to enable effective use. Currently GSRA is available to engineers via a spreadsheet tool which NR recognise is not sustainable. NR also recognise a future Policy update needs to clearly articulate how GSRA assists in highlighting wider earthwork vulnerability issues.

351 **Future Earthwork Policy and Standard updates should incorporate the applicability and use of the GRSA tool. However, the limitations of the GSRA methodology should be highlighted particularly at an individual asset level where the often highly transient and complex pore pressure conditions in a slope generally control stability. Further development (included in the Intelligent Infrastructure (II) programme) is required to the GSRA process to make it an effective earthworks decision support tool, including addressing the recommendations made in the GSRA report, NR (2017d).**

352 GSRA is not currently incorporated into the examination EHC algorithm or into the Earthworks Safety Risk Matrix (ESRM). GSRA is intended to provide a global assessment at portfolio level when developing earthwork workbanks at route level. Site specific information would need to be incorporated at a tactical level during more detailed evaluation and assessment work to provide credible outputs. NR do not currently have a process available to record site specific intelligence from assessment work back into tools such as GSRA – albeit this is a vision for the Intelligent Infrastructure (II) programme. The anticipation is that a future iteration of the GSRA tool could be used as an additional layer of information on the susceptibility of individual assets during earthwork evaluations and to validate intervention proposals.

353 The assimilation of the GSRA support tool into a common interface, along with the other geotechnical decision support tools will ensure that a single trusted integrated data source is available for effective earthworks risk management across the NR business. It is recognised that development and commissioning of the CSAMS (Civils Strategic Asset Management Solution) will meet this requirement (see also the recommendation in Para 359).

Civils Strategic Asset Management Solution (CSAMS)

354 The Civils Strategic Asset Management Solution (CSAMS), illustrated in Figure 7.15, is planned to provide strategic asset management capability for the NR Civil Engineering community (including Earthworks and Drainage). It is designed to create one trusted data source across NR's civils infrastructure, replacing numerous legacy systems, including the civils asset register and more than 20 other core systems, 90 data sources and one million documents. To complicate matters further, many of the systems duplicate components of others, often imperfectly, creating multiple versions of the truth

355 The creation of a single accurate data source is part of the overarching aim of the CSAMS project to meet NR's regulatory commitments to retire and replace the existing asset information systems and address outstanding data quality issues across the entire Civil Engineering portfolio. The solution was planned as a consistent way of maintaining civils asset management; the transition to new and better ways of working will give the civils asset management community the streamlined, up-to-date data needed to make better, more informed decisions.

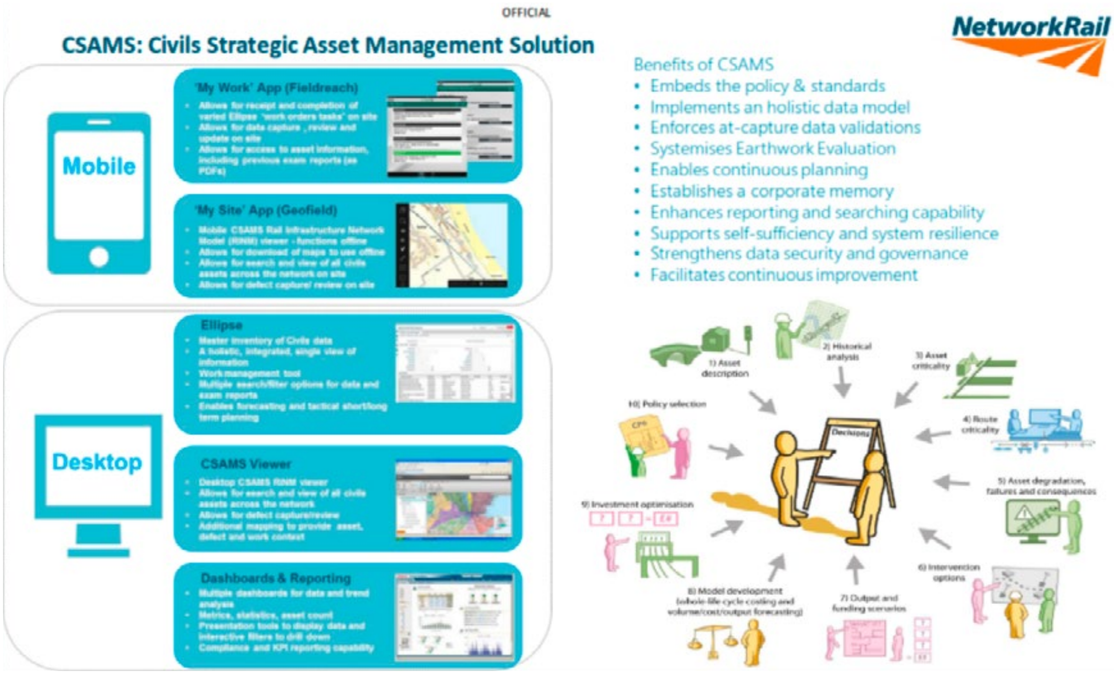


Figure 7.15: Civils Strategic Asset Management Solution (CSAMS). (taken from NR presentation Vision of Intelligent Infrastructure for Geotechnics 8th October 2020)

356 CSAMS should have originally been delivered in early CP5 but to date there has been limited progress. However, the delivery of CSAMS has now been included in the Intelligent Infrastructure II programme and implementation is anticipated to be completed in CP6.

357 **Multiple and disparate data sources are impacting on the ability of NR Geotechnical and Drainage Engineers to make accurate and efficient asset management decisions that consider all available information e.g. in the Evaluation of Earthwork assets following Examination**.

358 NR has some industry leading earthworks decision support tools. However, there is poor integration between datasets that is preventing the true value of the decision support tools being realised in terms of informing asset management decision-making. This was evidenced during our RAM interviews, with concern raised that the decision support tools and data are distributed across multiple platforms that cannot be integrated easily. This meant that a lot of time is spent using these tools/systems that could be saved if integrated better, allowing the RAM teams to concentrate on key issues. In some cases, the RAMS reported they were not using the tools provided (e.g., Powerpack). There is also concern that information could be missed that could lead to a decision error that could have significant negative impact. To combat this there is a need to have all tools/data available together in a common user interface, i.e. CSAMS.

359 ***We recommend that an overhaul of the Geotechnical and Drainage asset management systems is required to develop an interface that brings the existing data and decision support tools together in a common interface (CSAMS). This will provide the fundamental capability of NR engineering teams to properly evaluate and document the vulnerability of earthwork and drainage assets and accurately prioritise intervention activities required to safely manage the infrastructure***.

Route Weather Resilience and Climate Change Adaptation (WRCCA)

360 NR has recently published updated Route 2019–2024 CP6 Weather Resilience and Climate Change Adaptation Plans, NR (2020a). These CP6 plans report progress to date, explain the plans for the future and update the vulnerability and impact assessments to account for changes in NR's WRCCA Strategy and guidance. Key highlights include:

+ In 2017 the NR guidance used the UKCP09 medium scenario, 90th percentile probability 1. With the release of UKCP18 data, Met Office (2018) this has been updated to the UKCP18 Representative Concentration Pathway (RCP) 6.0 scenario, 90th percentile
+ Commitment to further investment to reduce the effects of extreme weather on NR's railway infrastructure
+ Further targeting of earthworks assets, to reduce the number deemed susceptible to failure during adverse weather. This will include rolling out more remote condition monitoring to help mitigate the associated risks at identified sites

361 Details of these plans and NR's approach to accounting for adverse weather conditions are given in Appendix E10, Para 1009 to Para 1026.

362 NR have a small team of weather specialists who work with the external weather forecast provider to support the operational railway with forecasts. The current weather forecast management approach uses extreme weather action teleconferences (EWATs) to advise NR routes of forthcoming heavy rainfall and thunderstorms and analyse historical weather events and delays to improve their response.

363 When action is triggered, EWATs bring together route control, maintenance, operations, and train and freight operators to amend timetables and make critical decisions to reduce safety risk. NR weather forecasting service provides a five-day outlook of weather conditions at a national and local level to provide alerts of adverse or extreme events. These forecasts are updated daily and communicated to operations control centres and to EWATs to improve response. Key is the response from the Earthworks Route team in determining the safety risk to the railway from real-time meteorological information regarding adverse weather and in particular extreme rainfall events.

364 When two or more routes may be affected by an impending weather event, a national EWAT is invoked led by the NR national operations centre (NOC) and attended by the Department for Transport (DfT). An equivalent system operates in Scotland's Railway with Transport Scotland. Route teams inform the national team and information is distributed across the industry. Plans and processes are reviewed based on learning points from events.

365 There will be occasions when additional speed restrictions will be required on particular lines if heavy rainfall is judged to present a heightened risk to earthwork stability. As technology to predict and warn of failures matures, and NR deploy it in more places, the expectation is that the risk of such disruption will reduce.

366 NR recognise that speed restrictions can cause disruption to passengers and freight services, and to some degree create additional safety issues if not managed appropriately, e.g. through crowding or frustrated passenger behaviour.

367 The ORR highlighted ongoing concerns regarding the Adverse/Extreme Weather Plans for Earthworks in their 2019/20 Annual Report of Health and Safety Performance on Britain's Railways (ORR, 2020a). "*Earthworks failures in extreme weather: A persistently wet winter, culminating in several storms in February 2020 resulted in a number of earthwork failures and these were particularly prevalent in the Southern Region. We engaged with NR to understand the causes and responses. None of these incidents led to a derailment or other serious incidents, although in some cases there was an element of good fortune involved, for example with trains striking ballast or landslips being discovered by trains on adjacent lines. These incidents highlight the importance of the effective implementation of the Extreme Weather Action Team procedures in mitigating the consequence of earthwork failures. They also show the need for routes to develop and implement weather resilience and climate change plans to mitigate against the risks of future weather events.*"

368 **A key challenge for the NR earthwork asset management is to focus on mitigating the effects of earthworks failures as currently it is not reasonably practicable to detect nor prevent all earthwork failures. Mitigation (recovery) controls are crucial to reduce the consequence of a failure should it occur**.

369 ***We recommend that NR place a high priority on undertaking a comprehensive review of the risk associated with the frequency and severity of extreme rainfall and climate change to further develop resilience and mitigation plans against rapid earthwork failures (mostly cuttings) , with little or no indication of visible instability prior to failure***.

Earthwork Risk Assessment

370 **A unique aspect of earthwork assets, as opposed to track or rolling stock for example, is their inherent variability. Even if information and knowledge of the change in condition and performance was perfect (which it never is), there would still be a variability associated with future predictions, related to the uncertain behaviour of geological materials. The behaviour of earthwork assets is also affected by environmental conditions, notably surface water and groundwater including rainfall events, which are also uncertain. Thus, a risk-based approach is essential to understand this variability, and to assign probabilities to future earthwork behaviour, particularly when controlling factors such as climate change and weathering are changing.**

371 Under UK safety law, the Health and Safety at Work etc Act (1974), asset management of existing earthworks has to follow the approach of reducing risk levels to 'as low as reasonably practicable' (ALARP), giving consideration to cost-benefit analysis of whether spending on interventions will result in a cost benefit over a realistic service life. The ALARP principle allows that safety improvements should not be pursued at any cost, but only if the cost of averting a risk is not grossly disproportionate to the risk averted.

372 The Management of Health and Safety at Work Regulations (1999) impose a statutory duty on NR to conduct regular risk assessments. This is to ensure that safety is not degraded, and that risks are maintained ALARP. The risk management process, therefore, permits a rational analysis of the safety risks; how these can be mitigated or controlled; and the associated funding requirements. Minimal extension of the scope of the risk analysis can have secondary benefits, such as identifying the exposure to non-safety-related business risks and helping to formulate business cases and overall investment plans. Risk assessment is, therefore, a tool that earthworks asset managers

apply to ensure that safety objectives are met within the NR business framework, and that funds are justified and allocated in response to safety and business needs.

373 The NR Earthworks Policy, NR (2018c), is risk based, with the management strategy for the earthworks portfolio of assets being driven and prioritised by the level of risk posed by individual earthwork assets. The Policy is centred on the management of safety risk, which NR measure by the distribution of assets within the Earthworks Safety Risk Matrix (ESRM). (Figure 7.6, Para 277).

374 We note that the term 'risk' is sometimes misused both in NR documentation and more generally when a 'hazard' or 'threat' is actually being described.

375 Earthworks safety risk is defined as the product of the probability or likelihood of a hazard event occurring (Earthworks Hazard Category) and the impact or consequence (Earthworks Asset Criticality Band) should that hazard event occur. Hence earthworks safety risk increases diagonally across the ESRM from bottom left to top right (Figure 7.6, Para 277).

376 The ESRM defines the level of risk that each earthwork presents; it is then necessary to determine whether this level of risk can be tolerated, or whether some form of intervention or mitigation is required to reduce the risk level.

377 Risks associated with NR's activities and infrastructure are governed by the Enterprise Risk Management Framework (ERMF), NR (2016b). This process sets out a principle-based approach for the management of enterprise risks in NR: the risk management principles detailed in this process require each business area to:

+ review its risk environment and how it may affect its objectives on a regular basis
+ analyse the likelihood and impact of the risk arising
+ evaluate that risk assessment against the corporate risk appetite
+ determine an appropriate management response
+ plan and monitor progress of that response and its effect on mitigating the risk; and
+ clarify impact area in relation to passengers, NR strategic objectives and NR business processes via the application of risk categorisation

378 The acceptability of risk across the Enterprise is agreed at NR Board level and expressed in terms of a Corporate Risk Appetite; this is represented by the Corporate Risk Assessment Matrix (CRAM), Figure 7.16).

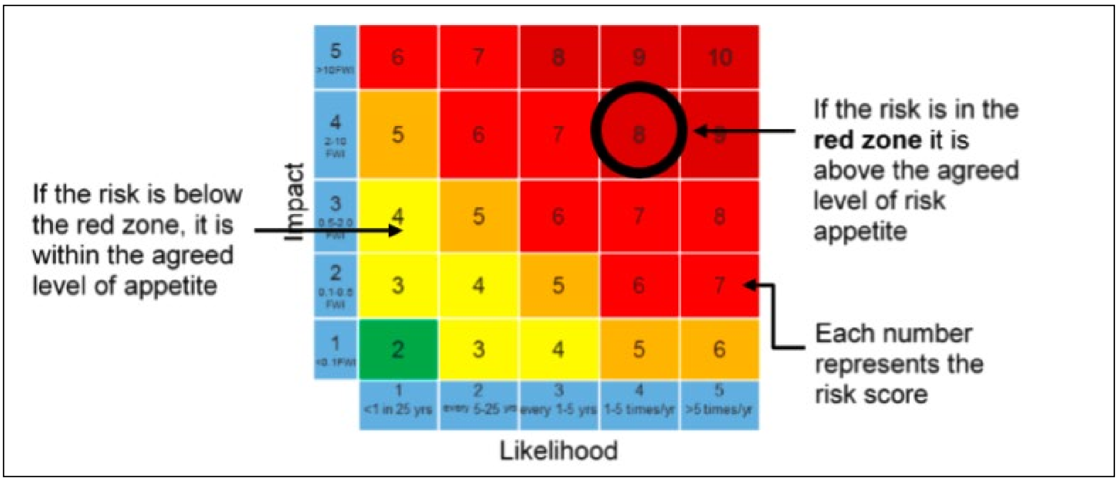


Figure 7.16: Corporate Risk Assessment Matrix (CRAM) – for Safety. (Taken from NR (2018c), Earthworks Asset Policy. Issue 8.)

379 The agreed level of risk appetite is shown by the green, yellow and orange cells on the CRAM. The red and dark red cells are above the agreed level of risk appetite. The risk score in each cell is the sum of the Likelihood score based on the frequency of occurrence of the event, and the Impact (Consequence) score defined in terms of fatalities and weighted injuries (FWI).

Earthworks BowTie Risk Assessments

380 The NR Earthworks Policy, NR (2018c) uses the risk BowTie approach, (Figure 7.17), for identifying 'hazard or threat events' related to earthworks.

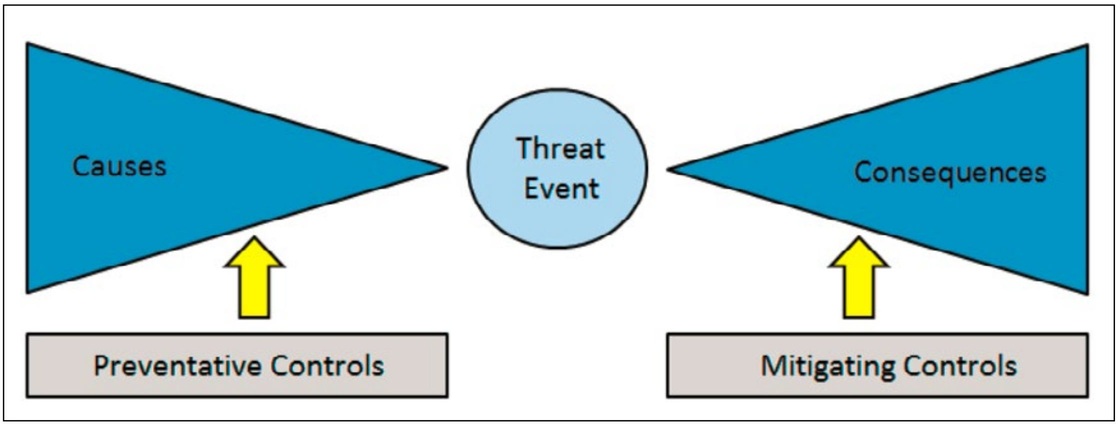


Figure 7.17: BowTie methodology for threats (hazards).

381 NR use the BowTie methodology in order to identify the:

+ potential causes of those risks occurring
+ impact and likelihood of those risks materialising; and
+ consequences/impact should the risk occur

382 The BowTie tool is defined by its centre (or "knot"), which is the threat (hazard) event within the scope. Some typical earthworks threat (hazard) events and their impacts are outlined in Table 7.2.

Earthwork Type	Threat (Hazard) Event	Impacts
Soil Cuttings	Slope failure leading to loss of the kinematic envelope e.g., failed material obstructing the track.	Mainly safety, but with associated performance, reputation and infrastructure impacts. Rarely environmental impact.
Rock Cuttings		
Embankments	Loss of track support.	
Soil Cuttings	Slope failure leading to loss of track support.	Mainly performance, but with associated reputation and infrastructure impacts. May also impact on safety in severe cases.
Rock Cuttings		
Embankments	Loss of track geometry.	

Table 7.2: Impacts from Earthwork Threat (Hazard) Events. (Taken from NR (2018c), Earthworks Asset Policy. Issue 8.)

383 Slope failure of either a cutting or embankment is the most common earthworks threat event, but other hazard events are also recognized, such as the shrinkage or swelling of a clay embankment, scour and inundation of an embankment in a flood plain, collapse of a dissolution feature or historical mining subsidence. The left-hand side of the bow tie details all the causes that could lead to the threat (hazard) event at the centre. The right-hand side details the effect (or consequences) when the threat (hazard) event at the centre materialises.

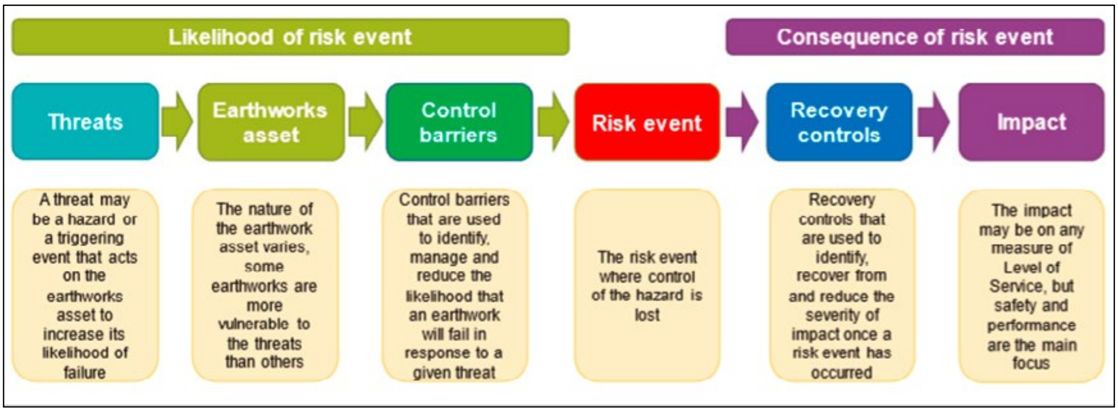


Figure 7.18: The Earthworks asset risk bow-tie diagram. (Taken from NR (2018c), Earthworks Asset Policy. Issue 8.)

384 Various threats act on the earthwork asset; they may be hazards such as underlying historic mine workings, or they may be triggering events such as intense rainfall. The nature of the earthwork asset is highly variable, and so some earthworks are more vulnerable to particular threats than others. The impact may be on any measure of level of service, but safety and performance are the main concerns. The bow tie also illustrates that risk control measures may be applied to either side of the threat (hazard) event: either control barriers to reduce the likelihood of the threat (hazard) occurring or recovery controls to limit the severity of the impact once the threat (hazard) event has occurred (see Figure 7.18). Business processes such as policies, and standards are included as both Preventative Controls (Control Barriers) to reduce the likelihood of an event occurring and as Mitigating (Recovery) controls to limit the consequence of an event.

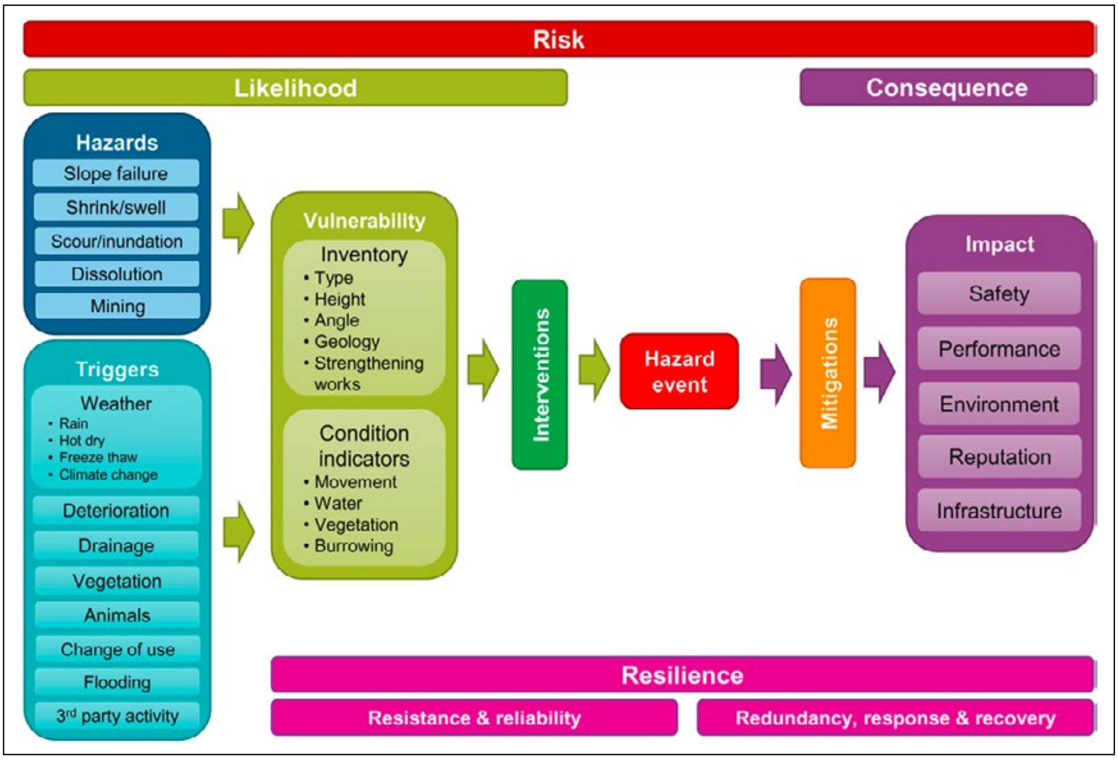


Figure 7.19: Earthworks overview risk bow-tie, after Spink (2020)

385 To reduce the likelihood of the threat (hazard) event occurring interventions (preventative controls) may be undertaken on the earthwork (Figure 7.19). An intervention is any activity that either reduces the vulnerability of the earthwork, controls the threats in some way e.g. managing the impact of intense rainfall events or, in a minority of cases, reduces or removes the hazard. For example, the earthwork may be modified by regrading the slope to a shallower angle, or the slope may be strengthened by soil nailing or the construction of a retaining wall.

386 The effect of the hazards may be controlled by cleaning out the drainage ditches, or cutting back the vegetation, or eradicating the burrowing animals, or installing flood defence works. The weather threat to earthwork stability can be managed only indirectly by ensuring that drainage is maintained in a fully functioning state, and that the capacity of the drainage is adequate, including consideration of how this may need to increase because of climate change.

387 Regular examination is a part of surveillance which together with monitoring provide guidance on the level of or change in a threat. Slope monitoring also helps to manage the likelihood of the threat (hazard) event occurring by improving the understanding of the condition indicators to better anticipate the need for more major interventions and to plan their timing. It is occasionally possible to reduce or remove the hazard by, for example, grouting up the underlying historical mine workings, or installing bank protection to a stream that presents a scour or inundation hazard.

388 Mitigation (recovery) controls (Figure 7.19 above) are carried out to reduce the consequence of the threat (hazard) event, should it occur, by considering both the severity and duration of the potential impact. For example, a temporary speed restriction may be applied to a section of railway line when a major storm is forecast, so that should a slope failure occur the trains may be able to stop in time, or at least the speed of impact would be considerably reduced, reducing the severity. Mitigations may be used to manage the risk for a relatively short period of time until it can be permanently reduced by an intervention e.g. instrumented flexible barriers are a mitigation. They may also be used to manage risks that cannot be treated by intervention, such as the installation of a rock fall alarm system along the boundary fence to manage the risk posed by a third-party rock slope.

389 The overall earthworks risk is managed by carrying out a combination of interventions (preventative controls) to reduce the likelihood of a threat (hazard) event occurring) and mitigations (recovery controls) to reduce the impact should the threat (hazard) materialise. (Figure 7.20 below)

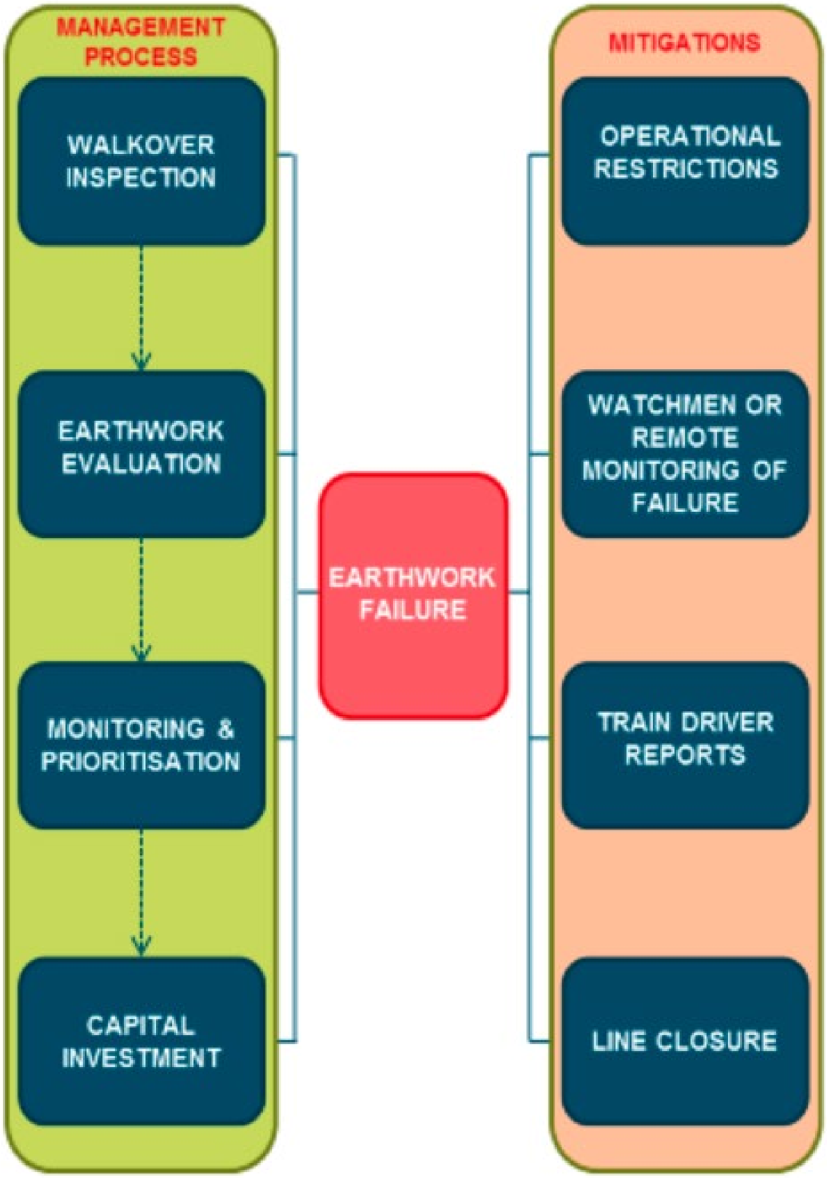


Figure 7.20: Simplified bow-tie diagram to illustrate typical interventions and mitigations used by NR to manage the risk of earthworks failure. (Taken from NR (2018c), Earthworks Asset Policy. Issue 8.)

390 We support the use of BowTie methodology to aid the understanding of earthwork threat hazard events and how the risks are controlled. It allows the visualization of complex earthworks threats (hazards) in a way that is understandable, yet also allows for the development of detailed risk-based improvement plans.

391 ***We recommend that NR undertakes a comprehensive review of the risk 'bow-tie' in relation to earthwork related threat (hazard) events to assess the performance of the risk management system and adequacy of the key preventative controls and mitigations. The review should specifically include:***

+ ***the hazards associated with the frequency and severity of extreme rainfall and climate change***
+ ***the mitigation (recovery) controls required to reduce the consequence of an earthwork failure event, should it occur***

Precursor Indicator Model

392 A Precursor Indicator Model (PIM) has been developed by the Rail Safety and Standards Board (RSSB) as a quantified risk model for understanding train accident risk. It is released periodically and demonstrates quantitatively the level of train accident risk and how it is changing. PIM is a lagging indicator, useful for assessing trends and comparative performance but not for forecasting future performance. Details of the Precursor Indicator Model are given in Appendix E11, Para 1027 to Para 1031.

393 Whilst the number of earthworks events is relatively low, the exposure profile in PIM is known to significantly increase following periods of heavy and sustained rainfall. It is considered that PIM is an outcome indicator that enables the measurement of events after they have occurred, giving an indication of the effectiveness of the risk controls in place. Care should therefore be used in predicting earthworks risk reduction from PIM following periods of benign weather.

394 As a result of the limitations of PIM for Earthwork assets NR has recently introduced a weighted earthworks risk score (ERS). Details of the ERS metric are included in the NR Executive Leadership Team (ELT) Board paper 20/25.21 dated 26 May 2020. The ERS is based on the distribution of earthwork assets that have both an Earthwork Hazard Category (EHC) and Earthwork Asset Criticality Band (EACB). As noted in the earlier section 'Earthwork Examination and Classification System' (Paras 268 – 277), the EHC category is predominantly based on the slope examination process to identify surface-visible precursor instability indicators. However, there are other hazards that have limited or no effect on the scoring in the examination algorithm e.g. high pore pressures in the slope, the impact of intense rainfall, third-party activity etc. Therefore, the EHC category may not always accurately reflect the probability of slope failure.

395 This ERS metric is still in its infancy. However it has the potential to provide a more informed long-term view on the risk profile of the earthwork asset base than the PIM and can be used in conjunction with whole life cost (WLC) models to inform strategic planning and associated key volume activity.

396 We recognise the limitations of the PIM for Earthwork assets and support the development by NR of the ERS metric to provide a more informed long-term view on the risk profile of the earthwork asset base. This should include further work to ensure the EHC category, which is a significant element of the ERS metric, more accurately reflects the probability of slope failure for all earthwork assets.

ORR Risk Management Maturity Model (RM3)

397 ORR developed the Risk Management Maturity Model (RM3), in collaboration with the rail industry, as a tool for assessing an organisation's ability to successfully manage health and safety risks, to help identify areas for improvement and provide a benchmark for year-on-year comparison.

398 The 2019-20 ORR Annual Assessment of NR, ORR (2020b), found that NR's risk management maturity was primarily at the managed and standardised levels (maturity is measured on a five-point scale: ad-hoc, managed, standardised, predictable, excellence.) The framework set by central functions is often more mature than the delivery of rules, standards and programmes by the Regions. In the view of the ORR, for NR's risk management maturity to improve further, the Regions need to more fully own the risk control framework.

399 ORR noted *"Risks on the network are changing – and the overall level of modelled risk has increased. This is mainly due to earthworks failures caused by more frequent and severe weather events. NR has a plan to mitigate the impacts of climate change but these events indicate that the plans are not keeping up with the pace of change".*

400 We note and support ORR's views regarding NR's Risk Management Maturity and the changing earthworks risk profile as a result of more frequent intense rainfall events on the network.

“*A key challenge for Network Rail’s earthwork asset management is to focus on mitigating the effects of earthworks failures, as currently it is not reasonably practicable to detect nor prevent all earthwork failures. Mitigation measures are crucial to reduce the consequence of a failure should it occur.*”

Whole-life asset management

401 Historically NR earthwork assets have not been treated holistically or considered throughout their entire life-cycle. Instead, asset strategies have been developed on an ad hoc basis, often on the basis of the funding available at any given point in time. Until relatively recently in the NR capital-constrained environment, there was a bias towards selecting solutions with the lowest initial cost rather than considering the whole-life total expenditure which includes capital, maintenance and operational costs.

402 Whole-life asset management balances maintenance, repair, refurbishment, renewal, replacement and upgrade activities to optimise the long-term value of an asset (Hooper, 2009). The concept of whole-life costing is described by Perry et al. in CIRIA (2003a). It can be a useful tool when comparing the capital cost of renewal schemes against longer term maintenance costs. Although whole-life asset management is a potentially useful tool it does have its limitations, particularly for existing earthworks that can be expected to have very long service lives. These limitations should be understood and the process used with care to ensure sensible results. In practice it is difficult to set up a reliable model for the management of existing earthworks because the performance requirements, the availability of expenditure and an appropriate discount rate over the likely service life are very difficult to estimate.

403 There is a risk that whole-life asset management models can become immensely complicated; however, if they are too simplistic this defeats the whole object of the exercise and their results may be misleading. The characteristics of NR earthwork assets bring their own particular challenges, including:

+ **managing a portfolio of largely existing assets that cannot economically be replaced, but must be maintained and in many cases see their economic lives extended**
+ **from an engineer's perspective, understanding the implications of practical asset life extension from current design codes and dealing with uncertainties associated with inherently variable earthworks**

404 The Asset Management Policy, NR (2018a), requires that all asset management interventions are based on whole life, whole system costs. NR has been active in the development and application of whole life cost models for over a decade and has built a portfolio of asset specific models, including earthworks, that provides effective support to the development of asset maintenance and renewal strategies and the strategic forecasting of activity volumes, costs and outputs. This work has supported the development of the earthworks

whole life cost model (SCAnNeR); this aims to produce an optimum mix of earthwork interventions (renew, refurbishment and maintenance) and their associated cost that will achieve the required aims of the NR earthworks management policy.

Decision Support Tools -SCAnNeR and Powerpack

405 In order to determine the most efficient and cost-effective means of utilising the available funding for earthworks interventions (maintenance, refurbishment and renewal), NR have developed a strategic whole life cost Decision Support Tool (DST) known as earthworks SCAnNeR (Strategic Cost Analysis for NR). SCAnNeR is an optioneering DST, that allows a large number of mixes of interventions to be applied to the asset portfolio, and to assess how these interventions impact on the condition of the portfolio, when balanced against modelled earthwork degradation.

406 It is essential that engineering judgement and experience is used, at a tactical level, to produce the workbank of exactly which assets are to be subject to an intervention. To aid in this decision making, NR have developed a tactical DST (called Powerpack) to allow a 10-year workbank to be built at individual earthwork level, guided by the outputs of the SCAnNeR model. Powerpack, which is a series of linked spreadsheets, brings together data from various sources into one place to enable workbank construction and portfolio level searching across different key parameters. This includes WERM3, GSRA and the CHOPS assessments from the outside party slopes work referred to earlier. It is possible to import the Powerpack data into the GeoRINM Viewer to visualise workbanks alongside a catalogue of other datasets in a GIS. Powerpack, as a spreadsheet tool, is not sustainable over the long term and is planned to be replaced as part of the NR Intelligent Infrastructure programme (this is covered in a later section 'Intelligent Infrastructure' Paras 432 to 435).

407 Further details of SCAnNeR and Powerpack Decision Support Tools are included in Appendix E12, Para 1032 to Para 1038.

408 **We recognise the value of the SCAnNeR and Powerpack tools in providing a rational basis for the investment decision-making process on a whole-life basis. We acknowledge that NR seek to ensure that the whole-life asset management decision support tools and the associated models are used appropriately – they are a tool for geotechnical engineers to make intelligent asset management decisions and judgements based on basic geotechnical principles.**

Earthwork Performance and Condition Trends

409 Prior to Carmont, the 1995 derailment at Ais Gill (HM Railway Inspectorate, 1997) was the last time NR had a fatality as a result of an earthwork failure. Frequency of derailments and high consequence failures were generally reducing over 5-year control periods, albeit the number of low frequency and high consequence events being considered to be above the NR corporate risk appetite. The Watford derailment in 2016 (RAIB, 2017) was a particularly high consequence event where the outcome was fortuitous.

Earthwork Failures

410 Up to the end of CP5 in 2019, NR experienced, on average, 500 earthwork failures per control period (100 per year), as shown in Table 7.3. The severity of these asset failures was however gradually reducing prior to Carmont. From the start of CP3 to the end of CP5 (2004-2019) there were 98 potentially high consequence earthwork failures (7 per year), with 18 of these events resulting in train derailments (1.2 per year). The majority of these failures related to cutting failures that generally occur rapidly where the inherent vulnerability of asset resistance to adverse / extreme weather is exposed.

Control Period	Date Range	All Earthwork Failures	Embankment Failures	Potentially high consequence earthwork failures	Earthwork attributable derailments
CP1	1994/95 – 98/99	*No data*	*No data*	*No data*	7
CP2	1999/00 – 03/04	*No data*	*No data*	*No data*	8
CP3	2004/05 – 08/09	477	156	40	8
CP4	2009/10 – 13/14	528	122	32	8
CP5	2014/15 – 18/19	488	137	26	2
CP6	2019/20 – 23/24	371 (up to 30/11/20)	96 (up to 30/11/20)	25	1

Table 7.3: Earthwork failures CP1 to CP6

411 **The trend of earthworks failures has significantly worsened since the start of CP6 (1st April 2019). 251[11] reportable earthwork failures were recorded across the NR network in 2019/20 (CP6 Year 1) with 140 of these having occurred during the 2019/20 winter period (December-February). There were 16 potentially high consequence earthwork failures but no earthwork attributable derailments in CP6 Year 1. The adverse trend in earthwork failures and potentially high consequence earthwork failures has also continued into 2020/21 (up to 30/10/2020).**

412 The 2019/20 winter was the fifth wettest on record with the wettest February on record (5th wettest month ever). Figure 7.21 below illustrates the significant geographical relationship between the 2019/20 earthworks failure locations and the rainfall distribution in February 2020.

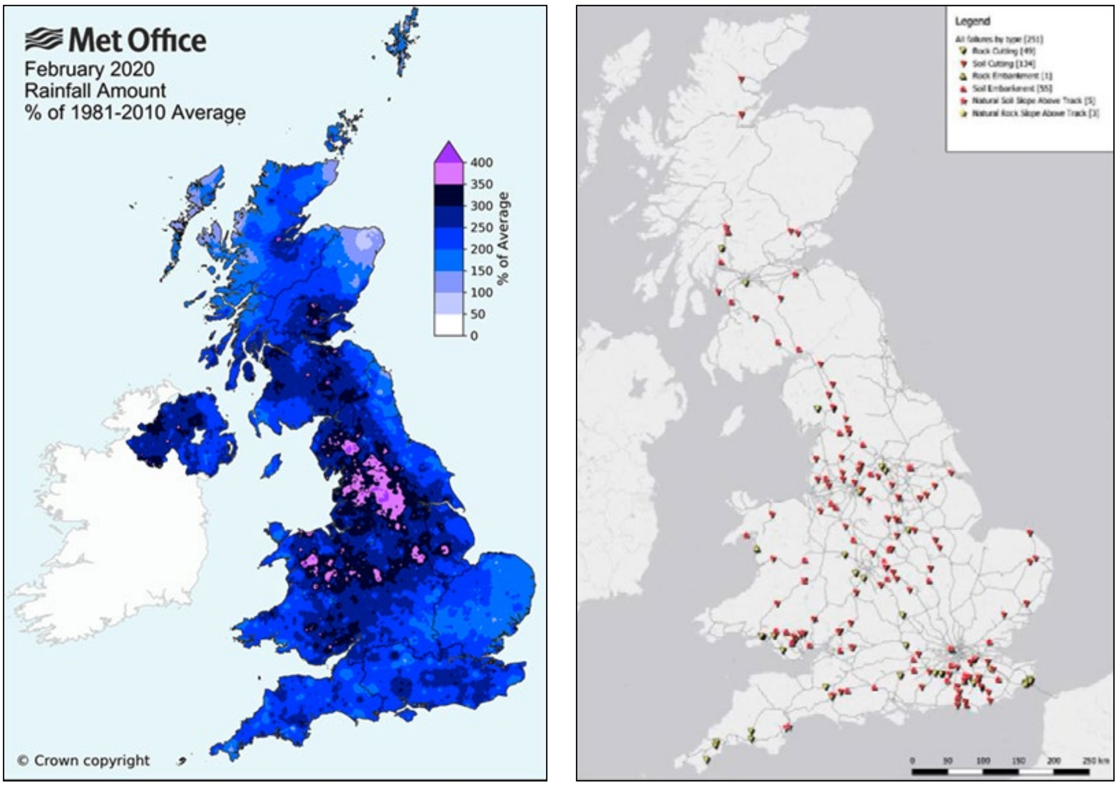


Figure 7.21: Illustrating the significant geographical relationship between 2019/20 reportable earthwork failures and February 2020 rainfall amount % of 1981-2010 average.

11 A review of the earthwork failures in 2019/20 subsequently established that 252 reportable earthwork failures occurred across the NR network in 2019/20 (CP6 Year 1)

	A	B	C	D	E	U
5	4	7	9	5	8	0
4	2	9	7	5	1	0
3	9	10	8	16	1	0
2	8	13	20	26	3	0
1	9	9	11	11	6	0
0	4	2	6	4	0	1
Total	36	50	61	67	19	1

Total reportable failures	251
Total not on ESRM (N = No Earthwork)	17
Total reportable failures on ESRM	234

Figure 7.22: Earthwork failure (numbers) in 2019/20 plotted on the ESRM

413 **59% of the 2019/20 earthwork failures were classified in EHC "A to C" pre-failure (Figure 7.22). There were 14% of the failures in the EHC "A" which statistically is the lowest likelihood of failure category. This demonstrates the current difficulty in forecasting earthworks failures utilising the examination algorithm and EHC category from an asset base that is inherently unpredictable, and where the failure rate is so dominated by antecedent rainfall. The 36 failed "A" assets represent only 0.04% of the total population of "A" category earthworks, whereas the 19 failed "E" assets represent 2% of the total population of "E" category earthworks (Figure 7.22). We have recommended in Para 291 that the shortfalls in the earthwork examination system need to be addressed, in particular reliance on an algorithm and EHC as a predictor of the likelihood of earthworks failure.**

Earthwork Hazard Category (EHC)

414 The distribution of the recorded number of earthwork assets, as at 2nd May 2017, by EHC by Route and as a percentage nationally and by Route are given in Figure 7.23 below, NR, (2018c). Those earthwork assets with an EHC of U comprise Unscored examinations, Incomplete examinations and Not examined earthworks.

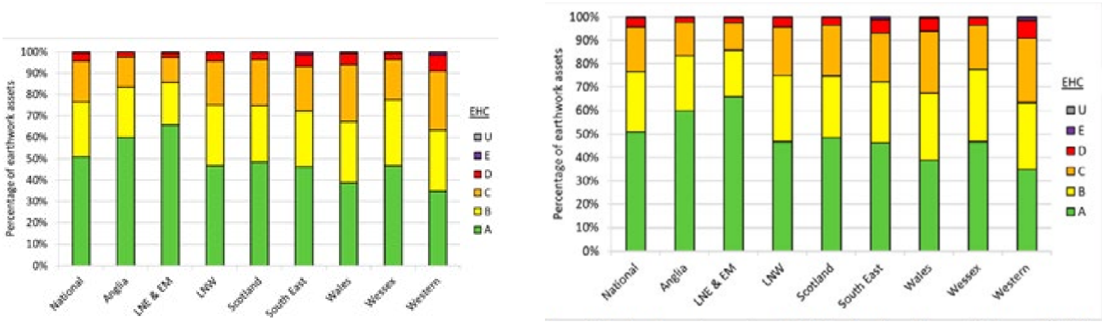


Figure 7.23: Number and % of earthwork assets by EHC by Route as at 2nd May 2017

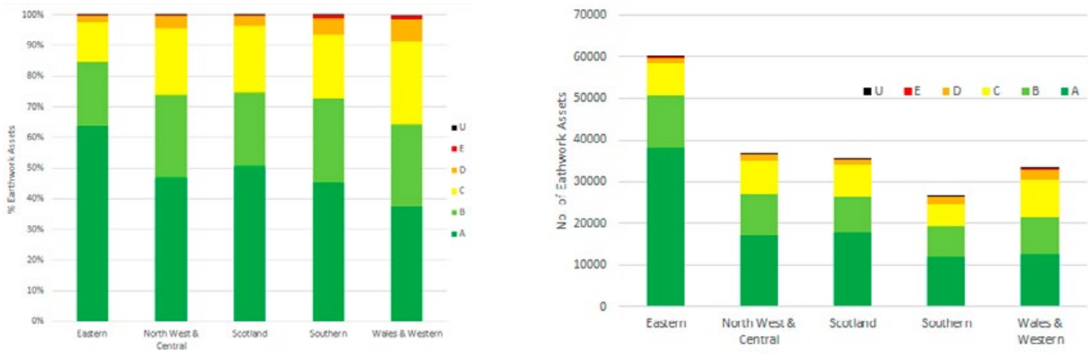


Figure 7.24: Number and % of earthwork assets by EHC by Region as at 31st October 2020

415 The distribution of the recorded number of earthwork assets by EHC by Region[12] and as a percentage by Region as at 31st October 2020 is given in Figure 7.24 above.

416 There has been very little significant change in the earthwork EHC distribution since May 2017, either nationally or by Route/Region.

12 The 2017 Routes have been re-organised into five geographic Regions (Eastern, North West & Central, Scotland's Railway, Southern and Wales & Western) and 14 underlying Routes.

Earthworks Condition Score (ECS)

417 The Earthworks Condition Score (ECS) is an ORR regulatory measure and the network wide score has been generally consistent throughout CP5 with a range of 1.74 to 1.76, Table 7.4. However, NR modelling (using the decision support tool SCAnNeR described in Paras 405 to 408) indicates that ECS will increase (deteriorate) throughout CP6 to a position in March 2023 of 1.81 (a deterioration in earthworks condition of 3%). At the end of March 2020 (Year 1 in CP6) ECS was at 1.77, aligning to the expected deterioration rate in asset condition.

Principal Asset	Description	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20
Earthwork	Earthworks Condition Score (ECS)	1.75	1.74	1.75	1.75	1.76	1.77

Table 7.4: Change in ECS from 2014/15 to 2019/20

Investment in Earthworks

418 The majority of earthworks capital investment prior to CP5 was typically spent on arresting actively failing assets or in the recovery of assets following catastrophic failure. NR are now becoming more pro-active than before in the targeting of capital investment. Investment to maintain, refurbish and renew earthworks and drainage has nearly doubled from CP4 (2009-2014) to CP6 (2019-2024) to £1.274bn. Investment in CP6 is 20% higher than CP5 (2014-2019). Earthworks investment is also expected to need to rise again for CP7 (2024-2029).

419 We understand that NR will also redirect risk funds as necessary to address immediate earthwork and drainage needs including responses to extreme weather event slope failures.

420 Also included within NR plans for CP6 is £33m to increase remote monitoring and sensing, improved weather services monitoring and diagnostics for earthworks and drainage, together with £31m on research and development specific to earthworks, drainage and resilience. Much of this activity is in collaboration with other operators to broaden access to knowledge and insights and forms part of a prioritised research and development portfolio that balances investment spanning all of NR challenges.

421 So far in CP6, NR are ahead of programme in terms of volume of work completed and expenditure (NR, 2020k). At the end of CP6 Year 1 (March 31st 2020) at a network level 22.5% of the earthworks CP6 delivery plan had already been completed. The earthworks delivery plans for North Western & Central, Scotland and Wales & Western have all delivered in excess of 20% of the original CP6 commitment. Southern and Eastern have delivered 6.2% and 5.0% respectively of their CP6 commitment and this slow start will need to be recovered. Whilst Southern are now forecasting to deliver 10.6% more effective renewal in CP6 than originally planned, Eastern have forecast a 1.2% reduction. Overall, at network wide level the current forecast is to deliver 9% more effective volume by the end of CP6.

422 In the 2019/20 Annual Assessment Report of NR, ORR (2020b) it was reported that NR delivered the earthworks renewals work (2019-20) that it had planned (see Table 7.5): *"This is a good result. If it continues to deliver over the control period, this will support long-term network condition and performance outcomes".*

Renewals (volumes)	Actual	Plan	% complete
Earthworks	3,408	2,856	119%

Table 7.5: Renewals delivery against plan, Great Britain, 2019-2020 (after ORR analysis of NR data, ORR (2020b))

423 Despite the very wet winter in 2019/20, NR significantly outperformed the earthwork renewal volume target, due to acceleration of schemes from 2020/21 and emerging work relating to mitigating the impact of asset failures. This is a very positive start to CP6, but NR still have more to do to achieve the CP6 earthwork renewal target and start to reduce the overall number of earthworks susceptible to failure as a result of extreme rainfall.

424 NR need to improve their ability to identify the most vulnerable earthworks to ensure that renewal investment is directed at those assets most susceptible to failure. Approximately two-thirds of the earthwork failures experienced in the early part of CP6 had no planned work in the control period (i.e. associated with the earthwork failure) which suggests that many of the most vulnerable earthworks to failure are not necessarily included in the Investment Plan. NR should therefore recognise that sustained increased investment will be required over multiple CPs if service-affecting earthwork failures are to be eradicated.

Business Planning Process for the next control period, CP7

425 NR's business planning process for the next control period, CP7(2024-2029), has commenced. The first round of CP7 model forecasts were issued to Regions in June 2020. These indicate a CP7 baseline expenditure for earthworks of £1,342m and a constrained expenditure of £910m (against a CP6 investment of £899m which will only strengthen approximately 3.6% of the whole earthworks asset base through refurbishment and renewal).

426 As the planning proceeds closer to CP7, the Regions will take more ownership of their plans, and the focus will shift towards bottom-up workbanks for CP7, with the whole life cost models used in an assurance and reporting role to support them. In addition, within a year, the Regions will have direct access to many of the models, via a common platform, which will enable them to look at scenarios themselves.

427 In this first set of assessments, two main scenarios have been used. They are broadly defined as:

+ Constrained. The national asset budgets for CP7 and subsequent control periods are limited to the current CP6 asset budgets
+ Baseline. Where possible, the asset budgets are set to maintain the network outputs expected at the end of CP6 through subsequent control periods, at the lowest whole life cost, consistent with the current asset policies

428 The earthworks model forecasts the renewal volumes, costs and long-term outputs for embankments, soil cuttings and rock cuttings. The modelled works include renewals, refurbishments and capital maintenance. They do not include reactive works e.g., response to earthworks failures which are not classified as capital expenditure.

429 The assessment steps are summarised below.

+ Download the latest earthworks inventories for embankments, soil cuttings and rock cuttings from the Examination of Earthworks database. The inventory includes each earthwork's route, track location, current condition data (EHC rating from A to E), and consequence score (EACB rating from 1 to 5)

+ The Powerpack Analysis Toolset (PAnTS) applies the known CP6 workbank (from the Routes' Powerpack datasets) to the current asset inventory (including current condition data as above) to forecast the earthworks condition distribution at the end of CP6. Powerpack is described in Appendix E12

+ The SCAnNeR model starts with the end-CP6 forecast condition distribution and applies a range of policy mixes to forecast the work volumes, costs, condition and relative risks at the end of each control period. SCAnNeR is described in Appendix E12

+ SCAnNeR is run for each route inventory condition distribution, and the optimal national policy mix is applied to find the final scenario outputs for each route

+ The renewal, refurbishment and capital maintenance volumes are costed using national average unit rates

+ The total cost of the earthworks baseline scenario in CP7 is 50% more than the current CP6 forecasts, ranging from only 6% higher in the Southern region to over 70% higher in NW & Central and Scotland

430 The relatively low allocation to the Southern region reflects the SCAnNeR model's focus on earthworks condition driven failures and consequent derailment risks, rather than earthwork serviceability performance. Although there is some correlation between the two, it is imperfect. For example, if an embankment suffers from desiccation during a dry spell, it can affect the track geometry, and speed restrictions may be imposed; this is much more likely in the embankments found in the Southern Region (containing a high proportion of high plasticity clay, and experiencing lower summer rainfall than in the west). Thus, if train performance is accounted for, the budget allocation to the Southern and Eastern Regions might be higher. It is not possible to address this issue with the current model configuration, because it does not distinguish between different earthwork geology, regional differences in climate, nor does it link earthworks condition to track performance. The updated earthwork geology groupings to be implemented in the model will enable this issue, among others, to be tackled in future assessments.

431 We support the future programme of whole life cost model refinement to improve the ability to more accurately forecast long term investment requirements, as earthworks are a very long-life asset for which the deterioration mechanisms impacting performance and condition are not yet fully understood. It is also critical that NR improve their ability to accurately identify those earthworks which require intervention before slopes approach the end of their service life or failure. If intervention works are not possible, practical or economic mitigation measures are required to manage the risk and prevent earthwork failures being first observed by train drivers.

Intelligent Infrastructure

432 Intelligent Infrastructure is NR's digital asset performance management programme, using technology to turn data into intelligent information so the frontline and supporting teams can work smarter and more safely to deliver improved services for passengers and freight customers. Ultimately the goal is to reduce expenditure whilst improving infrastructure availability by:

+ Understanding the probability of individual asset failure
+ Predicting when failure will occur
+ Forecasting the impact on the operational railway
+ Planning intervention prior to disruption to train services

433 The programme is not just about introducing huge amounts of new technology; it has been designed to look at how NR can maximise the value from the data they have whilst working closely with the NR research and development programme to make sure NR continue to be at the forefront of technology introduction.

434 Full details of the Intelligent Infrastructure programme are given in Appendix E13, Para 1039 to Para 1061.

435 ***We recommend that a priority should be to deliver the full scope of the strategic asset management solution for geotechnics and drainage through Intelligent Infrastructure. This delayed suite of data and technology upgrades will enable better decision-making by engineers and strengthen assurance capabilities. The implementation of the evaluation and prioritisation tools through the Intelligent Infrastructure (II) programme should pull together all datasets quantifying threat vulnerability and failure impact at the asset and network scales respectively. They should embed a structured and audited decision-making process such that decisions for assets and portfolios are traceable and accessible.***

Assurance Process

436 A key responsibility for the Professional Head of Geotechnics as the NR Technical Authority is to provide an assurance framework to ensure risks are managed to an acceptable level and that capability and competency continue to be developed for the safe, reliable and effective functioning of earthworks assets. It includes setting the framework and requirements for monitoring, assurance, investigation and benchmarking activities, and deriving and acting on intelligence from these activities as part of a continual improvement cycle. The assurance framework aims to continuously improve asset policies, asset standards and the processes which support them.

437 Typical assurance activities undertaken by Professional Head of Geotechnics and his team include but are not limited to:

+ Periodic (4-weekly) production of "period pack" and review at Asset Technical Review (ATR) with Regions/Routes
+ Investigation of incidents beyond the ATR review where criteria dictate (Technical/Class/Local/Formal Investigations)
+ Engagement with ORR and RAIB investigations or topic audits/ targeted assurance
+ Engineering verification programme – checks standards are being applied correctly to assets, 15-20 activities/year
+ Functional audit programme – checks standards are being applied correctly to portfolios, 4 activities/year
+ Management of recommendations arising from any of the above – e.g. monitoring of R&D project established to close out a recommendation
+ Cost and volume reporting (RF process) – maintenance and capital work vs. budget/plan, at least periodic. Approximately every quarter the figures will be analysed using the WLC modelling tools to understand the impact of the actuals and reforecasts in terms of earthworks condition score/M33[13] and other metrics. The Professional Head then writes a commentary, and the quantitative and qualitative assurance is published

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13 The M33 Condition Score is defined in NR/ARM/M33DF: *Definitions for the Reporting of M33 Earthworks Condition Banding* (NR 2014e) as "*A sum of the count of the number of examined earthwork asset 5 chains within each Hazard Index category, multiplied by a weighting factor derived from historic failure probability, divided by the total number of examined assets. Determined for all earthwork assets combined (soil cuttings, rock cuttings and embankments).*"

+ Annual return – pulling together key metrics from all of the above
+ Independent reviews of capital works (on agreement with Route/Region) – e.g. Teignmouth sea cliffs

438 **The Professional Head of Geotechnics as the NR Technical Authority provides effective leadership and promotes a partnership culture with the geotechnical staff in the Regions. In our view there is considerable benefit to the NR business from this single-point accountability for the oversight and assurance of all earthwork related asset management activities. A key challenge for the Professional Head of Geotechnics is to work collaboratively with the Regions – to ensure that investment is used effectively and efficiently to proactively enhance earthwork assets assessed as higher risk to deliver resilience to future climate change and ensure failures are not first observed by train drivers.**

Earthworks Competence framework

439 The Competence and Training in Civil Engineering specification, NR (2006) defines the requirements for the training and assessment of persons undertaking Civil Engineering work (including Earthworks and Drainage) on NR controlled infrastructure. Competence standards for the examination of earthworks have been developed (Appendix E, NR (2006) covering Earthworks Manager (EWE 1), Earthworks Examining Engineer (EWE 2) and Earthworks Examiner roles (EWE 3).

440 NR are currently transitioning between the Competency framework described by NR (2006) Specification and a new Professional Geotechnical Competence framework (currently described in an Excel spreadsheet ref Professional Competence Dataload Geo October 20). The new framework extends the previous Competency framework e.g., it differentiates between soil and rock slope examination and introduces a new competency category for Earthworks Management.

441 The current Earthworks Standards specify a mix of the “old” competency requirements e.g. Earthworks Examiner roles (EWE 3) in the Examination “065” standard, NR (2017a) and the “new” e.g. Earthworks Management GEO-OM-M (Level 3 Applying) competency for undertaking Landslide Hazard Assessment in the Geohazard Assessment standard, NR (2017c).

442 All NR Geotechnical Technical Authority and RAM team personnel have been assessed against the new Professional Geotechnical Competence framework. The NR Professional Head is no longer assessing RAM team personnel against the EWE1 Earthwork Manager competence, as he considers the new GEO-OM-M Level 3 to be equivalent to EWE1. As NR make the transition, both old and new competencies are in the NR online competence management system. This offers some infographics to check gaps against role requirements.

443 The Competence and Training in Civil Engineering specification, NR (2006), is currently being updated to reflect the new competence framework/ requirements and assessment. Training materials to provide the technical knowledge for the competencies are also in development. These will cover the technical knowledge required to support competence to Level 3 Applying (but will not in themselves provide the experience of application required to achieve Level 3 competence).

Chapter 8

Drainage Asset Management

Introduction

444 **The effective control of water and proper understanding and maintenance of drainage assets is of fundamental underpinning importance to the safe operation of the railway network. It is therefore imperative that NR understand the nature and size of its drainage catchments, including those parts outside the railway boundary, in order to be able to effectively manage water flow both now and in the future with climate change. The stability of earthworks is critically dependent on the drainage system and water management. However, the NR drainage system was not originally "designed" as a means of ensuring slope stability.**

445 It is only in the last few years that the NR drainage system has been recognised as an asset to be managed in its own right. Historically there was a belief in NR that drainage was of secondary importance "*out of sight and out of mind*". Drainage was considered to be a "Child" asset (and therefore not as important) to Track, Structures and Earthworks. Until very recently the NR drainage system has been largely neglected and has suffered from significant under-investment over many years. As a result, NR have a dated drainage system about which they have little knowledge. The current approach to maintaining earthworks drainage assets is largely reactive. This is very costly in whole life cost terms and does not address the issue of needing to understand where to invest to halt the deterioration. The inadequacies in the NR drainage system have significant safety and cost implications for the earthworks asset, including an increase in the likelihood of earthwork failures, poor track geometry, line closures and delays.

