

RSSB 1386 (Revised) The effects of railway traffic on embankment stability

Final Report

March 2011
RSSB

RSSB 1386 (Revised) The effects of railway traffic on embankment stability

Final Report

March 2011

RSSB

Block 2, Angel Square, 1 Torrens Street, London, EC1V 1NY

Issue and revision record

Revision	Date	Originator	Checker	Approver	Description
0	04 February 2011	R Tan	G R Taylor	A S O'Brien	Draft for Comment
1	25 March 2011	R Tan	G R Taylor	A S O'Brien	Final Issue



This document is issued for the party which commissioned it and for specific purposes connected with the above-captioned project only. It should not be relied upon by any other party or used for any other purpose.

We accept no responsibility for the consequences of this document being relied upon by any other party, or being used for any other purpose, or containing any error or omission which is due to an error or omission in data supplied to us by other parties.

This document contains confidential information and proprietary intellectual property. It should not be shown to other parties without consent from us and from the party which commissioned it.

Content

Chapter	Title	Page
	Executive Summary	1
1.	Introduction	3
1.1	Alternative Strategy	4
1.2	Scope of Report	5
2.	Background	8
2.1	Modes of Failure	8
2.2	Limit States	10
3.	Literature Review	14
4.	Embankment Failure Review	16
5.	Changes in Heavy Traffic	19
6.	Embankment Vulnerability to Traffic Damage	22
6.1	Train Axle Load	22
6.2	Embankment Clay Fill Plasticity	24
6.3	Trackbed Configuration	25
6.4	Embankment Vulnerability Assessment	26
7.	Instrumentation Design	28
8.	Preliminary Modelling	29
8.1	Numerical	29
8.1.1	Numerical Model	29
8.1.2	Input Parameters	30
8.1.2.1	Railway Traffic Loading	30
8.1.2.2	Embankment Strength and Stiffness	31
8.1.3	Preliminary Numerical Modelling	34
8.2	Analytical	40
8.2.1	Analytical Model	40
8.2.2	Input Parameters	41
8.2.3	Preliminary Analytical Modelling	41
8.3	Comparison between Numerical and Analytical Modelling	42
9.	Practical Analytical Tools	45
9.1	Strategic Level Model	45
9.2	Tactical Level Model	46
10.	Conclusions	47
11.	References	51

Appendices	53
Appendix A. Embankment Failure Review _____	54
Appendix B. Embankment Vulnerability to Traffic Damage _____	55
Appendix C. Instrumentation Design _____	56
Appendix D. Preliminary Numerical Modelling _____	60

Executive Summary

RSSB research project 1386 (Revised), The effects of railway traffic on embankment stability, is concerned with the investigation of the effects of railway traffic loading on embankment stability, particularly where railway traffic loading has or is due to be increased. The objective of the study is to identify the damage to embankment fills, particularly those of clay core construction, which is attributable to railway traffic loading, and subsequently to develop an analytical model for assessment of potential damage due to changes in train axle loads and/or vehicle speed. It was originally intended that the research project be progressed in three stages, namely:

Stage 1 – review of historical embankment damage and site selection;

Stage 2 – site instrumentation and monitoring, and laboratory testing;

Stage 3 – development of an analytical model.

Stage 1 was intended to be the desk study phase of the project. Stage 2 was intended to comprise ground investigation and the installation of instrumentation (with subsequent monitoring) at a small number of representative sites together with laboratory testing (element/physical) as required. In Stage 3 analytical models (at both strategic and tactical levels), for the assessment of railway embankments subject to increased train loading, were to be developed.

The analytical models to be developed in Stage 3, were intended to draw on output from Stages 1 and 2 of the research project and provide a methodology for prediction of the effects of increased railway traffic load on load sensitive embankments. The models are intended to be used as tools for the development of business cases for renewal works, where embankment damage is predicted for increased railway traffic load, and to enable usage of the railway network to be maximised at a reasonable cost.

Mott MacDonald was commissioned by the Rail Safety and Standards Board to undertake Stage 1 of this research project in December 2009. This report summarises the work carried out under Stage 1 of the research project as amended by the Alternative Strategy. The following key tasks were completed:

Literature Review (Task 1 Sub-task (vii) and Task 3 Sub-task (i))

Embankment Failure Review (Task 1 Sub-task (ii)):

- Potential correlations between a range of factors and causes with incidence of failure;
- Assessment of the consequence of failure, and
- Determination of the potential failure mechanism.

Changes in Heavy Traffic (Task 1 Sub-task (iii)):

- Potential correlations between changes in railway traffic loading and the embankment failures reviewed under Task 1 Sub-task (ii).