446 **One of the greatest challenges facing NR in managing water is the current lack of asset knowledge. In many cases the location and condition of drainage assets are far from understood. Existing drainage systems have not in general been assessed to calculate whether they have sufficient hydraulic capacity to convey the required flow. These shortcomings present real challenges in making the case for investment in water management and the railway drainage system. A better understanding of its drainage system is a vital element to improving water management and control across the NR railway.**

447 Subsequent recommendations are made to address these deficiencies.

448 **The increasing frequency of extreme rainfall events requires NR to place greater emphasis on the control of storm water and surface water run off than they have done in the past. This is required to reduce the risk of washout and earthflow slope failures and to minimise the infiltration of water into clay slopes, particularly via shrinkage cracks after prolonged hot spells which are forecast to be more prevalent as a result of climate change.**

Changing patterns of land use adjacent to the railway corridor since original construction has reduced the ability of land to absorb rainfall e.g. through the introduction of hard, impermeable surfaces, changes in agricultural practice etc. These land use changes have resulted in an increase in the volume and rate of surface run-off as less water infiltrates into the ground. Localised heavy rainfall on impermeable or already saturated surfaces can generate surface water run-off beyond the capacity of the drainage network, resulting in overland flow. Channelling features, either natural or anthropogenic, concentrate overland flows at the top of cutting crests and increase the likelihood of slope failure from washout or earthflow. See also Paras 312 to 321 'Washout and Earthflow Risk Mapping (WERM) methodology'.

449 Pore water pressures arise from the presence of water in the soil matrix which may be introduced via natural precipitation and/or recharge from external sources. **NR has very limited knowledge of the distribution of pore water pressures in its earthwork slopes. However, the stability and resilience of earthworks is in most cases critically dependent on the control of water, in particular the magnitude and distribution of pore water pressure within a slope.**

450 ***We recommend that consideration be given to more widely monitoring pore water pressures in earthworks to obtain a more detailed understanding of the behaviour and stability of a particular slope or***

embankment that is judged to be critical. Initial proposals to improve knowledge of the distribution of pore water pressures in NR earthwork slopes are included in Para 789.

451 For all earthwork slopes, rainfall will enter the underlying soil through the surface in quantities which depend on the soil/rock type, topography and vegetation cover. Slope drainage can control the movement of surface water and also the subsurface pore water pressure in the slope. Drainage can be very effective in controlling pore water pressures if installed at the correct location within a slope. However, railway earthworks drainage has often been constructed on an ad-hoc basis, usually after slope instability or track deformation problems have become apparent.

Drainage System and Water Asset Management

452 NR manage water through drainage systems that collect surface and groundwater running towards, falling onto or issuing from the railway, delivering water to a suitable outfall. As increases in more extreme rainfall have occurred, questions regarding the capability of the drainage asset base have been raised, and NR recognise that they have significant work to do in improving water management in the organisation.

453 In order for NR to undertake more effective “intelligent” earthworks drainage asset management, a holistic water management system strategy is required with focus placed on the following:

+ What is the extent of the drainage catchment
+ What is the likely rainfall and risk of flooding in the catchment
+ How much maintenance/renewal does this drainage system need

Without being able to answer these questions, the potential to make the drainage asset management regime more efficient is limited.

454 **The effective management of a drainage system requires a complete understanding of its capacity to convey the required flow. This assessment should be based upon a holistic approach in which drainage is viewed and managed as a system from rainfall to outfall, rather than as individual components.**

455 Details of the NR Drainage Standards are included in Appendix F1, Para 1062 to Para 1064.

456 In the Drainage Asset Policy, NR (2017e), NR recognise that the water management system should be managed as a whole with no individual drainage parts being treated in isolation. However, this aspiration is proving difficult in practice because the responsibilities for managing the NR drainage system are very complex and are split between various parts of the organisation.

457 The Drainage Asset Policy, NR (2017e), has similar deficiencies to the Earthworks Policy, (2018c) in terms of content and structure (Para 254). We understand the Professional Head of Drainage is working with a consultant to update the Drainage Asset Policy into a Water Management Policy and Strategy document, with an aspiration to publish in May 2021.

458 **Currently, the NR business needs to have a greater appreciation of the importance of water management and drainage assets, including addressing the associated risk within the railway infrastructure system.** We consider that this deficiency is largely as a result of the following issues:

+ An asset silo culture
+ Interfacing asset systems evaluating risks in different models
+ A failure to develop drainage system maps (topological view)
+ Accountabilities and funding are unclear and misaligned for drainage within the Regions and Routes
+ An inability to report on drainage's impact on interfacing asset performance
+ A lack of awareness of the impact of interfacing asset design and construction schemes on the railway drainage system
+ A lack of awareness of the impact of drainage design and construction schemes on the existing railway drainage system
+ In general, existing drainage systems have not been assessed to calculate whether they have sufficient hydraulic capacity to convey the required flow from catchment inflow(s) to outfall
+ Design of new systems is often outsourced to consultants employed by framework contractors with little checking and approval of designs
+ There is very limited supervision of drainage work by NR, with a reliance on contractor self-certification; and
+ The addition of new drainage schemes into asset registers is patchy and in many cases there is no as-built record offered or demanded

459 ***We recommend that NR develops its asset management culture across the business to ensure that the effective control of water as a system is recognised as essential to the safe and economic management of railway infrastructure including earthwork assets. Therefore, NR will, inter alia, need to increase its resource of Drainage Engineers competent to effect proper water management and recognise its importance to the safety and performance of the railway.***

Drainage Asset People Responsibilities

460 The responsibilities for managing the NR drainage asset associated with earthworks are currently complex and are split between various parts of the organisation, in summary as follows:

Maintenance – Responsible for:

+ Inspections and surveys
+ Maintenance of all drainage system efficiency
+ Identification and justification of renewals

This includes all track and off-track drainage, boundary drainage and culverts

RAM (Drainage and Off-Track) – Accountable for:

+ Developing the Route's Drainage Management plans, to ensure compliance with NR Drainage Policy and Standards
+ Renewal of off-track drainage
+ Renewal of drains whose primary function is to drain the track support system

Includes:

+ Associated drainage renewed along with the track components
+ Non-associated drainage renewed independently of the track

The RAM (Drainage and Off-Track) is responsible for management of the drainage as a system regardless of ownership of individual elements.

461 Drainage Asset Management Roles and Responsibilities vary across Regions/ Routes between RAM (Track), RAM (Geotechnical) and RAM (Drainage) and often are confusing or in silos.

462 The Off-track maintenance team is responsible for the inspection and maintenance of drainage. This team is also responsible for the inspection, maintenance and renewal of level crossings, fencing, access points and vegetation management. They often are responsible for responding to incidents, dealing with public complaints or carrying out a variety of maintenance work on the infrastructure e.g. graffiti removal. As a result, the Off-track maintenance team is often diverted from drainage maintenance activities.

463 ***Maintenance of drainage systems is of paramount importance including regular cleaning. We recommend that more resource be put into this vital activity. Consideration should be given to having dedicated drainage maintenance teams across all routes, rather than drainage being only one of the activities for which off-track section managers are responsible. Off-track drainage maintenance should have its own budgets. There is a case for grading Off-Track Maintenance Engineers on a similar basis to existing Track Maintenance Engineer posts to ensure the importance of maintenance of drainage systems is recognised in the business.***

464 In 2015 NR made a significant step in recognising the importance of drainage and water management, by establishing a new senior engineering leadership Professional Head role for Drainage. A primary focus of this role has been to drive developments in the quality of information and tools available to effectively manage drainage assets and promote a broader and more integrated approach to the management of drainage assets. NR's Drainage Asset Management Policy and Strategy is now owned and administered by a central team headed by the Professional Head of Drainage, who sets out the approach to management of NR 's drainage asset that is to be followed by the Regions/Routes.

Drainage Competency and Resource

465 There is currently a lack of drainage competence and resource across the NR business to develop and implement the requirements of the Drainage Asset Policy, NR (2017e) and the associated Drainage standards, due to:

+ a lack of embedment of the competency framework
+ a lack of succession planning and deputising
+ a lack of corporate memory to retain best practice, lessons learned, and learning from root cause and operational issues
+ financial constraints

- poor dissemination of information including briefing process
- out of date, non-availability of training courses
- poor training prioritisation

466 ***We recommend, that as a priority, that NR address the lack of competence and resource to develop and implement the requirements of the Drainage Asset Policy, NR (2017e) and the associated Drainage standards. In particular, the development and implementation of specific competency requirements for staff undertaking safety critical drainage activities (Inspections, Evaluation, Assessment and Design) is fundamental.***

Drainage Management Plans and Decision Support Tools

467 A Route Drainage Management Plan (RDMP) which is prepared by the RAM (Drainage and Off-Track), describes the work activities required to manage the drainage systems in accordance with NR (2018f).

468 A number of Decision Support Tools (DSTs) are in use or in development for the drainage assets; these are summarised in Appendix F2, Para 1065.

Asset Knowledge and Drainage Inventory

469 Drainage asset groups are listed in Appendix F3, Para 1066. Most of the NR existing drainage pipes are in the form of just a few imperial sizes, selected historically either for economy or availability and not for their calculated capacity to handle water from a predicted amount of rainfall or catchment. We understand that NR are in the process of completing the drainage asset base inventory and capturing structural and serviceability condition for all its drainage assets.

470 Compared with the other principal NR asset types, including earthworks, the NR drainage asset base has historically been poorly known. Previous attempts to complete the asset register were attempted, most recently through the Integrated Drainage Project which was undertaken in CP4. Unfortunately, this project did not capture all assets associated with drainage systems

and predominately focused on capturing track drainage, overlooking assets obscured in the undergrowth away from the immediate permanent way (e.g. crest drains, slope flumes etc).

471 All Regions and Routes are now committed to completing the full drainage inventory and populating this into Ellipse (Network Rail's Drainage asset management database) by the end of CP6 (2024). Routes have approached the task in different ways but all routes except for one are using the 'My Work' App. This allows inspectors to collect drainage asset information digitally on iPads and iPhones including GPS co-ordinates and update existing drainage records with the current condition of the asset. This can all then be uploaded to the Ellipse system, allowing both one-off activity and cyclic work such as inspection and cleaning to be planned. The co-ordinates allow the drainage data to be mapped and allows them to be readily found should they become hidden by vegetation in the future. However, it is recognised that the 'My Work' App has no corporate system owner and can be cumbersome to use (requiring workarounds) that is inhibiting effective drainage condition data capture in some areas.

472 North West & Central (NWC) Region are collating drainage information in a separate system to the 'My Work' App, with the longer-term objective of mass migration into Ellipse once complete. This local decision in NWC was taken several years ago following early delays in the availability of suitable technology to capture drainage information in the field.

473 The drainage asset inventory in Ellipse is growing on a periodic basis as more assets are logged using the 'My Work' app. Since the start of CP6 (2019) the drainage inventory in Ellipse has grown c.2% and currently stands at c.350,000 assets. This is approximately 10% greater than the inventory count at the start of CP5 in 2014, but the inventory is by no means complete.

474 We consider that completion of the drainage asset base inventory and associated condition data be given a high priority and it should be finished no later than planned, by the end of CP6.

ORR Drainage Enforcement Action

475 Approximately 10 years ago in CP4, the Office of Rail and Road (ORR) had gathered evidence of NR's poor state of understanding of its drainage assets, and consequently required progress to identify the location of all drainage assets on the network. In ORR's view, at that time, NR drainage was to an extent a 'Cinderella' asset group – largely ignored in favour of other assets with a more immediate claim for attention.

476 Subsequent ORR inspections since CP4 have found improving railway drainage asset knowledge, but progress has been too slow in their view. ORR have also found variations in the approach, quality and completeness of different Routes drainage management plans, which are needed to address the drainage asset under-investment legacy. Following on from ORR inspection work in 2013-14, they served a national improvement notice in February 2015 requiring NR to identify critical drainage assets in high-risk earthworks and put in place plans for making sure that they are working effectively to mitigate potential landslip, and therefore train derailment risk.

477 The NR response, enabling closure of the ORR improvement notice, was a commitment to complete the drainage inventory within CP6 and in the short-term to focus on the inspection and maintenance of drainage at high-risk soil cuttings. We are pleased to note this and recognise that NR are making good progress to complete the drainage inventory by 2024.

478 In 2019-20 ORR reviewed the adequacy of drainage at high-risk soil cuttings and tunnel portals as the focus of a nation-wide inspection programme. ORR inspectors within North West & Central Region have recently visited high-risk soil cuttings and found the presence of drainage assets that are not recorded in Ellipse. We understand these issues are being addressed.

Drainage Asset Condition and Performance

479 Further details of drainage asset condition and performance are given in Appendix F4, Para 1067 to Para 1069.

480 There are two components to drainage asset condition:

+ Structural condition: relates to the fabric of the asset and the severity of the structural defects that affect its integrity. Structural defects are addressed by repairing or replacing the asset
+ Service condition: relates to the water carrying capacity of the asset and the severity of the defects that reduce its capacity below its original design level, but is independent of the structural condition. Service defects are addressed by maintenance of the asset such as cleansing or vegetation clearance

481 From the available drainage condition data (dating from 2017) in Appendices F5, F6. F7 and F8 the following can be concluded:

+ There is little overall condition data for the majority of the NR drainage system pipe assets (from CCTV surveys), although condition has been assessed for a higher proportion of the earthwork drainage pipes than the track drainage pipes
+ The channels and ditches show the worst overall condition profile with a high proportion of marginal and poor assets
+ Combining the condition data nationally for all surveyed asset types, and excluding those for which condition was not inspected, the service condition profile is significantly worse than the structural condition profile

Drainage Asset Degradation

482 It is important to distinguish between the structural and service degradation of drainage assets, and the differences in the modes and rates of degradation between the "hard" drainage assets (pipes, channels, chambers etc. made of concrete, brick, stone, earthenware) and the "soft" assets (ditches and ponds excavated within the soil). More detail on degradation of drainage assets is given in Appendix F10, Paras 1082 to 1087.

483 The "hard" drainage assets typically have a long service life, typically of the order of 50 to 150 years, before the physical integrity of the structure is likely to fail and will need to be renewed. For example, most of the culverts on the network date from the original construction of the railway lines, the majority being over 100 years old, and whilst culvert failures are not unknown, they are rare. The "soft" assets have a shorter service life, typically of the order of 10 to 50 years, before their banks will have degraded and will need to be reprofiled to restore their capacity.

484 The service life of all drainage assets is significantly shorter than their structural life. All drainage assets can become reduced in capacity or blocked by silt, debris and/or vegetation, and this can happen in a matter of months to a few years if no maintenance is carried out. This is the main reason why drainage assets benefit from a proactive approach to maintenance. The asset can be maintained in a serviceable condition over the long-term if relatively low-cost proactive maintenance (cleaning) is carried out on a regular basis, and the longer-term structural degradation of the assets becomes of lesser concern.

Impact of Drainage on Earthworks Stability

485 Detailed analysis has been carried out by Mott MacDonald of the records of earthworks failures that have occurred on the NR network from 2003 to 2011 (NR, (2017e). Part of this analysis included assessing the causes (triggers) of the failures, as determined by evidence where available, or by the judgement of the reviewing engineers. Where more than one trigger was determined, a primary (dominant) and secondary trigger was recorded.

486 Triggers were identified for 414 of the 454 failures analysed and of these heavy or extreme rainfall was identified in 42% as a primary or secondary trigger (the relationship to the drainage provision in the failed earthwork was not established as part of the study). In 30% of the cases poor drainage, blocked drainage or water concentration features were identified as a primary or secondary trigger for the recorded earthwork failures.

487 The Impact of Drainage on Earthworks Stability study by Mott MacDonald (NR, 2017e) quantitatively demonstrates that maintaining and upgrading the drainage asset is a key element in preventing earthworks failures.

Drainage Inspection and Evaluation

488 Inspections are the first control in preventing the failure of a drainage system. The requirements for carrying out Drainage inspections, including Defect Inspections and Condition Inspections, are described in NR (2018g).

489 Drainage inspections are carried out:

+ in alignment with the scheduled frequency recorded in the Route Drainage Management Plan (RDMP)
+ in response to a fault (for example through the Fault Management System, urgent defect report); and/or
+ in response to extreme or adverse weather event risk assessment

490 The drainage inspection regime is a visual inspection based on a scoring system from 1-5 to assess both the structural and service condition of individual drainage assets, as well as an overall condition of 10 chain (200m) drainage section. The inspections can be subjective because they are based on a judgement made by an inspector. These inspections are carried out at a minimum of once every five years with some routes carrying out yearly.

491 A more frequent inspection and maintenance regime is generally carried out on higher risk assets. This means that most of the data contained within Ellipse (the master data source for drainage) varies from one day to five years old. The variability in age and quality of data makes it difficult to prioritise maintenance and renewals based on this data and many routes rely heavily on the local knowledge of inspectors and maintainers.

492 Drainage Evaluation NR (2018h) uses the information gathered from inspections and other available sources to apply a risk-based assessment that allows informed decision-making regarding the required interventions to the asset to meet its required duty.

493 Drainage Inspections and Evaluations are undertaken by Off track Maintenance Technicians who have generally attained an appropriate level of knowledge through relevant experience, in contrast to Earthwork examinations which are undertaken by professionally qualified Engineers or Geologists.

494 Currently the Drainage standards lack any specific competency requirements for Technicians undertaking Drainage Inspections and Evaluations (see recommendation in Para 466 Drainage Competency and Resource)

495 ***We recommend that consideration is given to undertaking drainage inspections with sufficient and professionally qualified competent staff under the control of the RAM-Drainage, as is done for earthworks examinations, rather than the current arrangement where the NR Maintenance off-track team is often overloaded with inspections of drainage system.***

Survey and Assessment

496 If adequate asset data is unavailable through the existing inspections, then a General Survey, Intrusive Survey or Assessment may be required. Survey and assessment requirements are described in:

+ NR/L2/CIV/005/05, Drainage Surveys, NR (2018i)
+ NR/L2/CIV/005/08, Drainage Assessment, NR (2018j)

497 An Intrusive Survey uses trial holes or CCTV methods to record the attributes and condition of sub-surface assets that cannot be visibly assessed from the surface.

498 A Drainage Assessment is undertaken if further information is required to inform the Evaluation process. Drainage Assessments are a precursor to renewal scheme development and are considered to be part of the capital investment of the drainage system.

Drainage Maintenance

499 Maintenance of drainage is currently carried out as a response to an event such as flooding; or as a result of a defect found during inspection. However, it is difficult to prioritise which assets or systems to maintain first without understanding the rate of degradation and the influence of other external factors such as adjacent land use.

500 It is also difficult to prioritise drainage maintenance over other assets as the perceived risk of drainage failures is generally lower. Most of the time a drainage defect cannot be seen until there is an event such as flooding, which leads to a cycle of reacting to failures rather than solving the root cause of the problem and proactively maintaining the drainage assets.

501 To date, NR have employed a cyclical maintenance strategy to maintain the earthworks drainage system. This regime has focused largely on cleaning with some replacement (generally like-for-like) and ad hoc renewal. With current NR accounting practices, it is difficult to reliably disaggregate the costs or volumes of all drainage system maintenance works (see Appendix F9 Para 1081).

Data Systems

502 Effective asset management planning and decision-making relies on having the appropriate data available to those who need it and for that data to be reliable and accurate. Drainage asset data is currently held in multiple systems and assets are not represented as a connected system. Details are given in Appendix F11, Para 1088 to Para 1091.

503 Key to progressing the NR drainage asset management strategy is the development and use of a Drainage Strategy, Engineering & Asset Management System (StrEAMS), based on Ellipse, and an online Geographical Information System (GIS); this needs to be an easy-to-use, centralised system that can be accessed by all those requiring drainage inventory, condition and work flow information on the NR network.

504 ***We recommend that an integrated Drainage asset management system be developed, combining StrEAMS and GIS, where live data from multiple sources is accessible and the workflow management is open and transparent across the business (i.e. from inspection to renewal).***

"The effective control of water and proper understanding and maintenance of drainage assets is of fundamental underpinning importance to the safe operation of the railway network."

Drainage Design

505 Drainage design is undertaken in accordance with NR (2018k).

506 An effective slope drainage system manages the control of runoff and groundwater both within the railway boundary and from external natural catchments. External water flow is typically generated from flooded or ineffective land drains, elevated watercourse levels and run-off from catchments outside the railway boundary. The unrestricted flow of surface water entering the railway boundary can result in soil erosion and slope instability. Historically the first line of defence in minimising the influx of external surface water flows is generally provided by a ditch located on the crest of cuttings just inside the boundary fence.

507 Natural catchments adjacent to the NR railway will vary significantly in size, shape, type of soil and vegetation cover, and the amount of runoff contributing to existing railway drainage systems can range from negligible to significant.

508 **NR has little or no detailed knowledge regarding the extent and run-off from its natural catchment areas both inside and outside its boundary.** This is in contrast to similar asset management organisations e.g. London Underground and Highways England. ***We recommend that the size, shape and location of all-natural catchments draining towards NR's railway be established, in order that the drainage system flow rates can be determined for the required design storm return periods with the relevant allowance for climate change in accordance with NR (2018k).***

509 This catchment knowledge should be used to develop a hydraulic model of at-risk earthworks to simulate rainfall runoff flow to predict drainage capacity requirements under storm conditions.

510 Advice on the identification of natural catchment areas is provided in Highways England (2020b), CD 522 'Drainage of runoff from natural catchments'. This document sets out the requirements and advice for dealing with surface water runoff from natural catchments draining towards motorways and all-purpose trunk roads, in order to limit the frequency and severity of flooding incidents caused by runoff from beyond the highway boundary.

511 Climate change is predicted to have a major impact on the NR network, resulting in more intense rainfall events, flooding and increased runoff and erosion. NR need to demonstrate that its infrastructure and in particular its drainage system can withstand the effects of these extreme weather events. The railway drainage system will be critical in increasing storage capacity, reducing runoff flow rates and therefore mitigating the risk of washout and earthflow slope failures in particular.

512 The investigation following a collision of a train with material washed out from a cutting slope at Corby, Northamptonshire 13 June 2019 (Figure 8.1, RAIB (2020) found that the cutting slope had failed because it was not designed to cope with a large volume of water that had accumulated at its crest. Exceptionally heavy rainfall was not a factor in the incident. Although NR were aware that the cutting slope was at risk of a washout failure when the nearby ponds overfilled and had long-term plans to act, they had not taken any action to mitigate this risk in the short term. One of the RAIB (2020) recommendations was for NR to identify similar locations prone to safety critical flooding and review how they manage flood risk at each of those places.

Figure 8.1: Train collision with material washed out from a cutting slope at Corby, Northamptonshire, 13 June 2019 (RAIB 2020)

513 We consider that all drainage design should involve integrated water system management, taking into account the likely rainfall with allowance for climate change, the catchment, and the influence of outside party's drainage systems.

514 There have been a number of earthwork slope failures that have been triggered by defective unlined ditches along the cutting crest. Some examples are included in Appendix F12, Para 1092 to Para 1093 and Appendix H.

515 Recent NR earthworks renewal works practice has been to design and install piped drainage trenches along the cutting crest to intercept surface and groundwater (where applicable). An impermeable membrane has often been installed in these trenches below the invert and on the downhill side to

minimise the likelihood of collected water entering the slope. The absence of a membrane may result in an increase in pore pressures to the detriment of slope stability.

516 However, HS1 and London Underground have introduced perforated pre-cast concrete channels to replace both conventional piped trench drains (in the track and off-track environment) and unlined ditches along cutting crests (Figure 8.2). Concrete channels generally have a high hydraulic capacity and are highly effective where the risk of siltation from run off and/or root penetration is high, because they are much easier than perforated pipes to inspect and maintain – a simple operation of lifting the concrete channel cover. A modular system comprising trough and riser units of varying heights are selected to match the individual site requirements. They can be installed with a geotextile filter membrane if required.

Figure 8.2: Perforated Pre-Cast Concrete Channels as used on London Underground Earthworks

517 Network Rail Western Region have also installed a similar perforated pre-cast concrete channel product, albeit without a perforated concrete lid for an embankment toe drain (Figure 8.3).

Figure 8.3: Perforated concrete channel embankment toe drain (Western Region)

518 Network Rail Western Region have also used a flexible, concrete filled geotextile that comes on a roll and hardens on hydration to line drainage channels located along a cutting crest (Figure 8.4). A concrete lining is best suited to use as a carrier drain, whereas the perforated pre-cast concrete channel can also be used as a collector drain.

Figure 8.4: Concrete Canvas® was used to line a cutting crest drainage channel in Sherston, Wiltshire, Western Region.

519 **NR propose to review their standard ditch/channel drain design details and guidance following a number of cutting slope failures associated with defective unlined crest ditch drains. NR should not rely on crest drainage installed on 3rd party land outside their boundary and ownership. *We recommend that the use of perforated pre-cast concrete channels is more widely adopted by NR, in particular to replace unlined ditches which are susceptible to failure unless subject to an intensive inspection and maintenance regime*.**

520 Tunnel portals are particularly vulnerable to erosion/washout failures (see Para 37s 'A partial review of failures in soil cuttings and embankments'), because of the inevitable ground shape and topographic water concentration features. ***We recommend that, at tunnel portals, special drainage measures and slope shaping and protection should be provided. An example of the measures taken by the Japanese Railways at portals is shown in Appendix H Figure H24***.

Sustainable Drainage Systems

521 The extensive flooding that affected much of England in the summer of 2007 highlighted the unsustainable nature of traditional underground drainage systems. With a changing climate and a growing population, it is becoming increasingly clear that draining developed areas through a 'traditional' piped system can have serious consequences and should be avoided wherever possible in the future. Sustainable Drainage Systems (SuDS) offer a sustainable alternative for controlling surface water runoff.

522 Consequently, a current focus by many UK asset owners e.g. water, highways is a drive for SuDS (CIRIA, 2015); this is a way of managing rainfall that replicates natural drainage, managing it close to where it falls, replicating the infiltration found in natural environments and moving away from piped drainage systems.

523 From a railway point of view, where space allows (within NR ownership), the SuDS approach can offer good value for money as well as environmental benefits.

524 Natural solutions with minimal interference are likely to be cheaper to implement and maintain than heavily-engineered drainage systems. To date NR have not yet adopted the SuDS approach in the design of the drainage network. However, we recognise that adequate space will not always be available within the NR boundary space to accommodate SuDS. It will therefore be necessary in many cases to negotiate with adjacent landowners to provide areas for water storage in order to attenuate water flow before it enters the NR boundary.

525 ***We recommend NR adopt Sustainable Drainage Systems (SuDS) wherever possible, to better manage run-off (particularly from intense rainfall), to mimic natural drainage and encourage its infiltration, attenuation and passive treatment***.

Technical Strategy

526 The Professional Head of Drainage is developing the Technical Strategy for the NR Drainage system. One of the areas under investigation is the use of technology to monitor remotely the performance and condition of drainage systems in order to move towards a risk-based approach to inspection and maintenance. Real time data will be available, allowing for degradation rates to be calculated along with predictive outcomes, enabling proactive maintenance to be undertaken before a failure occurs. This is required as the current systems and data held for the drainage system are unreliable, and so there is considerable dependence on the local knowledge of inspection and maintenance teams. This is similar in approach to that adopted by many UK water companies who routinely use inspection tools such as SewerBatt for early blockage detection and Electroscan20 for monitoring infiltration.

527 Other infrastructure asset owners are continuing to seek cost effective opportunities to adopt Remote Condition Monitoring (telemetry). Under suitable conditions, sensors may be deployed to effectively monitor asset degradation and highlight the need to intervene before individual assets fail. Drainage remote condition monitoring is currently carried out in a disparate manner across the NR Routes. The Intelligent Infrastructure II project has commenced to create a common NR data platform.

528 With the help of joint funding from Innovate- UK and the Department for Transport, a collaborative research and development project was set up between Network Rail's Safety, Technical and Engineering and Research and Development teams; In-Touch Ltd; Lancaster University; and Connected Places Catapult (formerly Transport Systems Catapult), in order to undertake a feasibility study on the possibility of adapting a drainage management system developed and successfully rolled out on highways, for use in a railway environment. TrackWater is an Internet of Things (IoT) approach to rail water management and currently focuses on piped drainage systems with sensors installed in catchpits, which are chambers that act as silt traps to filter silt and debris out of the drainage system. The sensors measure the silt level of a catchpit at any given time and are also equipped with a flood sensor which will detect if the catchpit is flooded (Devan, O., 2019). The TrackWater project is currently proceeding with site trials. The Intelligent Infrastructure II programme is developing a common platform for TrackWater in NR.

529 The Professional Head of Drainage is funding research at Leeds University to develop improvements in earthworks drainage. This project will develop models of the precipitation, evapotranspiration, infiltration, runoff system for earthworks and their associated vegetation, and use this model to develop prioritisation guidelines for identified vulnerable asset groups. The model will include examination of the balance between improved earthwork stability linked to vegetation and the potential for leaves and roots to clog drainage

materials and disrupt pipes. The model will also couple to a holistic view of the drainage network to consider the impact of improved earthwork drainage on the overall drainage system including downstream capacity. The aim of the project is understanding the integrated slope-vegetation-drainage system for railway earthworks to permit prioritisation of drainage renewals and maintenance. The project outputs will include system models, identified vulnerable earthwork groups, improved renewals prioritisation guidelines and vegetation management strategies. We fully support this approach.

530 The Professional Head of Drainage is also funding research at the University of Sheffield on a drainage whole life cost model which incorporates degradation modelling into the whole life of the drainage system. The failure modes of drainage systems has been statistically modelled to provide an overall cost impact associated with timely interventions. The University of Birmingham was also commissioned to support the development and build of the Drainage Risk Model. When understanding the impact of drainage systems on the railway infrastructure, consideration into the different types of risk (safety, performance, environmental, reputational, etc.) and the costs of these incidents is key to quantifying drainage risk. We understand that the Drainage Risk Model is currently being validated in NR.

531 ***We recommend sufficient resources and funding are assigned to the development of the Technical Strategy for the Drainage system to ensure successful take up of new technologies, harness more value from data sets and to target interventions to enable long term improvements in railway infrastructure performance.***

Proactive Drainage Asset and Water Management

532 Historically, the approach in NR to repairing and improving earthwork drainage assets has been predominantly reactive, rather than pro-active.

533 Due to historic under-investment in the maintenance of earthworks drainage systems there is a significant backlog of defective drainage assets across the network. Addressing this backlog will require significant capital investment over a number of control periods to resolve the cause of the drainage issues rather than just the symptoms. By investing in capital drainage schemes, savings will be realised through reducing the disruption cost of earthwork failures as a result of inadequate drainage systems. The immediate future, to the end of CP6 in 2024, is the planned completion of the drainage inventory and condition data across the network. This will significantly improve the asset knowledge for this critical asset and begin to set the building blocks in place for future investment programmes of prioritised maintenance, refurbishment and renewal. It will also support and inform drainage asset management decision-making.

534 **Drainage is still generally regarded by NR as a "Child" asset that supports the performance of Earthworks and Track. Poor performance of the drainage system has a negative impact on its "Parent" assets. The historic lack of investment has led to a poor-quality drainage asset inventory, limited historic data and unmaintained assets, resulting in inconsistent water management decision-making. This situation has been compounded by a silo approach to drainage and water asset management.**

We consider it essential that the delivery of drainage system commitments, including sufficient funding and resources, is realised in CP6 and subsequent control periods to improve the railway water management safety and performance. NR should progressively shift their focus to proactively maintain and improve/upgrade the drainage system to support the delivery of a safe, serviceable and sustainable railway infrastructure into the future.

Chapter 9

Vegetation Asset Management

Introduction

535 Steam powered locomotives were used on the NR railway until the modernisation programme in 1950's when diesel and electric trains were introduced to replace them. Steam power carried with it the ever-present risk of lineside fires and, because of this, regular and heavy maintenance of the trackside vegetation was undertaken by lineside gangs. The earthwork slopes were subject to controlled regular burning and grass cover was more extensive than now as fire eliminates shrub and young tree growth preferentially. Other traditional land management techniques such as grass scything and tree coppicing were also employed.

536 Since the 1960's, the NR earthworks vegetation succession has advanced towards "climax", CIRIA (1990); the ecology of the railway has been able to diversify and develop to its present condition, with a wide range of sometimes mature and over matured plants and trees now covering the lineside earthworks. The mix of plants and trees at given locations is dependent upon local conditions, the competing factors between species for light, water and soil nutrients, and disturbance by animals or man. NR earthwork slope vegetation density now ranges from a sparse distribution of plant life through to dense mature woodland.

537 During the last 50 years vegetation management on the NR network has been kept to a minimum with the objective of keeping leaves away from the tracks in the autumn and preventing trees either striking trains or obscuring signals during the summer.

Influence of Vegetation on Earthwork Slopes

538 *'The influence of vegetation on the railway and earthwork slopes in particular is rarely, if ever, wholly beneficial or wholly detrimental but almost always manifests as some combination of the two extremes.'* Gellately et al (1995).

539 Greenwood et al (2004) explain that vegetation affects slope stability by altering the pore water pressure and soil moisture within the slope through the process of evapotranspiration. Additionally, vegetation through root reinforcement increases effective cohesion and reduces erosion. However, the weight of heavy trees may enhance stability or contribute to instability depending on their position on the slope.

540 Many aspects of the long-term behaviour of existing railway earthwork slopes are affected by vegetation (Glendinning et al., 2009). For example, earthworks slope vegetation can:

+ mechanically reinforce slopes, preventing shallow slope failures
+ reduce porewater pressures in clay slopes
+ increase seasonal slope movements by seasonal fluctuation in pore pressures within clay slopes caused by the high and low water demand from vegetation in the summer and winter respectively. Ultimately these seasonal slope movements have been found to induce progressive failure in high plasticity clay slopes
+ reduce water run-off and subsequent slope erosion
+ increase maintenance costs (because of vegetation management)
+ provide a visual and/or acoustic screen to neighbours
+ improve wildlife habitats
+ create problems with signal sighting or 'leaves on the line'

541 **The effect of vegetation on slope stability has been shown to be driven by a complex interaction between hydrological and mechanical mechanisms. Plant roots may reinforce slopes and increase their overall stability. Vegetation will take up and intercept water; potentially reducing pore water pressures and consequently increasing slope stability (at least seasonally).**

Root reinforcement in Earthwork Slopes

+ Plant roots play an important role in resisting the shallow landslip and erosion of slopes by increasing soil shear strength and this will stabilise the slope throughout the year. The Wu-Waldron model (Waldron, 1977, Wu et al., 1979) is a widely accepted model for quantifying the mechanisms of slope reinforcement by plant roots. In this model, the reinforced soil strength by plant roots is proportional to average root tensile strength and root area ratio, the two most important factors in evaluating the slope reinforcement effect of plant roots.

542 It has been long recognised that each species of plant has a unique root growth pattern. For a typical 20m high tree, roots with a diameter of around 30mm are unlikely to extend radially beyond two metres of the trunk (Biddle, 1998). The remaining roots are likely to have a diameter of less than 10mm and are unlikely to penetrate to a depth of more than 1.5m but may extend more than 20m from the trunk. The depth of influence for high water demand trees have been recorded to depths of 4 to 5m. Grass roots do not typically extend to depths greater than 0.3m and do not extend laterally in the same manner as a tree.

543 The NR innovation programme includes participation in the university led ACHILLES research programme (https://www.achilles-grant.org.uk/) which is developing models of deterioration and failure for earthworks across the infrastructure sector. ACHILLES will also incorporate output from the 'Rooting for Sustainable Performance' project led by the University of Dundee, which is currently developing new understanding and models for how plant roots mechanically stabilise the soil in slopes.

Pore Water Pressure in Earthwork Slopes

544 Pore water pressure changes in earthwork slopes are highly transient and complex. They are driven by rainfall infiltration, evaporation and plant transpiration, and variations in soil permeability with depth – including those resulting from changes to soil structure associated with plants and desiccation cracking. This makes understanding, and modelling pore water pressure changes complex (Powrie and Smethurst, 2019).

545 During the winter months deciduous trees and grasses do not photosynthesise and therefore little water is extracted from the ground. As this period generally coincides with the wettest time of the year, the soil moisture deficit (SMD) reduces. In areas covered by grass, the value usually reduces to zero; however, where trees are present, a persistent soil moisture deficit may remain. This is because trees extract much more moisture from the ground than grass and hence more moisture is required to bring the soil back to its field capacity. Therefore, periods when the SMD for trees reaches zero will be associated with particularly prolonged winter rainfall and hence higher pore water pressures (Ridley et al., 2004). It should be noted that SMD is a measure of moisture conditions in the near surface soil zone and may not be representative of pore pressure conditions at depth. In the spring when vegetation begins to grow a soil moisture deficit starts to develop at shallow depth. Vegetation growth over the summer increases soil moisture deficit until typically by mid-September by which point the soil is at its driest to the point that desiccation cracks form, increasing its overall mass permeability. Li and Zhang (2011) and Ng et al. (2001) demonstrated that soil permeability greatly affects the stability of a slope, as it influences the amount of water that infiltrates the soil during periods of precipitation. Intense rainfall falling on a desiccated cracked slope can result in a rapid increase in pore-water pressure and slope failure

546 Ng et al. (2001) showed that the type of slope failure is influenced by the duration and intensity of precipitation, with deep-seated failures occurring after rainfall events of low intensity and long duration, and shallow failures after rainfall events of high intensity and short duration. Likewise, O'Brien (2013) commented that deep-seated embankment failures are associated with modestly vegetated slopes and are likely to occur after wet periods, whereas dense vegetation is mainly associated with embankment serviceability problems, which are likely to occur in the late summer when demand for evapotranspiration is high.

547 The cycling of pore pressures in embankments constructed from high plasticity clays (mostly in the South East England and Midlands) creates seasonal cycles of shrinkage and swelling movements. The summer drying will cause a downward (and slight inward) movement of the embankment surface as the soil dries. In the winter the soil will rehydrate and there will be a tendency to swell, the swelling will be upwards but also outwards. The net result will be a downward and outward embankment movement on each cycle. The induced strains can cause the soil strength to reduce towards residual values, and consequently induce progressive failure in the embankment slope, see Paras 82 to 85 and Kovacevic et al (2001).

548 There are also serviceability issues relating to the deformation of the track on high plasticity clay embankments during dry summer periods, with localised settlement due to the proximity of high-water demand trees close to the track (Scott et al, 2007). Speed restrictions may need to be imposed or regular re-ballasting or tamping carried out to maintain consistent rail level and alignment.

549 However, the removal of trees may lead to an increase in pore pressures in embankments, thereby impacting adversely on the stability of the slopes. As part of a study (Smethurst et al., 2015) carried out for NR in 2006, instrumentation was installed to measure changes in soil water content, groundwater pressures and soil vertical and lateral movement in a London Clay railway embankment at Hawkwell, Essex. Shrinkage of the clay embankment caused by large deciduous oak and ash trees was giving rise to poor track quality and the need to apply train speed restrictions. The embankment was monitored for a year with the trees in place. The trees were then removed from the upper two-thirds of the embankment slope within the instrumented section, leaving trees only on the bottom third of the slope. After tree felling, monitoring continued for a further four years. Tree removal was effective in substantially reducing seasonal shrink/swell movements at the crest of the embankment, although the low groundwater conditions that were beneficial to slope stability were lost as the embankment rewetted. Any removal of vegetation on an earthwork slope needs to be carefully balanced between maintaining stability and reducing seasonal displacements.

550 Monitoring of long-term pore water pressure variation and embankment/track displacement is required to assess and quantify the impact of significant tree removal on high plasticity clay embankments, so that a managed approach to vegetation clearance and re-establishment may be developed that reduces both shrink/swell movements and the risk of deep-seated instability.

551 Similarly, in high plasticity clay cuttings, seasonal fluctuations in soil water content with associated problems of shrinking and swelling can in turn contribute to strain-softening and progressive slope failure (Smethurst et al., 2006). The progressive loss of strength as a result of seasonal stress cycles leading to strength deterioration and progressive failure means that high-plasticity clay cutting slopes can remain stable during one wet event but fail a number of years later due to a similar magnitude rainfall event (Take and Bolton, 2011); Postill et al., (2020).

“Vegetation management needs to balance the negative impacts of vegetation (blocked ditches and pipes, leaf fall, tree fall, desiccation adjacent to and beneath the track) against its positive impacts (reducing surface erosion, providing root reinforcement, avoiding channelling of flows, maintaining surface pore water suctions).”

Varley Report

552 In May 2018, the then Minister for Rail, Jo Johnson MP, commissioned an independent review to examine NR's approach to lineside vegetation management across England and Wales. John Varley was appointed to lead the review in June 2018, using his significant experience in environmental land management.

553 The Varley (2018) Review[14] assessed how effectively NR manages lineside vegetation on its estate, in accordance with its:

+ statutory responsibilities to ensure a safe and reliable railway
+ responsibilities to protect and enhance the natural environment

554 8,000 survey responses were collected, 100 key documents reviewed and 40 interviews conducted to gather the necessary evidence to make an assessment. The review team also observed lineside vegetation teams in action.

555 The findings of the Varley Review were published in November 2018. The Review recognised the £300 million annual cost of 'leaves on the line' and that the number of vegetation-related incidents has increased from 11,500 in 2009/10 to 19,000 in 2017/18. However, Varley highlighted that NR, as one of the country's largest landowners, have the opportunity to become one of the most environmentally responsible transport organisations in the world because of the substantial biodiversity and natural capital across its estate.

556 Whilst the importance of the environment was recognised by NR's leadership team and in official policy, this was not the case across the organisation. One of the key findings by Varley was that NR approaches to vegetation management were "reactive and inconsistent," with little thought given to their environmental impact. Safety and operational performance were instead the main focus of NR activity. Vegetation management was generally restricted to addressing sighting distances and tree fall plus leaves on the line.

557 The Varley Review concluded that vegetation management has been under-resourced. This is evidenced by the backlog of work that had led to all Routes being monitored closely by the ORR due to non-compliance to the Vegetation Management Standard. This was confirmed by all relevant stakeholders, with lineside management universally considered to be significantly under-funded and under-resourced. Vegetation management was often undertaken reactively to deal with specific issues rather than planned systematically. The Varley Review recommended that NR should regard lineside vegetation as an asset rather than a liability, balancing the operation of a safe and reliable

14 https://www.gov.uk/government/publications/network-rail-vegetation-management-review-valuing-nature-a-railway-for-people-and-wildlife

railway with positive environmental considerations. It recommended affording lineside vegetation the same importance as assets such as track and signalling which have asset management programmes, and stated: "…by not managing its vegetation as an asset, and in the context of wider policy, Network Rail risks increasing its whole-life costs and destroying valuable natural capital."

558 The Varley Review made six recommendations, each of which is accompanied by a timeline to deliver change.

559 In response to Varley, the DfT has set out a clear strategy for how it expects Network Rail to protect and enhance the UK's lineside environment, while ensuring the safety of passengers and services. 'Enhancing Biodiversity and Wildlife on the Lineside' was published in July 2019 with the headline challenge for Network Rail to achieve no net loss in biodiversity by 2024 and biodiversity net gain on each route by 2040. The ORR has been given a remit to monitor Network Rail's ongoing environmental performance as well.

560 NR welcomed the Varley Review and committed to addressing all of the Review's recommendations. In line with the Review's recommendations, NR committed to developing the standards that will see vegetation on the lineside estate managed as an asset. This will see the business make better use of environmental data to improve net biodiversity on the railway and contribute to the Government's targets on habitat and woodland creation.

561 NR have also started to develop a database of habitats and biodiversity across the network, to sit alongside other asset information. Network Rail is also progressing a cut and maintain/replace vegetation management strategy, rather than the previously commonplace "cut and forget" approach.

Management of Vegetation on Earthwork Slopes

562 Management of vegetation on earthwork slopes should maximise the beneficial actions while minimising the detrimental ones. Shallow failures in cutting slopes can occur sometime after widespread vegetation removal (see Para 37 'A partial review of failures in soil cuttings and embankments'). The necessity for vegetation clearance, bearing in mind its cost and potential negative impact on slope stability, needs careful consideration on an asset specific basis. However, the management of existing vegetation and replacement of vegetation with new species can result in improvements of slope stability and reduce erosion. It can also result in managing soil moisture fluctuations in the near-surface zone to reduce potential for desiccation cracks to form and to prevent significant shrinkage during drought.

563 The use of vegetation for slope stabilisation and erosion control is referred to as bioengineering which can in some cases be more appropriate and less expensive than traditional slope stabilisation methods. The bioengineering role of vegetation in the stability of earthworks has been discussed in detail by CIRIA (1990), Marsland et al. (1998), Marriott et al. (2001), and MacNeil et al. (2001).

564 Quantification of the benefits to slope stability, in terms of reducing the risks of both shallow and deep-seated failures are given by CIRIA (1990). Greenwood (2006) describes a routine slope stability analysis programme that includes the contribution of vegetation. The selection and evaluation of vegetation is also being specifically incorporated into 'bio-engineering' design for slope stabilisation (Stokes et al., 2009), Ollauri and Mickovski, 2017).

565 The role of plant roots is also increasingly being included in the geotechnical assessment of vegetated slopes (Switala and Wu, 2018; Ng, C.W.W. et al., 2019)

566 Although there is general agreement that the presence of plant roots increases soil strength both through mechanical enhancement and reduction in pore water pressure, the magnitude and reliability of these strength gains are difficult to quantify for routine practical applications. This knowledge gap currently limits the utilisation of managed vegetation and bioengineering in routine slope design and stability assessment.

567 NR have established their preferred vegetation layouts in the Management of Vegetation on Earthworks standard, NR (2018l). This document provides guidance to earthwork managers on the implementation of vegetation management strategies with regard to slope stability. **The use of managed vegetation and bioengineering to stabilise earthwork slopes is a cost-effective technique with the potential to be used more extensively on the NR earthwork slopes as a preventive and remedial measure. However, further work is required to quantify the effectiveness of managed vegetation and bioengineering for NR earthworks slopes and adapt the approach for routine practical application.**

568 ***We recommend further work is undertaken by NR to develop and implement vegetation management and bioengineering techniques to stabilise earthwork slopes as a cost-effective preventive and remedial intervention technique. NR have documented (Management of Vegetation on Earthworks, NR (2018l)) the optimum plant species and vegetation management schemes to enhance the stability and performance of NR earthwork slopes. This recommendation is particularly timely as NR move (post Varley) to a cut-and-maintain/replace vegetation management strategy, rather than the previously commonplace "cut and forget" approach.***

NR Vegetation Management Standards

569 With 20,000 miles of track and millions of trees growing along the railway, managing vegetation is hugely important to NR. If not managed well, trees and fallen leaves in autumn can pose a risk to the safe running of the railway and cause delays to trains.

570 The NR suite of Vegetation management standards as described below, have all been updated and re-issued over the last 12 months to reflect NR's commitment (post Varley) to manage vegetation on the lineside estate as an asset.

571 The Professional Head of Asset Protection and Optimisation (ASPRO), Drainage and Off-Track in the Technical Authority team has the responsibility for owning, developing and maintaining the Vegetation suite of standards across NR.

Lineside Vegetation Management Manual

572 The NR lineside vegetation management manual, NR (2020b), describes the process that uses risk assessment to contribute to the sustainable management of the lineside estate and the safe running of the railway infrastructure. The key principle that underpins this standard is that risk from lineside vegetation must be understood so that appropriate controls can be selected and applied. Risk may be related to safety, performance, loss of habitat, cost or reputation. Risks from lineside vegetation are identified, assessed and action is taken to control them. This is a continuous process, using the results of inspections and the full range of lineside vegetation asset information available.

573 Ellipse, the NR asset management database, contains the vegetation asset register and is used when creating the inspection and management plans. It stores the following asset information:

+ compliance with the requirements of the lineside vegetation management manual, NR (2020b)
+ output from inspections
+ work arising from reports for lineside vegetation
+ any work carried out on lineside vegetation

Lineside Vegetation inspection and risk assessment

574 This module, NR (2020c), describes requirements for inspection frequencies, minimum actions and maximum timescales. The module prescribes the production and implementation of an inspection plan that covers all lineside vegetation.

Lineside Vegetation management requirements

575 This module, NR (2020d) describes the principles of Lineside vegetation management. Vegetation is kept clear to a specified distance from the running line to allow for the safe operation of the railway. Planned maintenance avoids the need for the immediate response and reactive work. Lineside vegetation is managed to allow other assets to be inspected and maintained. Management also allows certain assets, for example drainage, to function safely.

Route Vegetation management plans

576 This module NR(2020e) provides the requirements for Route asset managers to develop vegetation management plans and sectional asset plans to support the sustainable management of the lineside estates and its habitats.

Tree Management

577 This module NR(2020f) contains the requirements for the management of trees. The following steps are described:

+ collecting data on trees
+ using data to evaluate the risk and to understand impact of interventions
+ establishing a consistent approach to tree management planning and undertaking work
+ requirements for tree planting; and
+ establishing a consistent approach to applying contingency measures to manage emerging and immediate threats

Management of Vegetation on earthworks

578 This module, NR (2018l) provides guidance to Route earthwork managers on the implementation of vegetation management strategies for NR earthworks with regard to slope stability. The module notes that there may be instances where the presence of vegetation on an earthwork is beneficial from a geotechnical engineering point of view; however, operational requirements may be impacted by the presence of vegetation, e.g. signal sighting or overhead line encroachment. In these cases, the Earthworks Manager will need to consider slope stability issues driven by tree management and manage the risks to the asset accordingly.

579 It allows earthwork managers to:

+ manage operational risk
+ control or mitigate the presence or absence of vegetation affecting:
  - soil cutting or embankment stability
  - drainage capability or capacity on earthworks
  - dislodged rocks falling on the track or outside party land
  - scour of embankment toes

580 The module requires Earthworks managers to take into account the effects of vegetation when vegetation management is planned.

581 It describes the beneficial effects of vegetation on Earthworks as follows:

+ canopy cover reducing rainfall infiltration into soil slopes
+ erosion protection
+ reinforcement through the mechanical effects of roots
+ extraction of soil moisture through hydrological effects
+ sound and sight barrier

582 It also describes the negative effects of vegetation on Earthworks as follows:

+ seasonal variations in moisture uptake by vegetation might lead to detrimental cyclical movements adversely affecting track support and performance; (dependent on soil type)
+ root jacking on rock slopes
+ access and visual inspections are hampered during Earthwork Examinations potentially masking underlying indicators of instability

583 The module identifies preferred vegetation layouts for new, renewed or refurbished earthwork slopes. The advice is that unless there is a vegetation management plan in place to confirm the vegetation is maintained for the design life of the asset, it should not be relied on as a design element of new or renewed earthworks. The need for future vegetation maintenance should be considered in developing planting schemes and building in safe slope access.

584 We recognise that NR have carried out a comprehensive review of their vegetation management standards post Varley and have very recently published updated versions. It is acknowledged that the revised standards require that vegetation is now to be treated as an asset. Given the scale of NR's ambitious vision for the future management of vegetation as an asset on the lineside estate, it is anticipated that the changed strategy and standards will be kept under regular review as a commitment to delivering the Varley recommendations and continuous improvement.

NR Environmental Sustainability Strategy 2020-2050

585 In September 2020 NR published an Environmental Sustainability Strategy, NR (2020g), which it describes as its 'most ambitious and forward-looking' to date, and a key part of its ambition to position rail as 'the cleanest, greenest form of mass transport'.

586 The strategy committed to 'use electric trains to reduce carbon emissions; make stations, tracks and trains more resilient to extreme weather; plant more trees to offset carbon emissions; and zero waste to landfill'.

587 With the Carmont derailment having highlighted the impact of severe weather on infrastructure, we welcome the confirmation from NR that the Environmental Sustainability Strategy includes 'important commitments around how we will protect the railway from the effects of climate change, improve biodiversity on our land and minimise waste'.

588 Successful delivery of the NR Environmental Sustainability Strategy will rely on integrating environmental sustainability into everything NR do. However, NR currently lack a bespoke Policy (Strategy) document specifically for the Management of Vegetation in contrast to Earthworks and Drainage, because it has only recently started to regard Vegetation as an Asset (post Varley). Action has been recommended elsewhere in this report (Para 255) to revise the Earthworks Policy and Technical Strategy documents to ensure that the role of vegetation management is recognised as an integral part.

589 **We support NR's ambitious vision for the future management of vegetation as an asset on the lineside estate and as part of the wider Environmental Sustainability Strategy. We expect that these improvements will explicitly include action to harness the beneficial effects of vegetation (reducing surface erosion, providing root reinforcement, avoiding channelling of flows, maintaining surface pore water suctions); and minimise the detrimental impacts (blocked ditches and pipes, leaf fall, tree fall, desiccation adjacent to and beneath the track).**

590 ***We recommend that NR progressively adopt a broader and more integrated approach to the management of Earthworks, Drainage and Vegetation, taking account of changing weather patterns, and breakdown the historic silos between these interdependent assets across the organisation to support the delivery of a safe, cost-effective and sustainable railway infrastructure into the future.***

Chapter 10

Mitigation – Monitoring, Surveillance and Interventions

Mitigation

591 NR uses the term “Mitigation” to describe the process to manage risk for a relatively short period of time until it can be permanently reduced by an “Intervention”, NR (2017g). Specifically, the Earthwork Mitigations Standard, NR (2017f), defines earthworks mitigation as “measures carried out on or near an earthwork asset that do not change the likelihood that the asset might fail, but that manage the consequences of failure and hence reduce the overall earthwork safety risk”.

592 According to the NR standard, NR (2017f), mitigation of earthworks covers:

+ operational restrictions
+ temporary restraints
+ geotechnical instrumentation array (GIA) systems
+ alert/alarm systems

593 A key challenge for NR is the detection of earthworks failure by means other than train drivers. The rapid nature and lack of precursor indicators of some slope failure mechanisms means mitigations are required to prevent trains interacting with earthwork failures. Some physical interventions can also be classed as mitigations as they do not stop the earthworks failure from occurring but they prevent the consequences. A good example is a flexible barrier between a slope and the track that could fail. It could be argued that flexible barriers fall under the temporary restraint category definition but, in reality, they will generally be installed for the long term.

Introduction to monitoring

594 Smethurst et al (2017) provide a comprehensive review of current and future technologies for monitoring the performance of transport infrastructure slopes. A report by Professor David Petley, a member of our Task Force, entitled 'The role of technology in slope management' is in Appendix G. The report comprises a high-level review of the ways in which new monitoring and surveillance technologies can provide enhanced approaches to slope management. It draws upon recent literature and case studies, and highlights that new technologies are rapidly developing in this area. The combination of new, low-cost sensors; novel terrestrial, aerial and space-based platforms; improved instrumentation; rapidly developing, powerful algorithms; and high-performance computing provides ample opportunities for innovation. The report focuses on individual technologies, although it emphasises that the greatest advances will arise where multiple technologies are used together. In the following parts of this Chapter, we draw on and refer to various aspects covered in the review in Appendix G.

595 **There is a need to adopt reliable methods of monitoring which can inform NR engineers of the condition of the more critical geotechnical assets, and importantly, of any significant changes occurring. NR recognise this need and have been impressive in investing significantly in R&D to investigate the potential for novel technologies.**

596 We comment on novel technologies for monitoring in the following sections, together with some comments on the technologies being used by NR that are now well-established.

597 **It is important to distinguish between two principal objectives of monitoring in the context of NR's earthworks:**

+ **Monitoring Objective A Failure detection (i.e. detection of rapid loss of functionality that may have a direct consequence on the safety of the railway) and reaction via alert alarm systems**

+ **Monitoring Objective B Provide data on the performance and condition of a slope or embankment, and possible precursors to failure**

598 Figure 10.1 shows a table indicating technologies for surface and sub-surface deformation monitoring, many of which NR are either using, researching or planning to trial. Three categories of failure response of the monitoring technology are shown: Slow (S), Rapid (R) and Instantaneous (I). Colour coding indicates the suitability of the technology for these three categories. It can be seen that the majority of the technologies are not suited to rapid or instantaneous failure responses, ie Objective A. However, many of them are suitable for Monitoring Objective B: by detecting movement over a period of time an indication can be given of a deteriorating performance of a slope or embankment. This is covered in more detail for some of the technologies in the following sections.

Monitoring Technique	Description & Comments	*Failure Category		
		S	R	I
Surface deformation monitoring				
Global positioning system (GPS)	GPS system receives time signals from orbiting satellites and positioning is based on signal travel times. Limited reception in topographic depressions and accuracy issues in forested areas (signal scatter)	o		
Photogrammetry	3D reconstruction of surface topography from overlapping at least 2 photographs taken from different positions. Complex post processing of data. Application limited by high cost and time requirements.			
Remote Sensing (InSAR, LiDAR)	Terrestrial, aerial or satellite based recording of reflected electromagnetic energy from the Earth's surface, Positional reflectors required to overcome vegetation. Complex and expensive data processing	o		
Distributed acoustic sensing (DAS)	Optical fibres used as a sensing device to measure acoustic energy generated by noise and vibrations; identifying threat events from normal background activity (i.e. rock falls).			o

Accelerometer & Geophones	Recording of ground surface velocity or acceleration.in response to rapid movements and earthquakes. Limited detection capability of low velocity ductile movements. Post-processing is complex.		o	
Electrode tracking using ERT	Electrical resistivity tomography (ERT). Measured resistivity can be inverted to track electrode / slope movement. Readings sensitive to sensor spacing. Complex installation and post-processing.	o		
Surface mounted tiltmeters	Microelectronic sensors capable of detecting changes from the vertical. Typically installed on the end of a pole inserted with suitable embedment. Wireless network required to create an array across an asset.		o	
Subsurface deformation monitoring				
Time domain reflectometry (TDR)	Deployment of cables in boreholes, locating displacement faults by measurement of reflections along conductor. No direct measurement of deformation or deformation rate. Sold as commercial systems.			
Shape acceleration array (SAA)	Comprise a string of microelectronic sensors at regular intervals and installed inside boreholes. Measures 3D displacement. High costs of instrumentation and processing. SAA string recoverable from borehole.	o	o	
Acoustic emission monitoring	Deformation of angular backfill in a borehole, creates high energy acoustic emission on a steel conductor waveguide. Most applicable to slopes failing along a defined shear surface. Sensitive to slow rates.	o		
Electrical resistivity tomography (ERT)	Moisture content mapping in 4D of earth structure via electrodes placed below ground level, using soil resistivity. Complex installation and post-processing. Readings sensitive to sensor spacing.	o		
Porewater suction / soil moisture probes	Variety of probes available for detailed measurement of soil and water interaction and soil water retention. Does not directly detect deformation. Careful calibration required and specialist expertise.	o		

Ground penetrating radar (GPR)	Measurements based on the propagation of electromagnetic waves in the subsurface. Commonly used to establish ballast depth in railway formations. Requires complex post processing.	o	o	
In place inclinometers and extensometers	Tubing installed into boreholes to detect zones of disturbance and determine whether movement is constant, accelerating or responding to remedial intervention. Possible to automate but expensive.	o	o	
o Technology that NR either use, have researched or plan to trial * Failure Categories; Slow (S), Rapid (R) and Instantaneous (I)				

Figure 10.1: Monitoring technologies (adapted by NR from Smethurst, 2017)

Instrumentation and monitoring

Current schemes

600 **In view of the very large number of earthworks sites, Network Rail rightly recognise that it is impractical to have widespread instrumentation and monitoring. Traditional measurement of pore pressures and soil deformations, by installing piezometers and inclinometers in boreholes, is essential, however, to obtain a more detailed understanding of the behaviour of a particular slope or embankment that is judged to be critical.** An example is shown in Figure 10.2 which illustrates inclinometer readings for a NR embankment on a London Clay slope in the Anglian region. The inclinometer readings were taken mainly manually but solar powered automated inclinometers were also trialled. The inclinometers clearly show an overall progressive deterioration over a period of three years, a good example of Monitoring Objective B (provide data on performance and condition).