- Potential correlations between changes in railway traffic loading and potential embankment monitoring sites suggested by Network Rail's Route Geotechnical Engineers.
- Potential correlations between changes in railway traffic loading and embankments identified as vulnerable to damage from railway traffic loading under Task 1 Sub-task (i).

Embankment Vulnerability (Task 1 Sub-task (i)):

- Identification of the key factors affecting embankment vulnerability to fatigue-type failure.
- A preliminary assessment of the distribution of potentially load sensitive embankments across the UK railway network.

Instrumentation Design (Task 2 Sub-task (ii)):

- the practical aspects of instrument installation;
- site access and rail safety requirements, both during installation and ongoing monitoring;
- data logging, storage and management, as well as data analysis and post-processing.

Preliminary Numerical Modelling (Task 1 Sub-tasks (iv) & (v), and Task 3 Sub-tasks (ii) & (iii))

- the development of a generic numerical model to provide preliminary simulation of the embankment fill response (i.e. the changes in stress and strain) under railway traffic loading, and
- assess the key input parameters, for example embankment geometry, material parameters, loading, etc.

Preliminary Analytical Modelling (Task 3 Sub-task (iv))

- consideration of the main requirements (inputs/outputs/functionality) of practical analytical models (at both strategic and tactical levels), and
- development of practical analytical tools at both strategic and tactical levels.

This report should be read in conjunction with the following sub-task reports:

- Literature review (267641/TPN/FNG/001);
- Instrumentation design (267641/TPN/FNG/002);
- Embankment failure review (267641/TPN/FNG/003);
- Changes in heavy traffic (267641/TPN/FNG/004), and
- Embankment vulnerability to traffic damage (267641/TPN/FNG/005).

1. Introduction

RSSB research project 1386 (Revised), The effects of railway traffic on embankment stability, is concerned with investigation of the effects of railway traffic loading on embankment stability, particularly where railway traffic loading has been, or is due to be, increased. The objective of the study is to identify the damage to embankment fills, particularly those of clay core construction, which is attributable to railway traffic loading, and subsequently to develop analytical models (at both strategic and tactical levels) for assessment of potential damage due to changes in train axle loads and/or vehicle speed. It was originally intended that the research project be progressed in three stages, namely:

Stage 1 – review of historical embankment damage and site selection;

Stage 2 – site instrumentation and monitoring, and laboratory testing;

Stage 3 – development of an analytical model.

Stage 1 was intended to be the desk study phase of the project. Stage 2 was intended to comprise ground investigation and the installation of instrumentation (with subsequent monitoring) at a small number of representative sites together with laboratory testing (element/physical) as required. In Stage 3 analytical models were to be developed for the assessment of railway embankments subject to increased railway traffic loading.

The analytical models to be developed in Stage 3 were intended to draw on the outputs from Stages 1 and 2 of the research project and to provide a methodology for prediction of the effects of increased railway traffic load on load sensitive embankments. The models are intended to be used as tools for the development of business cases for renewal works where embankment damage is predicted for increased railway traffic load, and to enable usage of the rail network to be maximised at a reasonable cost.

Mott MacDonald was commissioned by the Rail Safety and Standards Board to undertake Stage 1 of this research project in December 2009. The scope of work to be undertaken during this stage of the research project is summarised in Table 1.1.

Table 1.1: Tasks/sub-tasks and objectives.

Task	Sub Task	Objective	Document Reference/ Date of Issue
1 – Desk Study	(i)	Embankment vulnerability to traffic damage	267641/TPN/FNG/005 20 July 2010
	(ii)	Embankment failure review	267641/TPN/FNG/003 23 March 2010
	(iii)	Changes in heavy traffic	267641/TPN/FNG/004 01 July 2010
	(iv)	Input parameters for model	Separate report not required ¹
	(v)	Preliminary modelling	Separate report not required ¹
	(vi)	Coordination with NR	Sub-task redefined ²
	(vii)	Literature review (UK & Worldwide)	267641/TPN/FNG/001 18 January 2010
2 – Site Instrumentation and Laboratory Testing	(i)	Site identification	Sub-task redefined ²
	(ii)	Instrumentation design	267641/TPN/FNG/002 1 February 2010
	(iii)	Prepare Method Statements	Sub-task redefined ²
	(iv)	Laboratory testing programme	Sub-task redefined ²
	(v)	Monitoring timescale	Sub-task redefined ²
	(vi)	NR approval procedures	Sub-task redefined ²
3 – Preliminary Numerical and Analytical Modelling	(i)	Literature review of models	267641/TPN/FNG/001 18 January 2010
	(ii)	Set up preliminary numerical model	Separate report not required ¹
	(iii)	Preliminary model analyses	Separate report not required ¹

Notes: (1) Following the development of the Alternative Strategy Proposal the scope of this stage of the research project has been redefined and a separate sub-task report is not now required under this stage of the research project; the work undertaken during this sub-task is reported herein.