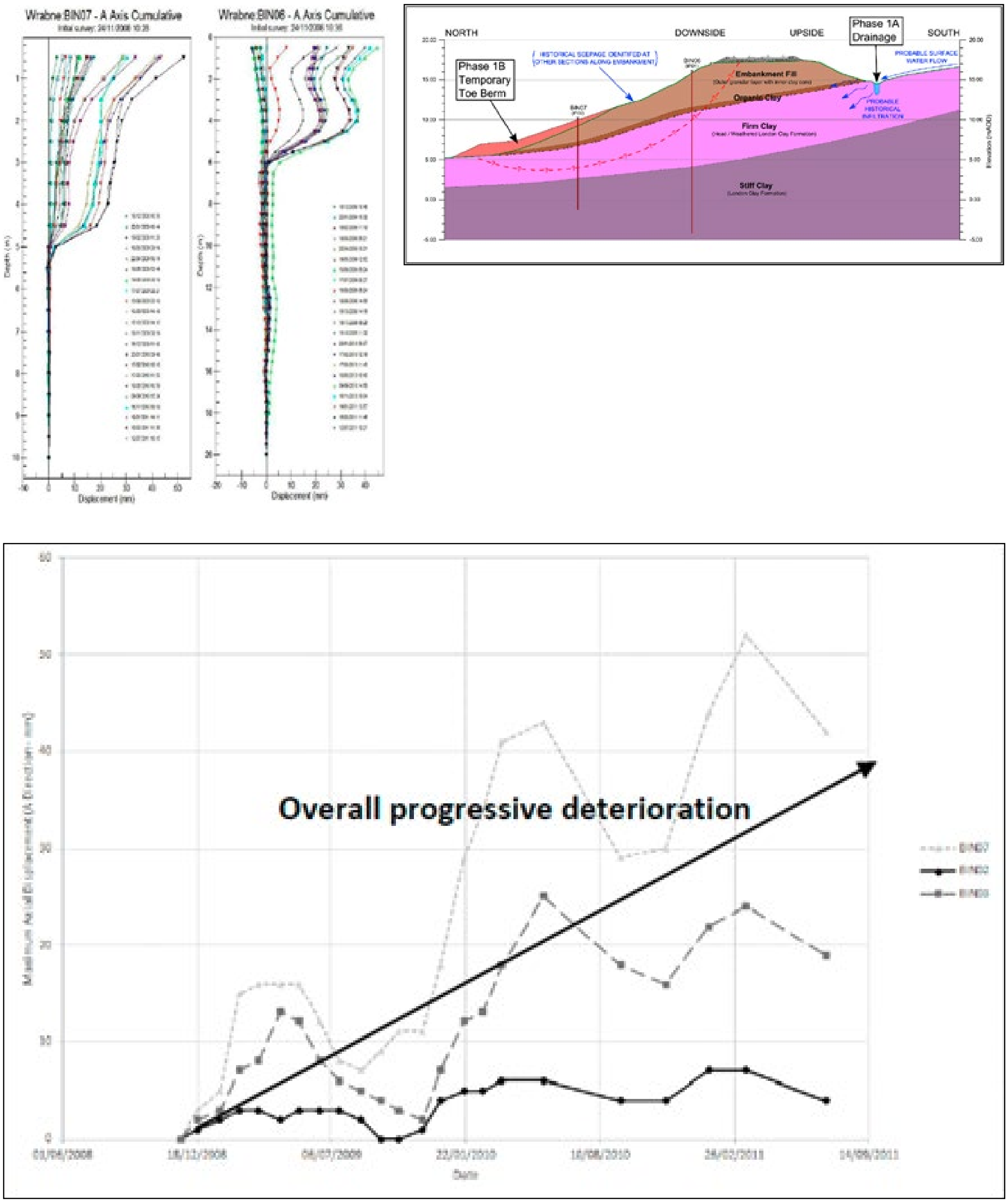

Figure 10.2: Example of inclinometer monitoring of performance of an embankment on a London Clay slope in Network Rail's Anglian Region

601 NR have been trialling various innovative technologies, some of which are referred to in the following sections.

Remote condition monitoring with automated tiltmeters

602 Proprietary systems of wireless tiltmeter nodes have recently been successfully installed on a number of NR slopes and embankment sites in Kent, with more in the pipeline; other Routes (e.g. Sussex and Wessex) are likely to adopt the technology. The tiltmeters transmit their measurements through a wireless communications network to a gateway, and thereby are loaded onto the internet. Readings can be taken every five minutes or at even higher frequencies, and alert levels set to give suitable warnings. Examples of installations of wireless tiltmeters around a NR tunnel portal and along an adjacent cut slope are shown in Figure 10.3.

603 **Wireless tiltmeter systems recently trialled by NR are an extremely promising application of innovative sensor development to the management of earthworks assets; they have considerable potential for Monitoring Objectives A and B. *We recommend that wireless tiltmeter systems be more widely adopted on earthworks slopes and embankments that are judged to be potentially critical.***

Figure 10.3: Wireless tiltmeters around a tunnel portal (Network Rail presentation, 9 October 2020)

Acoustic Sensing

604 In recent years Network Rail have trialled distributed acoustic sensing using fibre optic cables as a means of detecting rock falls. These trials have demonstrated that the technology has potential but there are a significant number of challenges to overcome. ***We recommend that acoustic sensing continue to be part of Network Rail's R&D programme in view of its potential as a new technology for detection of instability of soil and rock slopes.***

Helicopter surveillance

605 Since July 2020 NR own a helicopter, which is based at Cumbernauld in Scotland. The Air Operations Department offers aerial services to the organisation; the Scotland region makes considerable use of these services, currently amounting to 700 flight hours per year. High-definition photography and thermal images are obtained, the former being of considerable value in relation to earthworks asset management (the latter is valuable for detecting electrical breakdowns). Helicopter LiDAR surveys are also being undertaken on a national basis to obtain complete 3D point cloud data for Network Rail's 'Intelligent Infrastructure' programme.

606 **Helicopter flights are of considerable value, especially in hilly or mountainous terrain, for inspection and provision of visual evidence, particularly immediately after an extreme weather event that may have resulted in a failure, whether it be soil or rock instability or washout. In Scotland around five such flights are made each year specifically for earthworks inspections.** ***We recommend that consideration be given to more widespread use of helicopter flights for inspections of earthworks throughout the UK.***

Drone surveillance

607 Unmanned aerial vehicles (UAVs or drones) have reduced in price and developed rapidly from a technological perspective. We understand that NR presently have 55 drones and around 45 trained operators, as well as having framework agreements with a number of commercial drone operating companies. Drones can in principle add considerable value to earthworks management. They have primarily been used as follows (for more details, see Appendix G):

+ Hazard mapping and morphological analysis: drones can be used to collect LiDAR and/or optical imagery that allow landslides to be mapped, hazards to be assessed, inventories to be collated, site conditions to be assessed, and changes with time detected

- The collation of data after significant events: allowing documentation of site conditions, quantification of volumes, forensic study of process and a dataset for modelling

- Photographic and video images: these can be obtained from drones flying close to the asset in question, typically flying offset from the track. In principle it should also be possible to employ drones to give warning of debris on the track

608 The scale of data collection can range from the local, in which the operator collects data with a small drone flown within line of sight, to the regional (with the drone operating autonomously, noting that there are substantial regulatory hurdles in this respect at present). Large areas can be surveyed quickly and effectively, and response times can be short. There are several limitations: drones fly comparatively low in most cases, which can lead to substantial levels of distortion in the images collected by optical type sensors. This can be overcome with ground control points, but these greatly increase the effort and time required to collect the data. Distortions can also result from difficulties in maintaining a stable platform.

609 There are also limitations in the areas in which drones can operate, with restrictions on their use around large groups of people, airports and other key infrastructure assets. The range and duration of operation can be short (typically around 30 minutes). Weather can severely limit operations, with notable problems being associated with strong winds and low visibility.

610 A key issue is the present Civil Aviation Authority (CAA) regulation that only permits flights for a distance of 500m within the Visual Line of Sight (VLOS). It is understood that a proof-of-concept flight for 20km is being proposed for Beyond Visual Line of Sight (BVLOS), requiring CAA approval.

611 **Despite some existing limitations, particularly in respect of CAA regulations, drone technology is a rapidly expanding area and there is considerable potential for drones to significantly enhance NR's earthworks management. *We recommend that more use is made of drone technologies as their capability develops*.**

Remote sensing

InSAR

612 InSAR (Interferometric Synthetic Aperture Radar) is a technology for mapping ground deformation using radar images of the Earth's surface which are collected from orbiting satellites. It measures change between pairs of radar images to detect deformation. Processing of imagery is complex but has become increasingly routine and automated in recent years, providing a tool with increasing levels of applicability. Further details are given in Appendix G.

613 The technology is capable of obtaining cumulative surface displacement measurements with millimetre accuracy. Many studies in recent years have been on the use of InSAR for monitoring of bridges, dams and landslides. In the opencast mining industry, InSAR is routinely used to monitor slopes in order to provide early warning of potential failures. Systems are available commercially, providing integrated tools that both collect the dataset and provide an analytical function that can provide warning of developing instability. There have been some applications of InSAR in the context of railway infrastructure, including for example the monitoring of bridges and excavation displacements associated with dewatering.

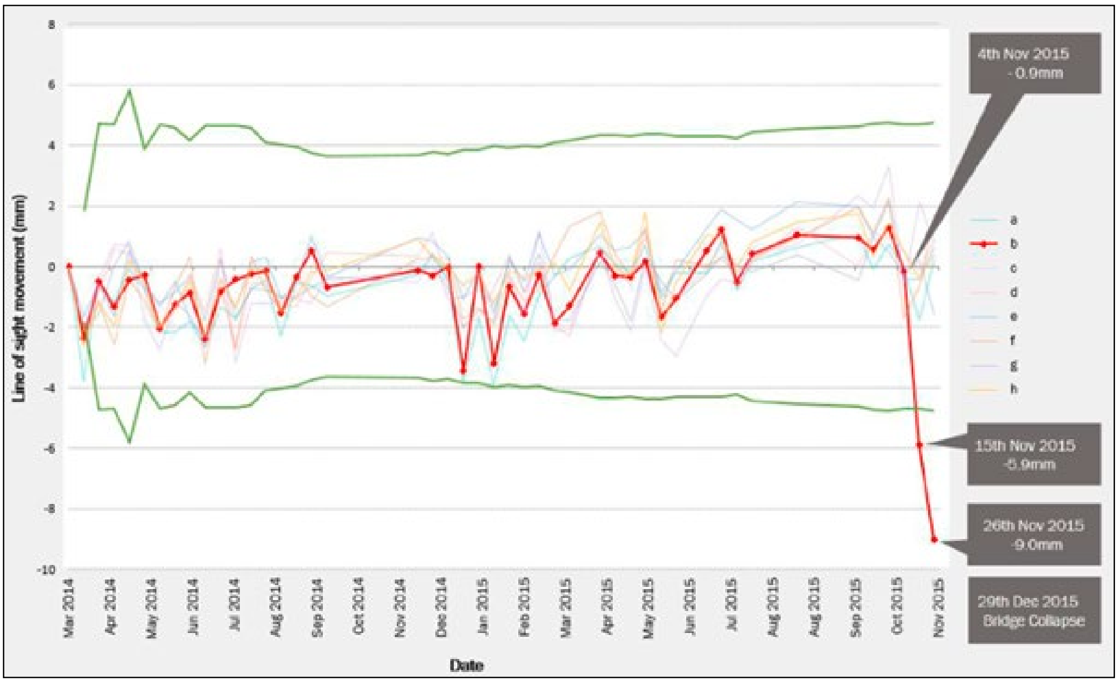

Figure 10.4: Vertical movements of masonry bridge at Tadcaster inferred from InSAR data, indicating rapidly increasing settlement several weeks before bridge failure occurred due to scour of its foundations during flooding of the River Wharfe (Selvakumaran, S et al, 2018)

614 An example of its potential use for providing warning of bridge scour is illustrated in Figure 10.4. On 29th December 2015, following a period of intense rainfall and flooding, the masonry bridge at Tadcaster suffered a partial collapse into the River Wharfe due to scour of its foundations. Figure 10.4 shows subsequent analysis of InSAR data indicating settlement of the bridge being a precursor to failure; measurements several weeks before the failure indicate rapidly increasing settlement, almost certainly caused by earlier flooding and scour (Selvakumaran et al, 2018). This is a good example of the potential for InSAR technology for Monitoring Objective B, i.e. providing evidence of the bridge settlement as a precursor to the subsequent failure.

615 An application of InSAR for railways is shown in Figure 10.5 (Ling Chang et al, 2018) in which the technology was applied to the entire railway network of the Netherlands, more than 3000 km long, using hundreds of Radarsat-2

acquisitions between 2010 and 2015, leading to the first satellite-based nationwide railway monitoring system. Ling Chang et al use a probabilistic method for the InSAR time series post-processing to efficiently scrutinize the data and detect railway instability. The resulting deformation map for the Netherlands railways is shown in Figure 10.5 (a), and a more detailed "flagging system" risk map is shown in Figure 10.5(b). The risk map, based on the satellite measurements and combined with expert judgement, shows areas with < –10 mm/year (indicating a settlement rate exceeding 10mm/year), and those with >+8 mm/year (indicating a heave rate exceeding 8mm per year); these are highlighted by the red and blue flags, respectively.

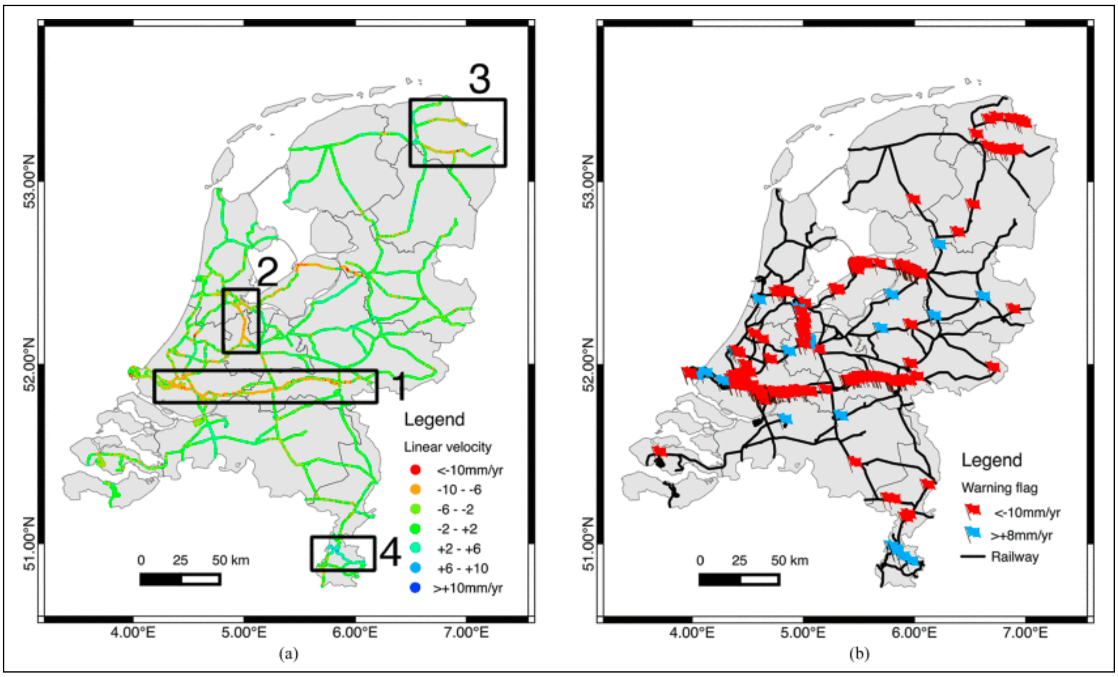

Figure 10.5: (a) Deformation map for Netherlands railway network derived from satellite observations. (b) Risk map, in which the coloured flags indicate the severity of the deformation (negative means settlement, positive means heave). Ling Chang et al (2018)

616 The handling, processing and synthesis of very large InSAR data volumes is complex and challenging, but the potential of rapidly increasing computational power, AI, deep learning algorithms and machine learning means that it is likely that these problems can be overcome.

617 A further difficulty is vegetation. Whilst measurement of points along the railway track is feasible, a challenge for slopes is the presence of vegetation. Without clear points on which satellite observations can be compared the technology is limited, unless suitable reflector markers are placed on the slopes. Satellite data can be enhanced with the placement of reflector markers – permanent targets located on the slope to generate a stable signal. This has allowed the detection of movement in landslide systems, and improvements in processing have permitted good movement records to be extracted, which have in some cases been benchmarked against movement records obtained from conventional monitoring; further details are given in Appendix G.

618 Even with the use of corner reflectors, slope monitoring using satellite InSAR has proved to be challenging. Nevertheless the capability of detecting differential deformation makes InSAR potentially a powerful and economical means for monitoring the performance of railway infrastructure on a weekly basis. Detection of changes in deformations of slopes or embankments could provide an invaluable means of detecting their deterioration, performance and changing condition (Monitoring Objective B).

619 We understand that Network Rail has already investigated InSAR technology in a recent project with Innovate UK, the Satellite Communications Catapult, the European Space Agency and the British Geological Survey, but with limited success. We note that a CIRIA research project is underway with significant involvement from Network Rail.

620 Recent research at Imperial College has developed a bespoke InSAR processing approach: a 'distributed scatterer' (DS) comprises contiguous point clusters that have lower amplitude and coherence than individual 'permanent scatters' (PS), but which collectively can provide reliable deformation time series in rural areas. The approach uses a land-cover classification that can recover reliable data from rural, vegetated, areas.

621 **InSAR is a promising technology which is developing rapidly, particularly with rapid developments in AI and machine learning, and should be given further attention. *We recommend that a number of critical slopes be equipped with reflector markers to overcome the problem of vegetation and that the potential for InSAR be explored further.***

LiDAR

622 LiDAR (laser imaging, detection, and ranging) is now a well-established technique. Examples of its application to landslides, particularly using airborne LiDAR, are given in Appendix G. The use of terrestrial laser scanning (TLS), which is ground based LiDAR, is also discussed in Appendix G in the context of change detection, especially for the characterisation of rockfalls and for monitoring of ongoing hazards and post-failure analysis.

623 LiDAR is used for measuring distances by illuminating the target with laser light and measuring the reflection with a sensor. Differences in laser return times and wave lengths are then used to make digital 2D or 3D representations of the target. Figure 10.6 illustrates the principle of LiDAR monitoring of a slope.

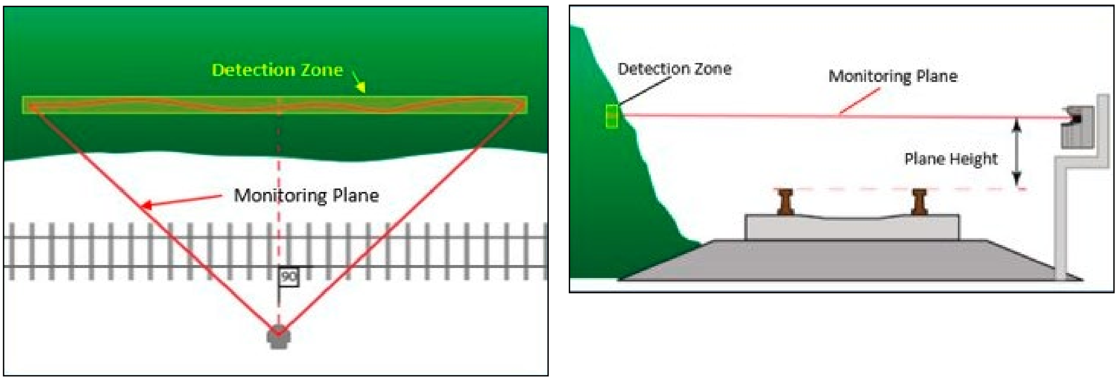

Figure 10.6: The principle of LiDAR monitoring of an earthworks slope (Network Rail presentation, 9 October 2020)

624 The technique has recently been successfully trialled by Network Rail on the Wales Route, on which two LiDAR monitoring systems have been installed. Following an occurrence of a slip, one of these was upgraded to a fully remote monitoring system that recorded a subsequent substantial slip movement. By installing a live CCTV camera on the LiDAR camera, with its view capable of being changed remotely, a combination of the LiDAR measurements and the TV image forms an email alarm system; a trigger value was set of 50mm of movement over greater than 1.5m linear distance (parallel to the track). The trial demonstrated that within a few minutes of the Control Centre receiving an email alarm, trains were stopped on the affected and adjacent line. This system has allowed the TSR (temporary speed restriction) to be raised from 20mph to 50mph.

625 Vegetation presents a problem (by moving between readings), but by averaging over an extended period of time it is possible to remove much of the variations and establish a true representation of a slope profile. Another limitation is the power needed for the LiDAR system. In the example described above, which cost around £50k, power was obtained from the signalling system; if an independent power supply is needed, the system will be more costly. There is also the potential problem of vandalism.

626 Despite these limitations, this impressive trial application by Network Rail illustrates the considerable potential for LiDAR. It is capable of fulfilling Monitoring Objective A (failure detection and reaction) as well as Monitoring Objective B (provide data on the slope performance and condition).

627 ***We recommend that consideration be given to installation of further LiDAR systems on a limited number of sites where the stability of the slope is judged to be marginal and interventions are not practical.***

628 A further promising application of LiDAR is to obtain more accurate data on the geometry and features of Network Rail's cutting slopes. There are proprietary train-mounted systems that incorporate 360° laser scanners together with panoramic imaging to provide ultra-high density LiDAR point cloud data of the entire Network Rail route. The laser scanner rotates at high speed, recording millions of points with time. Such a system can be mounted on a train to scan the complete rail corridor, including track assets, structures, earthworks and vegetation. In combination with a GIS system this has the potential to produce a highly accurate georeferenced or geopositioned point cloud. The technique can be combined with video and photogrammetry imaging.

629 ***We recommend that consideration be given to the potential for the train-mounted scanning LiDAR technique to be applied widely to the Network Rail system to update the geometry and features of cutting slopes.***

Photogrammetry

630 Photogrammetry has been used extensively in the assessment of sites and their hazards for many years. The primary medium has been aerial imagery, with archive images combined with new acquisitions allowing the interpretation of change through time. In Hong Kong, for example, the inventory of natural terrain landslides was initially collated using aerial imagery collected during a survey in 1963 as vegetation levels were much lower at that time, allowing better mapping of the terrain than is possible using more modern images.

631 In recent years, the use of photogrammetry has increased substantially. This has resulted from the availability of many more images due to increased capture from both ground and aerial sensors, and improved provision of online data (such as Google Earth for example). Improvements in software technologies allow rapid, automated orthorectification of images, providing data that is robust and that can be digitally combined with other technologies, such as digital elevation models.

632 Recent development of technologies allows the creation of 3D datasets from regular photographs, which can even be obtained from use of a typical smartphone. These can provide powerful tools for the collection of information about slope deformation using imagery. Combined with InSAR satellite technology, described in Para 612 to para 622, this provides a potential approach to pre-failure warning systems.

Track Geometry Data

633 Track geometry data to millimetre precision has been routinely collected by NR over the last 15 years using the New Measurement Train (NMT), (Figure 10.7), to identify track defects and subsequently plan track maintenance interventions. Transducers, accelerometers and a laser sensor provide information on track geometry, the shape and profile of the rail head, and the twist of the track. The NMT travels at 125mph, covers 15,000 miles in a year and will capture around 10TB of geometry data every 440 miles. The data processing involves calculation of the statistical measure standard deviation (SD) track geometry for track segments.

Figure 10.7: New Measurement Train (NMT)

634 A number of studies (Sharpe and Hutchinson, 2015; Nogy, 2016; Kite et al., 2020) have demonstrated that track geometry data can be a viable source to consider for early detection of railway embankment instability. In general, embankment movement pre-failure may be characterised by excessive deterioration in both the rail lateral alignment and difference in the rail vertical alignment across the track (dips or vertical irregularities in one or both of the rails are referred to by track engineers as "cyclic top").

635 However, embankment slopes will not always show signs of distress and can fail with limited, if any, indication of deterioration prior to rapid failure (O'Brien, 2013). It is therefore unlikely that the analysis of track geometry data alone will identify all potentially problematic embankments. Track geometry data can also in some instances be affected by the seasonal shrink-swell of embankment clay fill and track maintenance activities which can make interpretation difficult.

636 Earthwork movements generally affect track lateral and vertical alignment and cause differential settlement between the rails. In order to provide an objective measure to determine the rate of deterioration of track geometry pre-embankment failure, Sharpe and Hutchinson (2015) simplified the filtered raw track geometry data by taking the standard deviation (SD) at 10m intervals, using a base length of 36.6m (i.e. two rail lengths, which limits the influence of dipped welds). Sharpe and Hutchinson (2015) found that a combination of three parameters, Lateral Alignment SD, Right Top SD and Difference between Left Top and Right Top SD could be used to indicate whether deterioration in track geometry was due to earthwork movement. This study demonstrated (for a limited route length and number of embankment failures) that analysis of track geometry data collected on a monthly basis over a period of four years can identify evidence of earthworks instability at least three years before the point of earthworks failure.

637 Subsequently, Kite et al (2020) examined the track geometry data for 51 known embankment failure sites; of these, there were 28 sites which had enough data to allow analysis of the track geometry deterioration. Kite et al (2020) identified clear signs of embankment deformation pre-failure in 19 of these sites from the track geometry data. The maximum deterioration in the track geometry values ranged between 4.2 SD mm/yr and 12.8 SD mm/yr at the 19 embankment failure sites.

638 From these two studies (Sharpe and Hutchinson, 2015 and Kite et al., 2020) thresholds of track geometry deterioration have been suggested based on the observations prior to embankment failure (Table 1). These threshold values give an indication of the worsening of track geometry that is likely to be due to underlying embankment instability rather than normal track deterioration alone.

Risk Level	Track Geometry Threshold SD mm	Description
Negligible	<1 mm/yr.	Negligible infers that any track roughness would be addressed during the course of routine track maintenance and would not therefore be identified as an earthwork problem.
Minor	1 to 2 mm/yr.	May or may not be identified as an earthworks issue, could be dealt with through track maintenance assuming rates of deterioration do not increase.
Moderate	2 to 4 mm/yr.	Moderate movement which is more like to be identified and related to a potential earthwork issue
High	>4 mm/yr.	High risk is judged to be the point at which it is obvious that there is a serious earthwork issue that requires regular track maintenance (very regular for high line speed) to maintain track geometry and will require a long-term earthwork remedial solution

Table 10.1: Embankment instability metric threshold values (after Sharpe and Hutchinson, 2015 and Kite et al, 2020).

639 It should be noted that these risk thresholds are only intended as guidance. Presently, there has been limited calibration of these values and they are based on a relatively few known embankment failure sites.

640 The frequency of track geometry data recording is an important consideration in the development of this technique and data availability is a prerequisite for reliable analysis. Data coverage is one major limitation of this technique; typically, only a quarter of the network has sufficient data to analyse the past three sequential years of embankment performance analysis. Nonetheless it is considered that there is potential for greater exploitation of the track geometry data for the identification of embankment deformation and potential failure.

641 The interpretation of track geometry data collected by the NMT can offer a supplementary tool to identify potential embankment failure sites and unknown instability locations. This is actively being investigated by NR as a workstream within the R&D/Intelligent Infrastructure II programmes. The technique is unlikely to be useful to identify incipient cutting failure as the vast majority daylight at or above rail level.

642 Automated data processing software would need to be developed to analyse large quantities of data to provide early warning by highlighting trends of changes in track geometry which may be attributable to embankment deformation. This is a good fit within the NR Intelligent Infrastructure II research theme and would appear to be an ideal application for machine learning /AI, both in terms of identifying the characteristics of developing failure (especially change through time) and in delineating areas of potential failure from those that are stable.

643 **Routine analysis of track geometry data is a potentially valuable technique for the early detection of embankment instability. At present it is difficult on a routine basis to distinguish between ongoing track deterioration and underlying embankment instability, resulting in too many false positives and false negatives. Further development work is required to refine the analysis technique and in particular to establish an automatic data processing process. Potentially, this will reduce the time and cost required to process and produce trend data, calculate the deterioration rate and visualize the data for interpretation. *We fully support the NR track geometry data collection and analysis workstream to identify potential embankment failure sites within the R&D/Intelligent Infrastructure II programmes and recommend this is actively progressed.***

Instrumented barriers

644 Flexible barriers, comprising netting, are an effective means of preventing rockfalls from encroaching on the track. If they are instrumented they can provide warning of potential overload leading to rock material falling onto the railway line. Network Rail have been trialling such systems. One example at Teignmouth on the London-Penzance Route has been installed since 2009 on steep sea cliffs up to 50m high immediately adjacent to the railway. The netting is anchored by steep cables to the top of the cliff and load cells fixed to the cable. The load cells are connected to a data logger, which transmits a warning to a signaller if the load exceeds 10kN (1 tonne); the signaller then contacts a controller who issues an emergency call to stop all trains in the area.

645 A more recent example has been trialled at the Hooley Cutting, near south London, on the London to Brighton Route through the North Downs. The 30m-deep cutting slopes in chalk are susceptible to landslides and need measures to prevent rockfalls reaching the tracks. The cutting slopes have been covered with rockfall mesh to collect any falling debris, but there have been rock failures behind the mesh causing it to bulge towards the track. Such failures are hard to predict and a team of engineers is required to carry out regular inspections to monitor at-risk locations and ensure mesh integrity. Using a system developed by the Centre for Smart Infrastructure and Construction (CSIC) at Cambridge University, fibre optic cables have been attached to the mesh netting along a 100m length of the railway. An analyser is permanently installed on the site, requiring mains power. Strain changes

in the netting induced by rockfalls are recorded by the fibre optics, thereby identifying and predicting problematic areas before they impact on the safety of the railway; the data is transmitted wirelessly (Keenan et al, 2019).

646 The instrumented netting project at Hooley Cutting has demonstrated potential benefits for the future of rockfall monitoring. Recent developments have included integrating fibre optics into the manufacturing process for geotextiles. It will soon be possible to install geosynthetic netting as a barrier with fibre optic cables already incorporated into the netting when it is manufactured in the factory.

647 Instrumented flexible barriers to provide warning of potential overload leading to rock material falling onto the railway have been successfully trialled by NR. There is also recent international experience, for example in Hong Kong and Japan for rock material and residual soil.

648 **Instrumented flexible barrier systems could reduce the need for regular inspections; engineers would only be required to investigate locations to which the system has alerted them, thereby saving time, reducing risks and providing valuable information on rock slope condition and deterioration (Monitoring Objective A). Instrumented flexible barriers could also contribute significantly to improving rail safety if they were to be incorporated into an early warning system enabling train drivers to be alerted to the possibility of debris on the track (Monitoring Objective B).**

649 **Recognising that the location and timing of the shallow slope failures and washouts that threaten to impinge on the track cannot be predicted, yet are inevitable across the network, consideration should be given to installing flexible barriers at the toe of vulnerable lengths of the cuttings. The barriers will provide temporary containment of the slide and washout debris. By instrumentation of the mesh for strain, and of the support posts for inclination, warning can be provided of where failures have occurred and attention is needed. Precedents are provided by examples in Hong Kong and on the A83 in Scotland.** ***We recommend that consideration be given to wider use of instrumented flexible barriers for rock and soil slopes.***

“*The combination of new, low-cost sensors; novel terrestrial, aerial and space-based platforms; improved instrumentation; rapidly developing, powerful algorithms; and high-performance computing provides ample opportunities for innovation.*”

Interventions

Earthwork Interventions

650 Interventions are chosen to manage earthworks risks once cyclical examination is no longer considered to be acceptable for controlling asset risk.

651 Interventions include the following types:

Intervention Type	Description
Maintain	The earthwork is maintained in a more or less steady state by carrying out regular or targeted cleaning of drainage, management of vegetation and vermin, and minor repairs.
Refurbish	The likelihood of the earthwork failing is reduced by carrying out major repairs, local replacement, local re-profiling, or the installation of additional drainage works or local support.
Renew	The likelihood of the earthwork failing is significantly reduced by carrying out major works that result in permanent changes to the asset such as full regrading, the installation of major retaining structures or other major support measure.

Table 10.2: Earthwork Intervention type. (Taken from NR (2017g). NR/L2/CIV/086 Module 4 Earthworks Interventions.)

652 The Earthworks Interventions standard, NR (2017g), defines how the Route/Region Geotechnical team decide when, and at what level, earthworks interventions should be carried out.

Maintenance

653 Maintenance forms a critical part of the asset management regime and is undertaken in order to maintain the assets in their current condition and to minimise asset deterioration and degradation. Ideally preventative maintenance should be carried out on a routine basis, e.g. through vegetation management and cleaning drainage systems. The frequency of preventative maintenance is governed by the severity of any potential problems and their consequences. Corrective maintenance is undertaken where defects are observed during inspection or site walkovers. Prioritisation based on risk is used to determine the maintenance programme. Typical earthwork maintenance intervention options by asset type are shown in Table 10.3.

Soil Cuttings	Rock Cuttings	Embankments
Drainage maintenance	Drainage maintenance	Drainage maintenance
Vegetation management	Vegetation management	Vegetation management
Devegetation of drains	Devegetation of drains	Devegetation of drains
Devegetation of minor retaining structures	Individual geotechnical tree removal	Devegetation of minor retaining structures
Individual geotechnical tree removal	Vermin eradication and exclusion	Individual geotechnical tree removal
Vermin eradication and exclusion	Debris and refuse clearance	Vermin eradication and exclusion
Debris and refuse clearance	Routine cess clearance	Debris and refuse clearance
	Regular light scaling	
Servicing Engineered support	Servicing Engineered support	Servicing Engineered support
Clearing catch fences/ netting	Clearing catch fences/ netting	Clearing catch fences/ netting
Servicing GIA or alert/ alarm systems	Servicing GIA or alert/ alarm systems	Servicing GIA or alert/ alarm systems

Table 10.3: Typical earthwork maintenance intervention options by asset type. (Taken from NR (2018c). Earthworks Asset Policy. Issue 8.)

654 NR assume that Maintenance type activities balance earthwork degradation and maintain the asset at its current EHC.

655 In Chapter 8, we have highlighted the paramount importance of drainage system maintenance and water management. We have recommended that more dedicated resource be put into this vital activity and identified the need to rationalise and improve maintenance of the railway drainage system as a high priority.

656 In Chapter 9, we have recommended that NR progressively adopt a broader and more integrated approach to the management of Earthworks, Drainage and Vegetation and breakdown the historic silos between these inter-dependent assets. A key element of this recommendation is the improvement required to the current earthworks vegetation maintenance regime to harness the beneficial effects of vegetation on slope stability (reducing surface erosion, providing root reinforcement, avoiding channelling of flows, maintaining surface pore water suctions) and minimise the detrimental effects (blocked ditches and pipes, clay shrinkage and desiccation cracking).

Refurbishment

657 Refurbishment is undertaken to restore the performance of the earthwork asset by major repair, local replacement or re-profiling.

658 NR assign a nominal 20-year service life (often referred to incorrectly as 'design life') to the Refurbish option. NR assume that a Refurbish type activity moves the EHC of an asset back one step i.e. an EHC category D slope will move back to EHC category C. Some NR Earthwork managers question the long-term effectiveness of the Refurbish option and whether it represents good value for money.

659 Typical earthwork refurbish intervention options by asset type are shown in Table 10.4.

Soil Cuttings	Rock Cuttings	Embankments
Toe support – gabions	Local regraded slope (<10m)	Cess support – lightweight
Local toe retaining structure (<10m)	Scaling	Local cess support – heavyweight (<10m)
Local regraded slope (<10m)	Controlled rock removal	Retaining wall – gabions
Shallow excavate and replace	Isolated dentition (<10m or <10%)	Local toe retaining structure (<10m)
Limited deep excavate and replace (<10m)	Erosion protection system	Substantial geotechnical tree removal
Badger relocate and backfill	Rock dowels (<10m or <10%)	Local regraded slope (<10m)
Crest drainage	Rock bolts/anchors (<10m or <10%)	Toe berm
Slope drainage	Crest drainage	Shallow excavate and replace
Cess containment ditch	Slope drainage	Limited deep excavate and replace (<10m)
	Drainage refurbishment	Badger relocate and backfill
	Cess containment ditch	Grouting
	Local rock netting (<10m or <10%)	Slope drainage
		Toe drainage
		Catch netting

Table 10.4: Typical earthwork refurbish intervention options by asset type (Taken from NR (2018c). Earthworks Asset Policy. Issue 8.)

660 Payne et al (2020) describe embankment refurbishment work to address extensive rabbit burrowing through sandy embankment fill, which has resulted in a drop of the ballast shoulder, slipping of cable troughing route and lean on the line-side cabinet at Pesthouse Lane near Ipswich, East Anglia (Figure 10.8).

Figure 10.8: Extensive rabbit burrowing through the sandy embankment fill, at Pesthouse Lane. (after Payne et al, 2020)

661 At Pesthouse Lane the refurbishment work consisted of infilling of the burrows followed by netting the embankment slope to deter new excavations. Troughing restraint and a cess support structure were also required to support the particularly disturbed embankment shoulder areas, as illustrated in Figure 10.9.

Figure 10.9: Refurbishment at Pesthouse Lane including cess retention to support the troughing route and slope netting to resist future burrowing. (after Payne et al, 2020)

Renewal

662 Renewal works are undertaken to improve earthwork slope stability and serviceability to modern standards using current design codes. NR assign a nominal 120-year service life (often referred to incorrectly as 'design life') to the renewal option. NR assume that renewal works will move the EHC back to category A regardless of the original EHC of the asset. A wide range of renewal techniques is available; some of these are shown by asset type in Table 10.5.

Soil Cuttings	Rock Cuttings	Embankments
Toe retaining structure (≥10m)	Regraded slope (≥10m)	Cess support – heavyweight (≥10m)
Regraded slope (≥10m)	Heavy scaling	Retaining wall (not gabions)
Deep excavate and replace (≥10m)	Dentition (≥10m or ≥10%)	Toe retaining structure (≥10m)
Soil nailing	Shotcrete	Regraded slope (≥10m)
Ground anchors	Buttresses/anchored walling/beams	Deep excavate and replace (≥10m)
Deep slope drainage/ rock ribs	Rock dowels (≥10m or ≥10%)	Deep shear keys
Cess catch fence/wall/ bund	Rock bolts/anchors (≥10m or ≥10%)	Soil nailing
	Cess catch fence/wall/ bund	Ground anchors
	Rock netting (≥10m or ≥10%)	Soil mixing
		Shear piles
		Piled slab and embankment renewal
		Deep slope drainage/ rock ribs

Table 10.5: Typical earthwork renewal intervention options by asset type (Taken from NR (2018c). Earthworks Asset Policy. Issue 8.)

663 The 30m-deep Hooley Cutting which carries the main line from London to Brighton through the North Downs has experienced multiple slope failures (Figure 10.10), with two since 2000 resulting in train derailments.

Figure 10.10: Hooley Cutting Slope Failure

664 Extensive renewal works, consisting of slope regrading, slope meshing, soil nailing and a beam and grillage installation with micro piles have recently been completed in Hooley Cutting (Figure 10.11). Instrumented flexible barrier (slope meshing) for the Hooley Cutting is described earlier in this Chapter (Para. 646).

Figure 10.11: Hooley Cutting Renewal Works

Targeted Asset Management (TAM)

665 Some NR routes, e.g. Anglia, have developed what is termed as Targeted Asset Management (TAM), Payne et al (2019), as a proactive way to meet the Earthworks Asset Policy objectives and optimise budgets. The approach moves away from implementing a full renewal across an entire earthwork asset to targeting works at the parts in the worst condition. In our view the term TAM is a misnomer, and in reality, it describes a Targeted Renewal Works methodology. This approach uses value engineering principles to strengthen the earthwork areas in the worst condition and posing the highest risk whilst continuing to monitor adjacent areas. The approach allows limited funding to stretch to other high priority sites across the region meeting the NR earthworks asset policy objectives.

666 An alternative approach is to strengthen larger sections of vulnerability and renew whole earthworks rather than local strengthening. Recent works in Southern demonstrated this approach at Barnehurst Cutting where reputational risk required a substantial overhaul of a long problematic cutting in a blockade lasting 9 days in February 2020. Failures adjacent to previous areas of earthwork instability are a recurring theme across the network. This is related to the effects of the additional unloading resulting from the previous failure.

667 **We recognise that a pragmatic approach for interventions is often required to best manage safety and performance risk within the funds available, by targeting renewal works over the most critical earthwork lengths rather than the entire asset. However, it is very inefficient in terms of access and set-up costs in addressing repeat earthwork failures that commonly occur adjacent to previously stabilised areas. The reputation of NR also suffers from having to procure a number of works contracts at the same location in quick succession. *It is therefore recommended that wherever possible NR seek to renew the entire earthworks asset and associated drainage system rather than undertake inefficient and ultimately considerably more expensive local piecemeal works*.**

Drainage Interventions

668 The various intervention options that can be carried out on drainage assets are described in generic terms as Inspect, Survey, Maintain, Refurbish, Renew and New Build, NR (2017e). These are defined in Table 10.6.

Intervention category	Definition
Inspect	Routine inspection of the asset to assess its performance and identify locations requiring further intervention
Survey	Periodic detailed surveying of the asset to assess its condition (including the details of specific defects), capacity, inventory and physical attributes
Maintain	Maintaining the performance of the asset by cleaning (de-silting, vegetation removal, root cutting etc.) and minor repairs
Refurbish	Restoring the performance of the asset by major repair, local replacement or re-profiling
Renew	Wholesale replacement of the asset. May also include an element of asset improvement, for example to increase capacity to take account of future climate change
New Build	Installation of new assets to address a shortfall in drainage performance where there is currently no or insufficient drainage

Table 10.6: Definition of drainage intervention categories. (Taken from NR (2017e). Drainage Asset Policy Issue 4 March 2017.)

669 All methods of drainage repair or refurbishment aimed at improving the structural condition will also result in an improvement in the service condition as the asset has to be cleaned in order to carry out the repair or refurbishment. It should be noted that some interventions intended to cleanse the asset (i.e. improve its service condition) can have an adverse effect on the structural condition if the asset is already in a poor condition. For example, high pressure jetting of a clay pipe that has misaligned segments can wash out the backfill around the pipe and worsen the misalignment.

Chapter 11

What can be learned from other Earthworks Asset Owners?

Highways England

Introduction

670 Highways England (HE) replaced the Highways Agency organisation on 1st April 2015. It manages the strategic road network (SRN) in England consisting of 4300 miles of motorway and major trunk roads. The SRN includes only about 2% of the roads in England, but it carries around a third of all road traffic, HE (2020c). In contrast to NR, the peak of motorway construction of the SRN was in the 1960s to 1980s, with subsequent works being mainly road widening or upgrading schemes. HE's earthworks asset is therefore, in the main, less than 60 years old, designed and constructed to modern standards. Cutting slopes were engineered, embankment materials were carefully selected and compacted in layers in a controlled manner, and all earthworks were designed to acceptable factors of safety.

671 HE (2020c) reports that 97.3% of its geotechnical (earthwork)assets did not require (and are not recommended for) remedial interventions at the end of 2019-20. This is a slight improvement compared with the position reported at the end of 2018-19. The score represents an improvement of 0.7 percentage points since 2015-16.

672 HE (2020c) reports that it has drainage inventory data for 90% of its network, which is a decrease of 1 percentage point from its 2018-19 position. The percentage of the network with drainage condition data is 36% in 2019-20, up from 33% in 2018-19. Both indicators have improved over the current HE Road period (2015-2020).

673 Lane, M. et al. (2020) report from an earlier paper that established a quantification of the relationship between drainage problems and earthwork defects on HE's road network, using a mixture of GIS and database analysis. The results show that 74% of earthwork defects on HE's road network have been associated with drainage related problems.

ORR 2018 Management of Geotechnical and Drainage Assets Review

674 ORR (2018) completed an in-depth review into HE's management of geotechnical and drainage assets in June 2018. The review focused on understanding whether HE was managing these assets safely and efficiently in the long term. The review found that HE is improving how it manages its assets and applying many examples of good practice across its asset base. It identified that HE has robust, standards-led systems and processes, which drive asset interventions that are safe, add value, and are in keeping with the conditions of its operating licence. The review identified good practice in its management of geotechnical assets, where the availability of data supports effective long-term and risk-based decision making. However, the condition of HE drainage assets was raised as a concern, particularly as subsurface asset condition data is only known for a third of the SRN. This lack of asset knowledge limits the extent to which HE can carry out mitigation or intervention before the asset fails. This position is common for similar UK infrastructure asset organisations, including NR.

675 In the view of the ORR (2018), HE has demonstrated a consistent approach to the management of their geotechnical and drainage assets through three key factors:

+ alignment of documentation and processes with operating license requirements
+ governance by experienced and technically expert professionals, guided by embedded standards, systems and structure
+ assurance by consistent monitoring and reporting

676 ORR considered this is particularly true of HE's management of geotechnical assets where the availability of data promotes effective long-term, risk-based and criticality focused interventions. The more dynamic nature of drainage, however, coupled with less availability of subsurface asset condition data, currently makes efficient predictive intervention more difficult. Again, this is consistent with NR and other similar UK infrastructure asset owning organisations.

677 In ORR's (2018) view, as HE's asset condition data and deterioration profiling improve (particularly with respect to drainage assets), it will become more practical to adopt a 'just in time' model of intervention, minimising cost of delivery through less reactive intervention, and minimising loss of whole life asset value by intervening at the right time. HE is using innovative tools and techniques (such as Sewerbatt10 and LiDAR) to accelerate the validation and collection of drainage asset data. However, there is work to do in relation to developing, for example, the practicality of gravity fed surface water drain deterioration modelling before HE can adopt a truly predictive approach.

678 In 2020, HE launched its first Asset Management Policy and Strategy (2020e). It covers the whole lifecycle of HEs assets and aims to build a strong asset management culture across the Company. A key aim is to create a link between strategic planning and service delivery. This will be supported by the creation of individual Asset Class Strategies that set out the approach to managing specific asset groups (such as drainage and geotechnics) in response to the commitments and funding agreed for the current Road Period. The asset management approach is also one of continuous improvement and is underpinned by a transformation programme supported by research and development.

HE Geotechnical Database Management System (GDMS).

679 A key element in the HE geotechnical asset management strategy has been the development and use of the HE Geotechnical Data Management System (GDMS), shown in Figure 11.1, an online Geographical Information System (GIS). GDMS was rolled out across England in 2002. It is an easy-to-use, centralised system that can be accessed by all those requiring information on the HE geotechnical asset (Power et al, 2012).

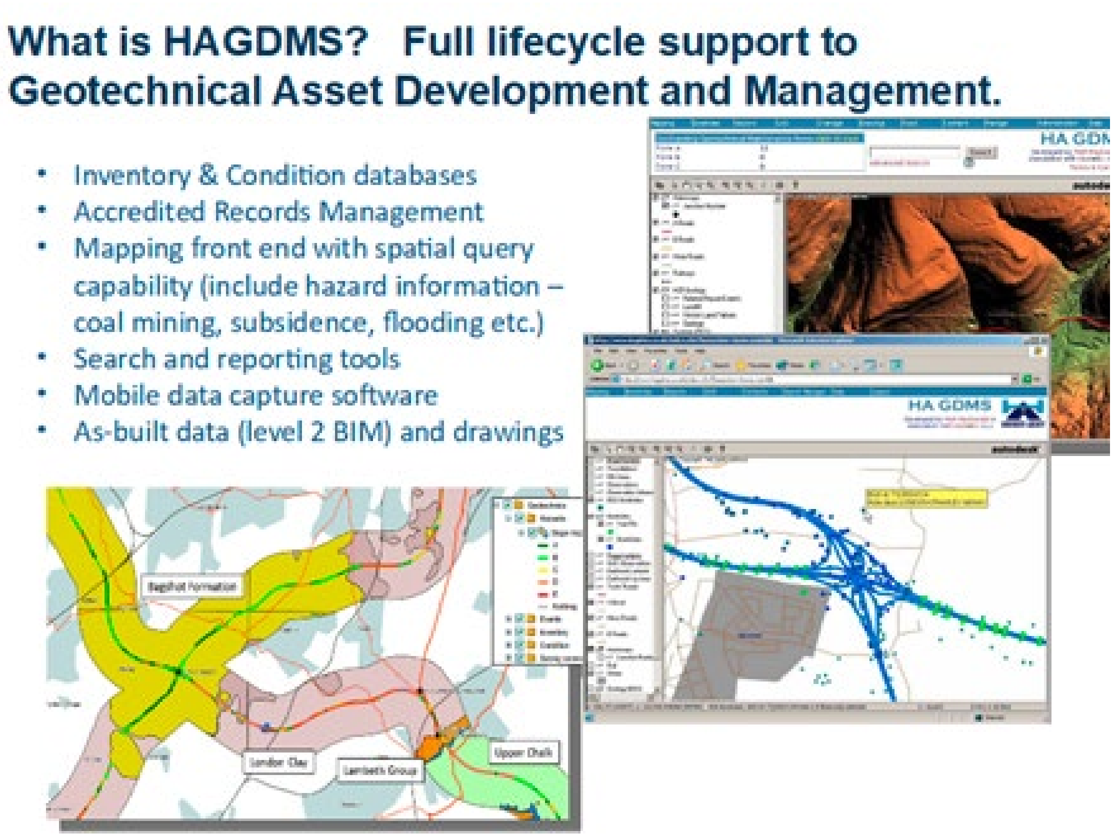

Figure 11.1: HE GDMS – Full lifecycle support to Geotechnical Asset Development and Management

680 HE GDMS includes a layered mapping interface combined with a database of the following key geotechnical information:

+ Records for c. 50,000 earthwork assets along with 250,000 inspection observations, which allow the overall condition of the earthwork to be assessed

+ GDMS also holds information on earthwork failures, including information such as when the failure occurred and the nature of the defect, as well as any information on planned remedial works and monitoring

+ A technical archive of over 13,000 geotechnical reports, including nearly 9,000 scanned copies of the reports available to view or download. These reports are stored with key descriptive metadata, allowing intuitive searching, and are linked to the map to allow discovery of reports that are applicable to certain roads or sections of roads

+ An archive of exploratory hole data held by HE, and the ability to upload scanned exploratory hole logs or Association of Geotechnical and Geo-environmental Specialists (AGS) format electronic ground investigation data

+ Links to the borehole archive of the British Geological Survey, 1:625 000 scale geological solid and drift maps and a reference mapping layer of BGS district geologists

+ Links to the HE Drainage Data Management System (DDMS), the sister system that provides the complete asset management system for the HE drainage asset; this is discussed in Para 696 onwards

681 GDMS is regarded by HE geotechnical staff as an effective data management resource for acquiring information for earthworks evaluation, speeding up the process and exposing information that may otherwise may have been overlooked. In particular, AGS data (if available in GDMS) is considered to be a high value resource. Key data sources in GDMS include desk study reports, interpretative reports, design reports and, especially, Geotechnical Feedback reports from relevant nearby projects and repairs to the earthworks that can provide extremely valuable input for earthworks evaluation. These convey knowledge, i.e. lessons learned, as well as data.

Earthwork Inspections

682 HE adopts an approach where the frequency of their earthwork examinations is based on assessment of the risk posed to the network, considering both likelihood of a failure and consequence of failure. Principal inspection frequencies may vary from low frequencies, possibly with a return frequency between 6 and 10 years, to high frequencies possibly with more than one inspection a year, HE (2020a). In contrast, NR's examination frequencies are determined based on asset failure likelihood (via Earthworks Hazard Category (EHC) scoring), with the assets considered most likely to fail subject to the most frequent examinations and vice versa. However, NR earthworks examinations are generally undertaken at similar frequency to HE i.e., 1-10 years. In Chapter 7 Para 296 we have recommended that the NR earthwork examination frequency should be more risk based.

683 Geotechnical inspection data is captured by inspectors using HE's Pocket GAD tool, which is due to be replaced by an improved Tablet GAD in 2021. Features are graded in-situ and the tool allows the submission of photographic evidence alongside field notes. Each inspection dataset is uploaded directly to GDMS where it is held in quarantine until validated by the Area Geotechnical Maintenance Liaison Engineer (GMLE). Only then is it available for use in identifying the need for mitigation and intervention. This is a similar approach to that adopted by NR.

Ground-related hazard maps to aid risk management

684 In recent years, significant events have highlighted the impact ground-related hazards can have on the running of the SRN, including collapse of mining features, solution features in chalk and failures of engineered slopes. In particular, the collapse of a previously capped mine shaft on the A1 carriageway near Gateshead in June 2016 raised the profile of mining-related hazards, Eden (2016). In response to this, HE commissioned a task to create a series of hazard rating maps for a 1000 m wide corridor centred around the SRN, which combine and summarize the best available data for each hazard. Hazard maps are extremely powerful as they present data in a simplified visual format, which is known to be an effective way of communicating information, particularly to non-specialists (Forster and Freeborough, 2006). The concept of the maps is that they will flag up areas of potential ground-related hazards in a simple, clear and accessible way to non-technical specialists, who can then review hazard-specific resilience guidance information and engage experts to determine whether further investigation is required. It is then the task of specialists to review the source data to better understand the site-specific circumstances and determine whether mitigation or intervention are required, Neville et al. (2020).

HE Geotechnical Assets Resilience Review

685 In October 2015, Arup was commissioned to undertake Task 634 'Resilience of geotechnical assets on the SRN to severe weather events'. The overall objective for the task was to: "*Develop an improved categorisation of the resilience of Highways England's geotechnical assets to a range of severe weather events. The demand that these events can impose should be compared to the basis of design of geotechnical assets and to our understanding of their current condition (including underlying hazards).*"

686 The aim of the categorisation was to: "*ultimately assist Highways England decision makers seeking to understand the potential impact of severe weather events forecast in the short term and long-term climate change on geotechnical assets and consequently on the SRN.*"

687 The report, Arup (2016), presented a resilience framework focused on "*identifying and prioritising 'vulnerable' geotechnical assets*" and the aim of the resilience framework was: *"to allow Highways England to prioritise those geotechnical assets which present the highest risk due to severe weather events and therefore require appropriate and proportionate resilience measures. For example, the framework could be used to inform reactive responses when severe weather is forecast or for planning pro-active interventions."*

688 HE (2020d) published a two-part document by Arup, which followed their earlier (2016) report, that provides their approach for assessing the resilience of the SRN to ground-related hazard events. It is aimed at those responsible for managing the potential impact of hazard events on the SRN. The assessment can be used to proactively assess resilience or be used reactively following an event. The framework assists in understanding the risks posed to assets from hazard events, in terms of the performance that assets deliver to HE. However, the process also considers preparedness as a complementary measure to identify and prevent additional threats. Moreover, it informs adaptation and recovery, should a hazard event occur, to help HE to expedite restoration of normal road services. It can also be used to consider strategic approaches to adapt the network to longer term issues (e.g., climate change). NR is also reviewing the resilience of its earthworks, particularly in the context of severe weather planning for climate change adaptation and would benefit from benchmarking the HE approaches to determine if there are any lessons to be learnt.

Asset Systems

689 HE is developing an asset systems strategy that will inform the long-term planning for its asset management systems. At present there are several existing platforms that support geotechnics and drainage asset management.

Asset Visualisation and Information System (AVIS) data

690 HE is making use of their Asset Visualisation and Information System (AVIS) data for geotechnical asset management. The following data is held within AVIS:

+ 'Ground-based' Imagery – Road survey vehicles record images from four cameras every two metres. In AVIS v3, new higher definition survey imagery has been released (5 Megapixel, accurate to ~50mm), and this definition will continue to be collected in future
+ 'Ground-based' LiDAR – survey vehicles record point clouds to make a 3D image of everything that the vehicle passes. LiDAR point clouds are currently spatially accurate to 30mm, with measurement of objects accurate to 10mm
+ Aerial Imagery and Aerial LiDAR – aerial imagery (5cm resolution) and LiDAR captured in 2017 is displayed in the system

691 AVIS is part of a range of asset management tools and knowledge re-sources that are available and forms part of the business' remote sensing capability. HE uses AVIS for geotechnical asset management in the following situations and advised in a recent Technical Note (HE 2020f):

+ Enriching asset knowledge and reducing the need for physical inspections
+ Remote assessment of Special Geotechnical Measures (SGMs) (e.g. retaining walls, rock netting, visible drainage etc)
+ Remote assessment of geohazards and high-risk earthworks

692 AVIS has proved to be a useful tool for geotechnical applications and it permits general observations about geotechnical assets and can support 'remote inspection' of cuttings. This can save time for undertaking physical inspections, and can be used to complement Principal Inspection programmes to support reducing their frequency to assist inspection where personnel access is highly constrained. However, if detailed observations are to be made with high confidence the system requires additional and improved datasets. Image quality of the Mobile Mapping System imagery is such that only relatively large slope features can be identified.

Application of Remote Survey Data for Geotechnical Asset Condition and Performance

693 This task, 'Application of Remote Survey Data for Geotechnical Asset Condition & Performance', was awarded by HE to Arup AECOM in 2017 to evaluate the potential and realisable benefits that remote surveying techniques could bring to HE's geotechnical asset management. The project brief states that the objective of the work was to: "*Understand the potential roles of land and aerial based remote sensing techniques within geotechnical asset management, specifically in developing knowledge of asset condition and performance and application in the fields of asset deterioration modelling, maintenance and renewal.*"

694 The following conclusions were drawn by Arup AECOM (2017) from this work:

+ Application of remote surveys to monitor condition and performance of geotechnical assets has shown improvement since previous research. Improved capability is due to advances in sensor technology and processing methods
+ LiDAR datasets (both Mobile Mapping System and rotary wing) have been found particularly useful for assessing condition and performance of geotechnical assets
+ LiDAR point cloud data shows promise for carrying out automated change detection. It offers a relatively rapid way of assessing geotechnical asset condition at high levels of detail and, if comparable surveys are undertaken on a relatively regular basis, then appropriate change detection algorithms can be implemented
+ Whilst satellite (InSAR and multispectral) imagery seems to be still not ready for geotechnical asset management application, hyperspectral imagery showed potential, particularly for identification and assessment of performance of slope drainage features which may not otherwise be identified

695 HE is currently investigating the use of slope mounted reflectors to improve the accuracy and resolution of InSAR monitoring data as a means of control monitoring via task 1-447 – Geotechnical Asset Performance Monitoring and task 1-1077 – Geotechnical Asset Performance: Earth observation techniques and InSAR . These projects will provide information and guidance on the effectiveness and practicality of the method.

Drainage Database Management System (DDMS).

696 HE's drainage inventory and condition information are held within the national Drainage Database Management System (DDMS), (Figure 11.2). This contains c.2.5 million drainage assets (including earthworks drainage) that have been recorded from either field survey or the digitizing of as-built engineering drawings. These assets are split into three groups: point assets (such as manholes), continuous assets (such as pipework) and region assets (such as ponds). Information and data about flooding events is also recorded in DDMS.

Figure 11.2: DDMS – Primary repository for HE Drainage Construction records, Condition Surveys and Flood events

697 Multiple and disparate data sources are impacting on the ability of NR Geotechnical and Drainage Engineers to make accurate and efficient asset management decisions. We have recommended that existing geotechnical and drainage data and decision support tools should be brought together in a common interface (CSAMS). The HE GDMS and DDMS are considered to be industry-leading database asset management systems; overall, the level and quality of data captured across the life cycle of HE earthworks and drainage assets is advanced in relation to NR. The development of CSAMS by NR can gain significant benefit utilising the best practice and innovation from the HE GDMS and DDMS.

Drainage Surveys

698 HE has adopted some innovative approaches to accelerating their progress in understanding their drainage assets, most notably a recent LiDAR survey of all surface visible assets and the use of connectivity surveys to assess the service condition of sub-surface drainage assets. Connectivity Surveying is a useful tool and is enhancing HE's ability to detect and maintain underperforming assets before they impact on the safety and availability of the highway; however, without also understanding the structural health of subsurface assets, it will remain difficult for HE to predict asset failure across the wider drainage portfolio and intervene in a timely, more efficient manner in advance of failure. HE is planning to develop a Drainage Decision Support Tool which may facilitate investment decisions, aligned to HE's strategic outcomes, using lower volumes of data or different data to that currently collected.

Drainage Catchments and flow rate estimation of runoff flow rate

699 In contrast to NR, it is a requirement of HE standards that earthworks drainage shall generally be kept separate from the road drainage network unless there is a specific benefit in connecting them. HE captures and records drainage asset data in DDMS on a catchment basis. A catchment is defined as a section of road, from a high point through the low point and back to a high point, that all drains to the same low point. Converting NR drainage asset data to catchment data sets will help manage the drainage assets more effectively in future.

700 HE (2020b) gives guidance on how to deal with surface water runoff from natural catchments draining towards the road network, in order to limit the frequency and severity of flooding incidents caused by runoff from beyond the road boundary. It details methods for estimating runoff from natural catchments and determining suitable earthworks drainage.

701 Department for Transport (DfT), Circular 2/2013 (clause 50), DfT (2013) also requires that no new 3rd party drainage asset may be connected to the HE drainage asset, and that any pre-existing 3rd party drainage connections to the HE drainage asset may only be allowed to continue connection so long as there is no change in status. This seeks to ensure no unquantified risks or pressures are placed on the HE drainage asset.

702 NR has little or no detailed knowledge regarding the extent and run-off from its natural catchment areas both inside and outside its boundary. We have therefore recommended in Chapter 8, Para 508, that the size, shape and location of allnatural catchments draining towards NR railway shall be established, in order that the flow rates can be determined for the required design storm return periods with the relevant allowance for climate change in accordance with NR (2018k). Depending on the catchment and ground characteristics and topography, a suitable flow assessment method can be selected from HE (2020b) or CIRIA (2015).

Summary

703 The HE and NR earthwork assets are different, particularly with regard to the age of construction and differing methods and standards of construction. As a result, they present some differing challenges; however, the risk-based approach from both organisations to managing earthworks at a strategic level is similar. HE and NR are both founding members of the Geotechnical Asset Owners Forum (GAOF), that provides a platform for those involved with the management of geotechnical and related assets to share and exchange ideas, information, research themes and other issues. The Forum offers an opportunity for HE and NR, as maturing asset organisations with a culture of continual improvement, to collaborate on the journey to exemplary asset management. It could be particularly beneficial for the development of water asset management in both organisations, given their current relatively limited knowledge of drainage condition data and deterioration models. *We recommend that NR could gain particular benefit from reviewing HE practice in the following areas:*

+ **Utilising the best practice and innovation from HE GDMS and DDMS to inform he development of NR CSAMS**
+ **HE approaches to assessing the resilience of the SRN to ground-related hazard events**
+ **HE methodology for determining drainage catchments and estimating runoff flow rate**

Transport Scotland

704 Transport Scotland are 'Supporting Members' of CIRIA's Geotechnical Asset Owners Forum.

705 Transport Scotland in conjunction with TRL instigated the 'Scottish Road Network Landslides Study' after a series of serious and disruptive debris flows in August 2004. This study was published in 2008. The 2004 incidents arose from a period of very wet weather that contained spells of particularly intense rain.

706 They were followed over the following months and years by further mostly weather-related failures. The most serious of these was a debris flow that occurred in October 2007 and crossed the A83 below the pass at the Rest and be Thankful (RabT) and closed the road. This was the beginning of the ongoing serious problems at RabT, referred to in Chapter 6.

707 One of the outputs of the Study was a Geographical Information System (GIS) based hazard assessment of slope hazards on the Scottish road network. From this, higher risk sites were additionally assessed using traditional desk study data and preliminary walkover surveys, followed in some cases by detailed site inspection.

708 The digital data used in the GIS assessment included geo-referenced high-resolution aerial photography, where it was available, digital versions of BGS 1:50000 geological data and relatively newly available commercially available digital terrain models. This terrain data was less detailed and less accurate than can be achieved with modern airborne LiDAR techniques.

709 This hazard identification and ranking process has been used by Transport Scotland to develop and plan slope management strategies and to direct the focus of future research. This overall identify, classify, and rank approach is broadly similar to that adopted by NR. The key difference between the approaches is Transport Scotland's focus on upland debris flows.

710 Chapter 6 outlines NR's limited experiences with upland debris flows to date and suggests that the there is a clear risk that some parts of the NR network in the Highlands may see an increased frequency of debris flows associated with increasingly wet and stormy weather. Chapter 6 goes on to recommend NR undertake a GIS based assessment of debris flow risk like that undertaken by Transport Scotland, but using airborne LiDAR data as a basis for initial geomorphological mapping.

711 Transport Scotland have used the ongoing difficulties at RabT to trial a number of remote monitoring systems, mostly focused on detecting change on the slope above the RabT road. These include the use of long range Terrestrial Laser Scanning (TLS); high resolution panoramic photography; high resolution time lapse photography; real time remote monitoring of weather data; ground based synthetic aperture radar (GB-SAR); dGPS monitoring stations near infra-red and colour 'trail' cameras and seismometers. All this equipment is being trialled in the context of a slope with sporadically active debris flows. The trials are ongoing and no firm conclusions have been drawn to date (Bainbridge and Dunning, 2020) but all the techniques listed above show considerable promise in specific circumstances, with the exception of GB-SAR, which in the RabT setting had issues with cost, power supplies and the stability of its foundations.

712 Transport Scotland, in conjunction with TRL have developed Quantitative Risk Assessment methodologies for upland debris flows and have published reports on developing rainfall intensity thresholds for upland debris flows.

713 Research published by a team at Dundee University on the fundamentals of debris flows is an additional source of information that could be incorporated into any future debris flow assessment process. This is summarised by Milne (2015).

714 ***It is recommended that all of Transport Scotland/TRL's post 2004 work on upland debris flows should be considered by NR in the development of any future NR strategy for identifying, assessing and managing debris flow hazards.***

London Underground

Introduction

715 London Underground (LU) and NR are founding members of the Geotechnical Asset Owners Forum along with HE.

716 The LU railway comprises some 463 route kilometres of track, with just in excess of half of this forming the surface section of the system. There are approximately 239 km of earthworks over the LU rail network, 116 km of cuttings and 123 km of embankments. Most of these earthworks were constructed towards the end of the 19th century railway boom period and are generally over 100 years old. A large proportion of them are constructed of or through London Clay.

717 As with the equivalent NR earthworks, construction pre-dated modern soil mechanics. They were built essentially by trial and error and are generally operating at lower safety factors and steeper slopes than would be considered prudent today.

718 In the early 1990's many of the LU earthworks were showing increasing signs of deterioration and distress with a corresponding requirement for increased maintenance and the imposition of track speed restrictions. Failures occurred especially after prolonged wet periods, resulting in a safety risk to the travelling public, major disruption to LU services and expensive emergency repair work. Historically, there was a lack of detailed knowledge of the nature and causes of the many earthwork problems facing LU; remedial work was generally carried out on a reactive basis following disruption to train services or to reduce excessive maintenance at particular locations. LU also lacked any formal engineering standards and procedures for the effective management of earthworks. This was in contrast to LU bridges and structures assets which had been subject to a formal inspection regime since the 1930's. The term "earth structures" was therefore adopted for LU earthworks to emphasise the need for parity with bridge and structures assets in terms of asset management processes and allocation of adequate resources.

719 Over the 1990's LU developed a comprehensive suite of earth structures standards, manuals of good practice and proactive asset management regime to provide the framework for the management of its earth structure assets. These procedures and requirements have been subject to continuous development and are today broadly equivalent to those in NR. One notable

exception is that LU's definition of earth structures is embankments and cutting slopes greater than 1m high whereas the NR earthwork definition is greater than 3m high.

720 The LU Earth Structures asset management strategy is designed around the need to intervene before slopes approach the end of their service life or failure. If intervention works are not possible, practical or economic, mitigation measures are implemented to manage the risk.

721 The following topics and experiences from LU practice in managing earth structures are highlighted for consideration in the future development of NR earthworks asset management.

LU Analytical Assessment Programme

722 Where the results of LU earth structure inspection ('examination' in NR terminology) indicate that the condition rating is "poor" or "marginal", LU standards require a detailed slope stability analytical assessment to be undertaken. This process (which is significantly different to the NR Evaluation and Assessment process) includes a ground investigation and associated monitoring (generally displacement and pore water pressure) in order to provide a detailed assessment of the condition of the earth structure and to accurately quantify slope stability and serviceability. This process also identifies those earth structures that require priority interventions when formulating asset management investment plans. The programme of earth structures analytical assessment across the entire LU network commenced in 1993 and was substantially completed early in 2011. However, any deterioration of an earth structure to "poor" or "marginal" condition continues to trigger a requirement for an analytical assessment. Long term observational monitoring is also undertaken to confirm pore water pressures and soil parameters used in the slope assessment analysis.

723 The observational approach and extensive asset knowledge from the analytical assessment programme has enabled LU to prioritise slope stabilisation works on a risk basis, in order to ensure that the assets are maintained in a good or serviceable condition and over time address all significant safety and business risks arising from the earth structures asset base.

724 The LU earth structures analytical assessment programme and the resulting risk-based renewal works to address the identified slope stability and serviceability concerns have been very effective. LU has not had a significant earth structure failure that has resulted in a track closure since the mid 1990's. LU Earth Structures have performed consistently well during the 2013–2014 and 2019/20 very wet winters. Targeted investment in the renewal of the LU Earth Structure Asset Base over the last 25 years has significantly reduced the risk of disruption to railway operations and improved the resilience against the effects of heavy rainfall and future climate change.

725 LU have established that the key to the effective analytical assessment of earthwork slopes is a combination of analysis and monitoring (i.e. an observational approach). Monitoring and analysis, undertaken appropriately can relatively quickly identify those slopes that are most at risk of a failure occurring. This knowledge allows accurate prioritisation of renewal works to address significant earthworks safety and business risks.

726 We recognise that given the scale of the NR earthwork asset base, it is impractical to have widespread instrumentation and monitoring. ***However, we recommend the adoption of a programme of targeted analytical assessment in conjunction with observational monitoring. This will result in a significant improvement in the understanding of behaviour (and failure mechanisms) in NR earthworks and allow prioritisation decisions to be undertaken with a greater degree of certainty.***

Pore Pressure Measurement of LU Embankments

727 In the 1990s LU identified a need to improve knowledge of pore water pressures within its earth structures, in order to better manage risk of slope failures. Over 150 piezometers (of which most were capable of monitoring both positive and negative pore water pressures) were installed in a targeted number of 'representative' London Clay embankments and cuttings across the LU network.

728 In 2000/2001, UK experienced the wettest weather since records began in 1766. Ridley et al (2004) made a series of measurements of the piezometers installed in the clay embankments to try to assess the influence of the very wet period of weather on pore water pressures. They showed that some pressure heads measured in the spring of 2001 reached hydrostatic below a zero-pressure line located at the embankment clay surface, suggesting that this could form an upper bound pore pressure profile for design and analytical assessment purposes. However, as an upper bound this is likely to be overly conservative for many embankments, as the data (measured in the spring of 2001) indicated a significant number of measurements below hydrostatic, and some with negative (suction) values.

729 The Ridley et al (2004) piezometer measurements were re-analysed by Briggs et al (2013a) to understand the conditions contributing to the range of measured pore water pressures, and to identify the range of factors that should be considered when assessing appropriate pore water pressures for design and analytical assessment. The clay embankments constructed above a higher permeability (Terrace Gravel or Chalk) foundation were found to maintain low pore water pressures (during and following the very wet winter 2000/2001), significantly below hydrostatic from the clay slope surface. Those on a clay foundation, of possibly lower permeability than the tipped clay fill, were generally found to have much higher pore water pressures, tending towards hydrostatic from the slope surface. So even during an extremely wet winter, clay embankments with good underdrainage maintain low pore water pressures, and are more likely to remain stable, compared with those founded above clay. This behaviour was confirmed by back-analyses using an unsaturated finite element analysis of a typical earthwork, with suitable imposed infiltration boundary conditions (Briggs et al, 2013a).

730 **The monitoring of piezometers installed in LU embankments during the wet winter of 2000/2001 and subsequent analysis has illustrated the complexity of the pore pressure regime that can develop in these embankments. This detailed knowledge and understanding of the pore pressure regime in its embankments has greatly informed the LU analytical assessment programme and stabilisation works design. However, NR has very limited knowledge of the distribution of pore water pressures in its earthwork slopes. We have recommended in Chapters 5 and 8 that consideration be given to monitoring pore pressures more widely in NR earthworks, to obtain a better understanding of the behaviour of a particular slope or embankment that is judged to be critical**.

Embankment Deformation

731 Track speed restrictions are often required during dry summers as a result of significant deformation from high-water demand trees on embankments causing shrinkage of the high plasticity clay fill. (Figure 11.3)

Figure 11.3: LU Uxbridge Branch – significant track and cable run deformation arising from high-water demand trees on embankments causing shrinkage of the high plasticity clay fill

732 Several studies have been undertaken by LU to better understand the deformation of the track on these embankments during dry summer periods with localised settlement (Scott et al, 2007). The field observations suggest that a ratchetting-type deformation mechanism can develop in these embankments, and this helps explain the 'coat hanger' shape of these embankments that is frequently seen.

733 A study (Briggs et al, 2013b) was undertaken on behalf of LU to assess whether the National House Building Council (NHBC) guidance, considering tree species and the ratio of the distance of the tree from the track, Dt, to the mature tree height, Ht, might be applicable to trees located on railway earthwork slopes. Excessive seasonal track movement was shown to correlate with the presence of high water demand (HWD) tree species located within a certain Dt/Ht ratio of the track, but not other tree species.

734 A robust landscape management and vegetation control regime has been applied by LU with engineering standard S1165, LU (2017), to minimise seasonal track deformation in these high plasticity embankment slopes. This standard requires that the species and associations of grass, trees, shrubs and other plants for landscaping shall be selected on the basis of their growth characteristics and site conditions; except that only low water demand trees, as defined by National House Building Council 2003 Building Near Trees NHBC (2011), are planted to ensure an even water demand on slopes. This approach requires close liaison between the earth structures engineers and the maintenance team responsible for vegetation management in order to ensure that the slope beneficial vegetation is maintained and detrimental vegetation is removed or reduced.

735 The numerical modelling of the delayed failure of old railway embankments has been described by Kovacevic et al. (2001), Nyambayo et al. (2004) and O'Brien (2013). Seasonal shrink and swell movements in the slope develop increasing plastic strains starting from the toe of the slope and then, with an increasing number of seasonally induced pore pressure changes, the failure surface propagates towards the embankment core leading eventually to progressive failure. At failure, the clay-fill strength is close to residual in the vicinity of the embankment toe, whereas near the crest it is close to peak strength (refer to Chapter 3). This non-uniform mobilisation of strength has important practical implications for the design of potential stabilisation measures.

Risk Assessment

736 Management of earth structures within LU follows the approach of reducing risk levels to "as low as reasonably practicable" (ALARP), to satisfy statutory safety obligations. The ALARP approach allows that safety improvements should not be pursued at any cost, but only if the cost of averting the risk is not grossly disproportionate to the risk averted. In financial terms, however, the risk to safety arising from LU earth structures is currently very low in comparison to railway service loss risk e.g., speed restrictions, line closure etc. The LU Strategic and Tactical Risk Assessment (STRATA) process (Figure 11.2) therefore includes the exposure to service loss impacts resulting from earth structure instability. Risk assessment is based on engineering asset behaviour – in simple terms the earth structure asset only presents risk if it does something we do not expect or want it to do.

737 Risk is assessed using a two-level strategic and tactical approach – in general strategic assessment applies to the assets on a line or network basis, i.e. the general (compliant) population of earth structures that has a low likelihood of adverse behaviours – assessed as general likelihood value across a large population. Tactical risk assessment applies to individual assets that are non-compliant to Standards or are affected by external events.

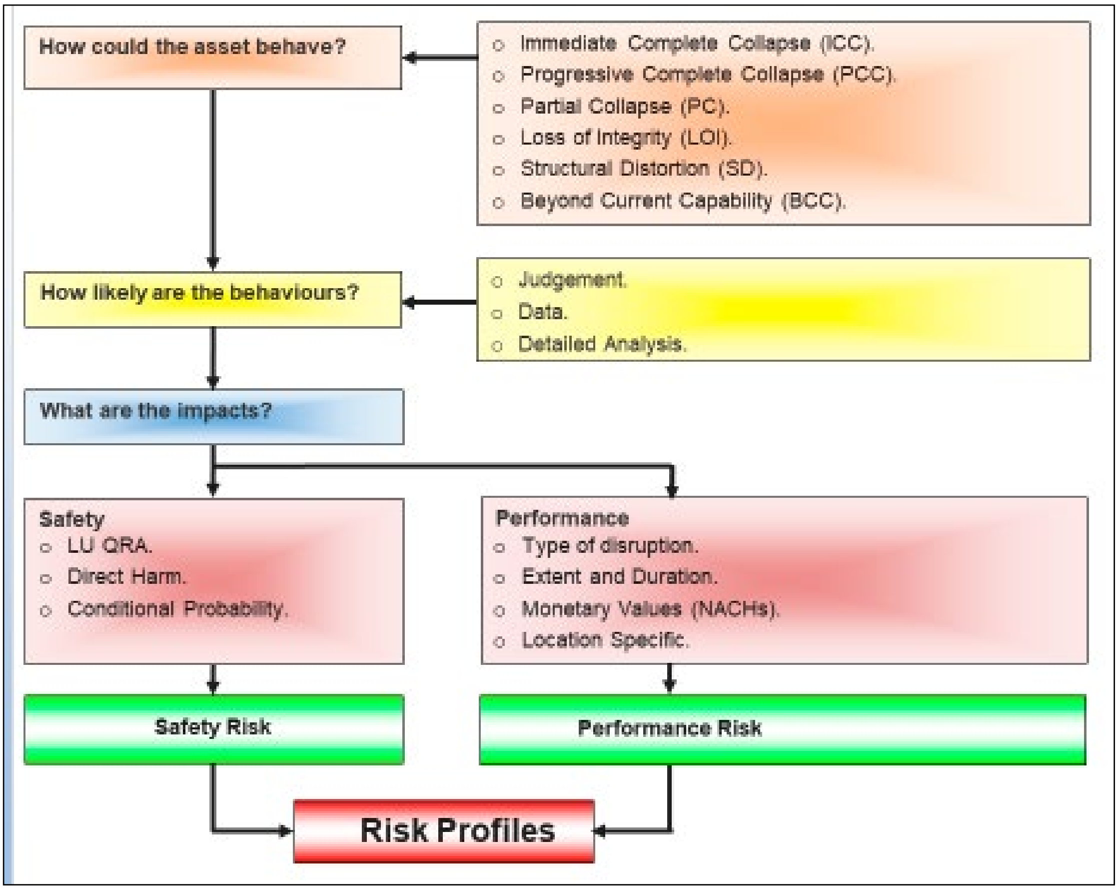

Figure 11.4: Overview of the STRATA process for assessing Earth Structure Risk

738 STRATA evaluates risk in a systematic and consistent way across the entire LU Civil Engineering asset base (not just Earth Structures) and generates a risk value (£k/year) for each individual asset.

739 STRATA generates a range of outputs, including service loss and safety asset risk profiles, service loss and safety risk values (£k/year) for individual assets and the workbank hierarchy risk for use in asset management and prediction of future investment requirements. STRATA also can provide quantification for the relatively higher safety risk associated with cutting failures, in contrast to the generally greater service loss from embankment failures.

LU Web GIS Asset Database

740 LU have developed a web-based GIS database that captures and stores all the relevant civil engineering data, including earth structure asset data. The creation of this single accurate data source was part of LU's commitment to retire and replace numerous legacy asset information systems and address data quality issues across the entire Civil Engineering portfolio. It has provided the LU asset management community with a streamlined, up-to-date data source needed to make better, more informed decisions more quickly and efficiently.

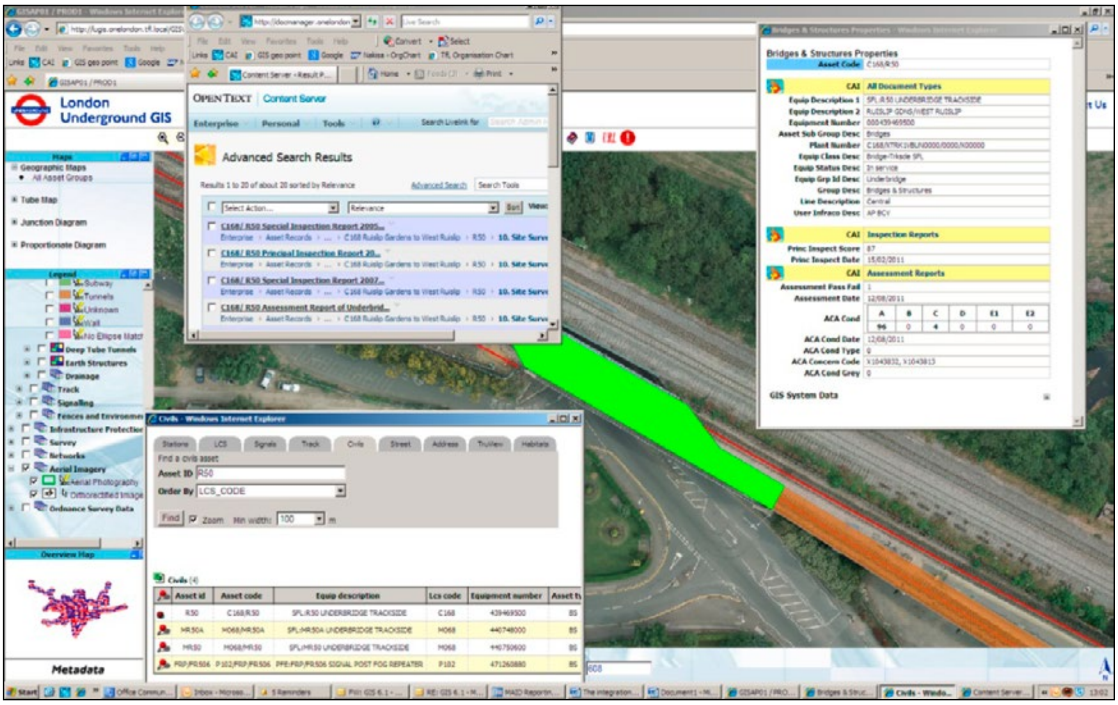

Figure 11.5: LU GIS Asset database

741 All the relevant earth structure inspection assessment and design reports can be easily retrieved from this database via the front-end GIS viewer.

742 In Chapter 7 we have recommended that an overhaul of the NR Geotechnical and Drainage asset management systems is required to develop an interface that brings the existing data and decision support tools together in a common interface (CSAMS).

Drainage Modelling Catchment Study

743 Historically, maintenance of the surface water track drainage system serving the LU network was limited to discrete like-for-like repairs in response to deteriorating asset condition. The use of modelling software to gain an accurate understanding of the hydraulic performance of the system has been limited by incomplete and often inaccurate data, due to the fact that the railway was constructed in parts over many decades and contains numerous peculiarities. In 2010 LU established a track drainage modelling project, Snell et al (2012), to bring together significant quantities of disparate data to produce hydraulic models and allow 'intelligent track drainage asset management'. The use of a GIS to collect sub-catchment characteristics, linked to the database of conduit data, allowed for all the variables used in the model to be centrally stored. Macros set up within the database allowed the data for individual catchments to be exported into a format that could be directly read by the Microdrainage modelling software. The track drainage was modelled as a system that included earth structure drainage and the catchment outside the LU boundary as appropriate.

744 In Chapter 8 we have recommended that the size, shape and location of all-natural catchments draining towards NR railway be established, in order that the flow rates can be determined for the required design storm return periods with the relevant allowance for climate change in accordance with NR (2018k).

Environment Agency

Introduction

745 The Environment Agency (EA) is a non-departmental public body, established in 1995 and sponsored by the Department for Environment, Food and Rural Affairs (DEFRA), with responsibilities relating to the protection and enhancement of the environment in England (and until 2013 also Wales). EA are also responsible for managing the risk of flooding from main rivers, reservoirs, estuaries and the sea. In 2013, that part of the Environment Agency covering Wales was merged into Natural Resources Wales, a separate body managing the Welsh environment. The Scottish Environment Protection Agency (SEPA) is Scotland's environmental regulator and national flood forecasting, flood warning and strategic flood risk management authority.

746 The EA is the principal flood risk management operating authority. It has the power (but not the legal obligation) to manage flood risk from designated main rivers and the sea. Managing flood defences involves setting crest levels and geometry to limit overtopping, together with ensuring that the stability of the defence is resistant to breaching and damage, even when overtopped.

747 The EA also provides flood forecasting and warning systems and maintains maps of areas liable to flood, as well as preparing emergency plans and responding when an event occurs. In partnership with the Met Office the EA runs the Flood Forecasting Centre (FFC) which provides warnings of flooding which may affect England and Wales. Formed in 2009, the FFC is based in the Operations Centre at the Met Office headquarters in Exeter (Slingo et al. (2021).

748 The EA is also a member of the Geotechnical Asset Owners Forum alongside NR, HE and LU.

Visual Condition Inspection

749 The EA manages over 8000 km of raised flood defence assets (embankments, walls and structures). It does not have any cutting slope assets.

750 EA flood defence embankments are managed to minimum targets that are expressed as a condition grade: a number between 1 (Very Good) and 5 (Very Poor) that is determined by visual inspection given in Table 11.1.

Grade	Rating	Description
1	Very Good	Cosmetic defects that will have no effect on performance
2	Good	Minor defects that will not reduce the overall performance of the asset
3	Fair	Defects that could reduce performance of the asset
4	Poor	Defects that would significantly reduce the performance of the asset. Further investigation needed
5	Very Poor	Severe defects resulting in complete performance failure

Table 11.1: Inspection Condition Grades

751 In total the EA inspects 144,400 assets annually to a risk-based frequency. To achieve this the EA currently directly employs 129 trained inspectors, many carrying out inspections as part of a wider role.

752 The flood defence assets are inspected to a variable frequency, based on flood risk, so that the assets that pose greatest risk are inspected most frequently, making best use of resources. The matrix in Table 11.2 shows how the inspection frequency is chosen.

Standard asset inspection frequency in months

Consequence of failure within inspection unit	Probability of Failure within the Inspection Unit: Low	Medium	High
High	24	12	6
Medium	36	24	6
Low	60	36	18

Table 11.2: Inspection Frequency Matrix

753 The EA has a tiered approach to the further detailed assessment of flood defence assets following visual inspection (Figure 11.6).

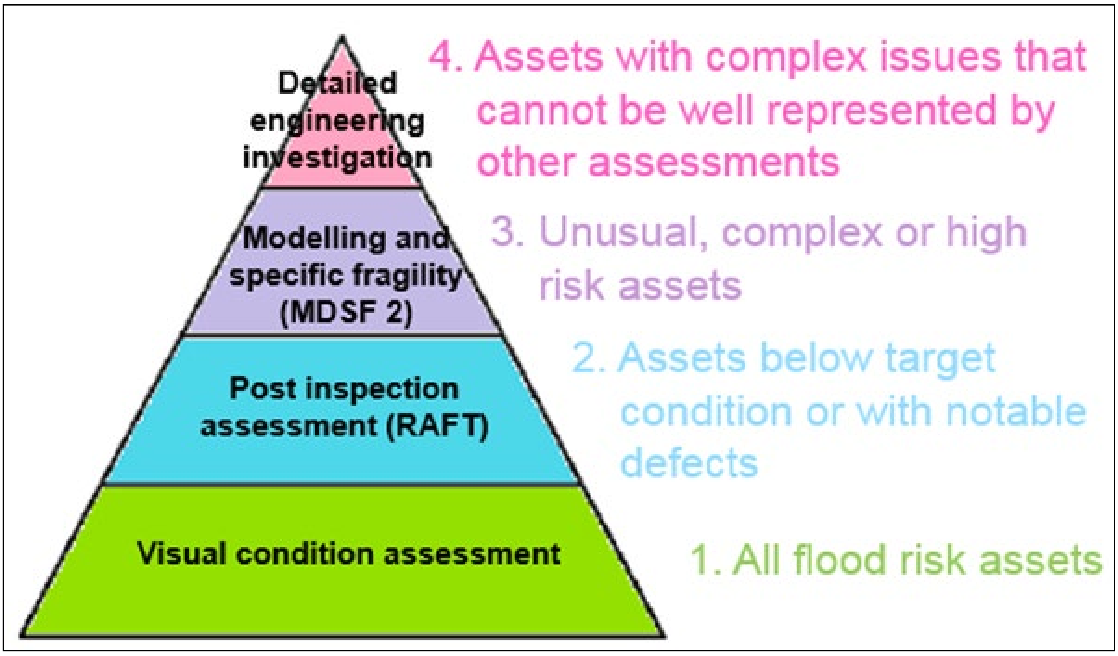

Figure 11.6. Tiered Approach to Flood defence risk assessment

Target condition

754 Each flood defence asset has a target condition, against which the visual condition score is compared. At 31 March 2018, 97.7% of EA maintained flood risk assets in high consequence flood risk management systems were in the required condition. Assets that are below the required condition require additional maintenance work. It does not mean they have structurally failed or that performance in a flood is compromised. If an asset's performance is reduced, EA takes action to effectively manage flood risk until it is fully repaired or replaced.

Tier 2 assessments

755 If following visual inspection, the assets are below target condition or have notable defects a Tier 2 assessment is triggered; this is comparable to the NR earthworks evaluation process. The EA requirement is that the Tier 2 assessment should be undertaken within 30 days of the inspection so that the level of risk can be rapidly understood. The Tier 2 Assessment utilises a spreadsheet-based tool RAFT to estimate the annual probability of failure based on a library of fragility curves held within the tool. A fragility curve seeks to quantify the relationship between the flood loading on the embankment and the conditional probability of failure given that loading (Casciati and Faravelli, 1991). Fragility curves enable the performance of flood defences to be taken into account in a system-wide probabilistic risk analysis.

756 Once assessed, the resulting risk can be attributed to individual assets (Gouldby et al., 2008) and hence the likely change in risk that would result from an engineering intervention (whether maintenance or improvement). The generic EA fragility curves are reviewed and assessed following each major flood event to see how predicted performance compares to that seen in reality. Generally, when looking at the performance of the asset base as a whole (their original intention) they are good predictors but when applied to individual assets they are less precise, particularly if those assets are atypical. The longer-term aim is to develop site-specific fragility curves that more accurately represent the performance of the assets at those sites. RAFT is designed to minimise the data or modelling requirements, with the majority of data embedded directly within the tool itself. Some asset specific data is required but this has been chosen to be either readily available or easily gathered by the user. The Tier 2 assessment is overseen by the local Catchment Engineer, who is a Chartered Civil Engineer, to ensure professional judgement is used to complement the decision support tools.

Tier 3: Detailed modelling

757 A Tier 3 assessment comprises similar principles to Tier 2, but with more detailed modelling and therefore less implicit assumptions. The key modelling tool used is Modelling and Decision Support Framework 2 (MDSF2). The tool significantly improves consequence modelling and has greater flexibility around performance modelling than RAFT.

Tier 4: Detailed engineering investigation

758 The EA does not have a standard framework for its Tier 4 assessments. These are activated where the preceding assessments are deemed insufficient to give a good understanding of the risk and where the risk is deemed high enough to make this significant additional investment in investigation worthwhile. For this type of investigation, a specialist consultancy firm would always be engaged, with a site-specific commission to work alongside EA local asset experts.

759 **The EA processes for the visual inspection and analytical assessment of its flood defence embankments are broadly equivalent to the NR earthwork examination, evaluation and assessment procedures. However, there are some key differences: the EA inspection frequency is determined on a risk basis and the period between inspections (6 months to 5 years) is mostly much shorter. We have recommended in Chapter 7 that the shortcomings in the NR earthworks examination system need to be addressed, and it is advised that a comparison with the EA flood defence embankment inspection and assessment process is undertaken as part of this review.**

Deterioration Curves

760 As well as assessing the probability of failure associated with an asset being below the required condition at various loading conditions, the EA post inspection process uses asset deterioration curves to establish the residual life of different types of flood defence assets. The curves are based on the five condition grades (Table 11.1). The deterioration curves consider the type of environment (fluvial or coastal) in which the asset is based, the type of material it was built with, width of the asset, whether maintenance is carried out and whether the asset has rear protection. These allow a simplified quick assessment of potential for deterioration.

“International experience indicates that the most promising surveillance technologies for slope and landslide management are LiDAR and photogrammetry (both aerial and land-based). Wireless sensors have been shown to be effective for monitoring of slope movements, provision of warning systems and detection of flexible barrier deformations.”

Impact of climate change on asset deterioration

761 In conjunction with a number of other stakeholders, the EA has undertaken an impact of climate change research project, EA (2020), to review the deterioration processes for 47 different asset types (both natural and man-made), across fluvial, estuary and coastal environments. The project concentrates on how changes such as increased sea levels and river flows may affect the process of asset deterioration to see which types are most vulnerable. The study concludes with an initial high-level estimate of the overall total impact of climate change upon flood defence asset deterioration, in terms of the possible level of additional investment required to address the issue.

762 **There are distinct similarities in the failure mechanisms between washouts as a result of water flow eroding material from the surface of cutting slopes and the erosion of the landward face of a flood defence embankment by overtopping. *It is recommended that NR review, capture, and learn any relevant lessons from the risk-based approach (based on a considerable body of research) that the EA has developed for the assessment of their flood embankments subject to erosion following overtopping*.**

LiDAR

763 Remotely sensed data, and particular those data obtained from LiDAR systems, can provide valuable additional information to help better target visual and intrusive condition inspections. Furthermore, these data can provide useful information to help EA flood risk managers predict likely defence performance during flood conditions. The EA now has 70% of England's ground surface mapped with 1m resolution LiDAR. As survey techniques and data platforms continue to evolve at pace, and advances in mapping software and cloud-based data storage develop at a similar rate, large geospatial datasets are now readily accessible. It is therefore becoming increasing realistic to use multiple complementary sources of remotely sensed data in the operational environment. The EA has responded to this opportunity and developed a web-based mapping system that is providing a valuable insight into infrastructure asset performance. It has been working to develop specific LiDAR data layers showing a range of features that might not be readily identifiable during a visual inspection. This work has focused on identifying features categorised as weaknesses in flood defence embankments:

+ relative low spots along the crest of the embankment
+ embankments with excessively steep rear faces (typically >35 degrees); and
+ the points of intersection between palaeo-channels and other features that run underneath an embankment

764 A pilot has been completed on this work which has enabled proof of concept that this approach could be effective, and development and rollout of a full national tool based on this data is in progress.

POLDER2C's project

765 The POLDER2C's project with thirteen partners from the Netherlands, Belgium, France and the United Kingdom, including the EA, is undertaking full-scale destructive tests on a decommissioned flood defence embankment on the Dutch-Belgian border to help better understand the resilience from flood overtopping conditions. One set of tests is to determine the role of grass length in protecting embankments from damage. In steady overflow experiments, a continuous discharge of water is generated across the crest of the embankment. The tests are typically executed for many hours with periodic short breaks to assess damage.

766 We consider that there may be valuable lessons NR can learn from the POLDER2C's project in developing their understanding of washout failures mechanisms, following intense rainfall eroding material from the surface of cutting slopes.

Hong Kong

767 There is substantial experience of slope and landslide management in Hong Kong, dating back to the 1970s when a series of catastrophic landslides occurred leading to loss of lives. This is controlled and managed by the well-established Geotechnical Engineering Office (GEO), which was originally set up as the Geotechnical Control Office (GCO); they have been very innovative in the way they assess and manage risk. *For many years the Hong Kong GEO have had a Slope Safety Technical Review Board, which meets periodically to provide expert, independent input into the management of their earthworks assets. We recommend that NR give consideration to forming a similar Review Board.*

Surveillance and remote sensing

768 For landslide hazard identification, aerial photographs and satellite images are used, together with field mapping. Computer algorithms are being developed for identifying new natural terrain landslides from aerial photographs automatically using (i) deep learning and (ii) change detection methods. Airborne LiDAR surveys have also been undertaken, achieving good penetration through vegetation, providing accurate digital terrain models for geotechnical uses. These facilitate detection of landform change and form the baseline for reference for future surveys.

769 Handheld laser scanning, employing LiDAR, is a portable system comprising a lightweight laser scanner and a data logger. It can be operated manually without the need of a stable platform. This technology can provide rapid, high resolution topographic information for landform mapping and slope investigation in difficult site settings. Mobile laser scanning slopes from road vehicles has also been found to be very useful.

770 Satellite based InSAR is being used to monitor landslips and measure movements of slopes using corner reflectors; accuracy within a few millimetres is achievable although vegetation remains a challenge. Ground based InSAR technologies are also being trialled, with potential applications for monitoring the stability of rock blocks/slopes on steep hillsides.

Landslide detection and alert systems in barriers

771 Barriers are commonly installed on natural hillsides in Hong Kong to prevent debris from reaching facilities. In some cases these extend to several kilometres. Recent developments have included instrumented rigid and flexible barriers. For rigid barriers wireless impact switches have been trialled; these are activated when landslide debris impacts the barrier and are backed-up with a depth measurement system for recording whether the barrier is filling up. For flexible barriers wireless sensors have been trialled for measurement of the displacement of the barrier when landslide debris hits the barrier. Both technologies are at the development stage.

Rainfall based early warning systems

772 Real-time rainfall data are combined with rainfall forecasts and landslide-rainfall frequency correlations to predict landslides and, if necessary, issue landslip warnings. The rainfall data is obtained at one-minute intervals from around 120 automatic rainfall gauges located throughout Hong Kong and transmitted to the internet via the mobile phone network.

Japan

Wireless sensor technologies

773 Japan's Railway Technical Research Institute (RTRI) has been undertaking a number of trials to detect earthwork instability using wireless sensors, comprising soil moisture meters and tiltmeters, sometimes in conjunction with cameras, as well as instrumented flexible barriers. Most of these systems are still at the experimental stage.

774 One of the Japanese railway companies, Odakyu Electric Railway, manages 293 slopes over a length of 120km of railway line, and has applied a slope failure detection system to 57 of these since 2007. A sensor cable fixed to posts at the bottom of slopes and at the top of embankments detects contact and breakage of conductors inside the cable through deformation caused by a slope collapse or a rockfall. Within the cable, there is an inner conductor and an outer conductor. The reflection position of an electronic pulse changes when the sensor is bent beyond a specified curvature, or when the conductors inside and outside the cable come into contact due to deformation. When the sensor detects an abnormality, it activates a signal light emitter to notify the driver of the need to stop the train; it also notifies the command centre of the occurrence of the abnormality through a private communication line. This sensor system requires a stable external power supply.

Instrumented flexible barriers

775 RTRI has undertaken trials with instrumented flexible barriers. When soil or rock material accumulate on the back of the barrier, the resulting tensile force and displacement is detected by the sensor system. Both this and the slope failure detection technology described above serve principally as a warning system rather than as a means of identifying potential instability in advance of failure (i.e. Monitoring Objective A rather than B, para. 598).

Rainfall based early warning systems

776 In Japan potential risk of earthworks instability is principally determined from weather information. Radar rainfall information is already being used for control of railway operations, which will be suspended in sections where there is particularly heavy rainfall. Railway operators generally receive information of radar rainfall from meteorological companies. Systems have been developed that collect information from meteorological observation devices and detection sensors installed along railway tracks; this is transmitted in real time to command and track maintenance technology centres, and warns when it is necessary to stop railway operations. JR East has built a system that can predict and confirm weather forecast information at meteorological observation points along the track, by analyzing its own observation data and integrating it with information provided by private weather companies. Such systems are still in the development stage.

Canada

777 The Canadian Railway Ground Hazard Research Program (https://sites.google.com/view/railway-ground-hazard-research) is a collaboration between the rail industry, Government and two University research teams (The University of Alberta and Queen's University, Ontario). It has a wide remit beyond slope instability. Of particular interest is the use of land based remote sensing technology to monitor changes in slope geometry using ground-based laser scanning and photogrammetry

778 The focus of this research work in Canada is very large rock and scree slopes that have the capability to generate frequent rock falls. Since it is often impossible to provide physical protection for rail assets from these slopes the focus is largely on prediction (detecting precursor movements) and warning systems.

779 Canadian Railways also use instrumented rockfall detection fences and micro-seismic rockfall detection technologies as warning systems at these large high risk slopes.

780 This type of large rock slope is not present in the UK rail environment, but there is the potential for smaller scale uses of these technologies at higher risk NR sites with a history of repeat failures. Transport Scotland are trialling similar remote sensing change detection techniques at the A83 Rest and be Thankful site in Argyll (see Chapter 11).

781 International experience from Hong Kong, Japan and Canada indicates that promising surveillance technologies for slope and landslide management are LiDAR and photogrammetry (both aerial and land-based); satellite InSAR also has potential if reflector markers are used to overcome difficulties with vegetation. Wireless sensors have considerable potential for measurement of slope movements, provision of warning systems and detection of flexible barrier deformations.

Chapter 12

Research Funding and Applied Research

Introduction

782 A review of current research and its findings was not part of our remit for this study. However, in carrying out the study we have identified three items of applied research which we deal with under the headings of ‘Laboratory work’, ‘Fieldwork’ and ‘Desk study’. We believe that each could contribute to a significant improvement in the understanding of the causes of earthworks failures and their link to weather and rainfall patterns. With the background gained from this study a review of research aims and findings would be timely.

Research and Development Funding

783 NR has a £245m fund in CP6 for carrying out all its research and development (R&D). During 2019-20, NR has spent £30m (in line with its plan), and commenced approximately 100 projects. Planned expenditure for 2020-21 and the remaining years of CP6 is significantly higher, so continued effort is required to deliver over the control period.

784 Ultimately, the success of the fund will depend on developing ideas into products that help NR become more effective or efficient. The research and development programme finishes at concept demonstration and there is still a critical gap in the development and roll-out of solutions which the NR must resolve.

785 NR also needs to find an appropriate way forward, working with suppliers, to resolve questions of intellectual property rights on the work done. Through its research and development portfolio NR are developing new earthwork remote monitoring and sensing technologies in conjunction with algorithms to interpret data. Their review of the research portfolio has recently resulted in prioritising a £3m project to further improve the performance of earthworks, focusing primarily on assets that pose the greatest likelihood of derailment.

786 NR's research and development programme is complemented and underpinned by their participation in research led by world-leading universities. The ACHILLES programme investigates deterioration, performance, forecasting and decision support for earthworks across the infrastructure sector. NR are working to include consideration of climate change and future weather conditions in its studies to improve knowledge of how its assets will perform in the future.

787 **We fully support the doubling in NR's overall investment in research and development (R&D) from CP5 to CP6; it has brought R&D together under a single integrated portfolio, enabling over £30m to be invested at pace in projects specific to earthworks, drainage and resilience. The development of data analytics is also considered as a useful tool to manage a large and complex asset base and harnessing more value from existing data sets through smarter information.**

Laboratory work

788 Laboratory work in the ACHILLES research should be extended to studies on natural samples, taken from the test-bed sites referred to below, and subjected to pore pressure or suction cycles while under maintained shear stress. Model verification requires these tests results to be replicated. The testing programme should include load controlled triaxial tests involving swelling at a range of constant shear stresses to failure. Tests should be run on intact samples at initial conditions representative of summer and winter.

Fieldwork

789 **There is insufficient information on pore water pressures and suctions in slopes and embankments and on their response to different rainfall and weather patterns, yet these parameters are critical to an assessment of stability and of the efficiency of drainage. *Consideration should be given to identifying, in two distinctly different microclimates, the following:***

- ***an over-steep unfailed slope in plastic clay***
- ***a failed slope in plastic clay***
- ***an unfailed slope in low plasticity clay***
- ***a plastic clay embankment***
- ***a granular embankment***

790 ***Locations of vulnerable assets should be selected, possibly where instrumentation is already in place and can be augmented. At each site it would be preferable to carry out a closely specified and supervised ground investigation and then install an integrated instrumentation scheme which will enable the following measurements to be made and interpreted:***

- ***Pore pressures and suctions***
- ***Ground movements***
- ***Antecedent rainfall and rainfall intensity***
- ***Flow velocities in relevant drains***

At each test-bed site field observations should be made during and after rainfall.

791 The aim of such ground investigations and integrated instrumentation schemes is to provide the information needed to establish the links between pore pressures and rainfall patterns, and the link between pore pressures and ground movements. Observations and monitoring during rainfall will contribute to an understanding of how rainfall splits into infiltration, run-off and sub-surface flow and how this depends on slope angle, suction profile/degree of saturation, permeability profile (influence of cracking), antecedent rainfall and rainfall intensity. The information should also be viewed alongside data on SMD and data from the G2G hydrological model highlighted by the WATF Team.

"There is insufficient information on pore water pressures and suctions in slopes and embankments and on their response to different rainfall and weather patterns, yet these parameters are critical to an assessment of stability and of the efficiency of drainage."

Desk study

792 Historical rainfall data are now available on a relatively local scale (referred to in the WATF Report); slope geometry, geomorphology and overall setting of the asset (appreciation of catchments and third party threats) are now known with more certainty based on LiDAR surveys; mechanisms and triggers for failure are better understood on the basis of observation and numerical analysis. *We recommend a forensic reassessment of lessons learnt from all previous asset failures, including categorisation of failure modes and mechanisms, their link with local rainfall and weather patterns, and their link with geology and soil and rock characteristics.*

793 The study will allow a better assessment to be made of the vulnerability of slopes to the different forms of failure and the different contributing/triggering factors. Having assessed vulnerability, the priority for the most appropriate mitigation measures for different forms of failure (drainage, instrumented barriers, etc) can be determined with greater certainty.

794 The study should delve into history and examine the response of the assets to earlier exceptional years, e.g. 1976 when heavy rainfall followed prolonged drought and led to many shallow failures.

Chapter 13

Conclusions and recommendations

795 This chapter lists all the Task Force's conclusions and recommendations (recommendations appear in italics).

Background

796 Earthworks assets owned by NR comprise cuttings and embankments many of which were built over 150 years ago. Cuttings were excavated at angles which were stable in the short term, but, particularly in plastic clays, would not necessarily be stable in the long term. Embankments were formed by end-tipping of soil from adjacent cuttings and so can comprise granular or cohesive soil, sometimes mixed, and not subject to formal compaction. The preparation of the foundation to the embankment is not known in terms of benching, under-drainage and extent of removal of unsuitable materials. Embankment assets are associated, therefore, with major uncertainties and, as with cuttings, a high risk of instability. (Para. 18 [Chapter 2])

797 The stability of the cut slopes and embankments is dependent to a large part on drainage, which itself is also often over 150 years old and was installed to a pre-set 'design', which did not take account of catchment areas, run-off and water flow. The drainage system was also generally not designed as a slope stabilisation measure. Replacement drainage over the years has involved a like-for-like replacement and so the drainage system has not been enhanced. (Para.24 [Chapter 2])

798 In the 1/04/03-1/12/20 period, 1.73% of the rock cuttings failed, 1.34% of the soil cuttings failed and 0.54% of the embankments failed; some of the same cuttings and embankments may have failed more than once. Deep rotational failures occurred largely in the heavily overconsolidated plastic clays in the South and Midlands. Shallow translational failures and washouts were spread across the network. (Para.28 [Chapter 2])

799 In the one-year period 1/04/19 – 31/3/20, 0.24% of the rock cuttings failed, 0.27% of the soil cuttings failed and 0.06% of the embankments failed. Comparing these percentages with the average values over the 17.5-year period of 1/04/03-1/12/20, then more than three times the average number of soil cuttings failed in 2019/2020, twice as many embankments failed and about two and a half more rock cuttings failed. It is evident that in 2019/2020, shallow translational failures and washouts dominate in soil cuttings, while ravelling (and hence weathering) is the dominant factor in rock cuttings. (Para.30 [Chapter 2])

800 The correlation between earthworks failures and rainfall over the 2003-2020 period is very strong and the total number of earthworks failures per month appears to be increasing. (Para.31 [Chapter 2])

801 Observations of earthworks failures that occurred in the Southern Region in the winter of 2019/2020 highlight the importance of localisation of failures, the difficulty of predicting where failure might occur, and a reason why failures continue to occur. The statistics on earthworks failures in the 2019/2020 period also strongly support the link between these failures and rainfall. (Para.39 [Chapter 2])

Soil Mechanics of Earthworks

802 The fact that railway cutting slopes failed at increasing times after excavation, before pore water pressures had fully dissipated, demonstrates that the initial slopes were too steep and that delayed first-time failure is a relevant mechanism to consider. (Para.61 [Chapter 3])

803 Many of the shallow 'translational' failures reported by NR involve movement of a shallow weathered zone, so involving slides of 1m to 2m depth. The weathered zone has developed on slopes which are already 'over-steep' in many cases. *It is recommended that some measurements are made of the undrained strengths of the typical weathered zones in summer and winter.* (Para.72 [Chapter 3]).

804 Shear surfaces at or close to residual strength can be present in cut slopes in brittle plastic clays before there is overall failure of the slope. After there has been failure, a continuous shear surface at or near residual strength will be present. (Para.78 [Chapter 3]).

805 The key mechanism of progressive failure in a slope with a shallow weathered zone involves a rupture surface with reducing strength propagating upwards from the toe of the slope, along the interface between the weathered and unweathered soil; this is a mechanism that may well contribute to the shallow failures occurring on NR's cut slopes in plastic clays, failures which sometimes involve only the lower part of the slope. (Para.80 [Chapter 3]).

806 On the basis of observations it is likely that the majority of NR's plastic clay cuttings will have failed in the past (at least over part of their length), because they were built over-steep, typically at a gradient of 2 (horizontal) to 1 (vertical). (Para.96 [Chapter 3]).

807 There are a number of reasons why strength parameters may reduce in a slope and these could well play a part in the ongoing slope failures. In our opinion, by far the most important parameter which leads to strength reductions are increases in pore water pressure above equilibrium values previously reached after a long period following completion of construction. Pore water pressures can increase above these previous equilibrium values (a) if groundwater levels rise as a re-sult of prolonged rainfall and changing weather patterns; (b) if drains are missing, blocked or of insufficient capacity and/or depth; (c) if vegetation is removed. (Para.107 [Chapter 3]).

808 Prior to becoming NR's responsibility and during dissipation of negative excess pore pressures following excavation, first-time failures in the cut slopes are known to have occurred, resulting in the presence of low strength residual shear surfaces within plastic clay slopes. It is essential to be aware of the potential presence of low strength residual shear surfaces within plastic clay slopes and to have an inventory of historical first-time failures, and the interventions that were carried out, from literature and library reviews. (Para.121 [Chapter 3]).

809 Mitigation of washouts requires the provision and maintenance on cut slopes of crest drains of sufficient capacity to deal with third party flows, and channelling features need to be identified, catered for or eliminated. Absence of such mitigation has been the cause of a number of the reported washouts. Crest drains should be provided, regardless of whether they are present on neighbouring land. There is need for a more reliable distinction between washouts, earthflows and mudflows when reporting on failures. (Para.136 [Chapter 3]).

810 Addressing the question 'why are both the cuttings and embankments in a range of geologies continuing to fail?', observations show that stability of the assets is strongly related to weather patterns, in particular to antecedent rainfall and rainfall intensity. It follows that, while reductions in drained strength parameters over time and changes in vegetation may play a part, the dominant reason for continuing failures is the exposure of over-steep and previously failed slopes, including their weathered zones, to rainfall patterns and pore water pressure values not previously experienced at particular locations. (Para.143 [Chapter 3]).

Changing Weather Patterns

811 *A link between earthwork failure type and rainfall pattern is apparent and it is recommended that this link be explored using recent and historical data.* (Para.150 [Chapter 4]).

812 The threats posed by climate change may be summarised as:

- Longer periods of prolonged rainfall in winter months leading to rising groundwater levels and higher pore pressures in earthwork slopes which could trigger first-time slides and reactivation of previous slides in late winter

- More frequent periods of more intense rainfall which could trigger washouts and debris flows

- Hotter and drier summers that will increase serviceability problems on clay embankments and will increase the amplitude of cyclic pore pressure changes experienced on the slopes, promoting additional ratchetting failures. Intense rainfall falling on a desiccated cracked slope will result in a rapid increase in pore water pressure and the risk of shallow slope failures of the form described in Chapter 3

- Increased demand on drainage capacity and the risk of it being overwhelmed. (Para.156 [Chapter 4])

Vulnerability of earthworks assets to failures in the future

813 Weather patterns have changed. Longer periods of prolonged rainfall in winter have resulted in more infiltration and higher pore pressures that provide the trigger for new deep and shallow slides, and reactivation of old slides. Increasing rainfall intensity has led to more run-off and increasing numbers of washouts and debris flows. Hotter drier summers have led to increased depths of desiccation cracking. (Para.159 [Chapter 5]).

814 Localisation of failures means that predicting exactly where failures will occur is like looking for a needle in a haystack. In the case of the railway slopes the practical approach is to search for the haystacks, i.e. the vulnerable lengths of slope. The fact that a localised failure has occurred is a strong indication that the remainder of the similar slope is vulnerable to future failures. *Having identified the lengths of slope that are vulnerable to shallow failures, we recommend that consideration be given to the installation of instrumented barriers of the form described in Chapter 10.* (Para.160 [Chapter 5]).

815 Rainfall patterns are predicted to continue to change: periods of prolonged rainfall will increase, resulting in more infiltration and rising pore water pressures; rainfall intensity will increase, resulting in more surface water run-off. Drainage and other stabilising measures will continue to deteriorate. It follows that soil cutting and embankment failures and slope movements will continue, taking the form of deep-seated and shallow slips, earthflows, washouts and debris flows. These are the challenges facing NR when trying (a) to minimise the risk of failures; (b) to identify failure locations immediately; and (c) to mitigate the effects of failures by the use of restraining measures. (Para.161 [Chapter 5]).

816 There is insufficient information on pore water pressures and suctions in slopes and embankments and on their response to different rainfall and weather patterns. *We recommend that consideration be given to more widely monitoring pore water pressures in earthworks to obtain a more detailed understanding of the behaviour and stability of a particular slope or embankment that is judged to be critical.* (Para.167 [Chapter 5]).

817 Currently use is being made of Soil Moisture Index, SMI, in some of NR's analyses. We and the WATF Team have reservations about this parameter. *We recommend that, instead of SMI, use is continued to be made of*

Soil Moisture Deficit, SMD, but in combination with and with much greater emphasis on cumulative antecedent rainfall and rainfall intensity. (Para.168 [Chapter 5]).

818 We note that neither NR nor RAIB tend to carry out post-failure intrusive ground investigations for forensic purposes; in the case of NR this is driven by the priority to re-open the track as quickly as possible and to obtain information for the design of remedial works. *Investigations of earthworks failures should provide information on: the extent of the catchment; the rainfall pattern that has been experienced, in terms of antecedent/cumulative rainfall and rainfall intensity; the vegetation in place at and in the vicinity of the failure; soil and rock properties (to be considered on a site-by-site basis based on complexity and size of failure) – as a minimum bulk samples should be taken of the material involved for measurement of composition and plasticity; geometry of the slope and failure, including run-out distance; state of the adjacent ground, including depth and strength of the weathered layer; potential contributors to localisation and trigger, including evidence for concentration of flows, local weaknesses, infiltration versus run-off, water seepages; the drainage that is in place – its state, capacity and prior maintenance.* (Para.169 [Chapter 5]).

819 The risk of future deep-seated cut slope failures is likely to be highest in cuts in stiff plastic clays:

+ which are over-steep and have not failed previously
+ which have failed previously, are still over-steep, and rely on deep drainage and other stabilising measures for safety against reactivation

The main threat is a rise in groundwater levels, and so rise in pore water pressures, associated with climate change or with a deterioration in drainage function, or both. (Para.170 [Chapter 5]).

820 The risk of shallow translational failures in cuts is likely to be highest:

+ in stiff plastic clays on which a softened weathered zone has formed on an over-steep slope which has undergone downslope ratchetting movements that will continue with larger amplitudes of cyclic pore pressure changes
+ In more permeable soils in which groundwater rises to such an extent that water enters the overlying weathered and vegetated layer. (Para.171 [Chapter 5])

821 The risk of washouts is likely to increase because of increasing rainfall intensities and rates of over-ground flows. Erodible soils in cuts and embankments will be most at risk. Debris flows remain a threat. The lack of prior warning for washouts and debris flows and the speed at which they develop are a major problem for NR. (Para.172 [Chapter 5]).

822 The risk of failures of embankments is likely to be highest:

+ in embankments comprising uncompacted clay fill in which standing water levels can exceed previous maxima; Briggs et al (2013a) provide information on the importance of the relative permeabilities of the embankment and its foundation
+ in embankments comprising permeable soils through which increased rainfall can pass through, causing erosion
+ in embankments on sidelong ground. (Para.173 [Chapter 5])

823 A key factor in determining future stability is the provision and maintenance of drainage of sufficient capacity to cater for the increased demands arising from climate change and changes in neighbouring land use. (Para.174 [Chapter 5]).

Rock Cuttings and Vulnerability

824 Quantification of the potentially increased risks for rock cuttings would require enhanced geological and hydrogeological knowledge of the ground below, behind and above cutting faces. *It is recommended that NR give consideration to incorporating an enhanced classification of rock cuttings that incorporates a desk-based view of the geological and hydrogeological conditions below, behind and above cutting faces into any future revisions of its processes.* (Para.199 [Chapter 6]).

825 It is expected that the assessment of the consequence of a natural slope failure for NR track in upland areas (in accordance with NR/L2/CIV/086 Geohazard Assessment) ensures that the difficulty of rescue and recovery at those locations is considered alongside an assessment of any additional factors that might increase the risk of death or injury in the event of a derailment. (Para. 212 [Chapter 6])

826 *It is recommended that the feasibility of using instrumented anchored catch fences linked to warning signals be further researched for use in remote upland areas with high hazard potential for debris flows.* (Para.218 [Chapter 6]).

Earthworks Asset Management

827 NR have put considerable resource into the development of a comprehensive asset management system for their earthworks and we commend the very substantial effort in achieving this. (Para.224 [Chapter 7]).

828 The Earthworks Asset Policy NR (2018c) is not well integrated with the equivalent Policy documents for Drainage and Vegetation. There are also some key omissions from the Earthworks Policy e.g. Roles and Responsibilities, Competence, Assurance etc. The content structure of the Earthworks Policy document can be improved by addressing the omissions and, in line with best practice and relevant standards (BS ISO 55000), to be more concise, succinct, clear and better organised. We understand that NR are transitioning to an ISO accredited Asset Management System, which is likely to help address these issues. (Para.254 [Chapter 7]).

829 *We recommend that the Earthworks Asset Policy, NR (2018c) is updated to address the current identified deficiencies in content and structure. These revisions should be clearly communicated to the Regions and Routes to improve alignment and consistent understanding of the requirements across the business.* (Para.255 [Chapter 7]).

830 All the earthworks standards have been updated since 2017. Inevitably there are still some key omissions e.g. the absence of any reference to emerging earthwork decision support tools such as GSRA (Global Stability Resilience Appraisal). There are also a number of references to the Civils Strategic Asset Management Solution (CSAMS) which has not yet been delivered. We anticipate that the Earthworks Standards will be kept updated to address key omissions and as a commitment to continuous improvement in earthwork asset management. (Para.260 [Chapter 7]).

831 The Drainage (Water Management) Technical Strategy has not yet been developed and the Earthworks Technical Strategy, NR (2018d) does not consider Drainage (Water Management) or Vegetation Management in a meaningful way. (Para.266 [Chapter 7]).

832 The Earthworks Technical Strategy, NR (2018d), would benefit from a well-defined articulation of the vision and stepping stones to world class earthworks asset management through harnessing knowledge, continuous improvement and the exploitation of emerging technologies. *We recommend that the Earthworks Technical Strategy, NR (2018d), is kept regularly updated, particularly to reflect the technical developments NR are proposing for the management of the drainage and vegetation assets associated with earthworks.* (Para.267 [Chapter 7]).

833 The examination process should be improved by giving more consideration to drainage condition and water management associated with earthwork slopes. We consider that for those earthworks vulnerable to washout and earthflow failure mechanisms, examinations during or shortly after heavy rainfall are essential. The use of drone and/or helicopter surveys should be considered for these examinations. (Para. 280 [Chapter 7]).

834 Earthwork examiners observe drainage assets and record defects but this is only incidental to their earthwork inspections. They are also limited in the inspection of hidden or buried drainage assets. Consideration should be given to better integrating earthworks and drainage examinations. (Para. 281 [Chapter 7]).

835 Examiners are not expected to go outside the railway boundary, and safety considerations (e.g. very steep slopes) sometimes prevent examiners reaching the boundary. These constraints mean that collection of information about slope instability features outside the railway boundary may be restricted. In particular the identification of deficient or inadequate water management from catchments beyond the boundary fence is likely to be limited especially if the examinations are not undertaken during or following heavy rainfall. (Para. 283 [Chapter 7]).

836 *We recommend that consideration be given to formally including April in the Earthworks Examination season.* (Para. 284 [Chapter 7]).

837 The examination process could be improved by earthworks examiners formally advising the slope de-vegetation requirements to facilitate the next examination. (Para 285. [Chapter 7]).

838 We recognise that full condition inspection and assessment of the extensive NR earthwork asset base is challenging. However, we consider that slope stability cannot be determined on the basis of surface observations from examination alone. The inherent factor of safety against slope failure of the earthwork is not included in the algorithm derived EHC condition grading system which is largely based on surface-visible precursor indicators of failure from examination and does not take account of two key parameters in any slope stability assessment: shear strength and pore water pressures. The rapid failure of cutting slopes is especially difficult to predict by the EHC condition grading system, particularly when failures are triggered by intensive local rainfall. (Para.287 [Chapter 7]).

839 *We recommend that shortfalls in the earthwork examination and risk assessment system need to be addressed, in particular reliance on algorithms largely based on surface-visible features and defects, slope geometry and material type as predictors of earthworks failure with limited consideration of inherent slope stability and generally without engineering calculations.* (Para.291 [Chapter 7]).

840 Reliance on mainly using the algorithm-derived EHC to determine whether the RAM team review examination reports in an Earthwork Evaluation, NR (2017b) means that NR can be unaware of important slope characteristics or defects if these have limited or no effect on the scoring in the examination algorithm. (Para.294 [Chapter 7]).

841 The frequency of examination is not generally linked to consequence or risk (EACB), although the prescribed examination frequencies for rock slopes (which typically pose a higher consequence of failure) are higher than those for soil cutting slopes, which are in turn higher than those for embankment slopes. (Para.295 [Chapter 7]).

842 *We recommend that the limitations of mainly using the EHC category to trigger Earthwork Evaluations and examination frequencies are addressed.* (Para.296 [Chapter 7]).

843 A 5 chain (100m) soil cutting or embankment in EHC "A" will receive a "partial" (depending on access, weather, vegetation etc), visual examination, typically undertaken in 30 minutes every 10 years and the results will not looked at by a competent NR Geotechnical Engineer unless something is specifically highlighted. In 2019/20 there were 36 slope failures (14% of the yearly total) in earthworks classified (pre-failure) in EHC "A". (Para.297 [Chapter 7]).

844 *We recommend that NR should review and improve its processes (in the absence of routine track patrolling) for identifying, and responding appropriately, to changes outside and within the railway boundary which could adversely affect earthwork stability between routine examinations. We have also recommended (Paras 605-611) that consideration be given to more widespread use of helicopter flights and drone technology for inspections of earthworks including the identification of any changes in condition between formal examinations.* (Para.300 [Chapter 7]).

845 *Given the need to detect, where reasonably practicable, precursors of slope failure and emerging problems on outside party land, with the potential to exploit new technology, we recommend that NR review their methods of identifying and managing geohazards on outside party land that have the potential to adversely impact on the safe performance of the railway.* (Para.311 [Chapter 7]).

846 *We recommend the process for the identification of localised water concentration features at the top of cutting crests and the likelihood of failure from washout or earthflow is fundamentally reviewed. The aim is to improve the prediction rate for rapid cutting slope failures, with little or no indication of visible distress prior to failure. A forensic re-assessment of the significant number of previous washout and earthflows would be invaluable for calibration of the current examination and evaluation process and provide lessons learnt for future risk assessment.* (Para.321 [Chapter 7]).

847 Earthwork Evaluations should not be considered just as an examination report sign off. *We recommend that more resources be made available to enhance the RAM teams and enable thorough Earthworks Evaluations to be undertaken, including site visits, which in our view should be mandatory.* We anticipate that at the next revision, the Earthwork Evaluations standard, NR (2017b), will include the requirements and guidance for the use of existing NR geotechnical support tools e.g. WERM, GSRA, CHOPS etc. (Paras.326, 327 and 328 [Chapter 7]).

848 It is considered that NR should include significantly more comprehensive guidance and description of the techniques and value of engineering geomorphology mapping in their earthwork asset management processes. *We recommend that there would be significant benefits in formally incorporating and encouraging the use of relatively low-cost engineering geomorphological mapping within the overall earthworks risk assessment framework.* (Paras.335 and 336 [Chapter 7]).

849 In the global stability assessment high vulnerability zone (Figure 7.14), there are a significant number of earthworks standing at heights and/or angles that should not be feasible for the particular geology and the "best case" assumed pore water pressure conditions in the GSRA analysis. A high proportion of these earthworks appear to be in good condition with EHCs of A or B, Spink (2020). (Para.345 [Chapter 7]).

850 The GSRA analyses, based on assumed parameters, frequently show that earthwork stability is more sensitive to pore pressure conditions than to variations in the geological material properties. However, NR have very limited knowledge of the distribution of pore water pressures in its earthwork slopes. The full effect of vegetation, particularly large trees, on stabilising a slope through porewater reduction and root reinforcement has also not been included in the global stability appraisal, and this may account for the apparent stability of some of the lower, steeper slopes. (Para.346 [Chapter 7]).

851 Future Earthwork Policy and Standard updates should incorporate the applicability and use of the GRSA tool. However, the limitations of the GSRA methodology should be highlighted, particularly at an individual asset level where the often highly transient and complex pore pressure conditions in a slope generally control stability. Further development (included in the Intelligent Infrastructure (II) programme) is required of the GSRA process to make it an effective earthworks decision support tool, including addressing the recommendations made in the GSRA report, NR (2017d). (Para.351 [Chapter 7]).

852 Multiple and disparate data sources are impacting on the ability of NR Geotechnical and Drainage Engineers to make accurate and efficient asset management decisions that consider all available information e.g. in the Evaluation of Earthwork assets following Examination. (Para.357 [Chapter 7]). *We recommend that an overhaul of the Geotechnical and Drainage asset management systems is required to develop an interface that brings the* *existing data and decision support tools together in a common interface (CSAMS). This will provide the fundamental capability of NR engineering teams to properly evaluate and document the vulnerability of earthwork and drainage assets and accurately prioritise intervention activities required to safely manage the infrastructure.* (Para. 359[Chapter 7]).

853 A key challenge for the NR earthwork asset management is to focus on mitigating the effects of earthworks failures as currently it is not reasonably practicable to detect nor prevent all earthwork failures. Mitigation (recovery) controls are crucial to reduce the consequence of a failure should it occur. (Para.368 [Chapter 7]).

854 *We recommend that NR place a high priority on undertaking a comprehensive review of the risk associated with the frequency and severity of extreme rainfall and climate change – to further develop resilience and mitigation plans against rapid earthwork failures (mostly cuttings) , with little or no indication of visible instability prior to failure.* (Para.369 [Chapter 7]).

855 A unique aspect of earthwork assets, as opposed to track or rolling stock for example, is their inherent variability. Even if information and knowledge of the change in condition and performance was perfect (which it never is), there would still be a variability associated with future predictions, related to the uncertain behaviour of geological materials. The behaviour of earthwork assets is also affected by environmental conditions, notably surface water and groundwater including rainfall events, which are also uncertain. Thus, a risk-based approach is essential to understand this variability, and to assign probabilities to future earthwork behaviour, particularly when controlling factors such as climate change and weathering are changing. (Para. 370 [Chapter 7]).

856 *We recommend that NR undertakes a comprehensive review of the risk 'bow-tie' in relation to earthwork related threat (hazard) events to assess the performance of the risk management system and adequacy of the key preventative controls and mitigations. The review should specifically include:*

+ *the hazards associated with the frequency and severity of extreme rainfall and climate change*
+ *the mitigation (recovery) controls required to reduce the consequence of an earthwork failure event, should it occur.* (Para.391 [Chapter 7])

857 There is a risk that whole-life asset management models can become immensely complicated; however, if they are too simplistic this defeats the whole object of the exercise and their results may be misleading. The characteristics of NR earthwork assets bring their own particular challenges, including:

+ managing a portfolio of largely existing assets that cannot economically be replaced, but must be maintained and in many cases see their economic lives extended

+ from an engineer's perspective, understanding the implications of practical asset life extension from current design codes and dealing with uncertainties associated with inherently variable earthworks. (Para.403 [Chapter 7])

858 We recognise the value of the SCAnNeR and Powerpack tools in providing a rational basis for the investment decision-making process on a whole-life basis. We acknowledge that NR seek to ensure that the whole-life asset management decision support tools and the associated models are used appropriately – they are a tool for geotechnical engineers to make intelligent asset management decisions and judgements based on basic geotechnical principles. (Para.408 [Chapter 7]).

859 The trend of earthworks failures has significantly worsened since the start of CP6 (1st April 2019). 251 reportable earthwork failures were recorded across the NR network in 2019/20 (CP6 Year 1) with 140 of these having occurred during the 2019/20 winter period (December-February). There were also 16 potentially high consequence earthwork failures but no earthwork attributable derailments in CP6 Year 1. The 2019/20 winter was the fifth wettest on record with the wettest February on record (5th wettest month ever). The adverse trend in earthwork failures and potentially high consequence earthwork failures has continued into 2020/21 (up to 30/10/2020). (Para.411 [Chapter 7]).

860 59% of the 2019/20 earthwork failures were classified in EHC "A to C" pre-failure. There were 14% of the failures in the EHC "A" which statistically is the lowest likelihood of failure category. This demonstrates the current difficulty in forecasting earthworks failures utilising the examination algorithm and EHC category from an asset base that is inherently unpredictable, and where the failure rate is so dominated by antecedent rainfall. We have recommended in Para 291 that the shortfalls in the earthwork examination system need to be addressed, in particular reliance on an algorithm and EHC as a predictor of the likelihood of earthworks failure. (Para.413 [Chapter 7]).

861 Despite the very wet winter in 2019/20, NR significantly outperformed the earthworks renewal volume targets due to acceleration of schemes from 2020/21 and emerging work relating to mitigating the impact of asset failures. This is a very positive start to CP6, but NR still have more to do to achieve the CP6 earthwork renewals targets and start to reduce the overall number of earthworks susceptible to failure as a result of extreme rainfall. NR also need to improve their ability to identify the most vulnerable earthworks to ensure that renewal investment is directed at those assets most susceptible to failure. Approximately two-thirds of the earthwork failures experienced in the early part of CP6 had no planned work in the control period (i.e. associated with the earthwork failure) which suggests that many of the most vulnerable earthworks to failure are not necessarily included in the Investment Plan. NR should therefore recognise that sustained increased investment will be required over multiple CPs if service-affecting earthwork failures are to be eradicated. (Paras.423 and 424 [Chapter 7]).

862 *We recommend that a priority should be to deliver the full scope of the strategic asset management solution for geotechnics and drainage through Intelligent Infrastructure. This delayed suite of data and technology upgrades will enable better decision-making by engineers and strengthen assurance capabilities. The implementation of the evaluation and prioritisation tools through the Intelligent Infrastructure (II) programme should pull together all datasets quantifying threat, vulnerability and failure impact at the asset and network scales respectively. They should embed a structured and audited decision-making process such that decisions for assets and portfolios are traceable and accessible.* (Para.435 [Chapter 7]).

863 The Professional Head of Geotechnics as the NR Technical Authority provides effective leadership and promotes a partnership culture with the geotechnical staff in the Regions. In our view there is considerable benefit to the NR business from this single-point accountability for the oversight and assurance of all earthwork related asset management activities. A key challenge for the Professional Head of Geotechnics is to work collaboratively with the Regions – to ensure that investment is used effectively and efficiently to proactively enhance earthwork assets assessed as higher risk to deliver resilience to future climate change and ensure failures are not first observed by train drivers. (Para.438 [Chapter 8]).

Drainage Asset Management

864 The effective control of water and proper understanding and maintenance of drainage assets is of fundamental, underpinning importance to the safe operation of the railway network. It is therefore imperative that NR understand the nature and size of its drainage catchments, including those parts outside the railway boundary, in order to be able to effectively manage water flow both now and in the future with climate change. The stability of earthworks is critically dependent on the drainage system and water management. However, the NR drainage system was not originally "designed" as a means of ensuring slope stability. (Para.444 [Chapter 8]).

865 One of the greatest challenges facing NR in managing earthworks drainage risk is the current lack of asset knowledge. In many cases the location and condition of drainage assets are far from understood. Existing drainage systems have not in general been assessed to calculate whether they have sufficient hydraulic capacity to convey the required flow. These shortcomings present real challenges in making the case for investment in water management and the railway drainage system. A better understanding of its drainage system is a vital element to improving water management and control across the NR railway. (Para.446 [Chapter 8]).

866 The increasing frequency of extreme rainfall events requires NR to place greater emphasis on the control of storm water and surface water run off than they have done in the past. This is required to reduce the risk of washout and earthflow slope failures and to minimise the infiltration of water into clay slopes, particularly via shrinkage cracks after prolonged hot spells which are forecast to be more prevalent as a result of climate change. (Para.448 [Chapter 8]).

867 NR has very limited knowledge of the distribution of pore water pressures in its earthwork slopes. However, the stability and resilience of earthworks is in most cases critically dependent on the control of water, in particular the magnitude and distribution of pore water pressure within a slope. *We recommend that consideration be given to more widely monitoring pore water pressures in earthworks to obtain a more detailed understanding of the behaviour and stability of a particular slope or embankment that is judged to be critical. Initial proposals to improve knowledge of the distribution of pore water pressures in NR earthwork slopes are included in Para 789.* (Paras. 449 and 450 [Chapter 8])

868 The effective management of a drainage system requires a complete understanding of its capacity to convey the required flow. This assessment should be based upon a holistic approach in which drainage is viewed and managed as a system from rainfall to outfall, rather than as individual components. (Para. 454 [Chapter 8]).

869 Currently, the NR business needs to have a greater appreciation of the importance of water management and drainage assets, including addressing the associated risk within the railway infrastructure system. (Para.458 [Chapter 8]).

870 *We recommend that NR develops its asset management culture across the business to ensure that the effective control of water as a system is recognised as essential to the safe and economic management of railway infrastructure including earthwork assets. Therefore, NR will, inter alia, need to increase its resource of Drainage Engineers competent to effect proper water management and recognise its importance to the safety and performance of the railway.* (Para.459 [Chapter 8]).

871 *Maintenance of drainage systems is of paramount importance including regular cleaning. We recommend that more resource be put into this vital activity. Consideration should be given to having dedicated drainage maintenance teams across all routes, rather than drainage being only one of the activities for which off-track Chapter managers are responsible. Off-track drainage maintenance should have its own budgets. There is a case for grading Off-Track Maintenance Engineers on a similar basis to existing Track Maintenance Engineer posts to ensure the importance of maintenance of drainage systems is recognised in the business.* (Para.463 [Chapter 8]).

872 *We recommend, that as a priority, NR address the lack of competence and resource to develop and implement the requirements of the Drainage Asset Policy, NR (2017e) and the associated Drainage standards. In particular, the development and implementation of specific competency requirements for staff undertaking safety critical drainage activities (Inspections, Evaluations, Assessment and Design) is fundamental.* (Para 466 [Chapter 8]).

873 Drainage Inspections and Evaluations are undertaken by Off track Maintenance Technicians who have generally attained an appropriate level of knowledge through relevant experience, in contrast to Earthwork examinations which are undertaken by professionally qualified Engineers or Geologists. (Para. 493 [Chapter 8]). *We recommend that consideration is given to undertaking drainage inspections with sufficient and professionally qualified competent staff under the control of the RAM-Drainage, as is done for earthworks examinations, rather than the current arrangement where the NR Maintenance off-track team is often overloaded with inspections of the drainage system.* (Para.495 [Chapter 8]).

874 Drainage asset data is currently held in multiple systems and assets are not represented as a connected system. *We recommend that an integrated Drainage asset management system be developed, combining StrEAMS and GIS, where live data from multiple sources is accessible and the workflow management is open and transparent across the business (i.e. from inspection to renewal).* (Para.504 [Chapter 8]).

875 NR has little or no detailed knowledge regarding the extent and run-off from its natural catchment areas both inside and outside its boundary. *We recommend that the size, shape and location of all-natural catchments draining towards NR's railway be established, in order that the drainage system flow rates can be determined for the required design storm return periods with the relevant allowance for climate change in accordance with NR (2018k).* (Para.508 [Chapter 8]).

876 NR propose to review their standard ditch/channel drain design details and guidance following a number of cutting slope failures associated with defective unlined crest ditch drains. NR should not rely on crest drainage installed on 3rd party land outside their boundary and ownership. *We recommend that the use of perforated pre-cast concrete channels is more widely adopted by NR, in particular to replace unlined ditches which are susceptible to failure unless subject to an intensive inspection and maintenance regime.* (Para.519 [Chapter 8]).

877 *We recommend that, at tunnel portals, special drainage measures and slope shaping and protection should be provided. An example of the measures taken by the Japanese Railways at portals is shown in Appendix H, Figure H24.* Para.520 [Chapter 8]).

878 *We recommend NR adopt Sustainable Drainage Systems (SuDS) wherever possible, to better manage run-off (particularly from intense rainfall), to mimic natural drainage and encourage its infiltration, attenuation and passive treatment.* (Para.525 [Chapter 8]).

879 *We recommend sufficient resources and funding are assigned to the development of the Technical Strategy for the Drainage system to ensure successful take up of new technologies, harness more value from data sets and to target interventions to enable long term improvements in railway infrastructure performance.* Para.531[Chapter 8]).

880 Drainage is still generally regarded by NR as a "Child" asset that supports the performance of Earthworks and Track. Poor performance of the drainage system has a negative impact on its "Parent" assets. The historic lack of investment has led to a poor-quality drainage asset inventory, limited historic data and unmaintained assets, resulting in inconsistent asset management decision making. This situation has been compounded by a silo approach to drainage and water asset management. Para.534 [Chapter 8]).

881 *We consider it essential that the delivery of drainage system commitments, including sufficient funding and resources, is realised in CP6 and subsequent control periods to improve the railway water management safety and performance. NR should progressively shift their focus to proactively maintain and improve/upgrade the drainage system to support the delivery of a safe, serviceable and sustainable railway infrastructure into the future. Para.534 [Chapter 8]).*

Vegetation Asset Management

882 The effect of vegetation on slope stability has been shown to be driven by a complex interaction between hydrological and mechanical mechanisms. Plant roots may reinforce slopes and increase their overall stability. Vegetation will take up and intercept water, potentially reducing pore water pressures and consequently increasing slope stability (at least seasonally). (Para.541 [Chapter 9]).

883 The use of managed vegetation and bioengineering to stabilise earthwork slopes is a cost-effective technique with the potential to be used more extensively on the NR earthwork slopes as a preventive and remedial measure. However, further work is required to quantify the effectiveness of managed vegetation and bioengineering for NR earthworks slopes and adapt the approach for routine practical application. *We recommend further work is undertaken by NR to develop and implement vegetation management and bioengineering techniques to stabilise earthwork slopes as a cost-effective preventive and remedial intervention technique. NR have documented (Management of Vegetation on Earthworks, NR (2018l)) the optimum plant species and vegetation management schemes to enhance the stability and performance of NR earthwork slopes. This recommendation is particularly timely as NR move (post Varley Review) to a cut and maintain/replace vegetation management strategy, rather than the previously commonplace "cut and forget" approach.* (Paras.567 and 568 [Chapter 9]).

884 We support NR's ambitious vision for the future management of vegetation as an asset on the lineside estate and as part of the wider Environmental Sustainability Strategy. We expect that these improvements will explicitly include action to harness the beneficial effects of vegetation (reducing surface erosion, providing root reinforcement, avoiding channelling of flows, maintaining surface pore water suctions); and minimise the detrimental impacts (blocked ditches and pipes, leaf fall, tree fall, desiccation adjacent to and beneath the track). (Para.589 [Chapter 9]).

885 *We recommend that NR progressively adopt a broader and more integrated approach to the management of Earthworks, Drainage and Vegetation, taking account of changing weather patterns, and breakdown the historic silos between these interdependent assets across the organisation to support the delivery of a safe, cost-effective and sustainable railway infrastructure into the future.* (Para.590 [Chapter 9]).

Mitigation – Monitoring, Surveillance and Interventions

886 There is a need to adopt reliable methods of monitoring which can inform NR engineers of the condition of the more critical geotechnical assets, and importantly, of any significant changes occurring. NR recognise this need and have been impressive in investing significantly in R&D to investigate the potential for novel technologies. (Para.595 [Chapter 10]).

887 It is important to distinguish between two principal objectives of monitoring in the context of NR's earthworks:

- Monitoring Objective A Failure detection (i.e. detection of rapid loss of functionality that may have a direct consequence on the safety of the railway) and reaction via alert alarm systems
- Monitoring Objective B Provide data on the performance and condition of a slope or embankment, and possible precursors to failure

(Para.597 [Chapter 10]).

888 In view of the very large number of earthworks sites Network Rail rightly recognise that it is impractical to have widespread instrumentation and monitoring. Traditional measurement of pore pressures and soil deformations, by installing piezometers and inclinometers in boreholes, is essential to obtain a more detailed understanding of the behaviour of a particular slope or embankment that is judged to be critical. (Para.600 [Chapter 10]).

889 Wireless tiltmeter systems recently trialled by NR are an extremely promising application of innovative sensor development to the management of earthworks assets; they have considerable potential for Monitoring Objectives A and B. *We recommend that wireless tiltmeter systems be more widely adopted on earthworks slopes and embankments that are judged to be potentially critical.* (Para 603 [Chapter 10]).

890 *We recommend that acoustic sensing continue to be part of Network Rail's R&D programme in view of its potential as a new technology for detection of instability of soil and rock slopes.* (Para.604 [Chapter 10]).

891 Helicopter flights are of considerable value, especially in hilly or mountainous terrain, for inspection and provision of visual evidence, particularly immediately after an extreme weather event that may have resulted in a failure, whether it be soil or rock instability or washout. We understand that in Scotland around five such flights are made each year specifically for earthworks inspections. *We recommend that consideration be given to more widespread use of helicopter flights for inspections of earthworks throughout the UK.* (Para.606 [Chapter 10]).

892 Despite some existing limitations, particularly in respect of CAA regulations, drone technology is a rapidly expanding area and there is considerable potential for drones to significantly enhance NR's earthworks management. *We recommend that more use is made of drone technologies as their capability develops.* (Para.611 [Chapter 10]).

893 InSAR is a promising technology which is developing rapidly, particularly with rapid developments in AI and machine learning, and should be given further attention. *We recommend that a number of critical slopes be equipped with reflector markers to overcome the problem of vegetation and the potential for InSAR explored further.* (Para.621 [Chapter 10]).

894 *We recommend that consideration be given to installation of further LiDAR systems on a limited number of sites where the stability of the slope is judged to be marginal and interventions are not practical.* (Para. 627[Chapter 10]).

895 *We recommend that consideration be given to exploring the potential for the train-mounted scanning LiDAR technique to be applied to the Network Rail system to update the geometry and features of cutting slopes.* (Para. 629 [Chapter 10]).

896 Routine analysis of track geometry data is a potentially valuable technique for the early detection of embankment instability. At present it is difficult on a routine basis to distinguish between ongoing track deterioration with underlying embankment instability resulting in too many false positives and false negatives. Further development work is required to refine the analysis technique and in particular to establish an automatic data processing process. Potentially, this will reduce the time and cost required to process and produce trend data, calculate the deterioration rate and visualize the data for interpretation. *We fully support the NR track geometry data collection and analysis workstream to identify potential embankment failure sites within the R&D/Intelligent Infrastructure II programmes and recommend this is actively progressed.* (Para.643 [Chapter 10]).

897 Instrumented flexible barrier systems could reduce the need for regular inspections; engineers would only be required to investigate locations to which the system has alerted them, thereby saving time, reducing risks and providing valuable information on rock slope condition and deterioration (Monitoring Objective A). Instrumented flexible barriers could also contribute significantly to improving rail safety if they were to be incorporated into an early warning system enabling train drivers to be alerted to the possibility of debris on the track (Monitoring Objective B). (Para.648 [Chapter 10]).

898 Recognising that the location and timing of the shallow slope failures and washouts that threaten to impinge on the track cannot be predicted, yet are inevitable across the network, consideration should be given to installing flexible barriers at the toe of vulnerable lengths of the cuttings. The barriers will provide temporary containment of the slide and washout debris. By instrumentation of the mesh for strain, and of the support posts for inclination, warning can be provided of where failures have occurred and attention is needed. Precedents are provided by examples in Hong Kong and on the A83 in Scotland. *We recommend that consideration be given to wider use of instrumented flexible barriers for rock and soil slopes.* (Para.649 [Chapter 10]).

899 We recognise that a pragmatic approach for interventions is often required to best manage safety and performance risk within the funds available, by targeting renewal works over the most critical earthwork lengths rather than the entire asset. However, it is very inefficient in terms of access and set -up costs in addressing repeat earthwork failures that commonly occur adjacent to previously stabilised areas. The reputation of NR also suffers from having to procure a number of works contracts at the same location in fairly quick succession. *It is therefore recommended that wherever possible NR seek to renew the entire earthworks asset and associated drainage system rather than undertake inefficient and ultimately considerably more expensive local piecemeal works.* (Para.667 [Chapter 10]).

What Can Be Learned From Other Earthworks Asset Owners?

Highways England (HE)

900 HE and NR are both founding members of the Geotechnical Asset Owners Forum (GAOF), that provides a platform for those involved with the management of geotechnical and related assets to share and exchange ideas, information, research themes and other issues. The Forum offers an opportunity for HE and NR as maturing asset organisations with a culture of

continual improvement, to collaborate on the journey to exemplary asset management. It could be particularly beneficial for the development of water asset management in both organisations, given their current relatively limited knowledge of drainage condition data and deterioration models. *We recommend that NR could gain particular benefit from reviewing HE practice in the following areas:*

+ Utilising the best practice and innovation from HE GDMS and DDMS to inform he development of NR CSAMS

+ HE approaches to assessing the resilience of the SRN to ground-related hazard events

+ HE methodology for determining drainage catchments and estimating runoff flow rate. (Para.703 [Chapter 11])

Transport Scotland

901 *It is recommended that all of Transport Scotland/TRL's post 2004 work on upland debris flows should be considered by NR in the development of any future NR strategy for identifying, assessing and managing debris flow hazards.* (Para.714 [Chapter 11]).

London Underground (LU)

902 LU have established that the key to the effective analytical assessment of earthwork slopes is a combination of analysis and monitoring (i.e. an observational approach). Monitoring and analysis, undertaken appropriately can relatively quickly identify those slopes that are most at risk of a failure occurring. This knowledge allows accurate prioritisation of renewal works to address significant earthworks safety and business risks. We recognise that given the scale of the NR earthwork asset base, it is impractical to have widespread instrumentation and monitoring. *However, we recommend the adoption of a programme of targeted analytical assessment in conjunction with observational monitoring. This will result in a significant improvement in the understanding of behaviour (and failure mechanisms) in NR earthworks and allow prioritisation decisions to be undertaken with a greater degree of certainty.* (Paras.725 and 726 [Chapter 11]).

903 The monitoring of piezometers installed in LU embankments during the wet winter of 2000/2001 and subsequent analysis has illustrated the complexity of the pore pressure regime that can develop in these embankments. This detailed knowledge and understanding of the pore pressure regime in its embankments has greatly informed the LU analytical assessment programme and stabilisation works design. However, NR has very limited knowledge of the distribution of pore water pressures in its earthwork slopes. We have recommended in Chapters 5 and 8 that consideration be given to monitoring pore pressures more widely in NR earthworks, to obtain a better understanding of the behaviour of a particular slope or embankment that is judged to be critical. (Para.730 [Chapter 11]).

Environment Agency

904 The EA process for the visual inspection and analytical assessment of its flood defence embankments are broadly equivalent to the NR earthwork examination, evaluation and assessment procedures. However, there are some key differences: the EA inspection frequency is determined on a risk basis and the period between inspections (6 months to 5 years) is mostly much shorter. We have recommended in Para 291 that the shortcomings in the NR earthworks examination system need to be addressed, and it is advised that a comparison with the EA flood defence embankment inspection and assessment process is undertaken as part of this review. (Para.759 [Chapter 11]).

905 There are distinct similarities in the failure mechanisms between the washouts NR experience as a result of water flow, following intense rainfall eroding surface material from the surface of cutting slopes, and the erosion of the landward face of a flood defence embankment. by overtopping. *It is recommended that NR review, capture, and learn any relevant lessons from the risk-based approach (based on a considerable body of research) that the EA has developed for the assessment of their flood embankments subject to erosion following overtopping.* (Para.762 [Chapter 11]).

International experience

906 *For many years the Hong Kong GEO have had a Slope Safety Technical Review Board, which meets periodically to provide expert, independent input into the management of their earthworks assets. We recommend that NR give consideration to forming a similar Review Board. (Para. 767 [Chapter 11])*

907 International experience from Hong Kong, Japan and Canada indicates that well-established surveillance technologies for slope and landslide management are LiDAR and photogrammetry (both aerial and land-based); satellite InSAR also is promising if reflector markers are used to overcome difficulties with vegetation. Wireless sensors have considerable potential for measurement of slope movements, provision of warning systems and detection of flexible barrier deformations. (Para.781 [Chapter 11]).

Research Funding And Applied Research

908 We fully support the doubling in NR's overall investment in research and development (R&D) from CP5 to CP6; it has brought R&D together under a single integrated portfolio, enabling over £30m to be invested at pace in projects specific to earthworks, drainage and resilience. The development of data analytics is also considered as a useful tool to manage a large and complex asset base and harnessing more value from existing data sets through smarter information. (Para.787 [Chapter 12]).

909 There is insufficient information on pore water pressures and suctions in slopes and embankments and on their response to different rainfall and weather patterns, yet these parameters are critical to an assessment of stability and of the efficiency of drainage. *Consideration should be given to identifying, in two distinctly different microclimates, the following:*

+ *an over-steep, unfailed slope in plastic clay*
+ *a failed slope in plastic clay*
+ *an unfailed slope in low plasticity clay*
+ *a plastic clay embankment*
+ *a granular embankment*

(Para.789 [Chapter 12]).

910 *Locations of vulnerable assets should be selected, possibly where instrumentation is already in place and can be augmented. At each site it would be preferable to carry out a closely specified and supervised ground investigation and then install an integrated instrumentation scheme which will enable the following measurements to be made and interpreted:*

+ *Pore pressures and suctions*
+ *Ground movements*
+ *Antecedent rainfall and rainfall intensity*
+ *Flow velocities in relevant drains*

At each test-bed site field observations should be made during and after rainfall. (Para.790 [Chapter 12]).

911 Historical rainfall data are now available on a relatively local scale (referred to in the WATF Report); slope geometry, geomorphology and overall setting of the asset (appreciation of catchments and third party threats) are now known with more certainty based on LiDAR surveys; mechanisms and triggers for failure are better understood on the basis of observation and numerical analysis. *We recommend a forensic reassessment of lessons learnt from all previous asset failures, including categorisation of failure modes and mechanisms, their link with local rainfall and weather patterns, and their link with geology and soil and rock characteristics.* (Para. 792 [Chapter 12]).

Chapter 14

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Appendix A

Terms of Reference for Task Force

Earthworks Task Force

An external review of Network Rail's capability to manage and understand the implications of earthworks is requested, by Lord Robert Mair. This aim is to equip Network Rail with the expertise and competence in order that it can better manage earthworks in future.

The rail industry precursor risk model shows earthworks to be our highest risk asset. There have been several different failure modes, rock falls, rotational slips, wash-outs etc. and we need to recognise the differences but also the need to improve all aspects of earthworks safety.

1. Our controls framework for earthwork assets is described by our engineering standards. The task force is to undertake an independent review of this framework. Is it effective for controlling the risks we manage? Does it place realistic demands on our frontline engineers?

2. Do we have the skills needed to manage our earthworks and drainage assets? Do we need to strengthen our teams in the regions or nationally?

3. Do we manage drainage and earthworks assets in an integrated and effective way? Or do we need greater coordination between these two engineering functions?

4. Do other organisations manage earthwork risks more effectively and what might we learn from them?

5. Are we aware of the latest technology and do we deploy it effectively? There are significant numbers of innovative technologies for monitoring, many of which are already being used by NR – are there any recent innovations that can further enhance NR's capabilities?

6. The task force should be considering both cuttings and embankments. History of embankment construction will be important and reviewing the work that has occurred on this across Network Rail and London Underground. This should include vegetation change and its link with climate change, with age of both cuttings and embankments likely to be a significant factor.

There is a need for this earthworks workstream to interface with experts on climate change and the separate review workstream being led by Dame Julia Slingo and separately the task force may need advice from a monitoring specialist (INSAR satellite technologies etc).

Appendix B

Terms of Reference for Weather Advisory Task Force

Weather Advisory Task Force

Purpose:

An external review of Network Rail's capability to manage and understand the implications of rainfall is requested through a Task Force led by Dame Julia Slingo FRS. This aim is to equip Network Rail with the expertise and competence in order that it can better manage rainfall in the future.

Rainfall can affect the railway in many ways, from flooding, washing out ballast, damaging structures (particularly bridges and culverts), washing down debris, to triggering landslips and rockfalls.

Anything that undermines the strength of the railway formation, or that can be an obstacle to trains (and thus creating a risk of derailment) is a risk that must be mitigated.

Network Rail's Safety Management System provides an assurance process for management of the cuttings, embankments, structures and drainage. These have assisted Network Rail to limit the effects of rainfall on the infrastructure. The events at Stonehaven on 12 Aug 2020 have highlighted that these risks are only mitigated by the SMS, not eliminated.

Aims:

The review is requested to explore the following questions with the objective of shaping the organisation for moving forward, better equipped to understand the risk of rainfall to its infrastructure and operations. It should draw on the latest science developments in monitoring, real-time observations, weather forecasting and climate prediction, to contribute to the following questions:

1. What level of expertise in rainfall should Network Rail employ in order that it can either manage rainfall itself, or so that it can act as an informed client when procuring specialist services?

2. To what extent is Network Rail availing itself of data and research on historical, current and future rainfall and its effects on the operational railway? How should such information be used to:

    a. understand the likely levels of rainfall today, at a location level, that may pose a risk to the operational railway;

    b. understand the potential levels of rain today and up to 10 years ahead, that could fall at a location, in order to estimate the potential damage to infrastructure that such levels could inflict;

    c. ensure that future engineering decisions (such as for drainage specifications) take account of local weather factors, and to identify where existing assets are insufficient; and

    d. track how changing land use and/or river management policies near the railway affect how quickly rain enters and leaves the system.

3. How effectively does Network Rail make use of available forecasting technology to identify where rainfall could create a risk to the railway?

    a. How can it make better use of weather monitoring technology (such as rainfall radar) and state-of-the-art nowcasting to guide decision-making during a high-impact weather event?

    b. How can Network Rail ensure that it manages the risk while keeping the system open to passengers and freight who depend on the system?

4. How extensively has Network Rail explored the potential of real-time weather monitoring technology, particularly with augmenting of different data sources (such as its asset databases), to introduce better means of identifying location specific risks?

5. How could the EWAT process be improved to take advantage of such processes?

6. What real-time weather competence and capability would support a national organisation with devolved accountability?

7. How should Network Rail use such weather expertise and competence to provide input into longer term planning or procurement decisions? This could be in earthworks engineering, or providing guidance to track and rolling stock design specifications.

When considering the questions, best practice from other industries and sectors will be included where appropriate.

For clarity, the work should focus on Network Rail's ability to deal with current rainfall levels and the associated likely outcomes over the next ten years. It should however consider potential changes in rainfall out to 2050 to ensure infrastructure investments are climate-proofed.

It is understood that the above questions will involve the procurement of specialist resources including weather analytics and forecasting, as well as how best to translate rainfall extremes to high impact hazards (e.g. surface water flooding, river flooding, landslides). A process will be agreed as part of the remit to enable this.

Appendix C

Members of the Task Force

Expert Panel

Professor Lord Robert Mair CBE FREng FICE FRS (Chair)

Emeritus Sir Kirby Laing Professor of Civil Engineering, Head of Centre for Smart Infrastructure and Construction, University of Cambridge

Dr David Hight FREng FICE FRS

Senior Consultant, Geotechnical Consulting Group

Mr Brian McGinnity CEng CGeol FICE FGS MIMMM

Former Profession Head of Civil Engineering, London Underground.

Other members of Task Force

Mr John Davis EurGeol CGeol FGS

Senior Partner, Geotechnical Consulting Group

Dr Nesha Kovacevic CEng MICE

Senior Partner, Geotechnical Consulting Group

Professor Andrew McNaughton FREng FICE

Former Technical Director HS2 Ltd, Former Chief Engineer Network Rail

Professor David Petley FRGS CGeog

Vice-President for Innovation, University of Sheffield, Former Pro-Vice-Chancellor for Research and Enterprise, University of East Anglia, Former Professor of Hazard and Risk, University of Durham

Professor William Powrie FREng FICE

Professor of Geotechnical Engineering, Former Dean of the Faculty of Engineering and the Environment, University of Southampton

Appendix D

Meetings held by Task Force with Individuals and Organisations

Network Rail Earthworks Management Task Force

Tables of meetings

Abbreviations:

GCG – Geotechnical Consulting Group

RAIB – Rail Accident Investigation Branch

RSSB – Rail Safety and Standards Board

NR – Network Rail

CEDD – Civil Engineering and Development Department (Hong Kong)

ORR – Office of Road and Rail

GEO – Geotechnical Engineering Office (part of CEDD)

STE – Safety, Technical and Engineering (Part of NR)

No.	Date	Subject of meeting	Attendees
1	09/09/2020	Discussion on RAIB role and interface with NR	+ Simon French – Chief Inspector of Rail Accidents (RAIB) + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member
2	09/09/2020	Discussion on RSSB role and interface with NR	+ Johnny Schute – Chief Inspector of Rail Accidents (RSSB) + Ali Chegini – Director, System Safety and Health – (RSSB) + Lord Robert Mair – Lead expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member
3	09/09/2020	ORR meeting	+ Ian Prosser – Chief inspector of Railways (ORR) + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member

No.	Date	Subject of meeting	Attendees
4	16/09/2020	Meeting with Simon Abbott	+ Lord Robert Mair – Chair expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Simon Abbott – Professional Head of Geotechnics (NR)
5	16/09/2020	Meeting with Mona Sihota	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Mona Sihota – Professional Head of Asset Protection, Drainage & Off-Track (NR)
6	17/09/2020	Internal Task Force meeting	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member

No.	Date	Subject of meeting	Attendees
7	22/09/2020	Meeting with MacFarlane Alastair (RAM Scotland GDOT)	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + MacFarlane Alastair – Scotland Route Asset Manager Geotechnics, Drainage & Off-Track (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)
8	22/09/2020	Meeting with Derek Butcher Geotech RAM SE	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Derek Butcher – South East Route Asset Manager Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)
9	25/09/2020	Meeting with earthworks examiner	+ Gary Cowen – Amey Earthworks Examiner + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member

No.	Date	Subject of meeting	Attendees
10	29/09/2020	Meeting with NR internal stakeholders	+ Martin Frobisher – Technical Authority Director (NR) + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + David Castlo – Professional Head of Mining & Tunnels (NR) + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)
11	01/10/2020	Meeting with Dave Patterson	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + John Davis – Expert Panel Member (GCG) + Dave Patterson – Retired, Geotechnical Asset Manager (Highways England) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
12	08/10/2020	Vision of Intelligent Infrastructure	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Michael Brown – Programme Manager STE (NR) + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Mike Edwards – Principal Engineer (Geotech) (NR)
13	08/10/2020	Discussion with Neil Strong	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Neil Strong – Environmental Manager (NR) + Mona Sihota – Professional head of Asset Protection, Drainage and Off Track + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
14	09/10/2020	Earthworks technologies	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Mike Edwards – Principal Engineer (Geotech) (NR) + Ian Payne – Senior Asset Engineer (Geotech) (NR) + Nick John – Regional Asset Manager (Geotech – Wales and Western) (NR) + Manos Tsoukalas – Senior Asset Engineer (Geotech) (NR) + Alastair MacFarlane – Regional Asset Manager (Geotech – Scotland) (NR)

No.	Date	Subject of meeting	Attendees
15	12/10/2020	Meeting with Mott MacDonald	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Chris Power – Mott MacDonald + Tim Spink – Mott MacDonald
16	12/10/2020	Meeting with Mona Sihota	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Mona Sihota – Professional head of Asset Protection, Drainage and Off Track

No.	Date	Subject of meeting	Attendees
17	13/01/2020	Meeting with Chris Ford RAIB	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Chris Ford – RAIB
18	14/10/2020	Meeting with NR internal stakeholders	+ Martin Frobisher – Technical Authority Director (NR) + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + David Castlo – Professional Head of Mining & Tunnels (NR) + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
19	14/10/2020	Whole Life costing	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Mike Edwards – Principal Engineer (Geotech) (NR) + Sunny Modhara – Whole Lifecycle Costing Specialist (NR) + Andy Kirwan – Head of Advanced Analytics (NR)

No.	Date	Subject of meeting	Attendees
20	16/10/2020	Rainfall Diagnostics for Earthworks	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Mike Edwards – Principal Engineer (Geotech) (NR) + Oliver Bratton – Director, Network Strategy and Operations (NR) + Dame Julia Slingo – Lead Expert Panel (Adverse Weather) + Jason Jordan – Programme Manager (NR) + Paul Davies – Expert Panel member (Met Office) + Hayley Fowler – Expert Panel Member (Newcastle Uni) + Juliet Mian – ARUP + Chris Merrylees – ARUP + Drew Marchant – Project Manager (NR)

No.	Date	Subject of meeting	Attendees
21	19/10/2020	Geotechnical monitoring techniques as used by Hong Kong GEO	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + John Davis – Expert Panel Member (GCG) + Frankielclo – (CEDD) + Prof Philip CHUNG (CEDD) + Thomas K C WONG (CEDD) + Dr Julian S. H. Kwan (CEDD) + Sammy P Y Cheung (CEDD)
22	19/10/2020	John Varley Review	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + John Varley – Author of Varley review, 2018 + Adam Perrett – Head of Sustainable Development (RSSB)

No.	Date	Subject of meeting	Attendees
23	27/10/2020	Meeting with NR internal stakeholders	+ Martin Frobisher – Technical Authority Director (NR) + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + David Castlo – Professional Head of Mining & Tunnels (NR) + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
24	04/11/2020	AECOM policy review	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Paul Eaves – Associate Director (AECOM) + James Todd Director, Strategic Business, Environment and Ground Engineering London (AECOM) + Katerina Braun – Katerina Braun – Associate Engineering Geologist (AECOM) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
25	04/11/2020	ACHILLES project discussion	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Christopher Power – Engineering Geologist (Mott MacDonald) + Prof. Neil Dixon – Professor of Geotechnical Engineering (Loughborough University) + Dr. Tom Dijkstra-Senior Lecturer Engineering Geology (Loughborough University) + Prof. Stephanie Glendinning – Professor of Civil Engineering (Newcastle University) + Will Lever – Graduate Engineer (NR) + Usman Ahmed – Graduate Engineer (NR)
26	10/11/2020	PIM Discussion	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Brian Tomlinson – Chief Systems Assurance Engineer (NR) + Will Lever – Graduate Engineer (NR) + Usman Ahmed – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
27	10/11/2020	ORR Meeting with taskforce	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Howard Taylor + Christopher Davies + Will Lever – Graduate Engineer (NR) + Usman Ahmed – Graduate Engineer (NR)
28	11/11/2020	Discussion with David Hutchinson	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + David Hutchinson + Will Lever – Graduate Engineer (NR) + Usman Ahmed – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
29	12/11/2020	Meeting with Drainage and Off-Track Section Managers	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Mona Sihota – Professional Head, Drainage and Off-Track (NR) + Helen Kane – Off Track Section Manager (NR) + Adrian Mansfield – Off Track Section Manager (NR) + Michael Watson – Off Track Section Manager (NR)

No.	Date	Subject of meeting	Attendees
30	13/11/2020	Meeting with NR internal stakeholders	+ Martin Frobisher – Technical Authority Director (NR) + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + David Castlo – Professional Head of Mining & Tunnels (NR) + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)
31	13/11/2020	Meeting with Katerina Braun	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Katerina Braun – Katerina Braun – Associate Engineering Geologist (AECOM) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
32	18/11/2020	Meeting with Ian Prosser (ORR)	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Ian Prosser – ORR + Dame Julia Slingo – Lead Expert Panel (Adverse Weather) + Jason Jordan – Programme Manager (NR) + Hayley Fowler – Expert Panel Member (Newcastle Uni) + Drew Marchant – Project Manager (NR)
33	20/11/2020	Meeting with Julian Harms (RAM Drainage and Off Track)	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Julian Harms – Route Asset Manager (Drainage and Off Track)

No.	Date	Subject of meeting	Attendees
34	23/11/2020	Air Operations Meeting	+ Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR) + Rikke Carmichael – Head of Air Operations (NR) + Sean Leahy – National Aerial Survey Specialist (NR)
35	24/11/2020	Flood defence earthworks asset management discussion	+ Brian McGinnity – Expert panel member + Jim Barlow – Deputy director Asset Performance and Engineering (EA)
36	27/11/2020	Meeting with NR internal stakeholders	+ Martin Frobisher – Technical Authority Director (NR) + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)

No.	Date	Subject of meeting	Attendees
37	30/11/2020	Earthworks Failure Power BI	+ David Hight – Expert panel member (GCG) + Brian McGinnity – Expert panel member + Simon Abbott – Professional Head of Geotechnics (NR) + Will Lever – Graduate Engineer (NR) + Ed Moss – Mott MacDonald
38	11/12/2020	Meeting with internal NR stakeholders	+ Martin Frobisher – Technical Authority Director (NR) + Lord Robert Mair – Chair, expert panel (GCG) + David Hight – Expert Panel Member (GCG) + Brian McGinnity – Expert Panel Member + David Castlo – Professional Head of Mining & Tunnels (NR) + Simon Abbott – Professional Head of Geotechnics (NR) + Usman Ahmed – Graduate Engineer (NR) + Will Lever – Graduate Engineer (NR)

Appendix E

Earthworks Asset Management

E.1 History

912 The railway network in Great Britain was mostly built in the mid-19th century. Soil cuttings were excavated by pick and shovel, and rock cuttings were blasted using gunpowder. Horse-drawn wagons transported the material to fill areas where the soil or rock was end- or side tipped to form poorly compacted embankments, Skempton, (1996). Between 1834 and 1841, nine main line railways were built in England, totalling 1060 km with some 54,000,000 m^3 of excavation, most of it used in constructing embankments. This was a remarkable quantity feat, and was not achieved again on works of a comparable nature until the introduction of modern earthmoving plant on the first motorway contract, more than a century later.

913 Prior to rail privatisation in 2003, British Rail (BR) did not have a national strategy for the management of earthworks. The local BR permanent way organisation was responsible for the safety of the operational railway infrastructure and part of this was the inspection and minor maintenance of track formation, drainage and earthworks. A small, centralised BR soil mechanics resource was available to support local permanent way managers, by providing specialist support such as testing, analysis, interpretation and design capability.

914 Local permanent way teams were required to maintain a broad range of infrastructure activities, including drainage and vegetation works. The local permanent way teams routinely monitored identified problems with earthworks, carried out remedial works as far as they were capable and used specialist resources in a reactive manner when problems arose. When geotechnical requirements extended beyond the control, resources or understanding of the local team a request for specialist assistance would be made, initially through the Regional Civil Engineer's organisation.

915 After BR privatisation in 1994, Railtrack carried out its infrastructure maintenance, primarily using external contractors through infrastructure maintenance contracts. These contracts focussed on predictable day-to-day activities associated with track and signalling. In an attempt to make the maintenance contracts as efficient as possible, many specialist activities, such as earthwork inspections and related reactive works were placed outside their scope. At that time the overarching management requirements for earthworks were specified in a Railway Group Standard GC/RT 5151 "Safe Asset Management – Embankments and Cuttings", Railtrack (1995) which was first issued in 1996. This Group Standard set out the generic principles for categorising, recording, examining and evaluating earthworks. The details and criteria to be applied were to be determined by the infrastructure controller. The management of earthworks was a direct responsibility of the Railtrack Zone organisations, with consultants being engaged by the Zone to undertake technically specialised work. The responsibility for earthworks stewardship varied from zone to zone; generally being allocated to the Track Engineer or Structures Engineer. Budgetary provisions remained similar to BR's and focussed on remedial works to address emerging problems.

916 During the post privatisation period, a number of earthworks failures occurred which it was considered may have been preventable had an earthworks inspection and assessment regime been in operation. Consequently, in 1997 Railtrack issued a procedure for the management of embankments and cuttings, Railtrack (1997).

917 Railtrack North West was the first to appoint a Regional Earthworks Engineer in 2000. This was partly as a consequence of an incident at a site that had previously been inspected, but not acted upon. This particular appointment carried responsibility for asset stewardship within that Region. Other Regions followed with the appointment of earthworks engineers, but not all positions carried stewardship responsibility; some were in house specialist advisors.

918 The procedure, Railtrack (2002), for the management of embankments and cuttings was revised in 2002 and additionally covered the management of natural slopes as well as of embankments and cuttings.

919 Network Rail Ltd took over control of the railway infrastructure in Great Britain by buying Railtrack plc, which was in "railway administration", in October 2002.

920 In 2005 the NR standard for earthwork examination was introduced, NR (2005). A key feature of the new standard was the inclusion of the Slope Stability Hazard Index which used an algorithm to assess earthwork failure risk. 2005 also saw the introduction of a GISmo mobile handheld computing device to collect examination data electronically.

921 In 2004/05 formal Earthwork failure reporting commenced.

922 As more comprehensive earthwork inspection and failure records became available, the extent and cost of remedial works became evident. The NR Regions, now known as Territories, recruited more in-house earthwork engineers and engaged term-contractors for earthworks inspection and framework contractors for physical remedial works. These teams were led by Territory Earthworks and Drainage Engineers, and included specialists in the fields of both drainage and earthworks.

923 RAIB investigated earthwork failures at Oubeck in November 2005, RAIB (2006a) and Moy in November 2005, RAIB (2006b). The investigation into the derailment at Kemble on 15 January 2007 RAIB (2008a) found features in common with these earlier failures. This raised a broader question regarding the management of the earthworks on the NR network. As a result, the RAIB decided to investigate the overall Network Rail process for the management of its earthworks, RAIB (2008b). Six improvement recommendations relating to the management of earthworks were made to NR as a result of this investigation.

924 In 2012 an Asset specific CP5 Earthwork Policy, NR (2012) was issued for the first time. It has been regularly updated since and the current version 8 was issued in January 2018, NR (2018c).

925 Following a series of derailments of passenger trains as a result of earthworks failures in the unusually wet summer of 2012, RAIB undertook a Class investigation into landslips affecting Network Rail infrastructure between June 2012 and February 2013, RAIB (2014). Consequently, ORR carried out enforcement action. Recognising that NR earthworks could not quickly be brought up to modern, resilient design standards, ORR required NR to focus on the consequences of asset failure so that it could target contingency arrangements for extreme weather in a prioritised, risk-based way. This is the ORR philosophy: to optimise mitigation of risk where elimination is not reasonably practicable.

926 Although there have been comparable numbers of earthworks failures before and after ORR's Improvement Notice in 2012 there were far fewer derailments. In fact, until the derailment and subsequent collision of a passenger train at Watford tunnel on 16 September 2016, RAIB (2017) there had been no derailments since the response to ORR enforcement in 2012, indicating greatly improved management of the consequences of failure. This improved earthwork safety record was achieved despite Storm Desmond and other extreme events in December 2015 – the wettest calendar month on record at the time for the UK.

927 In 2014/15 an evidence based statistical examination system was deployed into the NR business (Power et al, (2016).

928 ORR served an Improvement Notice in February 2015 as NR had not demonstrated effective management of risks arising from drainage systems whose inadequate capacity, or degraded performance, may allow uncontrolled flow of water to affect the stability of soil cuttings, leading to landslip. The NR response enabling closure of the notice was a commitment to complete the drainage inventory within CP6 (2019-2024) and in the short-term a focus on the inspection and maintenance of drainage at high-risk soil cuttings.

929 In 2016 the NR Earthworks Asset inventory was completed.

930 In 2018 the Earthworks Technical Strategy, NR (2018d) was issued for the first time.

E.2 Standards and Procedures

931 The Management of Earthworks Manual, NR (2019) sets out process which at a high level defines the geotechnical controls mitigating the risks of:

+ loss of track support and/or track geometry
+ slope failure leading to loss of kinematic envelope and/or track geometry

932 This standard applies to all earthworks within the boundary of the NR infrastructure (including approach embankments, approach cuttings, slopes above tunnel portals, nailed or reinforced soil structures and any embankment that also acts as a coastal, estuarine or river defence – irrespective of its height).

933 The Management of Earthworks Manual, NR (2019) is supported by 13 modules, detailed in Table E1 below that comprise the procedures which form the overall earthworks management process.

Reference Number	Title	Issue	Publication Date
NR/L2/CIV/086	Management of Earthworks Manual	9	02/03/2019
NR/L2/CIV/086/Mod01	Earthwork Evaluations	1	02/09/2017
NR/L2/CIV/086/Mod02	Earthwork Assessment	1	02/03/2018
NR/L2/CIV/086/Mod03	Geohazard Assessment	1	02/03/2019
NR/L2/CIV/086/Mod04	Earthwork Interventions	1	02/09/2017
NR/L2/CIV/086/Mod05	Earthwork Mitigations	1	02/09/2017
NR/L2/CIV/086/Mod06	Earthwork Monitoring Strategy Selection and Implementation	1	02/09/2017
NR/L2/CIV/086/Mod07	Selection and Implementation of Operational Restrictions	1	02/09/2017
NR/L2/CIV/086/Mod08	Selection and Implementation of Temporary Restraints	1	02/09/2017
NR/L2/CIV/086/Mod09	Adverse/Extreme Weather Prioritisation	1	02/09/2017
NR/L2/CIV/086/Mod10	Geotechnical supervision of civil engineering works (to be developed)		
NR/L2/CIV/086/Mod11	Definition of Earthwork Derailment Risk Models	1	02/09/2017
NR/L2/CIV/086/Mod12	Definition of Earthwork Asset Criticality	1	02/09/2017
NR/L2/CIV/086/Mod13	Management of Vegetation on Earthworks	1	01/09/2018

Table E1: Management of Earthworks Manual and its supporting modules

934 Earthwork visual inspections are carried out in accordance with the Examination of Earthworks Manual, NR (2017a). These examinations are intended to confirm the asset failure likelihood and to qualitatively assess its ability to perform its function. This manual describes the procedures for carrying out earthwork examinations, and identifies actions to be taken to mitigate the following risks:

+ loss of track support or track geometry
+ slope failure leading to loss of kinematic envelope or track geometry

935 Further commentary on the Earthworks examinations is given in Para 268 to Para 300

936 The Examination of Earthworks Manual, NR (2017a) is supported by 4 modules, detailed in Table E2 below that comprise the procedures which form the overall earthworks examination process.

Reference Number	Title	Issue	Publication Date
NR/L3/CIV/065	Examination of Earthworks Manual	6	02/09/2017
NR/L3/CIV/065/Mod01	Definition of Risk Evaluation Matrix	1	02/09/2017
NR/L3/CIV/065/Mod02	Definition of Soil Cutting Hazard Index	1	02/09/2017
NR/L3/CIV/065/Mod03	Definition of Rock Slope Hazard Index	1	02/09/2017
NR/L3/CIV/065/Mod04	Definition of Soil Embankment Hazard Index	1	02/09/2017

Table E2: Examination of Earthworks Manual and its supporting modules

937 The procedure for reporting geotechnical incidents is undertaken in accordance with the Management of Reports of Safety Related Geotechnical Incidents procedure, NR (2020h). Appendix A in NR (2020h) defines the criteria for reportable and non-reportable geotechnical incidents. Reportable geotechnical incidents include the following earthwork failure types:

+ Slope failures
+ Failures of nailed or reinforced soil structures
+ Failures of rock slope support systems
+ Mining related failures

938 The procedure for reporting earthwork failures (referenced as the M6 regulatory condition measure which is reported by NR in its annual return to ORR as part of its operating licence) are documented separately under the reporting of the M6 Regulatory Measure for Earthwork Failures procedure, NR (2020i). The M6 Regulatory Measure is defined as the rolling annual average number of earthworks failures measured over five years (65 Periods). Earthwork failures are defined as cutting and embankment slopes in a state of collapse.

939 The aim of Network Rail's standards is to achieve a safe, high performing, cost efficient railway system. NR are aware that their supply chain often perceives the standards as overly complex and adding unnecessary cost. Therefore, NR invite suppliers and other stakeholders via their challenge process to raise a challenge to a standard where they consider it to be incorrect, not enable the application of modern/best practice, or drive increased cost without comparable benefit. Suppliers and other stakeholders can also proactively suggest better ways of maintaining and enhancing the railway.

E.3 Earthworks Examination Development

940 The current NR earthworks' examination regime has been developed through stages from the mid 1990's and the current principles and processes are comparable with the inspection process of other UK major earthworks asset owners.

941 BR did not have a formal process for the examination of earthworks. Following the privatisation of BR in 1994, Railtrack plc took control of the railway infrastructure and employed consultants to develop a method of examination and evaluation for earthworks. This resulted in the issue of the company procedure for the management of embankments and cuttings, Railtrack (1997). This procedure defined relevant earthworks as those greater than 3 m in height, and those below this height which were known sites of instability, (Figure E1). For the purposes of management and examination, earthworks were divided into 5 chain (110 yards, approximately 100m) segments as illustrated below in Figure E2.

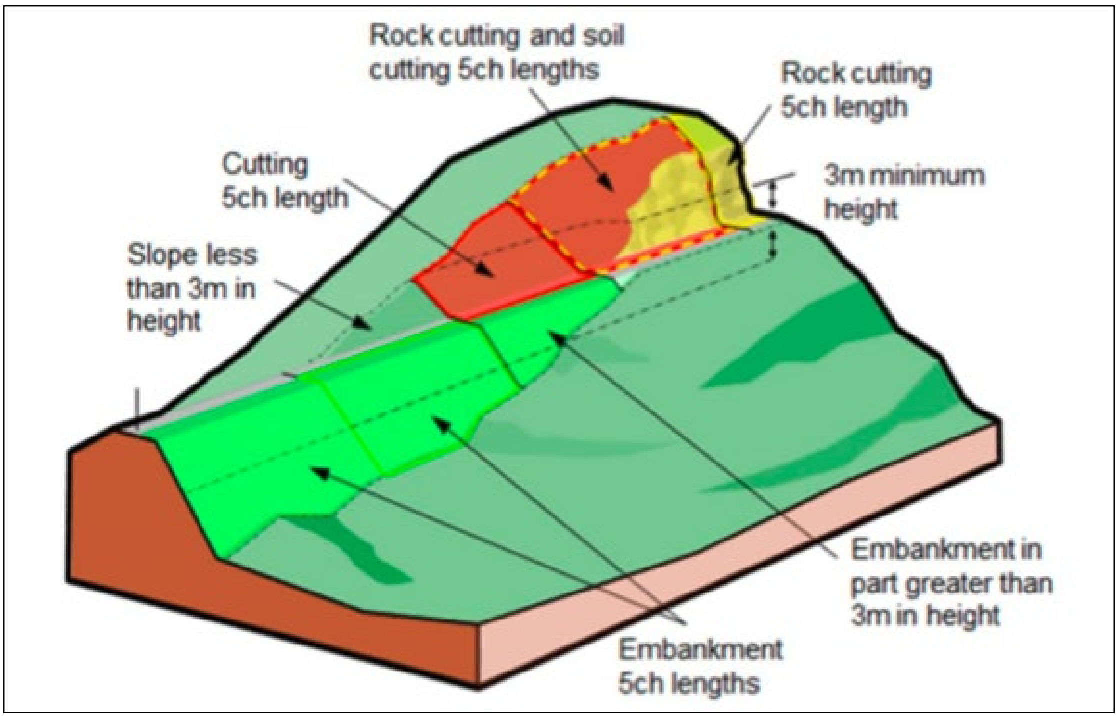


Figure E1: Definition of Earthworks, after NR (2018c)

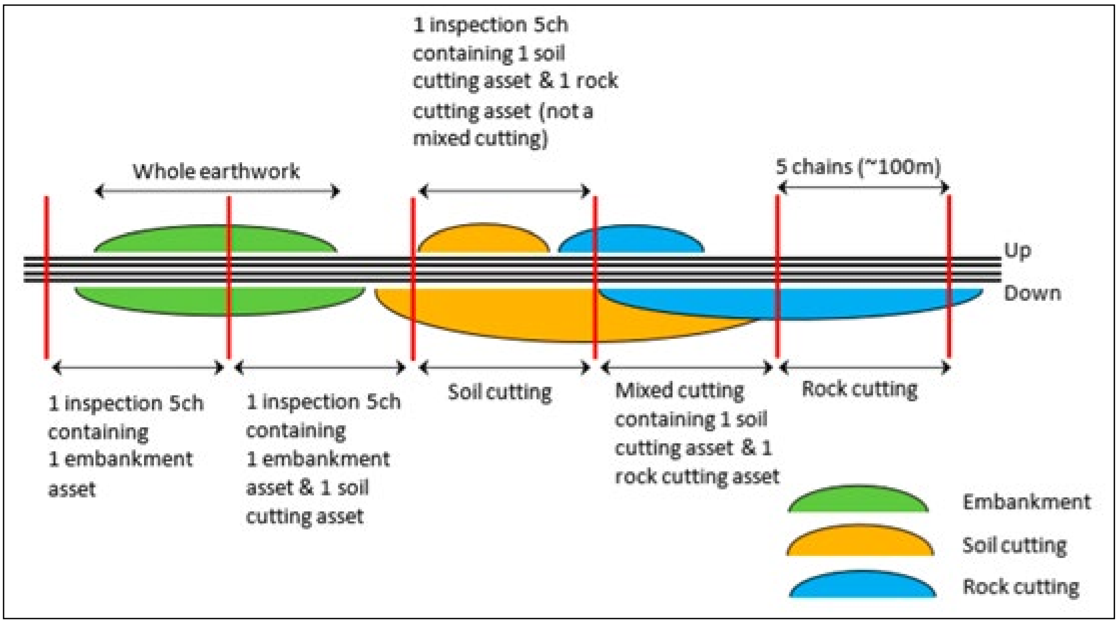


Figure E2: Segmentation of Earthworks, after NR (2018c)

942 The procedure, Railtrack (1997) required these earthworks and their associated drainage to be physically inspected and then evaluated for condition in accordance with the prescribed marking scheme.

943 The parameters that were recorded from the examination process could be broken down into three categories as follows:

+ Evidence of past, ongoing or imminent failures, such as toe bulge or tension cracks
+ Factors that could influence the likelihood of future failure, even if no failure has yet occurred, such as the geology of the slope, surcharging at the top of a cutting or the slope angle
+ Factors that could influence the magnitude of a slope failure, i.e. the slope height

Figure E3: Typical Slope Defects and Movement Indicators recorded in the Examination Process

944 The output from this examination process was also used to determine the requirement for any further assessment of the earthworks. The earthworks examination procedure, Railtrack (1997) was intended to provide a means of readily comparable results.

945 However, implementation of the Railtrack examination procedure was varied and inconsistent across the Railtrack Zones (which subsequently became Regions). Railtrack North West was the first to appoint an Earthworks Engineer in 2000. This was partly as a consequence of an incident at a site that had previously been inspected, but not acted upon. This particular appointment carried responsibility for Earthwork asset stewardship within that Railtrack North-West. Other Railtrack Zones/Regions followed with the appointment of earthworks engineers, but not all positions carried stewardship responsibility; some were in house specialist advisors.

E.4 Earthwork Classification System Development

946 The procedure, Railtrack (2002) for the management of embankments and cuttings and natural slopes introduced the concept of a classification system for each earthwork element as 'poor', 'marginal', or 'serviceable'. This procedure also prescribed earthwork examination frequencies of 1, 5 and 10 years respectively, with maximum permitted increases to inspection intervals of 4, 6 and 12 months respectively.

947 In order to manage the large amounts of condition data collected by Earthwork examiners and to promote consistency in the Earthwork management system, Railtrack (2002) implemented a process which allocated scores to many of the earthwork characteristics e.g., slope height, slope angle, drainage, vegetation recorded during examinations.

948 The process then used an algorithm to combine these scores and give a composite score intended to reflect the overall condition of the earthwork, Manley et al. (2003), Network Rail (2004). The algorithm was designed so that the output was transparent and could easily be tracked from the source data. The algorithm was not an analytical process, rather a semi-quantitative indication of general condition. It was based upon simple manipulation of empirical observations obtained from a combination of desk studies and site walkover inspections. This composite score, designated the Soil Slope Hazard Index (SSHI) for soil slopes was used to categorise the earthwork as "Serviceable", "Marginal" or "Poor" by comparison with predefined bands and was used to assess earthwork failure risk. A further category of "Top Poor" was added later to the Hazard Index.

949 NR took over control of the railway infrastructure in Great Britain by buying Railtrack plc, which was in "railway administration", in October 2002. The earthworks examination process was further refined, and in June 2005, Railtrack (2002) was withdrawn and the technical elements included in the Examination of Earthworks standard, NR (2005) which is often referred to as 'the 065 standard'.

950 The "065" standard, (NR (2005) introduced the Rock Slope Hazard Index (RSHI) for the examination, and categorisation of NR rock slopes. RSHI was largely based on the pioneering work by TRL for prioritising road rock slope cuttings in Scotland (TRL, 2011).

951 2005 also saw the introduction of a GISmo mobile handheld computing device to collect examination data electronically. Photographs of slope defects could also be captured digitally by the device. The structured examination data was synchronised onto a web based geographic information system (GIS) and used to undertake the earthwork examination and evaluation management.

952 The Soil Slope Consequence Index was a mechanism to provide a further level of risk differentiation between slopes assessed as being in otherwise similar condition. It used parameters associated with the operating railway to assess the risk to trains. The overall Soil Slope Risk Factor was the multiple of Slope Stability Hazard Index and Soil Slope Consequence Index

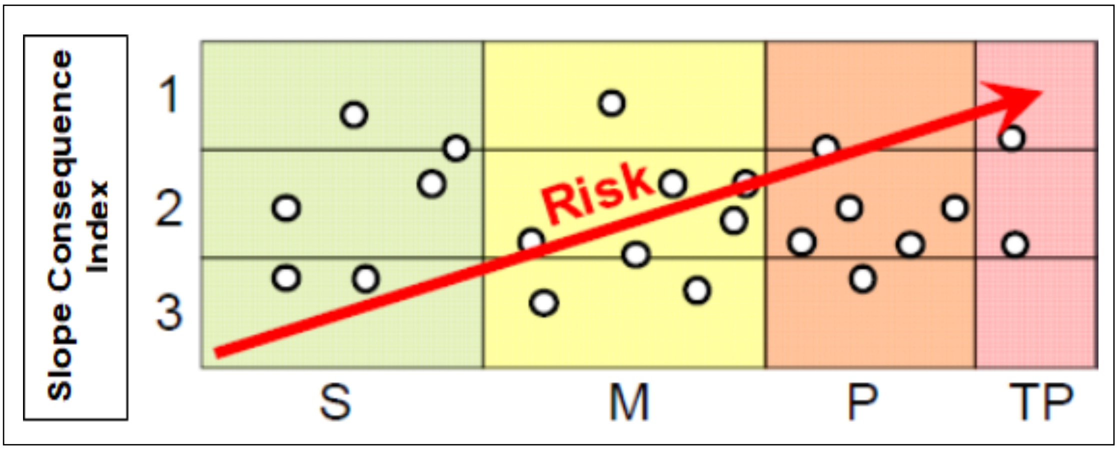


Figure E4: Soil Slope Risk Factor

953 The Risk Evaluation Matrix (REM) was also created, initially as a means of verifying that the newly introduced (quantitative) soil slope and rock slope hazard indices (SSHI and RSHI) were in broad agreement with engineering judgement of experienced railway earthworks inspectors.

Figure E5: Risk Evaluation Matrix (REM)

954 REM has been retained within the Network Rail examination methodology as a means of allowing engineering judgement to be recorded by examiners. Its calculated output against an earthwork inspection 100m asset did not feed into the overall Soil Slope Risk Factor (or its successor Earthworks Safety Risk Matrix). The REM is used to carry out a subjective assessment of the risk posed to the safe operation of the railway from earthworks subject to examinations, in line with NR (2017a).

955 In 2012, NR commissioned Mott Macdonald to review the Earthworks condition-based Soil Slope Hazard Index (SSHI) and Rock Slope Hazard Index (RSHI), Mott MacDonald (2012). The review concluded, whilst the Hazard Index was performing well as a works prioritisation tool, an unacceptable number of earthworks were failing that were indicated to be in the best two condition categories ("Serviceable", or "Marginal"). A decision was taken to attempt to improve the ability of the Hazard Index to predict earthworks failure insofar as possible with an asset group that is inherently unpredictable, and where failure is so dominated by climatic and other external factors.

956 The Soil Cutting and Embankment examination scoring process was addressed as a priority. The condition of NR earthworks is primarily evaluated through visual, site-based examination (inspection) of a number of parameters (such as tension cracks, presence of retaining walls, presence and performance of drainage), supplemented by desk study for further parameters (such as geological composition). An algorithm is used to combine scores given to each parameter to obtain a numerical score (Total Hazard Index) for each earthwork asset. This improvement work determined new optimised algorithms based on analysis of over ten years of legacy field examination data and failure records, NR (2014b).

957 Analysis of the available data, Power et al (2016) for both the whole population of earthworks, and just those examination records made prior to a recorded failure, was carried out for each parameter (approximately 200 for each of the soil cuttings and embankments), as shown in Figure E6.

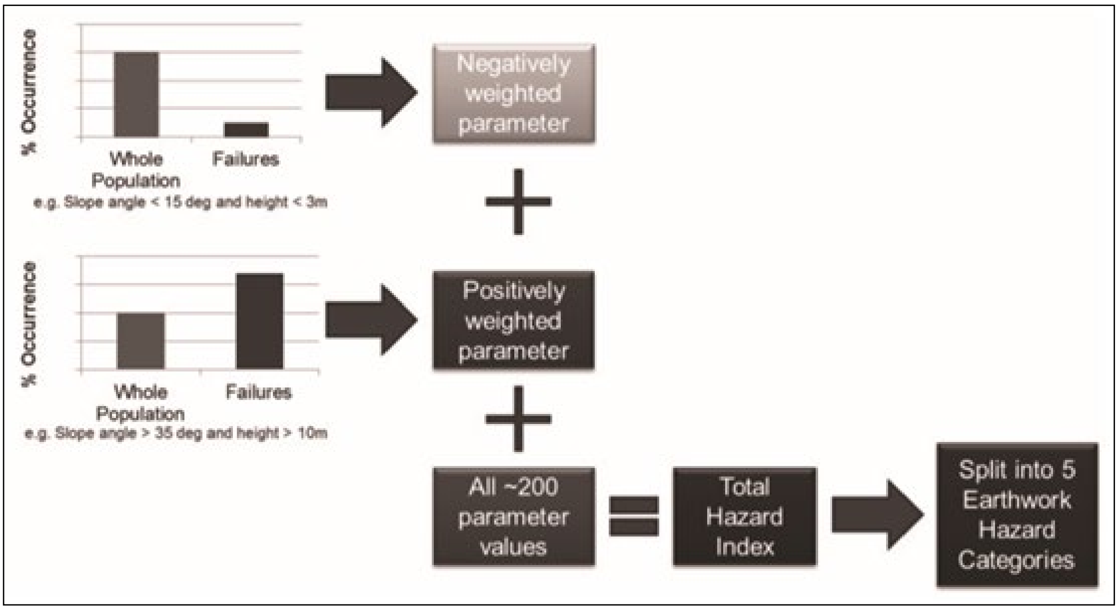


Figure E6: Analysis process to improve Hazard Index Algorithm (after Power et al (2016))

958 For each 100 m earthwork segment a hazard score was derived by applying a weighting to each observed parameter; the value of the weighting factor is derived by statistical analysis of the importance of each parameter as a precursor indicator of slope failure (Figure E7). Parameters more prevalent in the pre failure examination of failed earthworks than the whole population of earthworks were given a positive weighting in the new algorithm. Those more prevalent in the whole population were negatively weighted. The parameter weightings were then summed and the resultant Soil Embankment Hazard Index (SEHI) and Soil Cutting Hazard Index (SCHI) scores segmented into the five EHCs, ranging from A (lowest Hazard Indices, lowest likelihood of failure) to E (highest Hazard Indices, highest likelihood of failure).

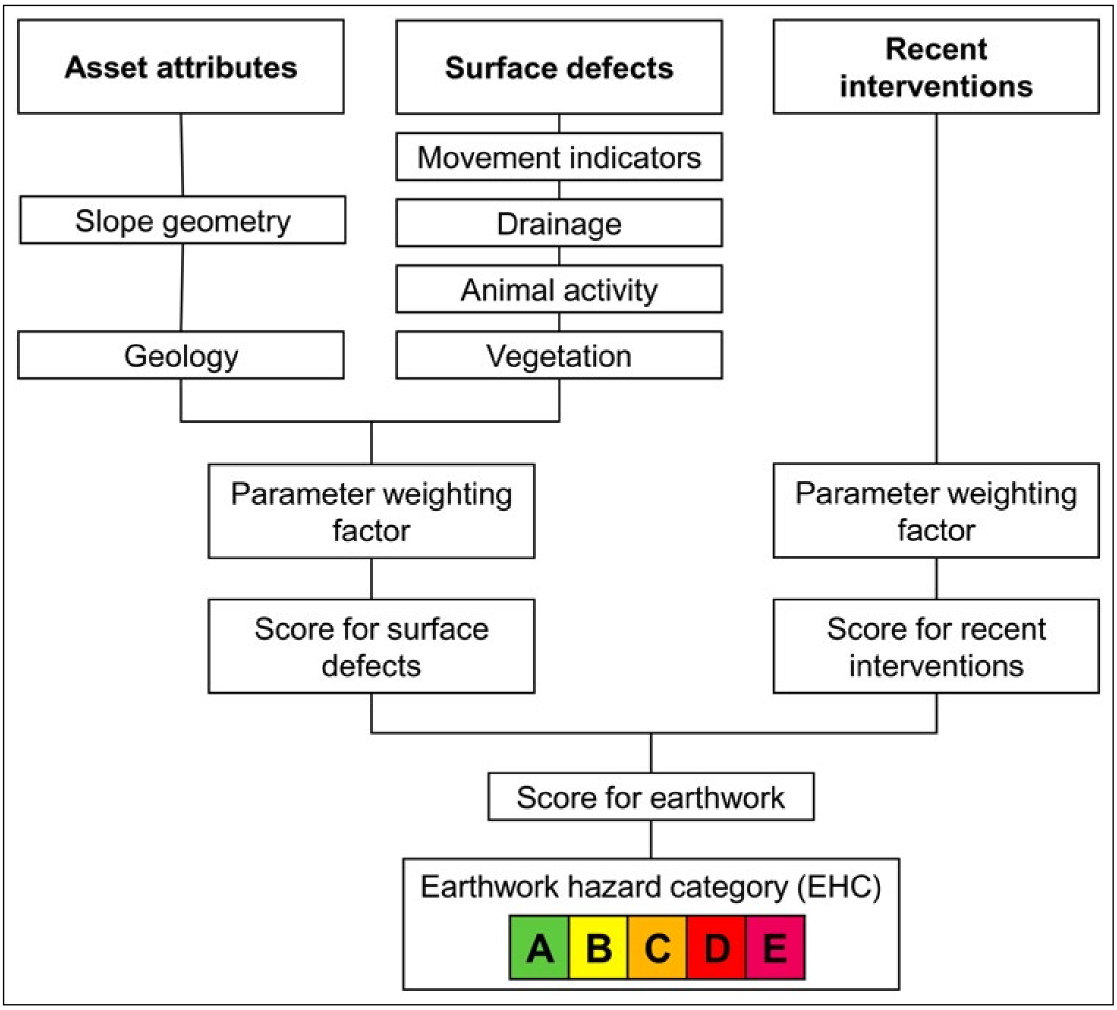
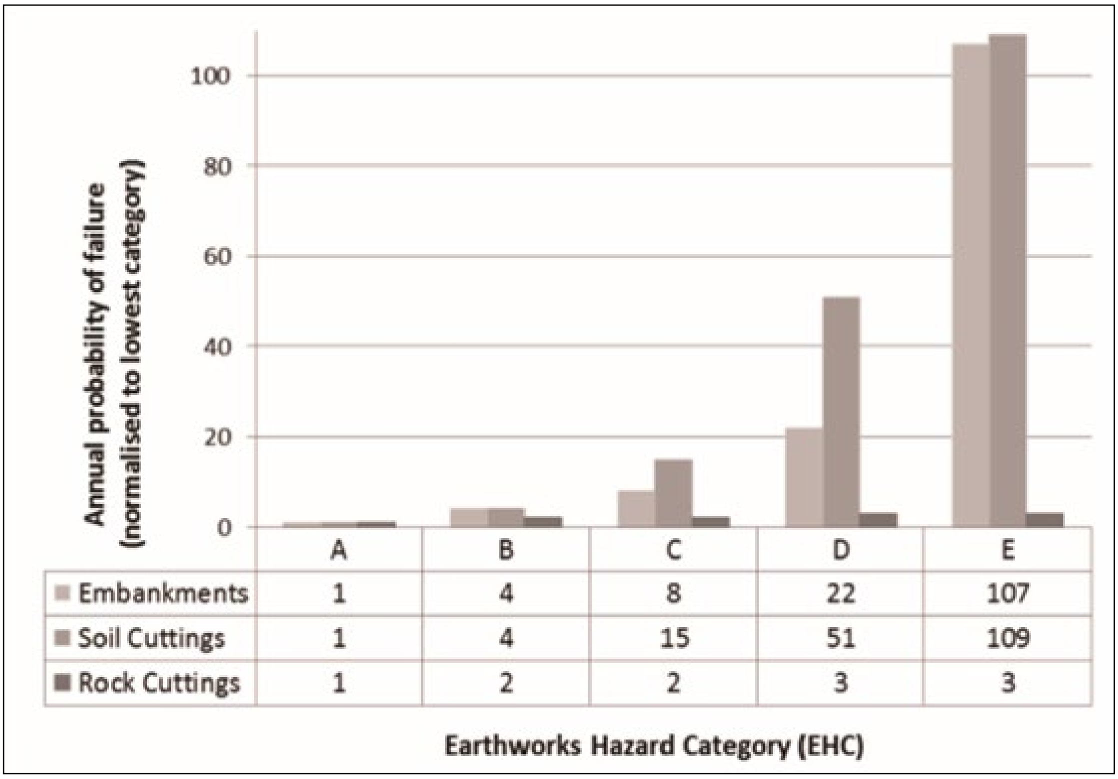


Figure E7: Derivation of the Earthwork Hazard Category (EHC) (after Spink (2020))

959 Because the number of assets in each EHC is known, and the number of failed earthworks in each category is also known, a comparison of the statistical likelihood of failure of an asset in each category can be carried out (see Figure E8 below).



	A	B	C	D	E
Embankments	1	4	8	22	107
Soil Cuttings	1	4	15	51	109
Rock Cuttings	1	2	2	3	3

Figure E8: Annual probability of failure (normalised to the lowest EHC category) for each EHC and each earthwork asset type) (after Power et al (2016))

960 In Figure E8, the annual probability of failure in each EHC has been normalised to the value in EHC A. With the previous Hazard Indices, an embankment or soil cutting in the worst condition category was 10 to 20 times more likely to fail than one in the best condition category. It can be seen in Figure E8 that this multiplier was improved by the new algorithms to over 100, an order of magnitude improvement in the ability to predict earthworks failure.

961 The Earthworks Asset Policy, NR (2014c) and Examination Standard, NR (2014d) were updated in 2014 with this new 5-band hazard-based classification system. For soil embankments and soil cuttings the previous failure likelihood metric (Soil Slope Hazard Index) was replaced with the Soil Embankment Hazard Index (SEHI) and Soil Cutting Hazard Index (SCHI) which NR believed better able to predict the propensity for failure as they exhibited a stronger correlation with its records of previous failed earthworks.

962 Mott MacDonald were commissioned by NR in 2018 to improve the Rock Cuttings Hazard Index (either by amending the existing algorithm, or by generating a new one) to bring rock cutting failure rates closer to those seen in soil cuttings and embankments, whilst preserving the existing historical data and ensuring that engineering sense was maintained. The new 5-band A to E hazard-based classification system was applied to rock cuttings in 2018 with the development of a Rock Slope Hazard Index (RSHI), NR (2018m).

E.5 Determination of the Consequences of Earthwork Failure

963 It is a fundamentally important feature of a risk-based prioritisation approach that asset management decisions are made on the basis of the consequence of a potential earthwork failure as well as its likelihood. In practice, this means that an earthwork in moderate condition could be prioritised for intervention above one in worse condition, if its failure could lead to a catastrophic safety incident, whereas the failure of the latter, for example being on a section of single track with lower speed trains, would pose an overall lower safety risk.

964 NR used a quantitative earthwork criticality as a measure of failure consequence for a number of years. However, as part of the enhancement of the risk management approach, a new criticality measure was developed known as the Earthworks Asset Criticality Band (EACB), Power et al (2016).

965 The range of possible Asset Criticality scores for each earthwork type is segmented into five bands designated 1, 2, 3, 4 and 5 termed the Earthworks Asset Criticality Band (EACB). The EACB can be related to the likely safety consequence of an earthwork's failure. Band 1 has the lowest consequence, and band 5 has the highest consequence. The units of EACB are Fatalities and Weighted Injuries (FWI) per earthworks failure and are used to allocate a band from 1 to 5. These bands are the same for each earthwork type (soil cutting, rock cutting and embankment) although the quantitative consequences for a given band vary between the earthwork types.

966 The EACB forms the y-axis of the earthwork's safety risk matrix (see Figure E9 below) which is utilised in a risk-based procedure to identify and prioritise earthworks interventions and mitigations, NR (2019)

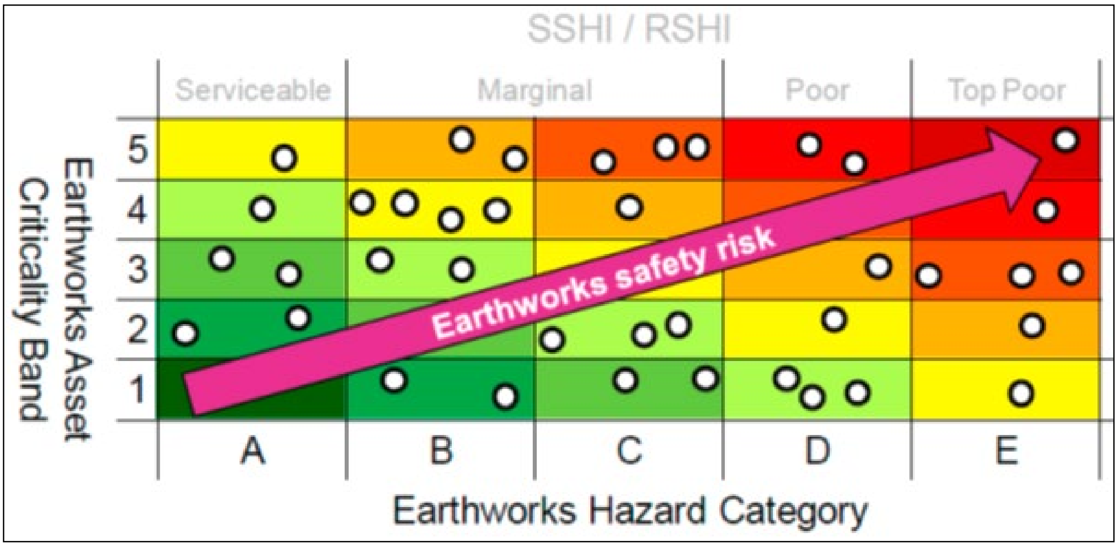


Figure E9: Earthwork Safety Risk Matrix – relationship of EACB (y-axis) with EHC (x-axis) – and the former SSHI and RSHI metrics

967 The EACB for an individual earthwork is a combination of two components:

+ The probability of an earthwork, having failed, causing a train derailment. This is based on a number of factors including the likely size and hardness of the failed material, but also factors such as the distance of the slope from the rails
+ The potential safety consequences of a train derailment at a given location derived through the NR Common Consequence Tool (CCT). It takes into account factors such as the maximum speed of trains on the line, whether a derailing train is likely to hit an oncoming train or a hard structure at the side of the track

968 The CCT component is 'agnostic' of the original cause of the derailment, but highly dependent on the location and the physical features present, factors which are in fact 'common' to a train derailment resulting from the failure of any asset type. CCT is also applied as part of the risk assessment to other NR asset types, not just earthworks. CCT uses the probability event tree approach illustrated in Figure E10 below to estimate the severity of a potential train derailment, expressed as the predicted number of deaths and injuries through a widely used safety metric, the Fatalities and Weighted Injuries (FWI).

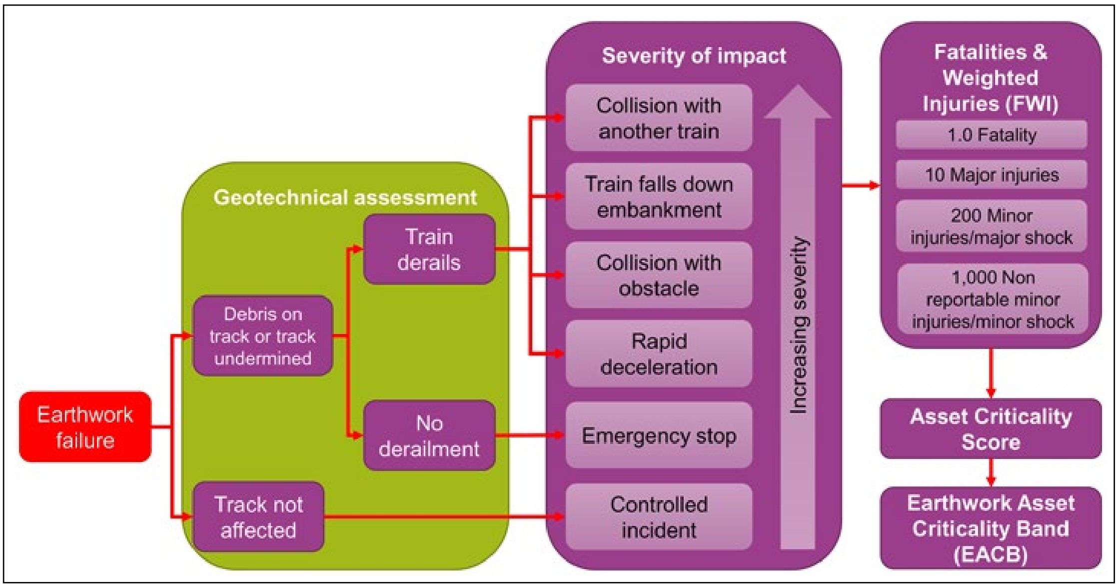


Figure E10: Derivation of EACB after Spink 2020)

E.6 Current NR Earthwork Examination Process

969 The examination of NR earthworks assets is currently undertaken in accordance with Examination of Earthworks Manual, NR (2017a) – 'the 065 standard'.

970 The 065 Standard applies to the following:

- All earthworks within the boundary of the NR infrastructure (including approach embankments, approach cuttings, tunnel cuttings, slopes above tunnel portals, nailed or reinforced soil structures and any embankment that also acts as a coastal, estuarine or river defence – irrespective of its height)
- Approach embankments applies to overline bridges that are equal to or greater than 3 metres high, except those owned by a Highway Authority, Roads Authority or other competent authority
- Reinforced soil structures apply to those whose face angle is less than or equal to 70 degrees to the horizontal

971 The NR earthworks examination process establishes asset condition by scoring a wide range of criteria which define the earthwork shape, its composition, drainage and surrounding environment and which could have a bearing on its stability or vulnerability to failure.

972 The examination of soil embankments, soil cuttings and rock cuttings, are evaluated to different criteria for each slope type, to reflect the different behaviour of each asset type.

973 Where an earthwork contains both soil and rock elements, both are examined using the appropriate system, so that it is possible for there to be two (or more) earthwork assets for the same inspection 5 chain (100m) length,

974 The factual examination data are analysed to determine a Hazard Index score for each earthwork asset. An algorithm is applied to the parameters observed in an earthwork examination to obtain a numerical score for each earthwork asset, NR (2014b), NR (2016a). The scoring algorithms are different for each earthwork type (soil cutting, rock cutting and embankment), and are defined in the following:

+ NR/L3/CIV/065/Mod02: Module 2. Definition of soil cutting hazard index. Issue 1. NR (2017h)
+ NR/L3/CIV/065/Mod03: Module 3. Definition of rock slope hazard index. Issue 1., NR (2017i)
+ NR/L3/CIV/065/Mod04: Module 4. Definition of soil embankment hazard index. Issue 1. NR (2017j)

975 The range of possible Hazard Index scores for each earthwork type is segmented into five categories designated A, B, C, D and E and termed the Earthworks Hazard Category (EHC). The EHC can be related to the statistical likelihood that the asset may fail. Category A is statistically least likely to fail, and category E is statistically most likely to fail. The categories A to E are the same for each earthwork type (soil cutting, rock cutting and embankment) although the failure probabilities for a given category vary between the earthworks type.

976 The EHC forms the x-axis of the earthworks safety risk matrix which is utilised in a risk-based procedure to identify and prioritise earthworks interventions and mitigations.

977 The NR Earthworks Policy (2018) is focused on the management of safety risk, which can be measured by the distribution of assets within the Earthworks Safety Risk Matrix (ESRM), (Figure E11) which is formed from the EHC (Appendix E4) and EACB (Appendix E5 above).

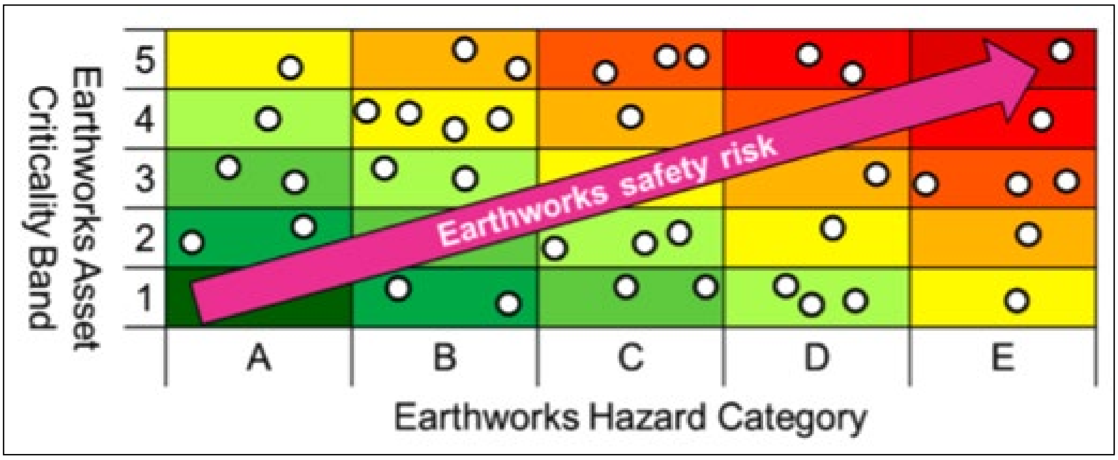


Figure E11: Earthworks Safety Risk Matrix (ESRM)

978 NR's examination frequencies are determined based on asset failure likelihood (via EHC scoring), with the assets considered most likely to fail subject to the most frequent examinations and vice versa. Considering that the condition of an asset has a strong correlation to the likelihood of an asset to undergo deterioration, this approach provides a means of limiting the level of uncertainty inherent in gathering data from periodic examinations. However, it is acknowledged that a degree of uncertainty will remain due to nature of the inspections and the potential for earthworks to undergo rapid deterioration or rapid failure with little precursors, e.g., in the case of rapid failure of granular soils when subject to intensive rainfall.

979 The periodic nature of the earthworks examinations introduces an additional degree of uncertainty in the asset condition data. Particularly if assets are exposed to threats such as adverse/extreme weather or third-party activity which may trigger deterioration of the asset in the intervening period between examinations.

980 Earthwork examiners are trained by NR to collect information about earthwork slopes within and outside the railway boundary by standing on the side of the track and, providing it is safe to do so, by walking up and down slopes within the railway boundary. They are not expected to go outside the railway boundary, and safety considerations (e.g., very steep slopes) sometimes prevent examiners reaching the boundary. These constraints mean that collection of information about slopes outside the boundary may be restricted

E.7 2020 update to Earthwork Hazard Category (EHC) Scoring Algorithm

981 In 2020 Mott MacDonald were commissioned by NR to further refine the Earthwork Hazard Category (EHC) Scoring Algorithm from the examination process to enhance its ability to predict of the likelihood of earthworks failure.

982 The work is still in progress and the workstream is summarised in Figure E12 below:

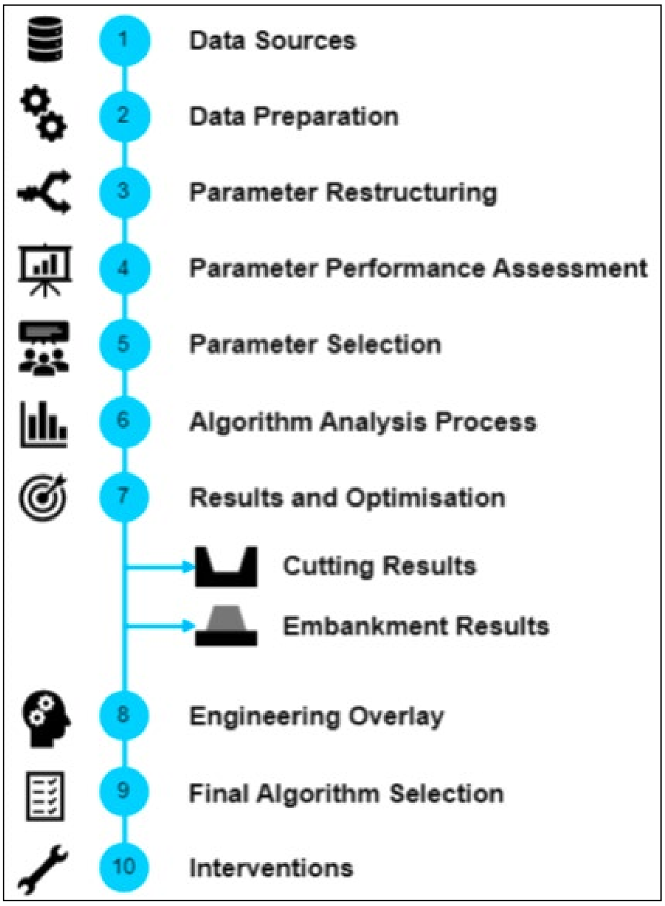


Figure E12: Scope of the 2020 work to revise the Examination Earthwork Hazard Category (EHC) Scoring Algorithm

983 It is planned that the revised algorithm is introduced in the 2021 examination season which starts in October.

E.8 Washout and Earthflow Risk Mapping (WERM) Decision Support Tool

984 The WERM methodology is used to locate water concentration features at the crest of soil cuttings in the NR earthwork examination asset database. Details of the approach are provided in Chapter 7 Para 312 onwards.

985 The WERM (Washout and Earthflow Risk Mapping) is a decision support tool to identify and assess cuttings at risk from the concentration of surface water runoff towards the railway that has the potential to adversely affect slope condition and cause serious safety incidents e.g., Watford 2016 (RAIB 2017), Figure E13.

Figure E13: Watford Cutting Slope Failure 2016 (RAIB 2017)

986 A digital terrain model has been created 100m either side of the railway using LiDAR data and photogrammetry. Analysis of this digital terrain model has identified low points that can channel water towards the railway. A concentration feature risk score from 1 to 12 is assigned to each 5 chain (100m) earthworks section, with 12 presenting the highest risk.

987 The WERM tool was initially calibrated against the history of earthworks failures in the LNW route. 47 cutting slope failures were evaluated and showed a broad trend of higher-than-average concentration feature risk score, confirming the significance of this feature as a precursor to failure. The study is described in further detail in the CP5 Earthworks Asset Policy, NR (2012).

988 A review of the initial WERM1 methodology NR (2014b) made recommendations for improvements to the means by which water concentration features are identified, namely:

- To improve the consideration of up-slope topography, by assessment of catchment areas away from the railway through the use of a digital terrain model
- To enhance the means by which the permeability of the ground in the catchment of potential water concentration features is assessed

989 These recommendations were addressed in the development of WERM2, NR (2016a) described below.

990 The WERM2 analysis uses a JBA Comprehensive Flood Map (CFM) embedded with a Surface Water Flooding Map (SWFM), (Figure E14) produced by JBA to calculate the flood risk for rainfall storm events at three return periods: 1 in 75, 200, and 1000 years at a spatial resolution of 5km by 5km (in line with the Flood Estimation Handbook).

Figure E14: JBA Surface Water Flooding Map showing a modelled flood (cross hatched) intersecting the crest of a cutting (red line)

991 These events are applied to the entire landscape of Great Britain, for a fixed period of time. The modelling technique calculates overland flow of water, based on the use of a digital terrain model, and a groundwater permeability dataset. At the end of the modelling period, the depth of water in each part of the map (based on 5m-by-5m pixel resolution) is calculated, and water standing at a depth greater than a threshold level is deemed to be flooded.

992 The SWFM indicates which areas of the landscape could expect to be flooded due to a particular extreme rainfall event. However, NR are primarily concerned with locations on the rail network where these flooded areas can be found above cuttings, particularly soil cuttings, where washouts and earthflow are a hazard. In order to determine these likely locations, the WERM2 methodology determines intersections between the location of the NR boundary above soil cuttings, and locations shown as flooding in the SWFM to identify water concentration features e.g. Watford Cutting in Figure E15 below.

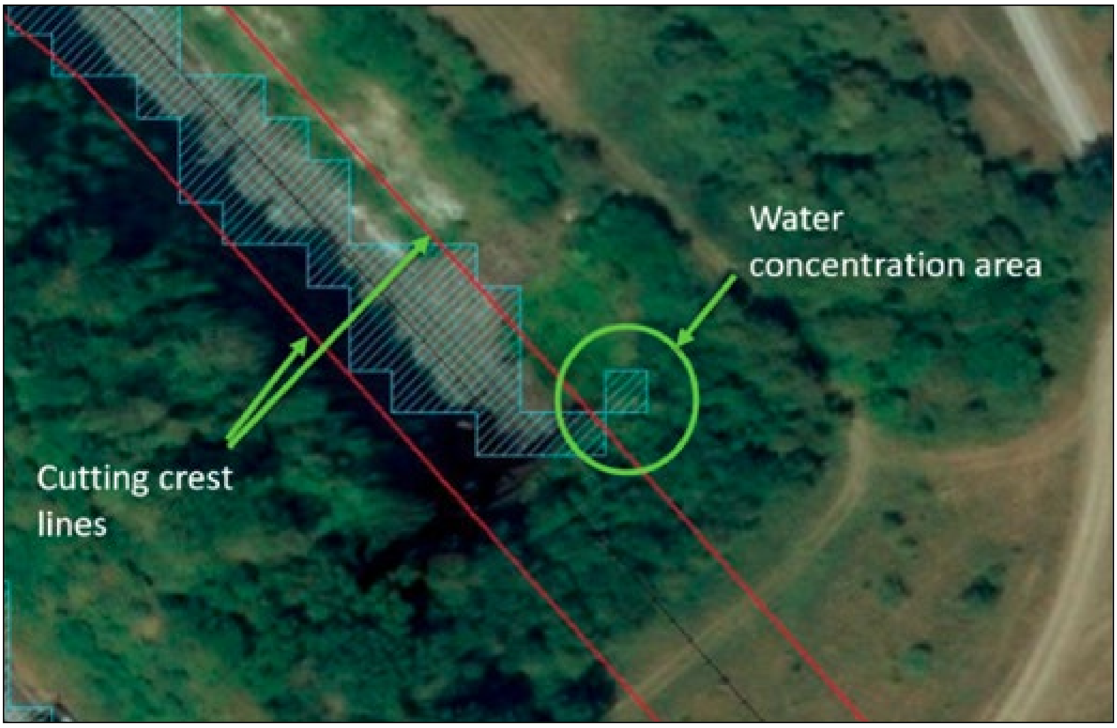


Figure E15: Aerial Photograph of the Watford Cutting overlaid with the September WERM 2 analysis (ref JBA WERM2 report)

993 This WERM2 assessment was carried out to determine those cuttings across the NR network that were intersected by a water concentration feature in either the 75, 200 or 1,000 return periods.

994 The results are reported in the Examination database using a WERM2 field. The majority of water concentration features are identified only under extreme rainfall conditions of the 1 in 1000-year return period storm.

995 The WERM2 indicator was added to the SCHI algorithm to improve the prediction of washouts and earthflows at locations of possible water concentration features. A new parameter (II4), for the 1 in 1000-year analysis was included in the SCHI with a weighting of 30. Parameters II1 to II3 for the 1 in 75 year and 200-year analysis were included for completeness but with weightings of 0.

996 The RAIB report following the Watford cutting failure of 16 September 2016 made the following recommendation: (RAIB, 2017, pp. 45-47): "*Network Rail should review, and if necessary, improve its process for identification of localised water concentration features which can channel significant amounts of water onto the railway with the consequent risk of slope failure.*"

997 The requirements of the RAIB report into the Watford failure were satisfied with the development of a new Washout and Earthflow Risk Mapping version 3 (WERM3) algorithm, NR (2018n). Initially, the performance of WERM2 in the Examinations database was reviewed against known failures and washouts. The data included cutting failures that have occurred since 1999 that were recorded in the Examinations database. The percentage of all soil cuttings identified as having a water concentration feature for each return period was calculated. The same procedure was applied to the failed and washout data. The data is plotted in Figure E16 below.

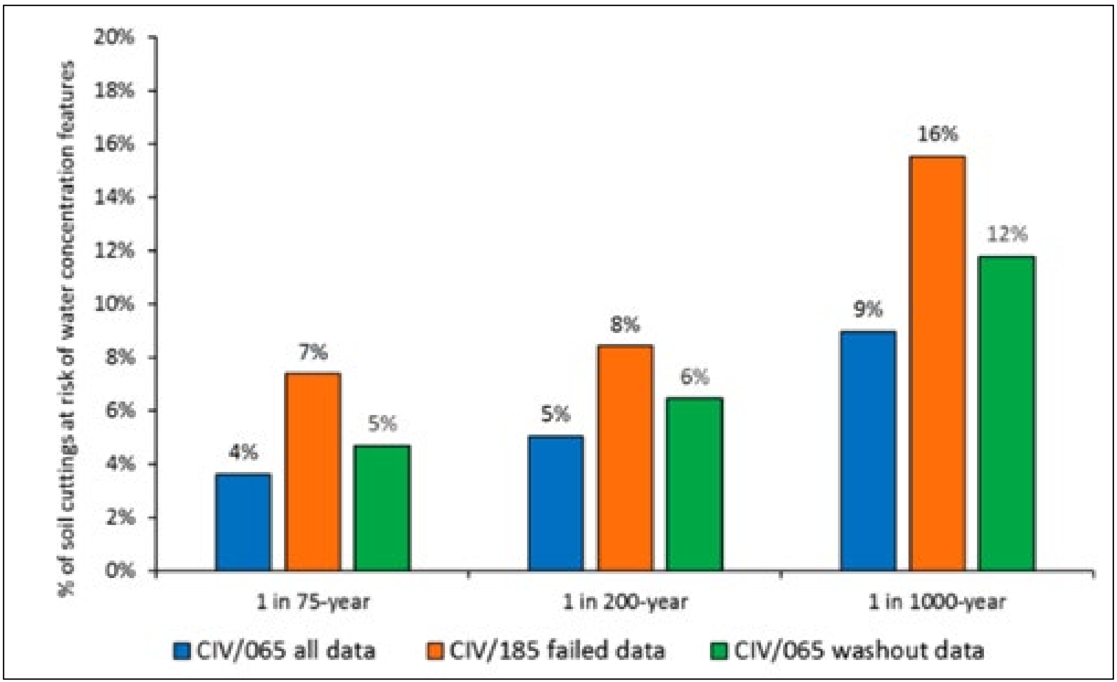


Figure E16: WERM2 soil cuttings at risk of water concentration features by rainfall return period for all, failed and washout data in 2018. (after NR (2018n)

998 For each return period, the percentage of soil cuttings identified by WERM2 as having a concentration feature is greater for the failed and washout datasets than for the all cutting assets data. In addition, as the rainfall event probability reduces (e.g. 1 in 75 years is more probable than 1 in 200 years rainfall event), the percentage of failed or washout soil cuttings identified by WERM2 increases. Overall, the correlation is strongest for the failed data.

999 The revised WERM3 methodology identifies the locations of water concentration features for three return periods (1 in 75, 200 and 1000 years) – similar to WERM2, but with the addition of consideration of water depth and volume within the water concentration feature at the crest of the cutting slope, NR (2018n).

1000 For each return period, the percentage of soil cuttings identified by WERM3 for all, failed and washout data in 2018 is plotted in Figure E17 below.

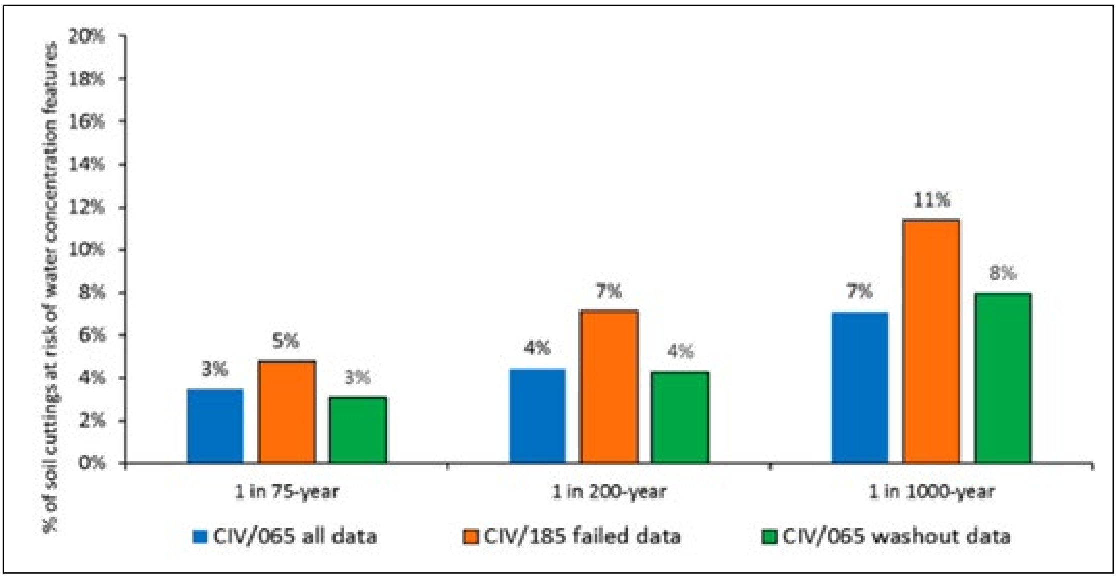


Figure E17: WERM3 soil cuttings at risk of water concentration features by rainfall return period for all, failed and washout data in 2018. (after NR (2018n))

1001 There are significant differences in the number of assets identified as at risk of water concentration features in WERM2 and WERM3 (Figures E16 and E17). These differences are believed to be due to:

+ For the assets "Not at risk in WERM2" and now found to be "At risk in WERM3"
+ Changes and improvements to the flood model
+ Improvements to the top of crest model, including at tunnel portals
+ Improvements to the track model
+ Potential changes/additions to the crest drain data

1002 The WERM3 predictions of the locations of water concentration features at the top of cutting crests for various rainfall return periods are considered more robust than the WERM2 outputs. Therefore, the WERM3 outputs replaced the WERM2 outputs in the JBA GISMO field tool and the SCHI examination algorithm.

1003 Whilst the presence of a water concentration feature is not the only parameter influencing slope washouts, this failure mode is not viable without the presence of water. The analysis given in NR (2018n). shows that nationally only 1 in 5 historic CIV/185 examination database failures occurred at a WERM3 water concentration feature location, and therefore at best, the WERM3 algorithm could predict no more than 20% of failures of any type. For washouts recorded in the examination database the percentage is lower at 13%.

E.9 Earthwork evaluations

1004 Details of the earthwork evaluation process are provided in Chapter 7 Para 322 onwards.

1005 The mandatory drivers for a NR Earthworks Manager undertaking an earthworks evaluation, NR (2017b) are as follows:

+ earthworks with an EHC of A, B or C that have deteriorated to D or E (following examination)
+ there is a deterioration to earthworks with an EHC of D or E (following examination)
+ there is an improvement to the EHC (following examination)
+ concerns regarding the ability of earthworks to perform their function, irrespective of the EHC
+ they need to confirm a required course of action, to maintain the safety of the operational railway
+ they have received an urgent defect report
+ they have received a geotechnical assessment report

1006 The non-mandatory drivers for the Earthworks Manager undertaking an Earthworks evaluation are as follows:

+ Earthworks with an EHC of C and a Risk Evaluation Matrix (REM) output of 'High Risk'
+ prior to a change of use or loading (such as a significant change in frequency or weight of rail traffic on an embankment, or an increase in the speed of traffic)
+ prior to works on or around the earthworks that might affect the stability, condition or performance of the earthworks
+ a special examination of the earthwork has been carried out
+ the presence of boulders is reported during the examination of a cutting or natural slope
+ a rapid response examination report is received
+ track maintenance engineers report exceptional changes in the track geometry to the Route Asset Manager (Geotechnical) (RAM (G)), which require geotechnical advice
+ a change in the nature or extent of use or in-service loading (such as the stockpiling of materials on a slope, an increase in the superimposed or live loading, or realignment of the track on an embankment)
+ works are scheduled or underway in or around the earthwork, which might affect stability (such as excavations for foundations to ancillary structures)
+ flooding or high fluvial flow has damaged the earthwork or adjacent infrastructure (for example, by overtopping or scour)
+ changes in the drainage system in and around the earthwork (such as the realignment of a watercourse, an increase in surface run-off due to construction works, reports of blocked drains or the ponding of water)
+ infrastructure supported by the earthwork is showing signs of distress
+ the earthwork is infested with burrowing animals
+ accidental or deliberate damage has occurred (such as a fire on an embankment)
+ new knowledge is received that casts doubt on the findings of, or the actions stemming from, an earlier evaluation
+ the risk evaluation matrix indicates earthworks with an EHC of A, B or C are at risk of rapid deterioration

+ the earthwork is at risk from outside party activities
+ the earthwork and infrastructure are at risk from outside party slopes
+ the earthwork is included in an adverse/extreme weather plan

1007 If the EM decides that an evaluation is not required, they are required to record the justification for this decision in the Civils Strategic Asset Management Solution (CSAMS). Note that in practice the Examination database is used to record the justification pending the development of CSAMS.

1008 From NR (2017b) the outcome of an evaluation should include recommendations for the following:

+ earthwork examinations (refer to NR (2017a)
+ geotechnical assessments (refer to NR (2018o)
+ geohazard assessment (refer to NR (2017c)
+ interventions, including maintenance (refer to NR (2017g)
+ mitigations including monitoring (refer to NR (2017f)
+ addition to/removal from adverse/extreme weather plans
+ liaison with other asset owners

E.10 Route Weather Resilience and Climate Change Adaptation (WRCCA)

1009 The earthworks asset is particularly vulnerable to adverse/extreme weather and this is addressed by the NR Earthworks Asset Policy, NR (2018c). .

1010 The impact of adverse/extreme wet weather on the likelihood of vulnerable assets to failure or performance degradation is recognised in the risk-based Management of Earthworks Manual, NR (2019).

1011 The identification of earthworks that are particularly vulnerable to adverse/extreme weather and the management of the risks they present is managed through Adverse/Extreme Weather Plans defined in the Earthworks Adverse/Extreme Weather Risk Assessment NR (2017k).

1012 Some indicators of weather-related hazard and vulnerability (such as adjacent catchment details, signs of gullying on the slope, high plasticity clay embankment materials etc.) are incorporated into the examination EHC algorithm.

1013 NR (2017k) defines the procedure that each NR Route/Region must adopt to develop an Adverse/Extreme Weather Plan (A/EWP) that includes a register to identify vulnerable assets, identify trigger thresholds for action and recommended actions such as speed restrictions, Figure E18.

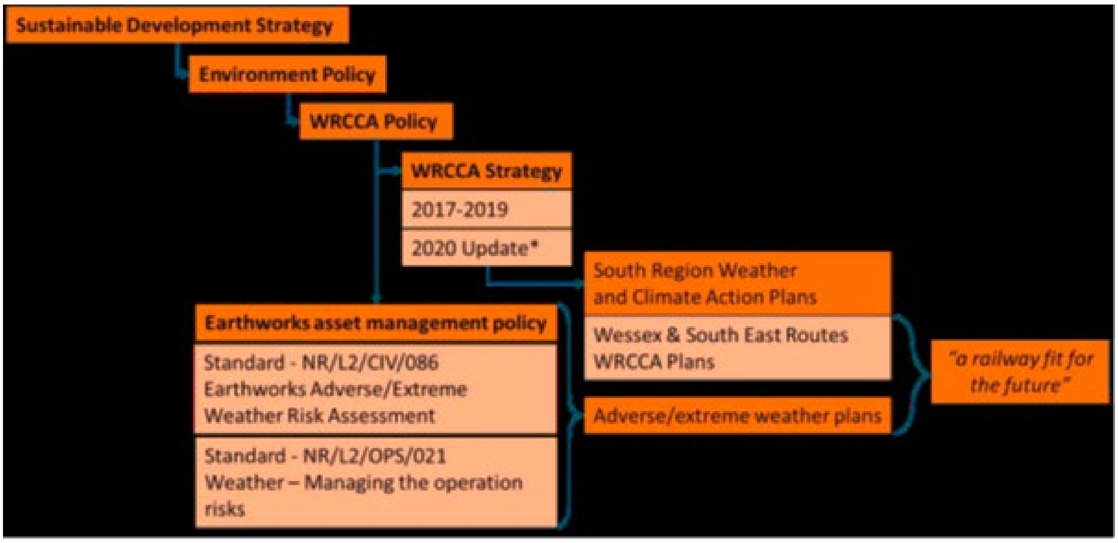


Figure E18: Network Rail weather resilience and climate change adaptation document structure (Southern Region example)

1014 There is a structured approach to identify which earthworks are to be included on the 'at risk' register, that considers both the likelihood of an earthwork failure and the potential consequence. NR assesses the likelihood of failure by taking account of historic instability and indicators suggesting possible future instability. These indicators include the EHC category recorded during the examination process (ref Appendix E4). The assessment of likelihood also takes account of any water concentration features identified by the 'washout and earthflow risk mapping' the WERM process (ref Appendix E8). This process identified areas where ground topography concentrates surface water flows at particular locations along the railway.

1015 The A/EWP details the mitigation measures that are to be adopted to manage the risks presented by the identified vulnerable earthworks. Each identified site may be linked to the nearest weather recording station, and when heavy rainfall is forecast that exceeds pre-defined trigger levels then an escalating series of pre-emptive control measures are put in place (see Figure E19 below for an example) to mitigate the severity of the impact should a failure occur. The mitigation measures are usually a combination of monitoring and operational restrictions.

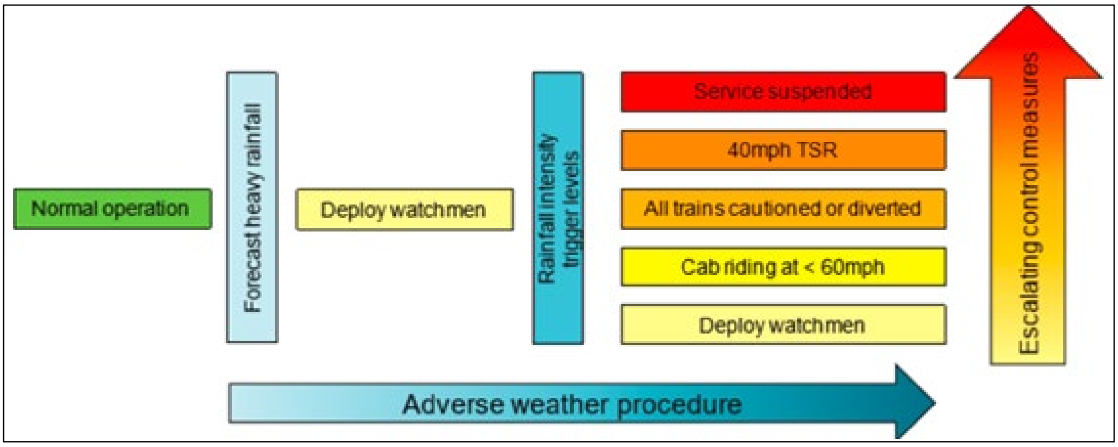


Figure E19: Example earthworks adverse/extreme weather procedure, after NR (2018c).

1016 Newly assessed trigger levels are currently under trial and have been defined in terms of total rainfall thresholds over 24-hour, 7 day and 14-day periods, in combination with a Soil Moisture Index (SMI) threshold. The thresholds have been established from the best fit correlation between historic weather data and the record of CIV028 (now CIV185) earthworks failures. The analysis was carried out at national level by considering rainfall and SMI severity and thus normalising the data for local variations in the weather patterns around the country, see Figure E20 below.

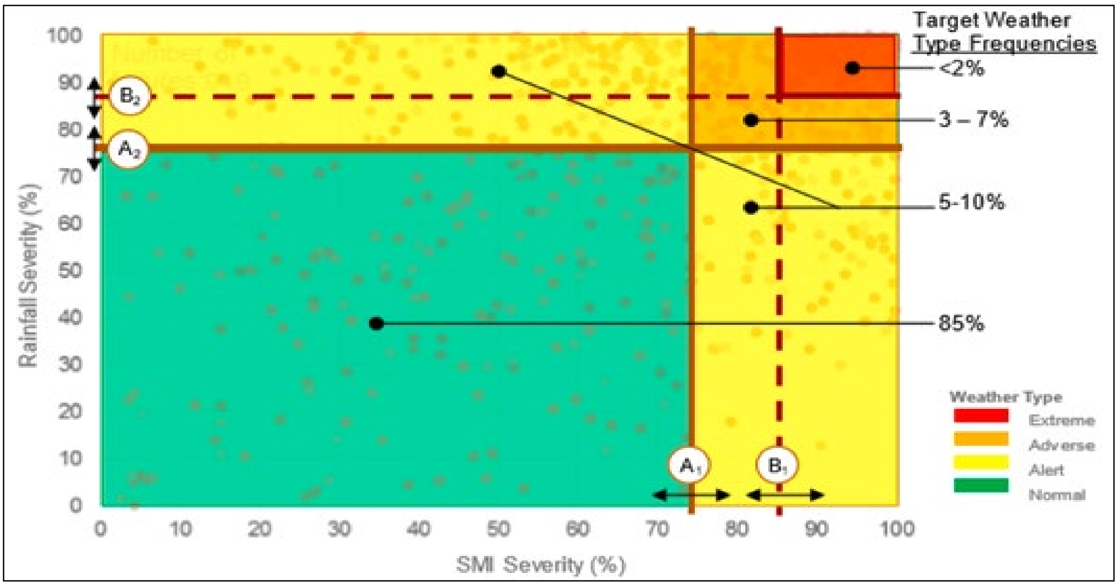


Figure E20: General relationship between rainfall and SMI severity, and the distribution of earthworks failures overlaid with the weather type trigger levels, after NR (2018c).

1017 The resultant national correlation was then applied to the historic data for each route, to obtain route specific thresholds for each of the weather types (Normal, Alert, Adverse and Extreme). Full details are given in the Task 20/Task 11 report – Weather triggers and weather normalised failures KPI., NR (2017l).

1018 NR have a small team of weather specialists who work with the external weather forecast provider to support the operational railway with forecasts. The current weather forecast management approach uses extreme weather action teleconferences (EWATs) to advise NR routes of forthcoming heavy rainfall and thunderstorms and analyse historical weather events and delays to improve our response, Slingo et al. (2020).

1019 When action is triggered, EWATs bring together route control, maintenance, operations, and train and freight operators to amend timetables and make critical decisions to reduce safety risk. NR weather forecasting service provides a five-day outlook of weather conditions at a national and local level to provide alerts of adverse or extreme events. These forecasts are updated daily and communicated to operations control centres and to EWATs to improve response.

1020 When two or more routes may be affected by an impending weather event, a national EWAT is invoked led by the NR national operations centre (NOC) and attended by the Department for Transport (DfT). An equivalent system operates in Scotland's Railway with Transport Scotland. Route teams inform the national team and information is distributed across the industry. Plans and processes are reviewed based on learning points from events.

1021 There will be occasions when additional speed restrictions will be required on particular lines if heavy rainfall is judged to present a heightened risk to earthwork stability. As technology to predict and warn of failures matures, and NR deploy it in more places, the expectation is that the risk of such disruption will reduce.

1022 NR recognise that speed restrictions can cause disruption to passengers and freight services, and to some degree create additional safety issues if not managed appropriately, e.g., through crowding or frustrated passenger behaviour.

1023 A NR Internal Audit on Earthwork Failure Management dated 25th April 2016 found that "There is a lack of a consistently applied, Route understood, methodology to identify at-risk sites for inclusion and exclusion in Adverse/Extreme Weather Plans. Without this there is a risk that sites which are of highest risk, or low frequency/high consequence, will not be consistently captured and monitored across the business."

1024 A summary of the audit findings was as follows:

+ Earthworks are included in Adverse/Extreme Weather Plans (A/EWPs) when there is a need to reduce the potential consequence of an asset failure during times of adverse/extreme weather
+ The original methodology for identifying at-risk sites in A/EWPs was developed in response to an ORR notice issued to the Scotland Route in 2012 and then rolled out business-wide. The methodology which has been subsequently updated, for site identification and refreshing of A/EWP lists, including the removal of sites from the at-risk list, is not, however, deemed by the Routes to be adequate or clear
+ This lack of clarity has led to confusion within the Routes on the right approach to be adopted and inconsistency in its deployment. South East (SE) Route, for example, has developed a local rationale relying on professional judgement of their Geotechnical Route Asset Manager (RAM) alone. In contrast, LNW has not updated its A/EWP at-risk sites since 2013. In 2015/16, LNW and SE have had 53 and 17 failures respectively. Out of these failures, 11 (21%) in LNW and six (35%) in SE were in the Routes A/EWP at-risk registers. For reference, it is not expected by the Head of Geotechnical that all failures will be within areas identified as high risk from the quantitative tools and qualitative assessments undertaken on the geotechnical portfolio

1025 The audit actions were as follows:

+ Head of Geotechnical in conjunction with Route Geotechnical RAMs to agree a clear and consistent methodology to identify at-risk sites for inclusion and exclusion in Adverse/Extreme Weather Plans
+ This will be formalised by updating the BCR code of practice for adverse/extreme weather or by revising the earthworks standard following stakeholder acceptance and user acceptance testing

  Owner: Simon Abbott, Head of Geotechnical

  Action Date: 1st November 2016

1026 The audit also required that the assessment of compliance to the mandated methodology to identify at-risk sites for inclusion and exclusion in Adverse/Extreme Weather Plans to be imbedded within Level 2 NR assurance regime.

E.13 Precursor Indicator Model

1027 The Precursor Indicator Model (PIM) is produced by the Rail Safety and Standards Board (RSSB) as a quantified risk model for understanding train accident risk. It is released periodically and demonstrates quantitatively the level of train accident risk and how it is changing.

1028 PIM comprises of a group of high-level safety performance indicators that are designed to illustrate underlying trends in train accident risk by tracking changes in accident precursor[15] events such as asset failures and reportable incidents and their associated risk ranking.

1029 Earthworks provide a major contribution to the PIM Infrastructure Asset Integrity risk. In this context, infrastructure asset integrity currently accounts for 27% of all train accident risk with earthworks failures taking the major share.

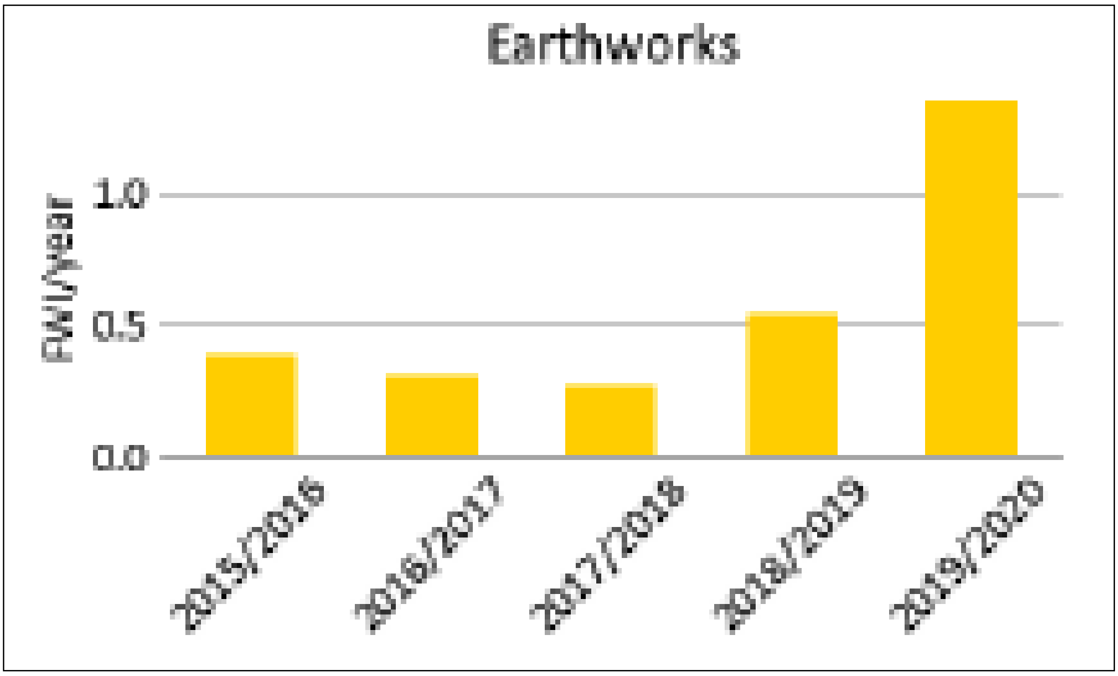


Figure E21: Earthworks contribution to train accident risk

15 For Earthworks, cutting failure and embankment failure are the only precursors for train accident risk

1030 Figure E21 above (from figure 2 RSSB Infrastructure Asset Integrity 2019/20 Report) shows earthworks contribution to train accident risk as measured by the PIM from 2015/16 to 2019/20. The predicted Earthworks risk, (from 2015/16 to 2019/20) varies from approximately 0.25 to 1.25 Fatality Weighted Index (FWI) per annum. This range equates to above 1 fatality per annum to 1 fatality every 4 years. Prior to Carmont, the last fatality associated with a NR earthwork failure occurred in 1995. The FWI per annum is currently at its highest level (1.25) since 2010/2011 due to the significant increase in the number of embankment and cutting failures observed in 2019/2020, compared to recent years. From Figure E22 the spike in the predicted Earthwork risk is associated with the significant number of earthwork failures during winter 2019/20 when the long-term average rainfall was exceeded in seven consecutive months culminating in the wettest February on record.

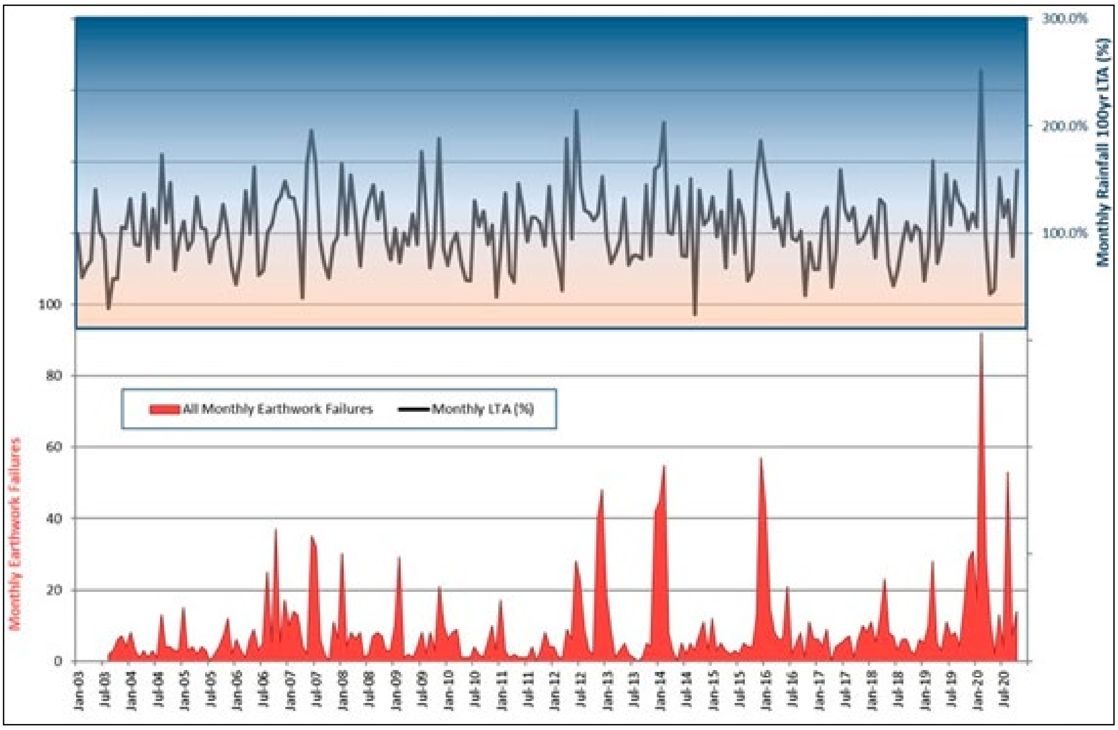


Figure E22: Earthwork failures (monthly) from January 2003 plotted against Monthly rainfall 100 year long -term average (%)

1031 The PIM output should only be interpreted as indicative, it doesn't give the complete picture of how the risk from earthworks failures is changing. PIM is a lagging indicator, and is useful for assessing trends and comparative performance. It is not generally suitable to be used in forecasting performance. The NR Risk Management team performs further analysis on PIM data so that they can highlight areas of interest.

E.12 Decision Support Tools – SCAnNeR and Powerpack

Strategic Decision Support Tool (SCAnNeR)

1032 With the understanding of the safety risk profile of the earthwork asset portfolio that NR now has through the Earthworks Safety Risk Matrix (ESRM) formed from asset condition data (hazard category) and consequence (criticality band), prioritisation of intervention works to maintain, refurbish or renew their earthworks can be undertaken in a systematic way. The NR budget for interventions is, however, constrained and in order to determine the most efficient and cost-effective means of utilising the available funding, NR have developed a strategic whole life cost Decision Support Tool (DST) known as earthworks SCAnNeR (Strategic Cost Analysis for Network Rail). SCAnNeR is an optioneering DST, that allows a large number of mixes of interventions to be applied to the asset portfolio, and to assess how these interventions impact on the condition of the portfolio, when balanced against modelled earthwork degradation. This modelling is carried out over a series of 20 five-year Control Periods, to allow whole life costs to be determined.

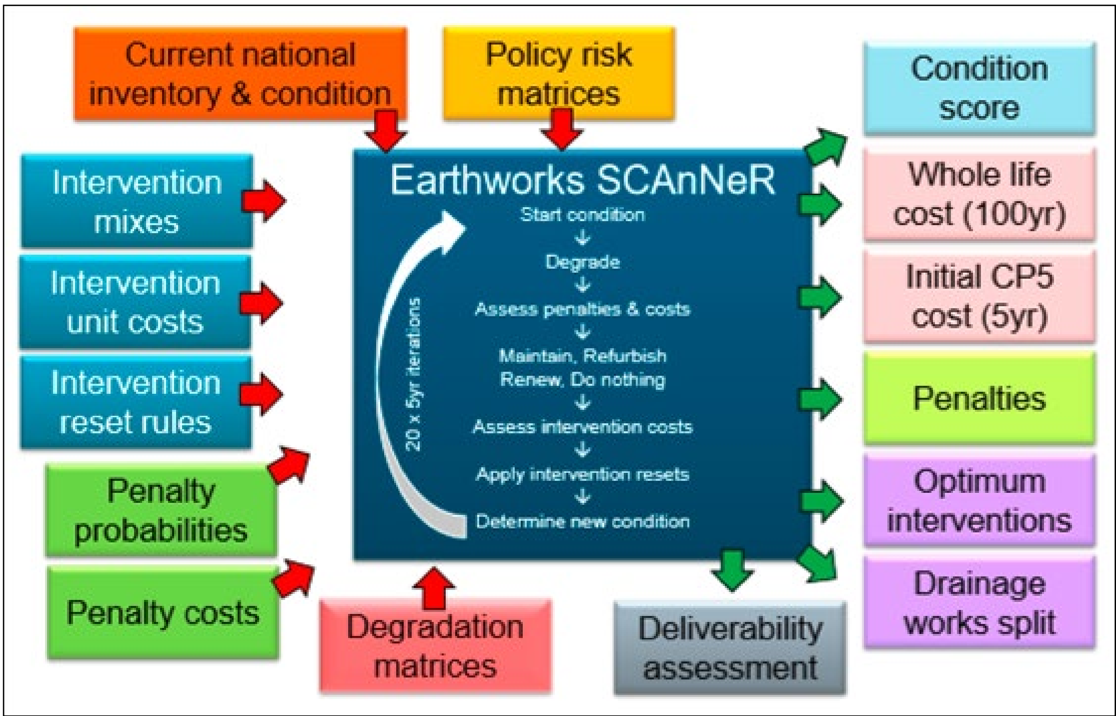


Figure E23: Earthworks SCAnNeR model after NR (2018c)

1033 It is a database driven model with inputs and outputs via linked spreadsheets (Figure E23).

SCAnNeR Inputs

1034 The inputs that the SCAnNeR model requires are as follows:

- The current national inventory of earthworks, in terms of their condition (EHC) and criticality (EACB)
- A pre-defined range of mixes of different interventions types, of which thousands of mixes can be modelled. The interventions are split into three types
- maintenance (light, rapid activities such as clearing drainage)
- refurbishment (heavier maintenance, such as scaling of rock slopes) and
- renewal (major engineering activities, such as the installation of sheet piling or soil nails)
- An understanding of the unit costs of each intervention type, varying by earthwork type
- Rules for the impact that each of the intervention types has on earthwork condition (in terms of changing the earthwork's EHC)
- The probability and cost of penalties that can be expected for a given portfolio condition, in terms of expected earthwork failures and costs associated with delays to the network
- The rate of degradation of the asset portfolio, in the absence of interventions

1035 Whilst all of the above inputs require significant work to determine robust, evidence-based values, assessment of earthwork degradation is particularly challenging. A Markov Chain analysis is carried out (see Figure E24), to determine the probability (within the modelled 5-year time steps of SCAnNeR (ref Spink et al).

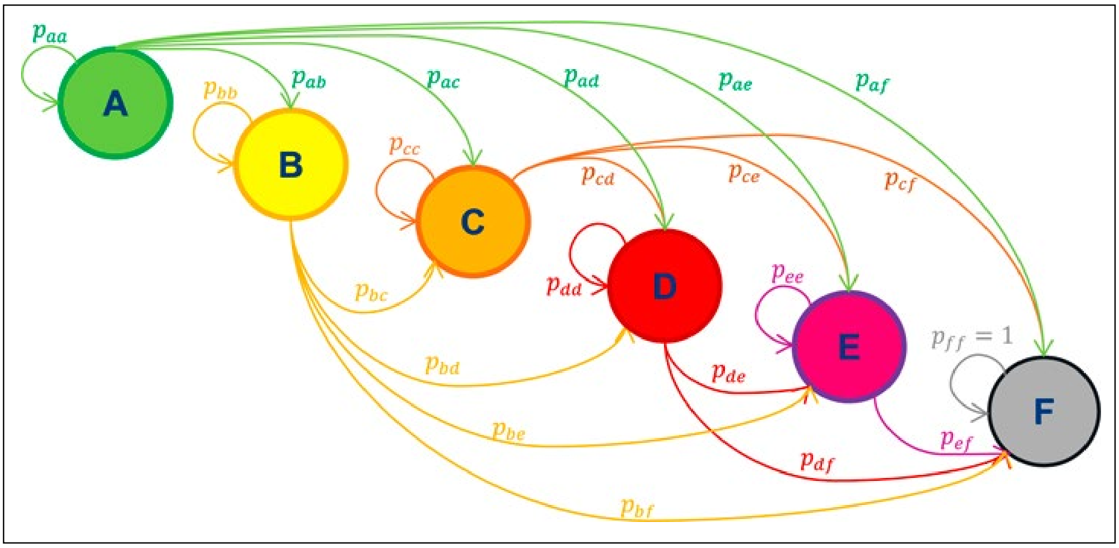


Figure E24: Markov Chain method for determination of earthwork degradation rates (A-E are the EHC values for an earthwork, F is failure)- after Spink (2020)

SCAnNeR Outputs

1036 For each 5-year NR control period modelling step, SCAnNeR determines a series of outputs:

+ Changes in the overall condition and risk level of the total earthworks population as measured by Key Performance Indicators (KPIs) such as Earthworks Condition Score (ECS)
+ Costs of the interventions undertaken, for each time step (allowing analysis of costs for a single Control Period, or of longer, whole life costs over periods of up to 100 years). Penalty costs are also calculated
+ An optimum mix of interventions, that achieves the required aims of the modelled scenario (such as a requirement to sustain overall portfolio condition), for the lowest whole life cost
+ An assessment of the deliverability of the intervention mix is also used to constrain the modelled intervention mixes to a realistic solution

1037 The SCAnNeR whole life cost model, produces an optimum mix of earthwork interventions (renew, refurbishment and maintenance) and their associated cost that will achieve the required aims of the national earthworks management policy. These intervention volumes and costs are then used to provide targets for the development of bottom up (engineering driven) workbanks. The SCAnNeR model works at a strategic level, generalising the complex behaviour of a large portfolio of earthwork assets, to allow funding decisions to be made. It is recognised that engineering judgement and experience is used, at a tactical level, to produce the workbank of exactly which assets are to be subject to an intervention in each CP.

Tactical Decision Support Tool: Powerpack

1038 To aid in this decision making, NR have developed a tactical DST (called Powerpack) to allow a 10-year workbank to be built at individual earthwork level, guided by the outputs of the SCAnNeR model. The Powerpack provides instant analysis of the degree of alignment of the developed workbank to the earthworks asset policy, and calculates estimated total intervention costs based on the same unit rates used by SCAnNeR. A further tool (the Powerpack ANalysis ToolSet), models the impact of the Powerpack workbank, offset by the assessed degradation of the earthwork's assets, to produce an estimate of the condition of the asset portfolio at the end of the period of time being considered.

E.13 Intelligent Infrastructure

1039 Intelligent Infrastructure is Network Rail's digital asset performance management programme, using technology to turn data into intelligent information so the frontline and supporting teams can work smarter and more safely to deliver improved services for passengers and freight customers. Ultimately the goal is to reduce expenditure whilst improving infrastructure availability by:

+ Understanding the probability of individual asset failure
+ Predicting when failure will occur
+ Forecasting the impact on the operational railway
+ Planning intervention prior to disruption to train services

1040 The programme is not just about introducing huge amounts of new technology; it has been designed to look at how NR can maximise the value from the data they have whilst working closely with the NR research and development programme to make sure NR continue to be at the forefront of technology introduction.

People and culture transformation

1041 Throughout all stages of the Intelligent Infrastructure programme, NR have recognised that there will be significant changes to how their teams interact with data and technology, and how work will be specified, planned and delivered. Successful delivery of NR plans will rely on NR's ability to enthuse and inspire their teams to work through this change, giving them tools that they will want to use because it will make their working lives easier, (Figure E25).

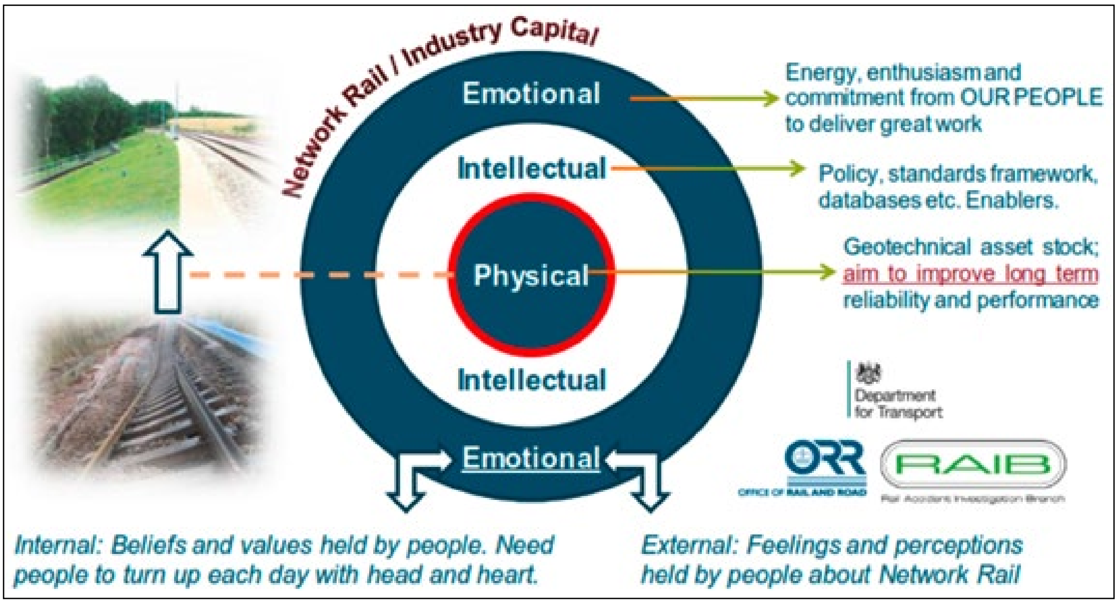


Figure E25: NR Long term vision for Intelligent Infrastructure all starts with people

Application of Research, Development and Technology

1042 The Intelligent Infrastructure Programme will apply Research, Development and Technology to improve existing capabilities, especially in the areas of monitoring assets, 'big data' analytics and work planning. This will be achieved by:

+ Embedding reliability engineering into products and maintenance regimes
+ Optimising embedded monitoring coverage
+ Evolving train-borne monitoring/maintaining existing vehicle monitoring capability
+ Transforming analysis and analytic capabilities
+ Exploiting information systems, making Ellipse the core of all asset management activity
+ Industrialising autonomous systems

1043 A huge amount of value will be derived from utilising advanced analytics and machine learning techniques to drive a greater understanding of asset condition and rates of degradation. These techniques, which will be applied across all asset systems, will use NR existing data sources and also help NR to understand what new data is required to drive efficiency and performance.

Visualising the railway

1044 When NR rolled out imagery and data from the first national aerial survey in 2016, it marked a major milestone in railway asset analysis and evaluation that could be carried out from the safety of the office. Using the NR GIS viewer Geo-RINM (GRV), (Figure E26) planning and maintenance teams could undertake preliminary asset reviews, measurements and analysis without the need to access the track.

1045 NR staff use the viewer to view thousands of miles of railways more clearly via aerial data which produces high-resolution images that can be extracted and used for 3D modelling. The digitalised operation allows engineering, maintenance and project teams to gain better visibility of tracks, earthworks or drainage assets. It is part of how NR are moving towards the ‘predict and prevent’ strategy instead of a ‘find and fix’ method. Engineers describe the viewer as an “incredibly powerful” tool which increases efficiency and reduces the hazard associated with inspections alongside live track.

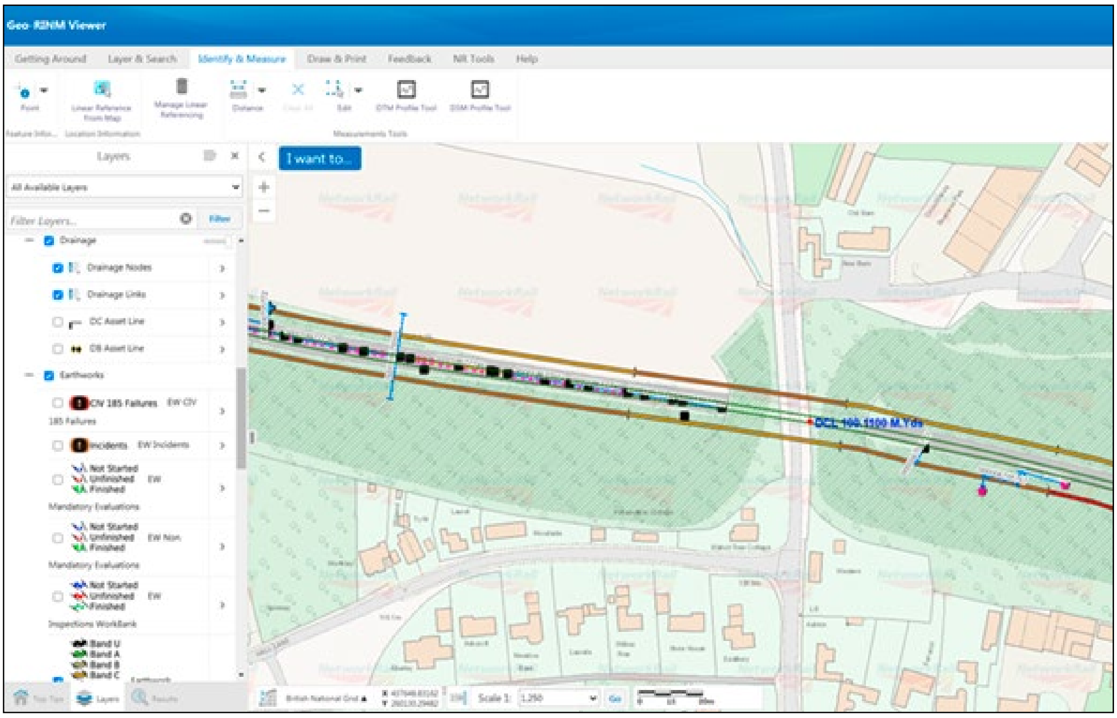


Figure E26: GEO-RINM Viewer used to access high quality imagery

1046 The GRV is also key for NR in managing its boundaries with imagery collected 50m either side of the boundary which allows easier identification of slopes and drainage assets immediately outside NR ownership.

1047 The aerial surveys were surveyed at a height of 250m by helicopter. There are three types of imagery in the GRV: Orthophoto RGB, digital surface model (DSM) and the digital terrain model (DTM). RGB is a representation of the real-world showing ground features at a resolution of 4cm, offering a massive improvement on former tools like Google Maps and OS imagery which can only reach 20 and 25cm respectively. The other two imagery surveys show users both the height of any features and what the ground itself is doing. The DSM provides elevation measurements for anything from trees and bridges, while the DTM focuses on above ground features like vegetation.

1048 Desktop access to high-resolution images and 3D digital terrain and surface model data, proved a resounding success. Routes requested updated data to keep pace with the changes taking place across the infrastructure. To meet this demand the Intelligent Infrastructure programme was asked to develop and improve on the first survey. Working with NR's Air Operations team, new surveys were carried out over the winter period – benefiting from reduced leaf and foliage cover to improve clarity of the network. This refreshed data has been rolled out to the business. Date labels and time sliders have been added to allow comparisons between old and new imagery so that accurate earthwork changes can be measured and changes to the infrastructure can be clearly seen.

Intelligent Infrastructure II programme

1049 In 2019 NR launched the Intelligent Infrastructure (II) programme, a five-year, Control Period 6 programme with the aim to deliver information derived from data that will support staff in the prioritisation and planning of the maintenance and capital work bank, (Figure E27).

1050 The Intelligent Infrastructure II programme is an evolution of several workstreams initiated in the CP5, Offering Rail Better Information Services (ORBIS), Ellipse Exploitation and Maintenance Effectiveness programmes, which are brought together to form a single integrated programme. This approach will enable a business transformation focussed on culture and people, with a strong alignment to Routes' initiatives and priorities.

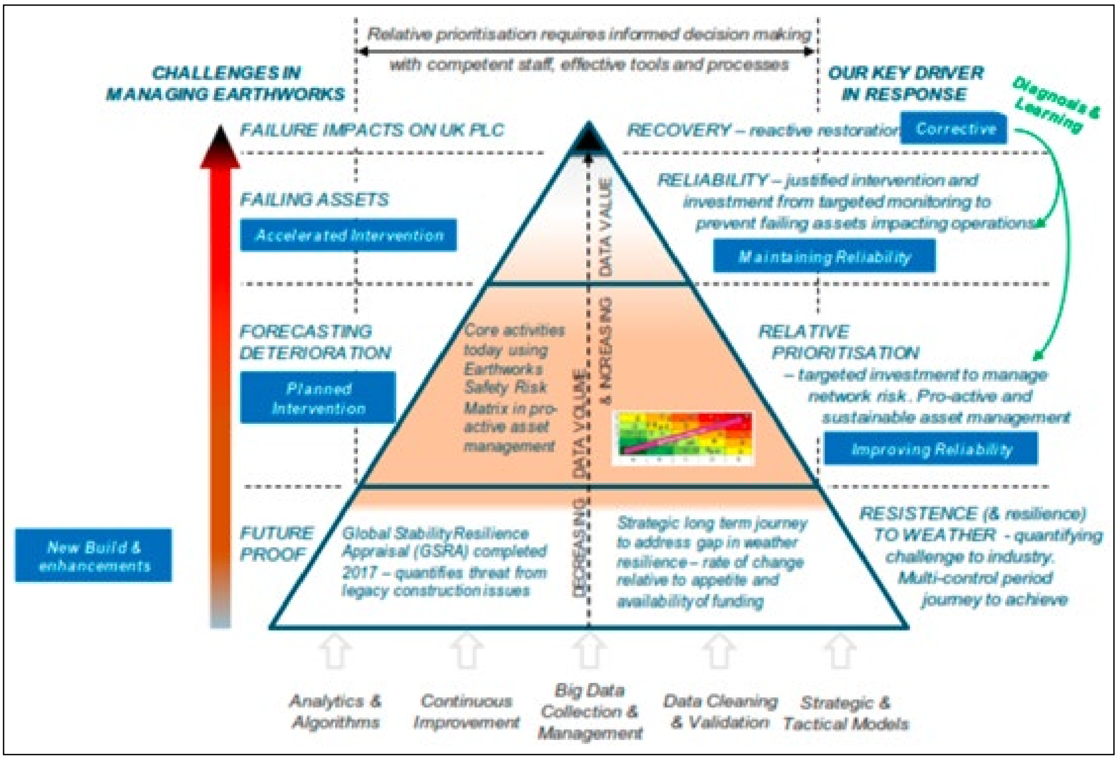


Figure E27: Data Driven Railway/Predict and Prevent/Remote Condition Monitoring

1051 Working directly with the NR Routes/Regions, the II programme will help the Routes move from time-based, fix-on-fail maintenance, to information-led predict and prevent regimes; capture, analyse and exploit asset data to help the routes prioritise the most critical work and to drive a 10 per cent service affecting failure improvement. This will be achieved through the development of automated network monitoring, advanced data analytics, aerial surveys and integrated decision support tools. The programme's workstreams include Track, Signalling, Ellipse (NR's central database) Planning, Civils and Operational Property.

1052 The II programme will apply Research, Development and Technology to improve existing capabilities, especially in the areas of monitoring assets, 'big data' analytics and work planning. This will be achieved by:

+ Embedding reliability engineering into products and maintenance regimes
+ Optimising embedded monitoring coverage
+ Evolving train-borne monitoring/maintaining existing vehicle monitoring capability
+ Transforming analysis and analytic capabilities

+ Exploiting information systems, making Ellipse the core of all asset management activity

+ Industrialising autonomous systems

Implications of Intelligent Infrastructure for earthwork assets

1053 The information NR extract from the data they hold is a key enabler to intelligent decision making across the breadth of earthwork asset management activities. Building on existing data management capabilities will facilitate how NR turn vast amounts of data into insight to optimise earthwork asset management decision making, whilst reducing the uncertainty associated with determining long term capital and operational funding requirements.

1054 Fully embedded earthworks monitoring (which would be disproportionately expensive across the network) is still unlikely to enable intervention in advance of all failures because of the variety of slope failure modes and mechanisms. The biggest opportunity that can be realised from these initiatives is for the integration of binary data (from remote failure detection technologies and train-borne monitoring) into operational procedures. With standardisation in data feeds and data platforms we could see improvements to safety and performance.

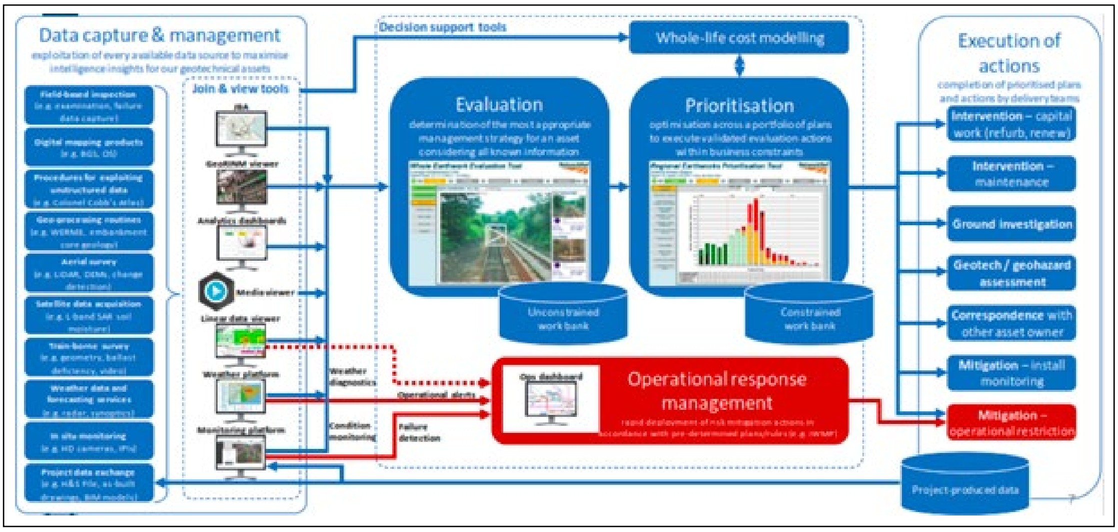


Figure E28: What does Intelligent Infrastructure mean for earthwork assets?

Linkage between R&D Programme and Intelligent Infrastructure II

1055 In an attempt to better target capital investments and strengthen the resilience of its earthworks, NR published the Earthworks Technical Strategy in 2018, NR (2018d) to show its commitment to accelerate R&D, harness more value from its data and exploit emerging technologies. https://www.networkrail.co.uk/wp-content/uploads/2018/07/Earthworks-Technical-Strategy.pdf

1056 The NR research and development portfolio involves development and trials of new earthwork monitoring systems, including surface 'tilt meter' technology to warn of sudden earthwork movement. Through research and development, NR aim to continue to adopt new remote monitoring and remote sensing technologies, and algorithmic interpretation of data. NR processes increasingly exploit technology including aerial derived laser survey (using helicopters and drones), train-borne survey, and asset monitoring using telemetry. This is improving the insight on the changing state of our assets and can provide early warning alerts. NR have also recently completed work applying 'machine learning' to enhance earthworks risk hazard scoring and targeting of interventions.

1057 The NR research and development programme are complemented and underpinned by participation in research led by world-leading universities. The Achilles programme investigates deterioration, performance, forecasting and decision support for earthworks across the infrastructure sector. NR are working to include consideration of climate change and future weather conditions in studies to improve knowledge of how assets will perform in the future.

1058 The linkage between the NR research and development programme and Intelligent Infrastructure II is illustrated in Figure E29.

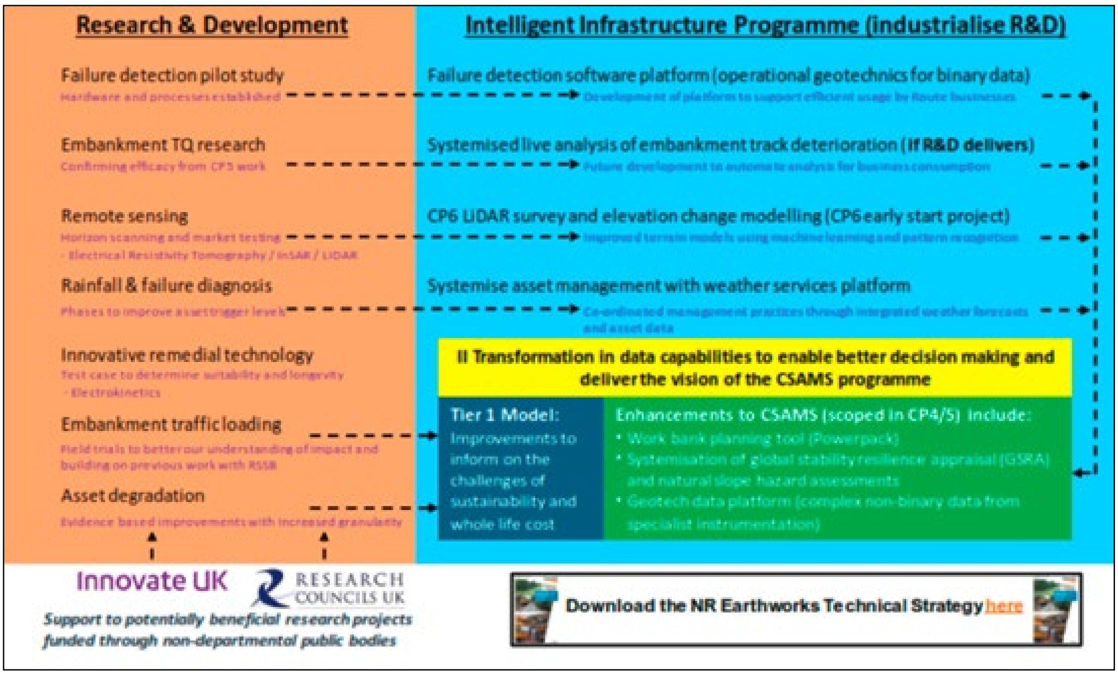


Figure E29: Linkage between the NR research and development programme and Intelligent Infrastructure II

Development of Evaluation and Prioritisation tools

1059 There are a number of evaluation and prioritisation decision support tools including GSRA and weather analytics that are awaiting full integration into the asset management system to enable effective use. Implementation has been included in the Intelligent Infrastructure (II) and is anticipated to be completed in CP6.

Earthwork Priorities for the Intelligent Infrastructure II Programme

1060 Initial funding of £20m has been allocated to the Geotechnics Technical Authority team for delivery of the following projects:

+ CGC01 Weather Services Platform & Diagnostics (Weather Project) – Weather Diagnostics leading to alerts to support Operational Response Management

+ CGC04 Failure Detection Platform RCM Project- Operational dashboard to assist Operational response management. Supporting the rapid deployment of risk mitigation actions in accordance with pre-determined plans/rules (e.g. IWMP)

+ CGC09 Planning Prioritisation and WLC (Powerpack & Tier 1) Cost & Volume Project Powerpack brings together data from various sources into one place to enable workbank construction and portfolio level searching across different key parameters. This includes WERM3, GSRA and the CHOPS assessments from the outside party slopes work referenced above. It will possible to import the Powerpack data into the GRV to visualise workbanks alongside a catalogue of other datasets in GIS. The replacement of Powerpack is an important objective of the intelligent infrastructure programme

1061 In the future the Intelligent Infrastructure II programme will also deliver the following geotechnical workstreams (subject to available funding):

- CGC00 Interactive decision support tool- A key earthworks asset management decision point is the Earthworks evaluation process following slope examination – this process currently utilises 15-20 data sources including the JBA examination database, GRV, WERM3, GSRA, CHOPS etc. The aim is to build on existing information sources in a structured way to develop an Evaluation interactive decision support tool
- CGC05 Instrumentation and monitoring data exchange platform (RCM Project)

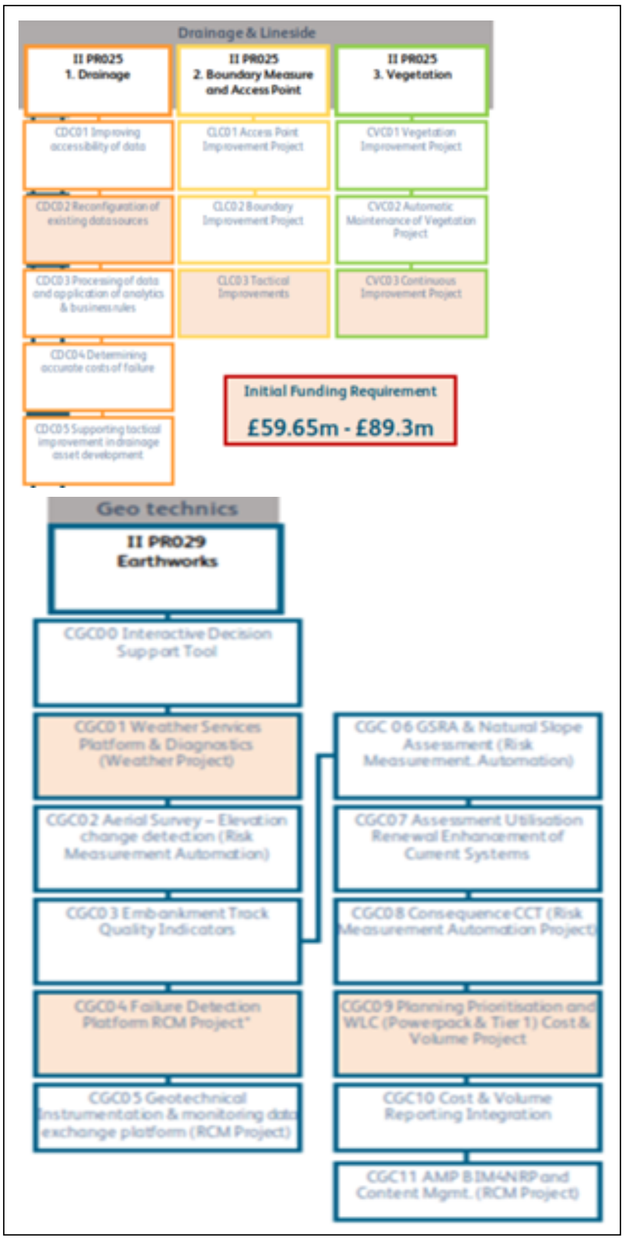


Figure E30: Full Proposed Scope Drainage/Lineside and Geotechnical – Intelligent Infrastructure II programme

Appendix F

Drainage Asset Management

F.1 Drainage Standards

1062 The Professional Head of Drainage in the Technical Authority team has the responsibility for owning, developing and maintaining the Drainage suite of standards across NR. The Drainage standards (Table F1) provide details on specific roles and responsibilities and dictate which procedures are mandatory (i.e. no variations permitted), which procedures may be varied subject to approved risk analysis and mitigation and which procedures are provided as guidance (i.e. they are to be used unless alternative solutions are followed). As a result, the Regions/Routes have authority to deviate from some of the procedures set out in the Policy, as allowed for in the standards. It is understood that this is a necessary provision to enable the RAMs to use their detailed local knowledge of their assets and Region-specific constraints, pressures and opportunities to effectively manage their drainage assets.

1063 The Drainage System Manual NR (2018e) helps mitigate the risk of drainage system failure by promoting a coordinated approach to the management of railway drainage assets.

1064 The purpose of this Manual is to define the requirements and provide recommendations for drainage whole life cycle activities. It comprises 15 modules (Table F1) which collectively:

+ promote a co-ordinated approach to the management of railway drainage systems
+ provide procedures for identifying risks, assigning priorities and determining measures to maintain safety and reduce performance loss attributable to defective drainage systems
+ provide details to those persons who have responsibility for inspecting, evaluating, maintaining, renewing and improving the drainage systems

Document Name	Reference Issue	Number	Publication Date
Drainage Asset Management	NR/CIV/005/01	1	02/06/18
Railway Drainage	NR/CIV/005/02	1	02/06/18
Drainage Management Plans	NR/CIV/005/03	1	02/06/18
Drainage Inspections	NR/CIV/005/04	1	02/06/18
Drainage Surveys	NR/CIV/005/05	1	02/06/18
Drainage Evaluation	NR/CIV/005/06	1	02/06/18
Drainage Intervention	NR/CIV/005/07	1	02/06/18
Drainage Assessment	NR/CIV/005/08	1	02/06/18
Drainage Design	NR/CIV/005/09	1	02/06/18
Drainage Installation	NR/CIV/005/10	1	02/06/18
Drainage Maintenance	NR/CIV/005/11	1	02/06/18
Maintenance of Chambers	NR/CIV/005/12	1	02/06/18
Maintenance of Pipes	NR/CIV/005/13	1	02/06/18
Maintenance of Channels including Ditches	NR/CIV/005/14	1	02/06/18
Maintenance of Culverts	NR/CIV/005/15	1	02/06/18

Table F1: Drainage Standard Asset Management Modules

F.3 Drainage Decision Support Tools

1065 A number of Decision Support Tools (DSTs) are in use or in development for the drainage asset, as follows:

+ Drainage SCAnNeR (Strategic Cost Analysis for Network Rail) is a portfolio level model used to simulate various Policy options for earthworks, track and structures drainage
+ Drainage Decision Support Tool (DDST) was developed to assist the Routes in prioritising drainage works. The shortcomings in the existing DDST requires the Infrastructure Intelligence Programme II to develop solution for a replacement DDST
+ DU Maintenance Planning Tool was developed to assist the Routes in developing a bottom maintenance plan

F.3 Drainage Asset groups

1066 Drainage asset groups are defined by NR in a classification that is compatible with CIRIA (2014). Assets of various types within each group have a similar form and function, and similar mechanisms of degradation.

+ Ponds: includes balancing ponds and wetland treatment systems
+ Ditches: includes unlined ditches and ditches lined with brick, concrete or stone slabs
+ Channels: include preformed segmental channels and flumes which carry water down slopes
+ Inlets and outlets: include headwall structures on culverts, and gratings to prevent debris blockage
+ Filter drains: include shallow gravel filled trenches on slopes to collect surface water, and deep counterfort slope drains to collect groundwater
+ Chambers: include catchpits to collect silt on drainage pipe runs, manholes at the junction of piped systems, soakaway chambers and interceptors

- Pipes and culverts: include perforated collected pipes in gravel filled trenches to collect surface and groundwater alongside the track, carrier pipes to carry water through, along and away from the railway, culverts to carry railway drainage and surface water courses under embankments, and syphons to take water under cuttings
- Pumped systems: carry water away from low points in the drainage system where that low point is not an outfall
- Other miscellaneous drainage asset types: include drainage blankets and weep holes behind and through retaining walls and tunnel linings, drainage blankets within earthworks, flow control

F.3 Drainage asset condition and performance

1067 The terms drainage asset 'condition' and 'performance' are often used interchangeably; Table F2 Drainage Asset Policy, NR (2017e) illustrates the difference.

1	No defects	Structural condition	Condition	Performance	Serviceable	Water is flowing freely through the drainage system
2	Superficial defects					
3	Minor defects					
4	Major defects				Marginal	Water flow through the drainage system is partially impeded
5	Not fit for purpose or unsafe					
1	Clear	Service condition				
2	Superficial deposits with no loss of capacity				Poor (including under capacity)	Water flow through the drainage system is severely impeded or blocked. And/or the drainage system is unable to carry the current peak volume of water
3	Capacity slightly reduced					
4	Capacity severely reduced					
5	Blocked or unsafe condition					
Size			Capacity			
Gradient						
Roughness						
					Absent	There is no drainage present

Table F2: Drainage condition vs. performance. (Taken from NR (2017e). Drainage Asset Policy Issue 4 March 2017.)

1068 There are two components to drainage asset condition:

+ Structural condition: relates to the fabric of the asset and the severity of the structural defects that affect its integrity. Structural defects are addressed by repairing or replacing the asset

+ Service condition: relates to the water carrying capacity of the asset and the severity of the defects that reduce its capacity below its original design level, but is independent of the structural condition. Service defects are addressed by maintenance of the asset such as cleansing or vegetation clearance

1069 Both structural and service condition are measured (for pipework) on a 1 to 5 grading system, with grade 1 being 'as new' and grade 5 being 'failed, blocked, not fit for purpose or unsafe'. These condition grades can be derived from all CCTV pipework surveys carried out to the British Standard, BS EN 13508-2:2003. NR has extended the grading system to all of its drainage assets, and this provides a useful descriptive shorthand for asset condition that will be used in prioritising drainage works and determining the most appropriate intervention option. The system adopted is compatible with CIRIA (2014).

F.5 Current condition of the drainage asset

1070 The drainage structural and service condition scores were captured in the CP4 surveys, although different classifications were used, they were migrated into the 1 to 5 grading system used in the Ellipse database. The results for all surveyed drainage (track and off-track drainage assets) with condition data are shown in Figure F1 for structural condition and in Figure F2 for service condition. Figure F3 presents the overall national drainage condition as August 2017.

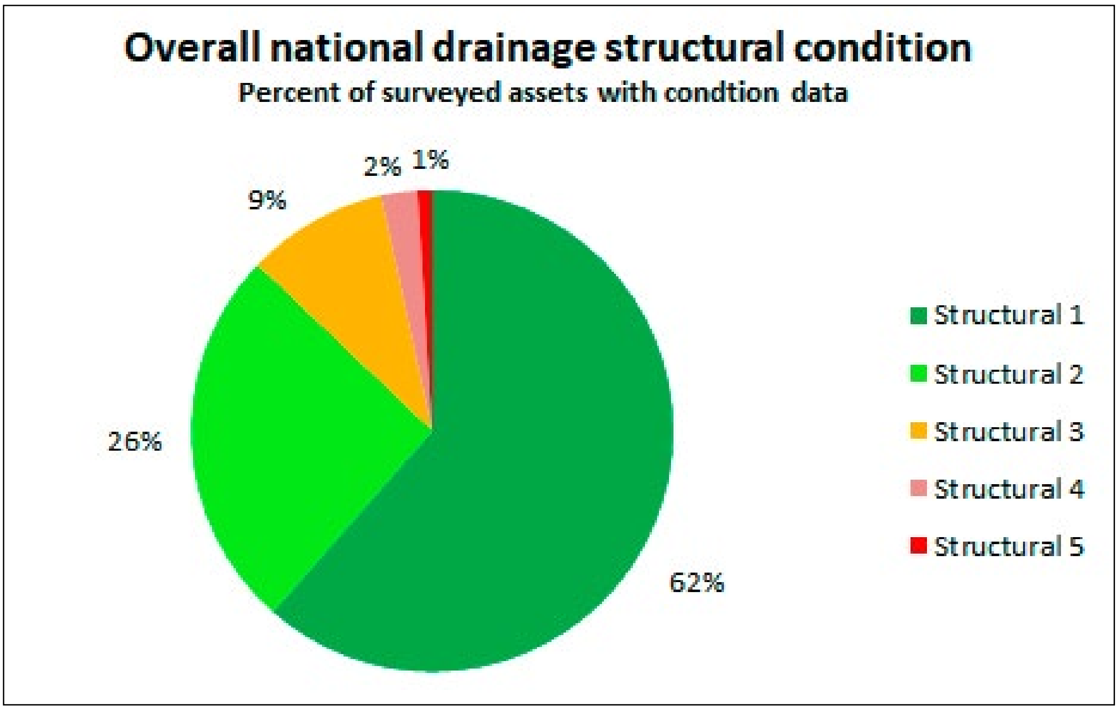


Figure F1: Overall national drainage structural condition (at August 2017)

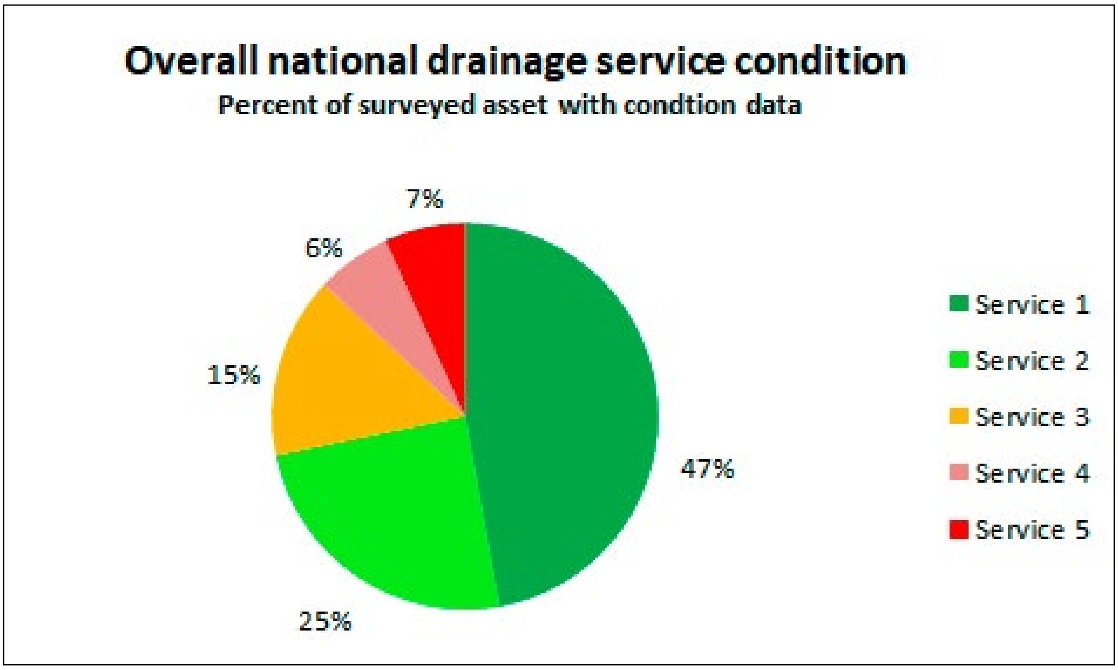


Figure F2: Overall national drainage service condition (at August 2017)

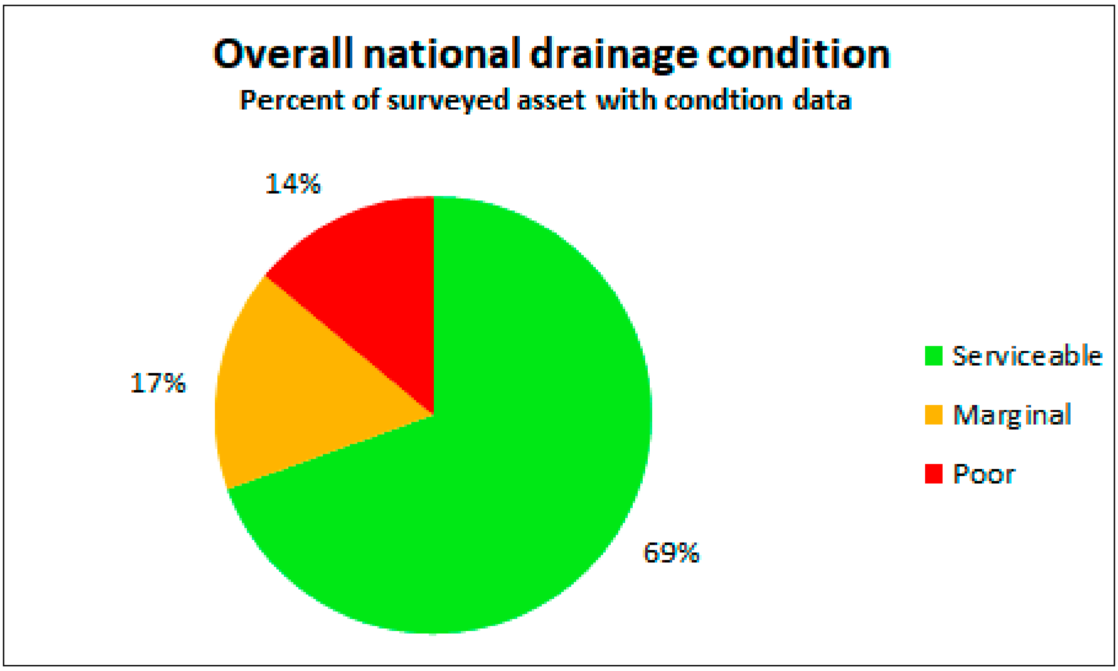


Figure F3: Overall national drainage condition (at August 2017)

1071 Condition could not be assessed for a significant proportion of the surveyed assets (just over 30%). In particular condition was not assessed for the majority of the pipes as these are buried assets. Buried asset condition is captured through detailed surveys such as using CCTV.

1072 Combining the condition data nationally for all surveyed asset types, and excluding those for which condition was not inspected, the service condition profile is significantly worse than the structural condition profile.

F.6 Drainage inventory groups condition

1073 For all the drainage inventory groups an overall asset condition is assessed being a combination of the structural and service condition grades as defined in Table F3. The overall asset condition considers that the performance of a drainage asset will be governed by the worst of the structural or service condition.

<table>
<tr><th>Structural Condition Grade</th><th colspan="5">Service Condition Grade</th></tr>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>1</td><td colspan="2" rowspan="2">Good</td><td rowspan="2"></td><td colspan="2" rowspan="5"></td></tr>
<tr><td>2</td></tr>
<tr><td>3</td><td colspan="3">Marginal</td></tr>
<tr><td>4</td><td colspan="3" rowspan="2">Poor</td></tr>
<tr><td>5</td></tr>
</table>

Table F3: Definition of overall asset condition. (Taken from NR (2017e). Drainage Asset Policy Issue 4 March 2017.)

1074 The overall asset condition (as August 2017) as assessed for each of the inventory groups and by asset owner is summarised in Figure F4 by the percentage of assets in serviceable, marginal or poor condition, as well as the number for which condition has not been inspected. From this figure it can be seen that:

1075 There is little overall condition data for majority of the pipes (from CCTV surveys), although condition has been assessed for a higher proportion of the earthwork drainage pipes than the track drainage pipes.

1076 The channels and ditches show the worst overall condition profile with a high proportion of marginal and poor assets.

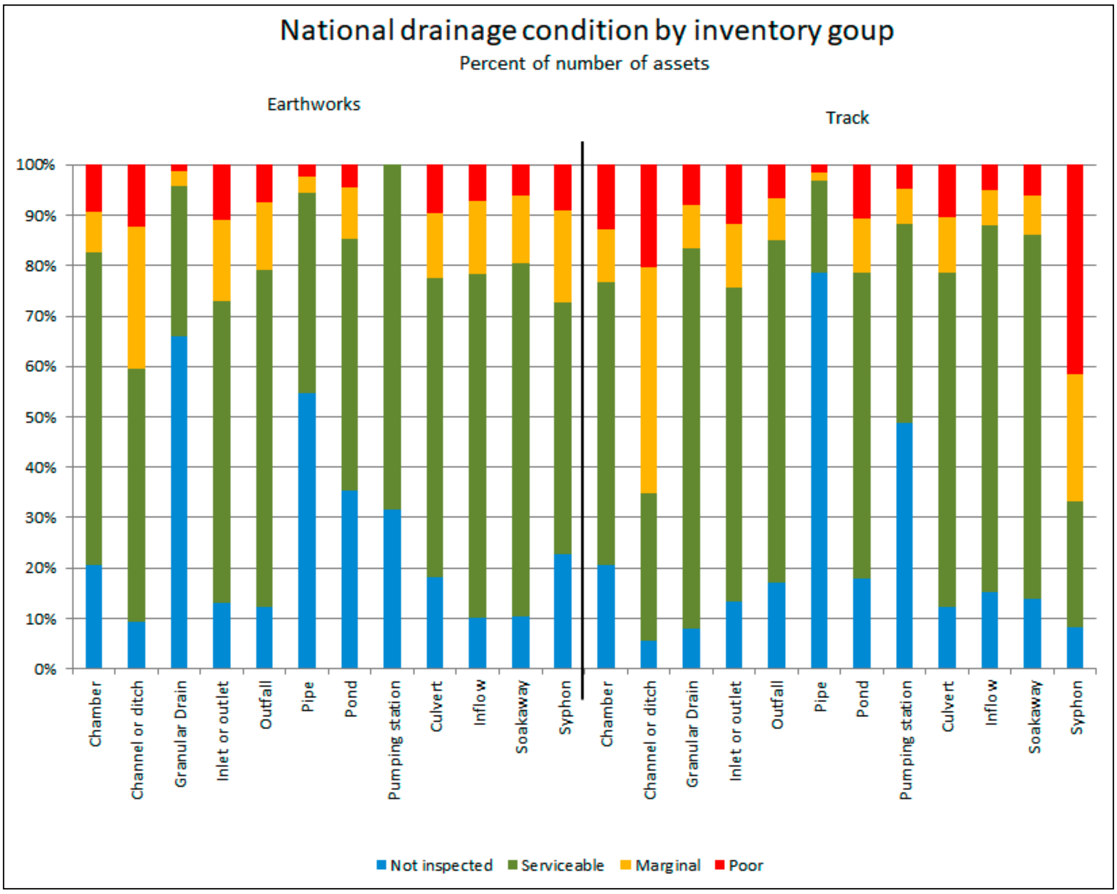


Figure F4: National drainage condition by inventory group (at August 2017)

F.7 Drainage 10ch (200m) sections overall condition

1077 The Ellipse database divides the national drainage asset into 10ch (200m or 1/8th mile) sections. The overall drainage condition of each 10ch section may be assessed as an aid to prioritising where to carry out drainage works. For those 10ch sections that contain any drainage assets for which condition has been inspected the worst overall condition of any single asset within the 10ch is taken on the basis that if one asset in a drainage system is in poor condition it acts as a bottleneck for the whole system upstream of it.

F.8 M37 Drainage Condition Banding

1078 The drainage performance measure is detailed in NR/ARM/M37DF, Network Rail Asset Reporting Manual: Definitions for the Reporting of M37 Drainage Condition Banding. The purpose of the measure is to monitor the condition of drainage assets by determining the average structural condition grade for all assets inspected.

1079 The M37 Drainage Condition Banding measure is defined as:

+ The sum of the count of the number of drainage assets inspected within each structural condition grade, multiplied by a weighting factor equal to the numeric value of the structural condition grade, divided by the total number of inspected assets. The measure is reported annually and is determined separately for drainage assets attributed to track and those attributed to off-track

1080 The condition data trends (Table F4) are erratic and are likely to remain so until the drainage asset inventory with associated condition grades is completed.

Principal Asset	Description	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20
Drainage	Track Drainage-M37 Condition Banding	1.48	1.49	1.54	1.51	1.44	1.41
	Earthwork Drainage-M37 Condition Banding	1.49	1.51	1.61	1.60	1.48	1.45

Table F4: M37 Drainage Condition Banding Trends

F.9 Maintenance and renewal volumes and expenditures

1081 The drainage asset is renewed and maintained as an integral part of the renewal and maintenance of the track, earthworks, structures and buildings assets. With current NR accounting practices, it is difficult to reliably disaggregate the costs or volumes of all drainage works from other works carried out on these assets in order to obtain historic total drainage expenditure

F.10 Drainage Asset degradation

1082 It is important to distinguish between the structural and service degradation of drainage assets, and the differences in the modes and rates of degradation between the hard drainage assets (pipes, channels, chambers etc. made of concrete, brick, stone, earthenware etc.) and the soft assets (ditches and ponds excavated within the soil).

1083 Figure F5 illustrates the different rates of degradation.

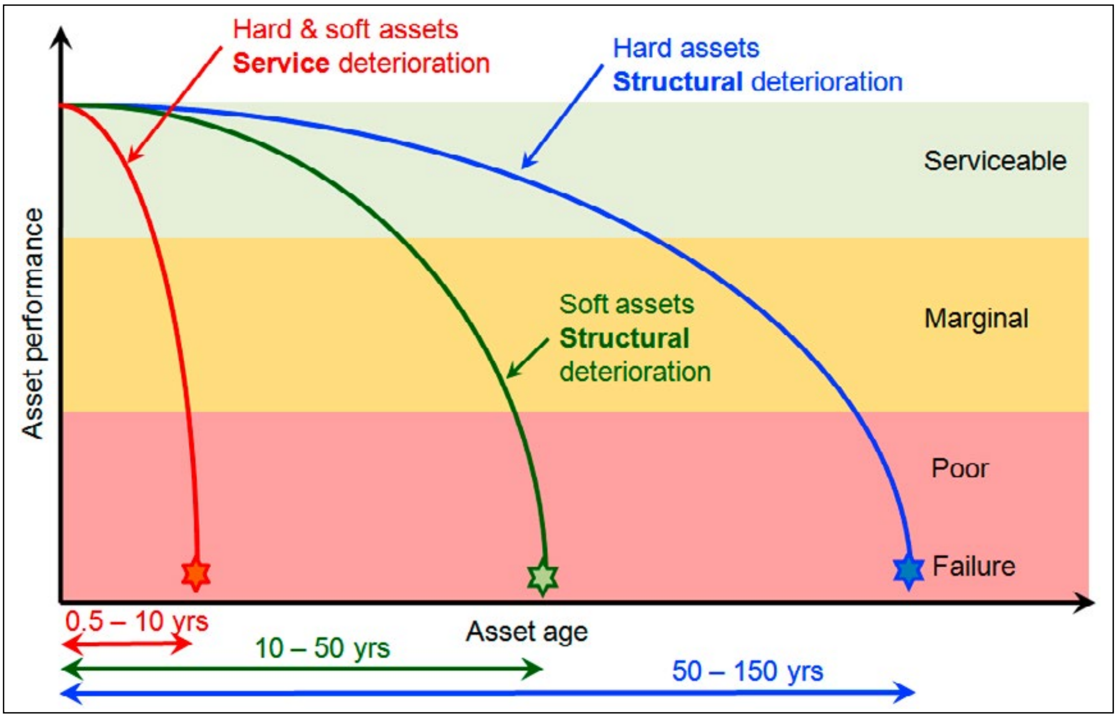


Figure F5: Rates of asset deterioration. (Taken from NR (2017e). Drainage Asset Policy Issue 4 March 2017.)

1084 The hard assets typically have a long structural life, of the order of 50 to 150 years, before the physical integrity of the structure is likely to fail and will need to be renewed. For example, most of the culverts on the network date from the original construction of the railway lines, the majority being over 100 years old, and whilst culvert failures are not unknown, they are rare. Whilst the soft assets have a shorter structural life, of the order of 10 to 50 years, before their banks will have degraded and will need to be reprofiled to restore their capacity.

1085 However, in contrast, the service life of all drainage assets is significantly shorter than their structural life. All drainage assets can become reduced in capacity or blocked by silt, debris and/or vegetation, and this can happen in a matter of months to a few years. Across all the drainage assets the service life (if no maintenance is carried out) is of the order of 0.5 to 10 years. That is, the service life is of the same order of magnitude as the 5-year duration of the Control Period. This makes the drainage asset the shortest lived of all of NR's assets, and is the main reason why drainage assets benefit from a proactive approach to maintenance. The asset can be maintained in a serviceable condition if relatively low-cost proactive maintenance (cleaning) is carried out on a regular basis, and the longer-term structural degradation of the assets becomes of lesser concern.

1086 Siltation is the commonest cause of service failure resulting in loss of section and leading to total blockage. The problem is exacerbated where pipes and channels have insufficient gradient to be self-cleaning, or where an asset is in poor structural condition and irregularities in the invert result in ponding of water. Vegetation growth in the surface drainage assets results in a reduction in flow velocity, causing more rapid accumulation of silt. If the assets are unmaintained for a long time, then the growth of trees or dense vegetation can severely restrict the water flow. Root growth in the below ground assets has a similar effect.

1087 The soft surface assets fail structurally by bank failure or animal burrowing. If the surface assets are unmaintained for a long period of time it may not be clear whether the loss of section is structural due to bank failure or a service defect due to siltation. However, the net result is the same and capacity can only be restored by excavation and re-profiling.

F.11 Data Systems

1088 The drainage asset data is held in Ellipse and generated from inspection, survey, assessment, maintenance and intervention activities. Prior to the start of each financial year, planned earthworks drainage maintenance volumes are agreed between the Maintenance Off Track Drainage team and the RAM Off-track Drainage.

1089 Records generated from drainage activities include, but are not limited to:

+ Asset inventory data
+ Asset condition data
+ Reports and records from surveys and assessment
+ Photographs
+ Monitoring records
+ Design documents
+ Installation records including as-built drawings

1090 Photographs recorded with the My Work App are linked to the asset and stored with the asset data within Ellipse for future reference. Records not held in Ellipse are required be stored in an approved shared filing system which will vary from Region/Route/Maintenance Depot.

1091 The Drainage Strategy, Engineering & Asset Management System (StrEAMS) project (Figure F6) will provide an integrated environment where live data from multiple sources is accessible and the workflow management is open and transparent across the business (i.e. inspection to renewal). The StrEAMS project is planned to be delivered by the Intelligent Infrastructure II programme by March 2024.

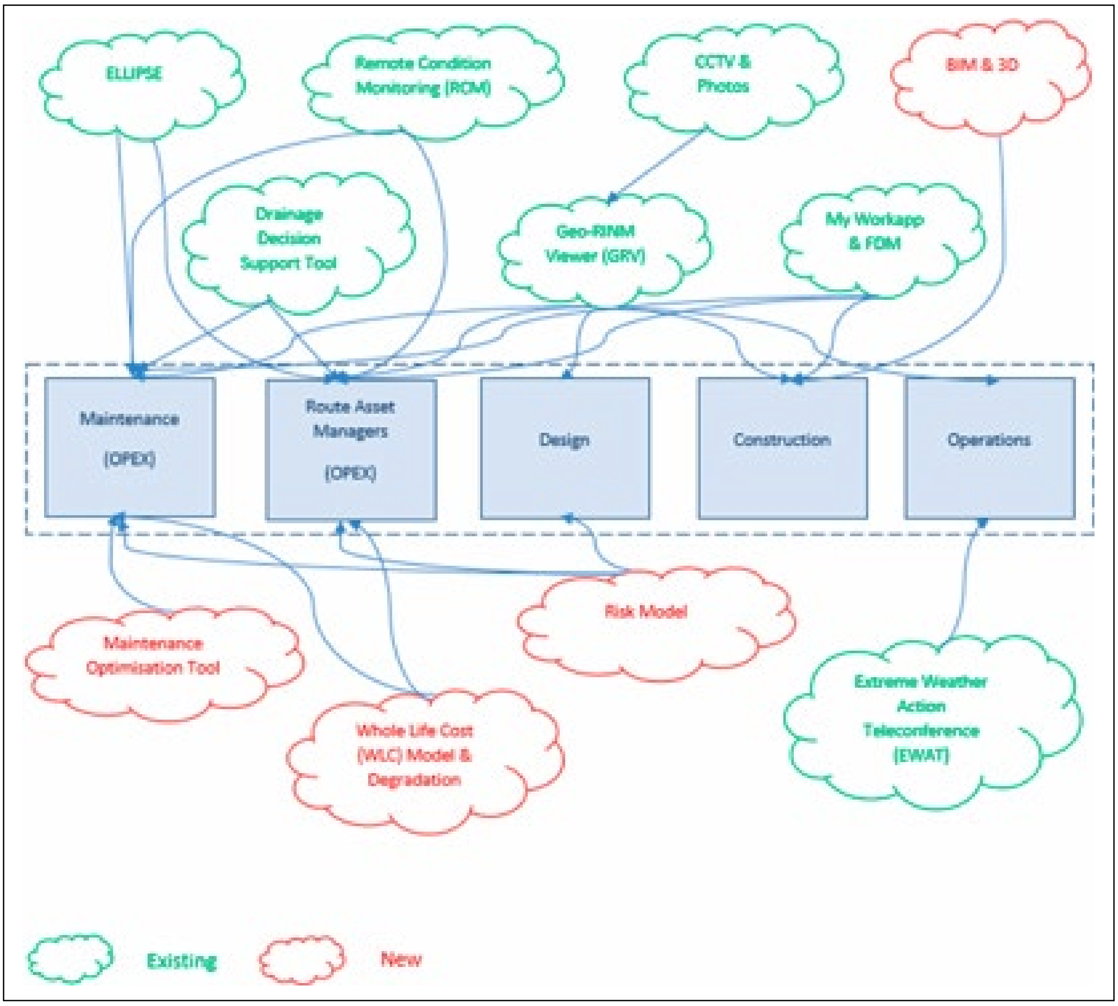


Figure F6: Drainage Strategy, Engineering & Asset Management System (StrEAMS) project

F.12 Cutting slope failures triggered by defective unlined ditches along the crest

1092 Robertsbridge Cutting in Kent (Figure F7) was one of four incidents over three months in early 2020 where animals have burrowed into unlined crest drains resulting in washout failure of the slope.

Figure F7: Robertsbridge Cutting, Kent: burrowing into an unlined crest drain led to washout of weathered interbedded siltstone/sandstone following heavy rainfall in December 2019

1093 On 28 November 2009, a London to Yeovil train ran into a landslip in a cutting on the eastern approach to Gillingham tunnel in Dorset. The leading carriage of the train became derailed and the train ran into the tunnel and stopped 200 metres inside. The landslip was caused by water overflowing from a blocked ditch at the top of the cutting slope, RAIB (2010). (Figure F8).

Figure F8: Gillingham Cutting failure 2009 which was triggered by water overflowing from a blocked ditch. (RAIB 2010)

Appendix G

The Role of Technology in Slope Management

Professor Dave Petley
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1. Introduction

This review provides a high level oversight into the ways in which new technologies can provide enhanced approaches to slope management. It draws upon recent literature and case studies. Whilst it is wide-ranging, it is not intended to be absolutely comprehensive given the range of topics.

New technologies are developing in this area with great rapidity. The combination of new, low cost sensors; novel terrestrial, aerial and space-based platforms; improved instrumentation; rapidly developing, powerful algorithms; and high performance computing is providing ample opportunities for innovation. This is likely to continue. Whilst the report focuses on the individual technologies, the greatest advances will come where multiple technologies are used together.

2. Early warning systems

2.1 Background and rainfall-based approaches

In recent years there has been considerable interest in the development of early warning systems for landslides of various types. In general the aim is to anticipate the likely occurrence and impact of landslides, but there are a range of temporal and spatial scales at which early warning systems operate. In some cases, especially when a regional warning is need, the approach is based upon meteorological data, most notably using rain gauges to detect precipitation in real time. The parameters most frequently used are rainfall magnitude (cumulative total) in the precipitation event and rainfall intensity. In general an intensity – cumulative rainfall relationship is defined, and the occurrence of landslides within this relationship is determined using either records of the occurrence of previous landslides or modelling. When the rainfall total exceeds the threshold landslides are considered to be likely, and appropriate warnings are issued.

Whilst this approach has proven to be robust, it requires a long, reliable record of rainfall and of the associated landslides. The greatest limitation lies in the density of the rain gauge network as precipitation is highly spatially variable, especially with regard to short duration, high intensity events in upland areas. It also assumes that landslides have common initiation thresholds - in terrain that is susceptible to landslides it is likely that some failures will not be defined by these parameters.

Some improvement to these approaches has been achieved with the use of rainfall radar, which can allow interpolation of rainfall patterns between the rain gauges. This allows cross correlation between the radar and the rain gauge data, providing a better spatial and temporal understanding of where the thresholds may be exceeded.

Further enhancement can be achieved with nowcasting, in which rainfall radar is used to detect incoming precipitation, and modelling is used to predict the likely rainfall pattern, and thus the resulting landslides are forecast spatially and in time. This requires a highly calibrated model of rainfall, but where available it can be used to identify locations and times in which rainfall is considered likely to exceed landslide thresholds.

Meteorological early warnings are covered in detail in the review by Dame Julia Slingo and are reviewed in detail in Piciullo et al. (2020). Probably the best example operates with great effectiveness in Hong Kong – see Kong et al. (2020).

2.2 Acoustic emissions

Rapid developments are occurring in the use of instrumental approaches to providing early warning of landslides. These developments are being driven by rapid advances in sensor technology, providing instruments that are comparatively cheap to deploy, are able to send data wirelessly, have low energy consumption and that provide high quality data. There are a range of approaches available. This section will focus on innovative approaches.

Material deformation can generate acoustic emissions – high frequency elastic stress waves that are able propagate through the material. Detection of acoustic emissions is, under the right conditions, comparatively straightforward. Thus, acoustic emission detectors can be an indication that deformation is occurring, providing an opportunity to detect failure. However, slopes are usually complex, formed of materials that may not allow simple transmission of elastic stress waves and they are often saturated when slope instability is likely. Thus acoustic emission based warning systems have proven to be challenging to implement.

Nonetheless, some successes have been noted. For example Berg et al. (2018) successfully monitored the deformation of a slow-moving landslide in Canada using a combination of conventional approaches and acoustic emissions. The data demonstrated that movement was associated with higher rates of acoustic emissions, even in a slow moving system, providing the possibility to utilise this approach as an early warning system. In China, Hu et al. (2020) have demonstrated that acoustic emissions can be a very sensitive indicator of movement where internal erosion and see page XX driven transport of small grains is occurring, although the authors noted that further research and validation is needed.

A successful solution application is the Slope ALARMS system of Dixon et al. (2018), in which a column of gravel is placed in the slope. As slope movement develops the gravel is deformed, generating strong acoustic emissions which are captured by a wave guide located within the gravel (Dixon et al. 2003). Calibration of the signals generated by deforming gravel allow interpolation of the deformation.

This approach has met with success in the monitoring of slopes, and provides the possibility of a system that might detect other types of trackside failure, such as gravel washout. Consideration could be given to the installation of such a system on known sites at regular intervals along the track, potentially giving an indication real time conditions along the alignment, even if failure has not yet occurred. This system could perhaps be co-located with rain gauges to provide a real time indicator of the development of potential earthworks problems along the track.

Of course the system can also be deployed to monitor slopes with known potential instability.

2.3 The detection of seismic energy radiated by failing slopes

Rapid landslides, such as debris flows, generate seismic energy due to basal friction between the body of the flow and the lateral boundaries, and in some cases within the flow itself. This energy can be detected via geophones located close to the edge of the landslide, or even in the case of very large landslides, by regional seismic networks. Considerable success has been met for the collection of seismic signals radiated by landslides – see for example Huang et al. (2008) for a debris flow and Ekström and Stark (2013) for large landslides.

A geophone located upstream of an asset can be used to provide an early warning. Two or more sensors located at known points along the path of a potential mobile landslide can be used to indicate the rate of movement of the flow. Furthermore, the seismic energy radiated from the landslide is related to physics of the movement. Seismic inversion can be used to extract characteristics of the landslide – for example, the maximum amplitude of the signal is related to the maximum discharge in the channel in a debris flow. Potential uses of these technologies for providing local early warning, or to indicate that failure has occurred, are given in Coviello et al. (2019) and Marchetti et al. (2019).

2.4 The detection of rock slope instability using microseismic monitoring

In slopes consisting of harder rock, deformation generates seismic energy that can be detected with seismic instruments. Considerable success has been achieved in detecting this energy to provide a warning, based on the observation that the seismic energy event rate increases as failure develops. A good review of this topic is provided in Feng et al. (2020). Three main applications can be highlighted:

1. The microseismic signals associated with an event can be used to indicate that failure is occurring. Inversion of the data can be used to extrapolate key information, such as the location, trajectory, volume, energy, and mechanism of the landslide (Ekström and Stark 2013);

2. Microseismic signals can be the basis of an early warning system using variations in the waveforms and seismic events detected. Analysis of the data can indicate the location of the failure in development (e.g. Schöpa et al. 2018).

3. There is strong evidence that many landslides are pre-empted by precursory events. This provides an additional basis for using microseismics to forecast failure where these precursory events can be detected (Feng et al. 2020).

In all cases these approaches remain reasonably experimental, but they show great promise for the provision of earthly warning systems.

2.5 Distributed fibre optic sensing

Fibre-optic sensors can provide a powerful technique to measure deformation. In recent years these techniques have evolved rapidly from the early instruments, which provided information about the location of deformation. These techniques, often termed optical time-domain reflectometry (OTDR) using ground-buried fibre-optic sensors used frequency shifts in reflected light in the fibre that occurred when the fibre was stressed. These approaches evolved with time, using for example improved quantitative interrogation approaches (most notably phase-sensitive or coherent OTDR – e.g. Juarez and Taylor 2007) and Brillouin OTDR (BOTDR, Kwon et al. 2002). Applications have been found in both the measurement of deformation in tunnels and in the measurement of circumferential strains in buried pipelines experiencing strains generated by ground movement.

In the last couple of years substantial improvements have been made through distributed fibre-optic strain sensors, buried in the ground, that are able to provide both high spatial resolution and detailed information about the amount of strain. Distributed fibre-optic sensing uses a mechanical soil model together with inverse analysis algorithms to compute the pattern of strain in the ground. The proof of concept study is provided by Friedl et al. (2019). In the geotechnical sphere, the use of this approach is described in detail by Puzrin et al. (2019), who have developed a fibre-optics based extensometer that can be emplaced in boreholes, and a fibre-optics-based inclino-extensometer, also placed in a borehole, that has been used to measure deformation in landslides. This has proven to be more robust than conventional monitoring approaches, providing better understanding of the spatial development of strain (for example, measurements can be obtained below and on the shear surface even when large strains have accumulated).

This approach has good potential for the ongoing measurement of known hazardous slopes. A small number of sensors can be combined with detailed measurement of surface deformation from, for example, continuous GPS (see for example Massey et al. 2016) or from optical sensors or radar-based measurements of surface movement to characterise landslide processes, enhancing the geotechnical model and allowing better anticipation of future behaviour. These approaches could also be used to provide an early warning system based on, for example, a threshold displacement, displacement rate or rate of acceleration. Thus, they provide a mechanism to protect the track against known hazards at specific sites.

3. Smart rigid barriers

The use of barriers of various types is an established approach to managing landslide hazard. For example, Sabo engineering approaches in Japan have frequently relied upon rigid barriers coupled with catch ponds, and similar approaches are widely used in the Alps (see for example Canelli et al. 2012). These approaches are effective when the design volume of the landslide is correctly determined.

In Hong Kong, the rigid barrier approach has also been adopted, with success, by the Geotechnical Engineering Office (GEO). In recent years they have trialled the development of smart rigid barriers, which are fitted with sensors that determine when the barriers have been used to retain a landslide (see for example Pun et al. 2020). The sensor suite generally consists of a combination of a pressure late to detect debris impact on the face of the barrier, distance measurement equipment to detect the depth of the debris and a camera that allows the operator to check that it is not a false alarm. These approaches use technologies that are tried and tested; the challenges come in guaranteeing a reliable power supply, given that the barriers are generally in comparatively remote locations, and in reliable communications, in particular during a weather crisis when communications may be physically disrupted and communication networks, such as mobile phone systems, might be saturated.

There are two key rationales for the installation of sensors to create smart barriers. First, these barrier systems are effective only whilst there is capacity within the catch pod. Once that capacity is lost, the landslide will overflow the barrier, and thus will pose a risk to downslope assets. The smart barrier system can provide a warning that such an event is likely. Second, in Hong Kong during periods of heavy rainfall there is the potential for multiple landslides in the same catchment, or in adjacent catchments. Thus, the smart barriers can provide a general warning to the local population, and to the disaster managers, that landslides are occurring. GEO is trialling the provision of visual displays and other warning systems in the area of the smart barriers to provide a warning to potentially affected populations.

The smart rigid barriers in Hong Kong have yet to be tested by a severe rainfall event.

4. Smart flexible barriers

Flexible barriers represent an approach to the mitigation of hazard with substantial advantages over rigid barriers, in the right setting. Flexible barriers are less intrusive (especially where vegetation is dense), lower cost and less environmentally harmful that rigid barriers, although clearly they have limitations in terms of energy and volume absorption. Flexible barriers have been deployed in the UK and overseas, with significant success, in particular against rockfall events. Their deployment to mitigate landslide hazard is becoming more common, and there are some notable successes, notably at the A83 Rest and Be Thankful site in Scotland. In Hong Kong, flexible barriers now form a major part of the mitigation measures in natural terrain catchments, and have been deployed extensively (Sze et al. 2018)

Smart flexible barriers seeks to install sensors to detect when the barriers are acting to contain landslides. Such systems are in development both commercially and by users of barrier technology. The rational is similar to that of smart rigid barriers. Instrumentation of flexible barriers can include impact switches or sensors that detect deformation of the barrier, for example on the brake elements, or that detect debris retained by the barrier. In flexible barriers there are likely to be a greater set of challenges around providing reliable data. They are usually located in sites that are more remote than those for rigid barriers, which is likely to hamper the provision of power and reliable communications. Flexible barriers often become overgrown, hindering the provision of solar power. They will tend to move in weather conditions or through the actions of animals. Thus the likelihood of sensor failure and of false positive detections is much higher than is the case for smart rigid barriers, but successful deployment of these systems will be valuable.

5. Remote sensing technologies

A review of the use of remote sensing for the monitoring and management of railway infrastructure is provided by Donzelli (2019) in work that has been undertaken in the EU Horizon 2020 Multi-scale Observation and Monitoring of railway Infrastructure Threats (MOMIT) project. Six primary applications are highlighted, of which the first three are relevant to this review:-

+ Monitoring of ground movements near to the track
+ Global supervision for natural hazards: anomalies along the track related to natural phenomena (as vegetation growth) are monitored using satellite data
+ Monitoring of hydraulic processes near to the track: a combination of optical and radar satellite data can be used to monitor soil moisture and water bodies close to the track
+ Electrical system monitoring
+ Civil engineering structures monitoring
+ Safety monitoring: anomalous and illicit activities along the track are detected and controlled using optical and radar satellite data

The remainder of this section will focus on the use of remote sensing tools in the context of earthworks assets. Note that this is a very large area of active research, so the review is not exhaustive.

5.1 LiDAR

LiDAR technologies are now routinely applied in the study of landslides. A good review is provided in Jaboyedoff et al. (2012). The primary applications are as follows:

1. To map the distribution of landslides across the terrain. LiDAR is especially effective at the production of digital terrain models in areas with forest cover or dense vegetation, allowing the detection of landslide scars and deposits that are otherwise invisible (Razak et al. 2013);
2. To provide a detail digital terrain model for the assessment of landslide susceptibility or hazard;

3. To provide a digital terrain model as an input for the simulation and assessment of landslide mobility and runout;
4. A provide detailed information about a landslide under investigation.
5. To provide monitoring of slope behaviour through the use of multiple epochs of imagery, allowing detection of change (e.g. Booth et al. 2020).

This list is not intended to be exhaustive, but these applications are now common.

However, LiDAR technology, and its application, continues to evolve rapidly. In part this is due to the availability of sensors with enhanced capabilities, including higher ranges, improved resolution and full waveform capabilities.

Key recent advances in the application of LiDAR in the investigation and monitoring of slopes include:

1. The use of LiDAR data to generate DEMs from which the geometry of expose landslide scarps can be extracted (Tang et al. 2020). Modelling using a polynomial surface allows the geometry of the failure plane to be assessed, assuming that it outcrops at the toe of the slope.
2. The combination of LiDAR data with Interferometric Synthetic Aperture Radar (InSAR) processing of ALOS and Sentinel-1 images to derive a decadal movement record for a large landslide in Oregon, USA (Xu et al. 2020). This type of approach allows post event investigation of the movement history of a slope even where no dedicated monitoring was in place. It can also be used to monitor slope movements in near real time.
3. The automatic extraction of landslides from a LiDAR-derived digital terrain model based upon persistent homology (i.e. the recognition of the morphological characteristics of a failure), potentially allowing more rapid and more consistent landslide mapping (Syzdykbayev et al. 2020).
4. A range of approaches have been developed to extract landslide features from LIDAR data, including a contour connection method (Leshchinsky et al. 2015), a cluster based approach (Deng and Shi 2014) and a semi-automatic object-based landslide identification approach (Li et al. 2015)

LiDAR has also proven to be extremely powerful for obtaining a rapid post-event understanding of landslides. The mobilisation of LiDAR equipped aircraft or drones allows the rapid survey of large areas. Massey et al. (2019) used a detailed comparison of pre- and post-event LiDAR data to analyse the landslide distribution triggered by the 2016 Kaikoura earthquake in New Zealand, whilst Stringer et al. (2020) combined LiDAR data with other datasets to analyse and monitor landslides associated with the same earthquake along the State Highway 1 and main rail trunk line transportation corridor.

An associated development has been the use of terrestrial laser scanning (TLS), which is ground-based LiDAR. The technologies associated with this approach have developed in parallel with airborne LiDAR, with scanners that can collect higher densities of points at a higher rate of capture over longer ranges and with more information in the signal. The use of TLS for collecting topographic data is well-established, and it is also widely used for collecting discontinuity data for rock mass assessment (e.g. Robiato et al. 2019). The greatest contribution of TLS has probably been in change detection, especially for the characterisation of rockfalls for example (e.g. Rosser et al. 2013), and this technique has been extensively used for monitoring of ongoing hazards (e.g. Bozzano et al. 2020) and post-failure analysis (e.g. Zhou et al. 2020)

5.2 SAR: InSAR, offset tracking and ground-based monitoring

Colesanti and Wasowski (2006) defined Synthetic Aperture Radar (SAR) is "an active microwave device capable of recording the electromagnetic echo backscattered from the Earth surface and of arranging it in a 2D image map, whose dimensions are the sensor-target distance (slant range or Line of Sight direction, LOS) and the platform flight direction (azimuth)". A range of techniques have been developed that use this technology to monitor the ground, of which SAR Interferometry (InSAR) is the best known. InSAR measures change between pairs of radar images to detect deformation. Processing of imagery is complex, but has become increasingly routine and automated in recent years, providing a tool with increasing levels of applicability. In high wall quarrying, and in the monitoring of some particularly hazardous slopes, ground-based InSAR (GB-InSAR) is commonly deployed – indeed in some high wall quarrying settings such systems are now routinely used. An associated application uses airborne SAR systems, although there are usually substantial challenges in deploying these systems practically.

InSAR has found two principal uses in the monitoring of slopes. In natural systems the primary application has been InSAR using satellite sensors, especially in recent years using the European Sentinel systems, although a range of other instruments are available.

The major challenge in the use of satellite-based InSAR has been the generation of pairs of images that are coherent. In many cases landslides occur on slopes that are steep, which can challenge the capacity of the sensor to gain a clear view of the site, and undergo regular surface changes that are not associated with the movement of the slope, such as the growth of vegetation or changes to land use due to farming (e.g. ploughing). These problems occur far less in urban settings, where buildings and other hard structures provide a consistent radar return. In rural areas the primary approach to mitigating this problem is to use so-called permanent scatters (PS) – objects located in the area of interest that generate a consistent return (Farina et al. 2006 for example). Typically these are buildings, but other objects such as large boulders, can also generate a stable signal. In some cases the satellite data can be enhanced with the placement of corner reflectors – permanent targets located on the landslide to generate a stable signal. This has allowed the detection of movement in landslide systems, and improvements in processing have permitted good movement records to be extracted, which have in some cases been benchmarked against movement records obtained from conventional monitoring (e.g. Bardi et al. 2014).

However, even with the use of PS and corner reflectors, landslide monitoring using satellite InSAR has proven to be challenging. In the last few years considerable improvements have been obtained through the application of the so-called SqueeSAR approach, which improves OS based InSAR through the inclusion of Distributed Scatters (Feretti et al. 2011). This approach has proven to be particularly effective in upland areas and those with vegetation, and is finding increasing application in the monitoring of slopes (e.g. Frattini et al. 2018).

Considerable improvements have been achieved in recent years through the application of another SAR-based approach, sub-pixel correlation methods, often termed “offset tracking”, which uses the amplitude channel of the SAR system. This approach, which is better suited to slopes with higher movement rates (which often prove challenging for InSAR analyses), has proven to be effective in a number of studies (e.g. Singleton et al. 2014). In general the applicability of these approaches is for the monitoring of slopes with known stability issues, and larger instabilities are usually the focus. This methodology continues to develop rapidly, with the development of techniques designed to provide more robust data. For example, Jia et al. (2020) describe an enhanced offset tracking method designed to improve the efficiency of the technique and to improve the confidence of the approach in heterogeneous areas.

In the specific context of railway infrastructure, the MOMIT project described above has designed “tools to help the detection and identification of ground movements using synthetic aperture radar interferometry (InSAR) data” (Navarro et al. 2020) that are optimised for railway settings. The outcome is a toolbox to allow InSAR data to be processed using the PS approach. The key tools include:

+ ADAfinder, a tool dedicated to the detection of active deformation areas, extracted from a displacement map generated using the PS methodology
+ ADAclassifier, a tool designed to determine whether areas of active deformation are caused by landslides, sinkholes, subsidence or construction settlements
+ THEXfinder, a tool designed to determine whether areas of active deformation are caused by expansive soils or thermal phenomena
+ los2hv computes the East-West horizontal and vertical components of the movement measured along the satellite line of sight (LOS)

The tools have been tested in Spain and Italy, with some success.

As noted previously, in the mining industry, GB-InSAR is routinely used to monitor slopes in order to provide early warning of potential failures (Antonello et al. 2004). Systems are available commercially, providing integrated tools that both collect the dataset and provide an analytical function that can provide warning of developing instability. There have been some applications of GB-InSAR in the context of railway infrastructure, including for example the monitoring of bridges (Kuras et al. 2020) and excavation wall displacements associated with dewatering (Serrano-Juan et al. 2016). The use of this approach in monitoring other railway infrastructure is worthy of further investigation.

A further potential opportunity lies in the development of national scale satellite based InSAR maps. The best known of these is InSAR Norway (https://insar.ngu.no/), produced by The Geological Survey of Norway (NGU), The Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Space Centre. It is regularly updated. This produces a map of deformation across Norway, with frequent updates. The density of monitored points is high. Users can select any point to derive a deformation time history extending back to 2015. Other nations and regions have attempted similar exercises including:

+ A one-off UK deformation map between October 2015 and October 2017 by Terramotion Ltd (https://mangomap.com/geomatic-ventures-limited/maps/72883/united-kingdom-relativedeformation-map#)
+ A nationwide deformation map for the Netherlands by Dutch Centre for Geodetics and Geo-informatics), SkyGeo and Technical University of Delft (TU) (https://bodemdalingskaart.nl/en-us/)
+ A one-off deformation map for Germany between March 2016 and March 2018 by Terramotion Ltd (https://mangomap.com/geomatic-ventures-limited/maps/72883/united-kingdom-relativedeformation-map#).

It is likely that over time these national or regional level deformation maps will improve in temporal and spatial resolution, providing the opportunity to gain information about ongoing sites with problematic behaviour comparatively simply.

5.3 High resolution satellite imagery

High resolution optical satellite imagery has been available for considerably more than a decade through commercial providers. Imagery with a lower spatial resolution is freely available, most notably through the ESA Sentinel-2 instruments, which were first launched in 2015. This data has a 10 metre resolution. Unfortunately this is not sufficiently high to allow high quality mapping of instability except for very large failures.

Higher resolution imagery is available commercially. For example, Planet Labs, based in California, operates a constellation of over 150 satellites with two different spatial resolutions. The PlanetScope instruments provide a spatial resolution in the range of 3 to 5 metres, with most areas on the Earth surface being imaged on a daily basis, with the obvious limitation of cloud cover. There has been demonstrable success in the use of these instruments to both monitor ongoing deformation and to collate information about recent failures. The spatial resolution presents limitations on smaller landslides. This imagery is collected continuously and archived; customers can order the images of use to them after previewing the available data.

The high resolution SkySat system provides imagery at 50 cm resolution, and in appearance is similar to high quality aerial photography. The constellation allows images to be collected up to twice a day. This imagery is exceptionally powerful in the analysis of surface conditions, and there are many examples of its application for landslides. In this case the instrument needs to be tasked to collect the imagery, but there are increasingly large archives of data for comparison.

Notable examples include:

+ High resolution (SkySat) images of the aftermath of the Luming soil failure in China: https://blogs.agu.org/landslideblog/2020/04/02/luming-mine-accident/
+ Medium resolution (PlanetScope) images of deformation of the rock slope at Gongo Soco in Brazil: https://blogs.agu.org/landslideblog/2020/02/03/gongo-soco/
+ High resolution (Skysat) images of the Brumadinho failure in Brazil: https://blogs.agu.org/landslideblog/2019/01/30/brumadinho-tailings-dam-failure/

In the coming years we are likely to see further advances in this area, from Planet Labs and other private sector providers. We are also likely to see higher spatial and temporal resolution images as cubesat technologies continue to develop, and these new technology companies are likely also to explore the collation of hyperspectral images and to move into radar products. These technologies are likely to find increasingly diverse applications, driving substantial innovation.

5.4 Unmanned aerial vehicles

Unmanned aerial vehicles (UAVs or drones) have reduced in price and developed rapidly from a technological perspective. A good review of the use of UAVs for the assessment of hazards is provided by Antoine et al. (2020), whilst a more general review of the use of UAVs in engineering geology is provided by Giodran et al. (2020). Whilst these reviews focus more generally, they have close applicability to railway earthworks. UAVs are of course primarily a mechanism for the deployment of other technologies, such as photogrammetry, multispectral data capture, thermal imagery, LiDAR, and potentially SAR, providing a flexible platform. The scale of data collection can range from the local, in which the operator collects data with a small UAV flown within line of sight to the regional (with the UAV operating autonomously, noting that there are substantial regulatory hurdles in this respect at present). Large areas can be surveyed quickly and effectively, and response times can be short.

At present there are substantial limitations in the use of UAVs however:-

+ A key factor is regulatory, with severe limitations on the use of UAVs beyond visual range of the operator. Regulation is becoming more strict with time, and threatens to stifle the innovation that UAVs can provide
+ UAVs fly comparatively low in most cases, which can lead to substantial levels of distortion in the images collected by optical type sensors. This can be overcome with ground control points, but these greatly increase the effort and time required to collect the data. Distortions can also result from difficulties in maintaining a stable platform
+ There are also limitations in the areas in which UAVs can operate, with restrictions on their use around large groups of people, airports and other key infrastructure assets
+ The range and duration of operation can be short (typically in the order of 30 minutes)
+ Weather can severely limit UAV operations, with notable problems being associated with strong winds and low visibility
+ UAVs can be subject to attacks from birds

  However, the development of UAVs over the last three decades has represented a very substantial technological advance. As Giordan et al. (2020) note "these technologies have transformed the capabilities of engineering geologists, mapping geologists, engineers, and researchers."

In the context of slope problems and earthworks, UAVs have primarily been used as follows:

+ Hazard mapping and morphological analysis: UAVs are typically used to collect LIDAR and/or optical imagery that allow landslides to be mapped (e.g. Comert et al. 2019), hazards to be assessed (e.g. Aditian et al. 2018), inventories to be collated (e.g. Tang et al. 2019), site conditions to be assessed (e.g. Lindner et al. 2016) and changes to be detected through time (e.g. Turner et al. 2015)

+ UAVs have also proven to be powerful in the collation of data after significant events, allowing documentation of site conditions, quantification of volumes, forensic study of process and a dataset for modelling (e.g. Stringer et al. 2020)

It is likely that these technologies will advance rapidly in the next few years, and the range of uses found for autonomous and remotely piloted military UAVs is demonstrating their potential applications. However, the major limitations may well result from the regulatory hurdles for non-military use of UAVs, which may substantially reduce their impact.

5.5 Photogrammetry

Photogrammetry has been used extensively in the assessment of sites and their hazards for many years. The primary medium has been aerial imagery, with archive images combined with new acquisitions allowing the interpretation of change through time. In Hong Kong for example the inventory of natural terrain landslides was initially collated using aerial imagery collected during a survey in 1963 as vegetation levels were much lower at that times, allowing better mapping of the terrain than is possible using more modern images.

But in recent years, the utility of photogrammetry has increased substantially. This has resulted from:

1. The availability of many more images due to increased capture from both ground and aerial sensors, and improved provision of online data (such as Google Earth for example);

2. Improvements in software technologies that allow rapid, automated orthorectification of images, providing data that is robust and that can be digitally combined with other technologies, such as digital elevation models;

3. The development of technologies such as Structure from Motion (SfM) that allows the creation of 3D datasets from regular photographs.

SfM in particular is proving to be a powerful tool for the collection of information about slope deformation using imagery. For example, Lopez-Vinielles et al. (2020) have described the use of SfM data obtained through photogrammetry to estimate the volumes and to explore the mechanisms of a large slope failure at Las Cruces in Spain. They conclude that this approach, combined with radar interferometry, provides a potential approach to pre-failure warning systems. Similarly, Guerin et al. (2020) describe the use of SfM to assess rockfall activity, using oblique photographs taken in 1976. These were compared with contemporary images, allowing 235 large rockfall events to be detected.

6. Concluding remarks

This report has briefly reviewed many of the recent technological developments available to support improvements in the understanding and safety of earthworks close to railway lines. It has not been exhaustive – there are many other technologies available, and it has not sought to cover all areas. Thus, for example, there is no discussion here of the use of artificial intelligence and machine learning, which is rapidly evolving, expansive topic.

The range of technologies under development is impressive. Whilst in this report they have been considered individually, the biggest advances are coming from cases in which a number of technologies are brought together to examine the problem. Thus, for example, a slope might be characterised with LiDAR collected from a UAV combined with aerial imagery, monitored using InSAR via the Squeesar approach, with an early warning system based upon the use of smart sensors. Whilst the individual technologies will evolve through time, the greatest opportunities will lie in the integration of multiple approaches to provide a comprehensive understanding of the asset.

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Appendix H

Examples of Slope Failures

Figure H1 **Rosyth 18 July 2012 (top)**

Bargoed 30 January 2013 (bottom)

Summer and winter shallow translational failures

Figure 6 Landslip obstructing up main line. 2K05 in background

Rosyth 18 July 2012 Derailment

Translational slide between vegetated layer and underlying glacial till after 55mm rainfall in 24 hours. Water concentrated beyond NR boundary

Example of localisation and effect of intense summer rainfall.

Bargoed translational failure on 30 January 2013 in soil cutting

15m high, 45degree slope, adjacent to failure in July 2012.

65.22mm rain fell on 29 Jan 2013, 250% above average. Slip occurred 3 hours after rain stopped.

Veneer of vegetated soil slides off.

Figure H2 **Cuxton Cutting 20 December 2019**

Cuxton Cutting 20 Dec 2019 EHC A

Washout of oversteep cutting triggered by third party run-off and heavy rainfall

Figure H3 Falls of Cruachan 6 June 2010

Figure 9: Falls of Cruachan: view after train moved clear of boulder shown on figure 8

Figure 12: Falls of Cruachan: material washed from cutting face

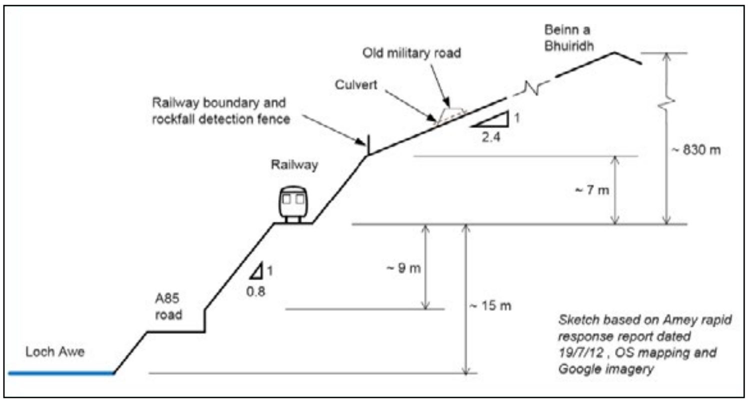


Figure 10: Falls of Cruachan: slope geometry (cross-section)

Falls of Cruachan 6 June 2010

Boulder displaced from slope by root jacking and soil erosion.

Figure H4 Un-named deep rotational failures in Kent and in London Clay

Figure H5 Hatfield Colliery 12/13 February 2013

Loading beyond NR boundary

Figure 31: Hatfield Colliery: aerial view (image courtesy of Network Rail)

Deep 'rotational' landslip caused by a spoil tip located outside the railway boundary and within Hatfield Colliery

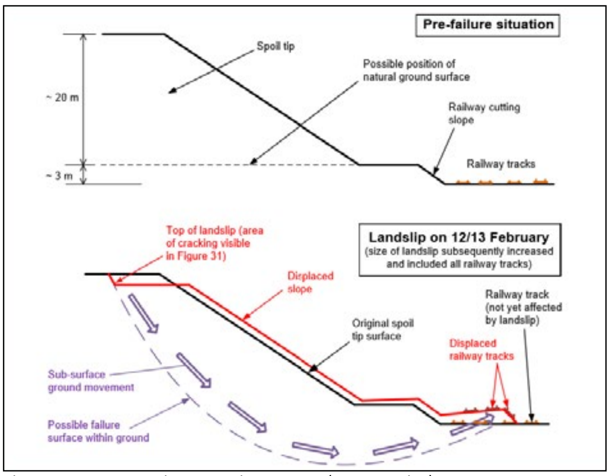


Figure 32: Hatfield Colliery: landslip geometry (cross-section)

Figure H6 Robertsbridge Cutting 20 December 2019

Robertsbridge Cutting 20 December 2019 EHC D

Near-crest burrowing into deteriorating unlined crest drain led to washout of weathered interbedded siltstone/sandstone amidst heavy rainfall

Figure H7 **Whitmore NW&C 26 June 2020**

Barnehurst Cutting Kent

Milborne Wick 28 March 2016

Typical shallow translational failures

Whitmore 26 June 2020
EHC C

Barnehurst Cutting

Milborne Wick 28 March 2016

Translational slide after heavy rain

Blocked third party crest drain.

Previous failures

Figure H8 **Murthat 16 November 2015**

Murthat 16 November 2015

Translational failure involving sliding of superficial soils on shallow rock face after 24 hours of rain.

Evidence of historical failures, including one 60 yds away that occurred 10 years before.

No crest drain in place; blocked field drain at crest

Figure H9	Ash Southern 11 March 2020

Slumping of toes of cut slopes

Figure H10 Gillingham Tunnel 28 November 2009

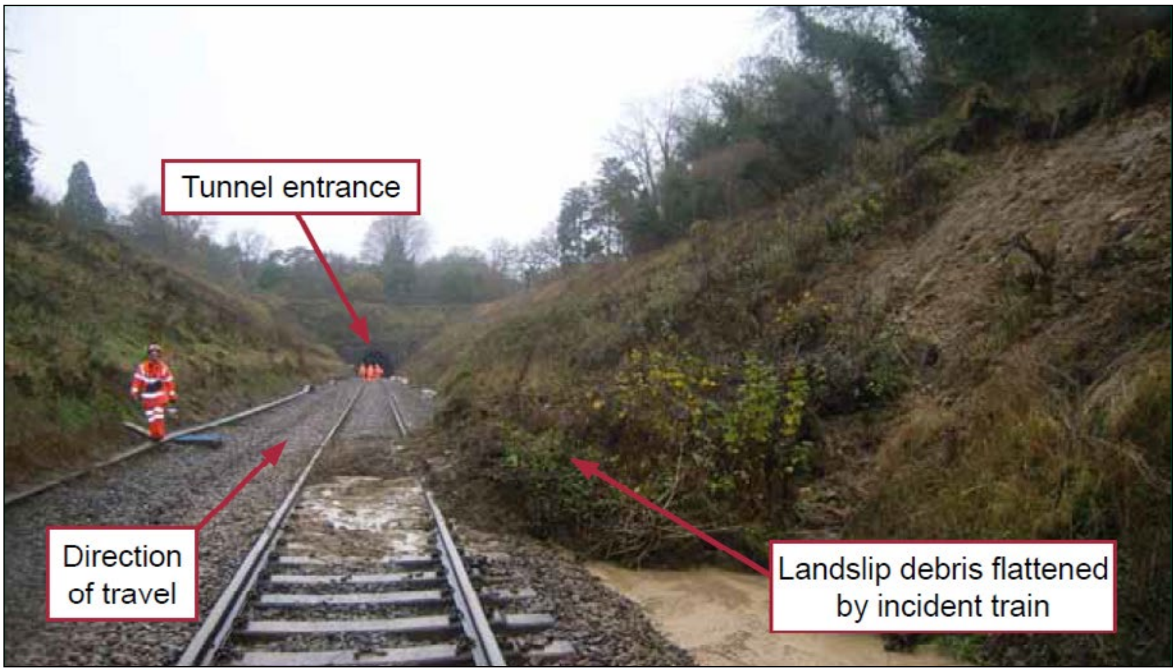


Figure 3: Track level view of accident site

The landslip was caused by water overflowing from a ditch at the top of the cutting slope, blocked by tree roots.

The cutting passes through alternating layers of limestone and mudstone at a slope of 1 in 1.2. Several previous failures had occurred, including immediately adjacent to the accident site. Vegetation had been removed in the recent past.

It was raining heavily before and during the accident but the rainfall was not exceptional. About 15 mm of rain had fallen at the accident site in the 24 hours before the accident. This included about 10 mm in the two hours immediately before the accident. The failure was not associated with unusual weather conditions.

Figure H11 Moy 26 November 2005

Figure 8: Backscar resulting from the landslip

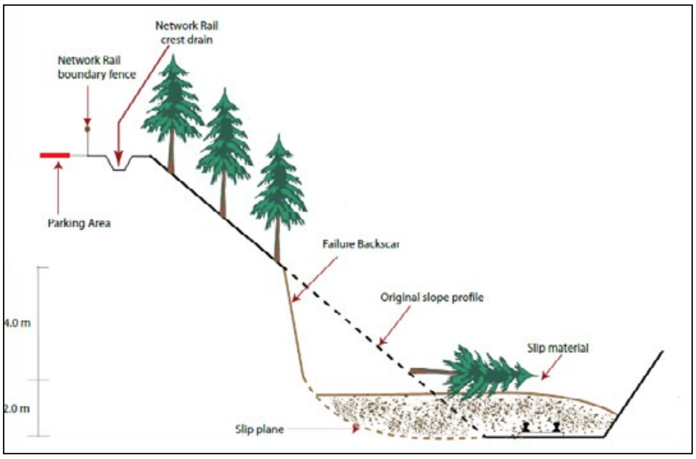


Figure 17: Observed landslip

Moy 26 November 2005

Water infiltrates into permeable zones in glacial till in Parking Area beyond NR boundary. These zones provide seepage paths into cut slope. Catchment experienced an intense one-hour period of rainfall six hours prior to the derailment. No collector drains in place. Groundwater level rises and groundwater exits at toe of slope, triggering toe failure. Unloading at toe triggers deeper failure followed by an earthflow.

Figure H12 Oubeck North 4 November 2005

Figure 5: Landslip at Oubeck North looking in the direction of traffic

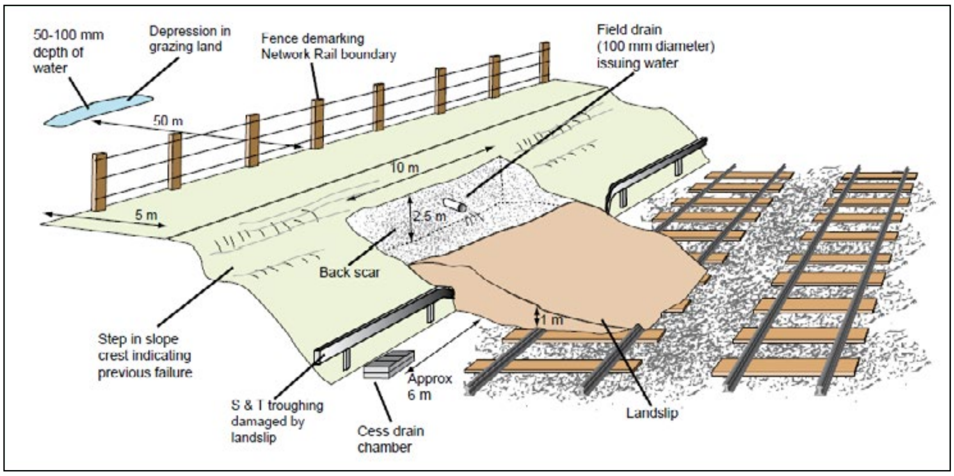


Figure 7: Cutting slope after landslip

Derailment at Oubeck North near Lancaster 4 November 2005

The cutting slope failed due to the volume of water flowing through a field drain into the body of the cutting slope comprising sandy clay/glacial till at the site of a previous failure

The rainfall in the vicinity of the landslip over the two weeks preceding the incident was 134.6 mm. The average for this two-week period since 1976 is 62.3 mm. The rainfall during the preceding day was 45.4 mm.

Figure H13 Templecombe 21 December 2019

Failure related to de-vegetation

Templecombe Cutting 21/12/19

Translational failure of mudstone weathered to cohesive soil and saturated by rainfall, groundwater and surface water.

De-vegetation of up-side of cutting despite EHC E category – cutting failed in first wet winter following tree removal. No information on thickness of softened zone between failures or on plasticity of clay.

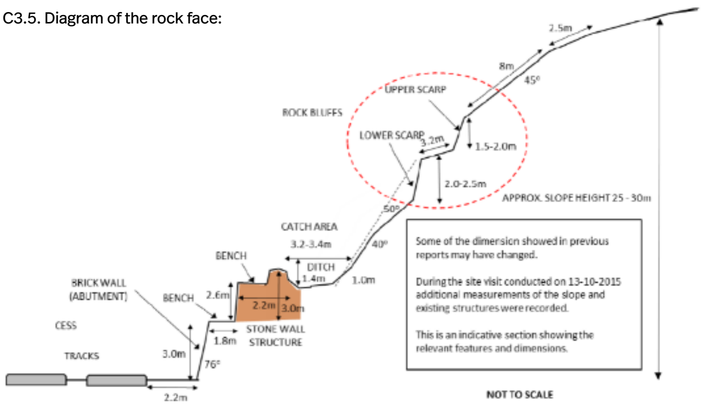
Figure H14 Chalford Rock Cutting 9 January 2017

C3.1. Photograph of the rock cutting taken in June 2015, before the failure and devegetation works:

Up Line Down Line

C3.4. After photograph taken 10 January 2017

C3.5. Diagram of the rock face:



C3.6. The site is located at S0901024 and the cutting face orientation is North. The slope is angled sixty to seventy degrees with an overall height of twenty-six metres.

C.3.7. The rock mass on the down slope is comprised of limestone and calcareous sandstone. The rock mass is blocky and foliated.

Chalford Rock Cutting Failure 9 January 2017

Failure in limestone cutting, possibly related to solution. Historical interventions at the site and major de-vegetation prior to engineering works and failure

Figure H15 **Cookspond Embankment 28 December 2019**

Liphook Embankment 26 December 2013

Ockley Embankment 14 January 2020

Winter embankment failures


Cookspond Embankment 28 December 2019

Shallow rotational movement following prolonged heavy rainfall


Liphook Embankment 26 December 2013

Failures occurred on both sides of embankment

Ockley Embankment 14 January 2020

Rotational movement following prolonged heavy rainfall. Previous failure on 26 December 2013

Figure H16 Stonegate Embankment 5 February 2014

Stonegate Embankment 5 February 2014

Rotational failure of oversteep clay embankment.

Tension cracks noted by track maintenance staff (upper photo) and track closed before main failure occurred (lower photo).

Recent heavy rainfall.

Figure H17 **Epsom Embankment 14 December 2019**

Epsom Embankment 14 December 2019

Deep-seated rotational failure driven by persistent, heavy rainfall, plus burrowing

Pre-existing movement indicators

Figure H18 Barrow upon Soar 27 December 2012

Figure 13: Drainage from the foot of the embankment to the River Soar (photographs courtesy of Network Rail)

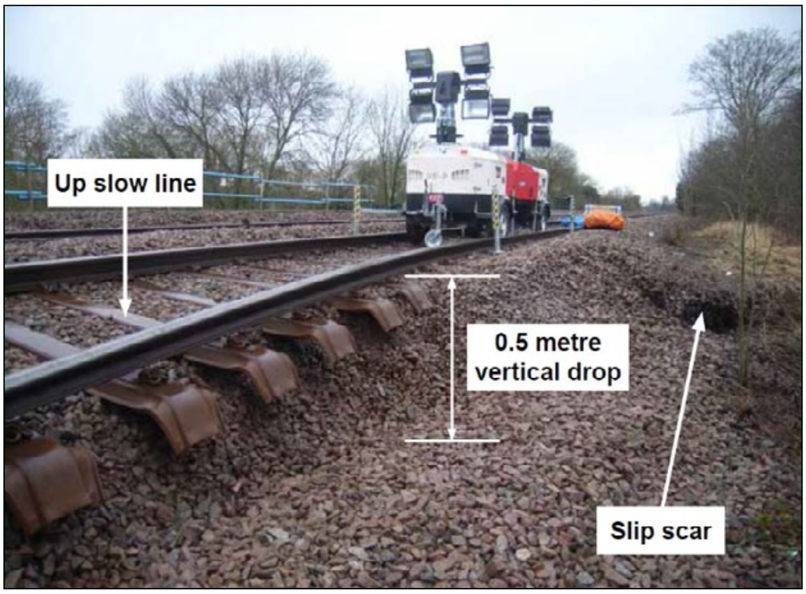


Figure 8: Scars showing embankment slip

Barrow upon Soar 27 December 2012

Rotational failure in embankment under weight of freight train (undrained cyclic loading) following persistent heavy rain (140mm in December, 113mm before accident).

Mercia Mudstone (Keuper Marl) fill softening as a result of embankment being flooded on both sides. Loss of track support, Track quality reducing before failure

Uncompacted clay fills not protected from entry of rainwater or floodwater which leads to softening and so trigger.

Use WERM to predict flooding of embankments.

Figure H19 Baildon 7 June 2016

Washout following highly localized flash flood

Figure 2: The washed out track and the embankment

Figure 7: Still image of the track damage taken from the forward facing CCTV footage from train 2D72 (image courtesy of Northern Rail)

There had been a heavy localised shower in the Baildon area on 7 June 2016. A weather station approximately one mile west of Baildon railway station recorded a rainfall of 17 mm between 15:30 and 16:00 hrs. However, records from two other weather stations, within a mile of the railway to the south, together with a third weather station 3 miles to the west, recorded no rainfall for the entire day. This indicates the intense and localised nature of the rainfall at Baildon that afternoon.

Culvert beneath

Previous washout in 2012

Figure H20 **Burrowing in embankments in Anglian Region**

From Presentation by Ian Payne

Badger-burrowing subsidence

Rabbit-burrowing subsidence

Figure H21 Clarborough Tunnel Portal 27 April 2012

Ineffective crest drain

Figure 1: The landslip outside Clarborough Tunnel

Clarborough Tunnel Portal 27 April 2012

Prolonged rainfall over 3 weeks and heavy rain immediately before collapse led to washout/shallow earthflow.

Ineffective crest drain on neighbouring land, with local low point above slip.

Evidence of localisation and difficulty of categorising form of failure.

Figure H22 Watford Tunnel North Portal 16 September 2016

Figure 3-2: Photograph of the failure at Watford (RAIB, 2017)

Watford Tunnel Cutting North Portal 16 September 2016

Washout of weathered chalk after intense summer rain (50-60mm in 3 hours) followed hot dry spell.

15m high cut at 42 degrees.

Topographic water concentration feature. Blocked or non-existent crest drain. Water from third party. Ongoing work removing vegetation, placing netting and erosion protection matting.

Previous failure in 1940.

Figure H23 St Catherine's Tunnel 20 December 2019

Wallers Ash Wessex 27 August 2020

St Catherine's Tunnel (Guildford Sand Tunnel) 20 Dec 2019

Erosion of weathered, weak sandstone cutting face caused by extended elevated rainfall; small toe structure buried

Previous failure 24 December 2018.

Wallers Ash Wessex 27 August 2020

Figure H24 Protection of portal by Japanese Railways

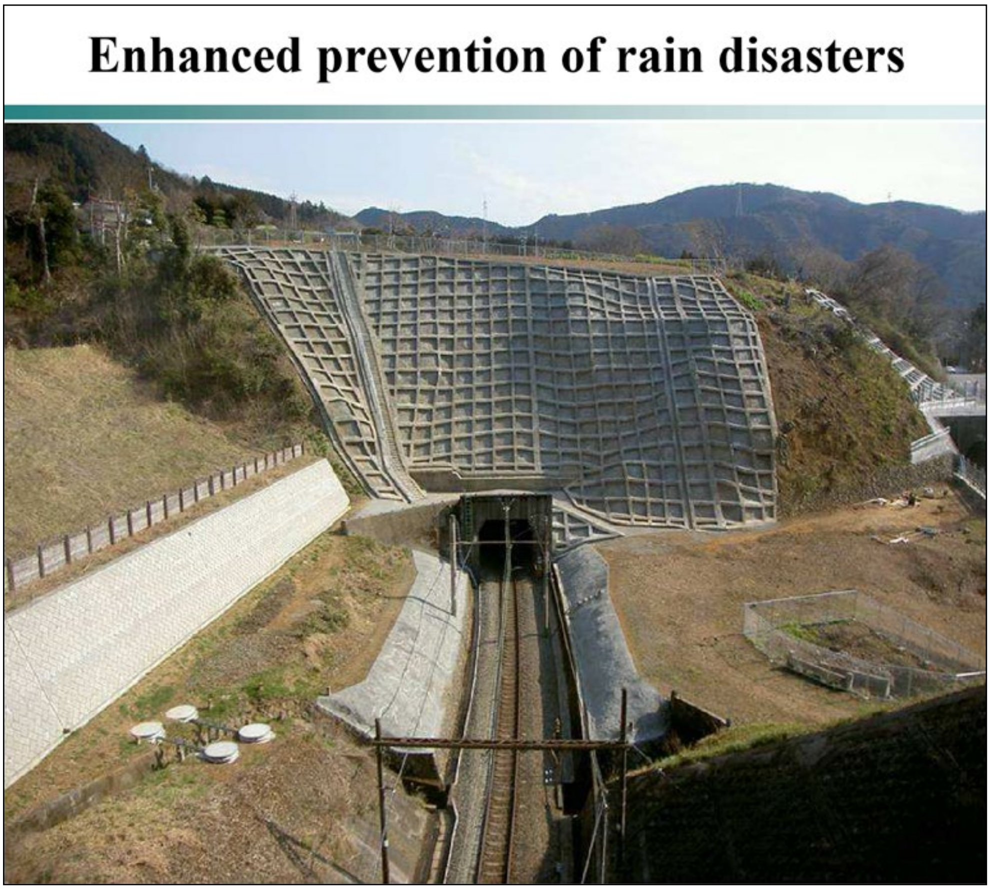


Figure H25 Loch Eilt 22 January 2018

Debris flow on natural slope

Figure 10: Side view of upper part of slip on natural slope

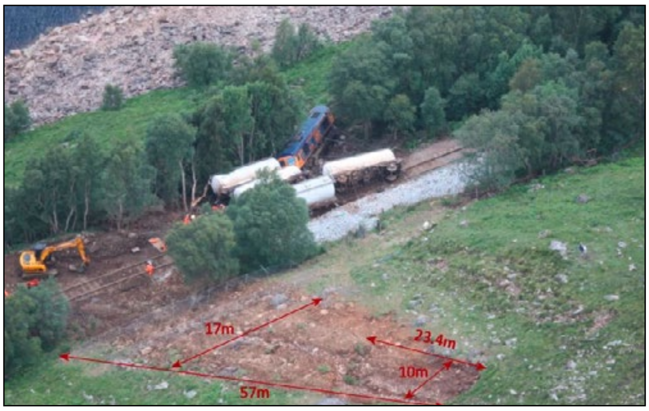
44 As the leading edge of the sliding debris approached the railway, it destroyed part of the catch-fence which had been installed in 2017 to trap falling rocks. It then spread out as a debris plume, 40 metres long below the level of the railway (figures 11 and 12). The displaced material included several large boulders, and a significant volume of water.

Loch Eilt 22 January 2018 Derailment

Debris flow on natural slope triggered by rainfall and rapid snow melt. Started upslope of NR boundary. Catch fence overwhelmed.

Importance of upslope geomorphology.

Figure H26	Loch Treig 28 June 2012 Derailment



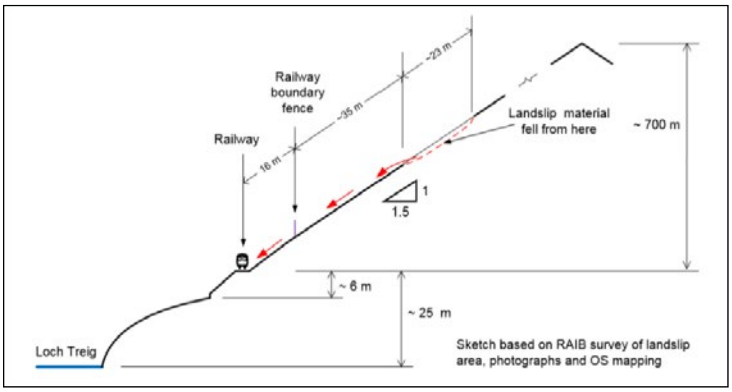


Figure 5: Loch Treig: slope geometry (cross-section)

Loch Treig 28 June 2012 Derailment

Washout became debris flow on natural rock slope, triggered by intense rainfall (52.6mm in 3 hours)). Started 57m upslope of NR boundary. Large boulder (1m) transported to track.

Importance of upslope geomorphology and intensity of summer rainfall.

Evidence of previous adjacent slips.

Figure H27 St Bees 30 August 2012

Figure 19: St Bees: landslip at 68 miles 59 chains (main image courtesy of Network Rail)

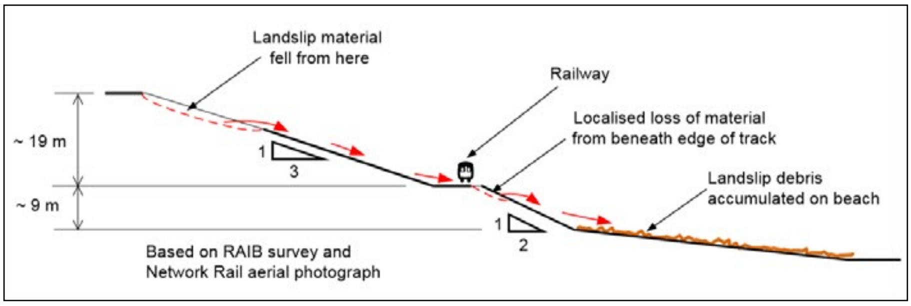


Figure 21: St Bees: slope geometry (cross-section)

St Bees 30 August 2012

Part cut, part embankment on sidelong ground. Catchment beyond boundary. Possible localisation by agricultural land drain? Water enters erodible bank and undermines track. No evidence of drainage measures

Recent heavy summer rainfall.

Figure H28 Localised washouts

Glacial Till/Norwich Crag

Figure H29 **Bradwell Abbey 15 October 2013**

Failures triggered by planned engineering works

Bradwell Abbey 15 October 2013

Temporary removal of embankment (over-excavation to near vertical face) along long length coincided with heavy rain and reactivated previous rotational failure.