(2) Following the development of the Alternative Strategy Proposal the scope of this stage of the research project has been redefined and the completion of this sub-task is not now required.

1.1 Alternative Strategy

The original intent of Stage 1 of the research project was to gather evidence from Network Rail (NR) records of embankment failures in order to assess the impact of future changes in railway traffic on embankment vulnerability to traffic damage. This was expected to inform future instrumentation and

monitoring of several sites across the network. The monitoring data would then provide information on the actual damage caused to embankments by railway traffic. The need for and scope of laboratory testing required to supplement the data obtained from the instrumented sites was also to be considered as part of the Stage 1 work. The instrumentation and monitoring, together with the laboratory testing, were intended to be carried out during Stage 2 of the research project. The results of this monitoring and laboratory testing, were to be used for development of analytical models (at both strategic and tactical levels), to assess the impact of railway traffic across the network. The need for future investment in embankment renewal and upgrading might then be justified with the Office of the Rail Regulator, in order to continue to safely accommodate increases in railway traffic across the network. However, it became apparent during the evidence gathering exercise that:

- The available NR records of “geotechnical” failures, actually only focus on the relatively large scale classical “slip circle” type failure or failure due to scour/washout incidents. These cannot be correlated to changes in railway traffic, since the primary causes are due to, inter alia, long term degradation of soil properties, increases in groundwater pressure (largely weather related), or erosion due to surface water flows/poor drainage.
- Monitoring the effects of railway traffic will require specialist equipment, to capture the rapid transient changes which occur beneath moving trains, for example high speed data loggers and geophones. This equipment is quite different to conventional geotechnical instrumentation which monitors slow changes in ground conditions over several months. Such instrumentation and monitoring would be relatively expensive and is rarely used on the operational railway. Hence, there was a risk with the original strategy that the instrumentation and monitoring programme would be overly costly and/or ineffective.

As a result, Mott MacDonald proposed a revised strategy for project delivery to RSSB. This was intended to ensure that useful information could be gathered at an earlier stage in the project lifecycle to inform the development of an optimal instrumentation and monitoring programme, and importantly, that a robust business case might be developed for the later stages of the research project. The new approach involves a reduction in the scope of some of the tasks included under Stage 1 of the original commission, whilst increasing others. This proposal was presented to representatives from RSSB, NR (joint Project Client) and the Department for Transport (Project Sponsor) – all of whom expressed their interest and support for this alternative strategy.

The alternative strategy proposal was subsequently presented to the Vehicle/Structure System Interface Committee (V/S SIC) in July/August 2010. On approval of the strategy by the V/S SIC, the RSSB invited Mott MacDonald on 18th October 2010 to tender for Stage 1 of the proposed alternative strategy.

The reduction in scope of Stage 1 of the original commission, which is to be completed in advance of commencing the ‘Alternative Strategy’, included the relaxing of sub-task reporting requirements as well as the deletion of some tasks entirely. The changes in scope are summarised in Table 1.1.

1.2 Scope of Report

This report summarises the work that has been carried out under Stage 1 of the research project as amended by the ‘Alternative Strategy’ proposal. The report addresses the following key tasks as summarised in Table 1.1:

Literature Review (Task 1 Sub-task (vii) and Task 3 Sub-task (i))

Embankment Failure Review (Task 1 Sub-task (ii)):

- Potential correlations between a range of factors and causes with incidence of failure;
- Assessment of the consequence of failure, and
- Determination of the potential failure mechanism.

Changes in Heavy Traffic (Task 1 Sub-task (iii)):

- Potential correlations between changes in railway traffic loading and the embankment failures reviewed under Task 1 Sub-task (ii).
- Potential correlations between changes in railway traffic loading and potential embankment monitoring sites suggested by Network Rail's Route Geotechnical Engineers.
- Potential correlations between changes in railway traffic loading and embankments identified as vulnerable to damage from railway traffic loading under Task 1 Sub-task (i).

Embankment Vulnerability (Task 1 Sub-task (i)):

- Identification of the key factors affecting embankment vulnerability to fatigue-type failure.
- A preliminary assessment of the distribution of potentially load sensitive embankments across the UK railway network.

Instrumentation Design (Task 2 Sub-task (ii)):

- the practical aspects of instrument installation;
- site access and rail safety requirements, both during installation and ongoing monitoring;
- data logging, storage and management, and
- data analysis and post-processing.

Preliminary Numerical Modelling (Task 3 Sub-task (ii) and (iii))

- the development of a generic numerical model to provide preliminary simulation of the embankment fill response (i.e. the changes in stress and strain) under railway traffic loading, and
- assess the key input parameters, for example embankment geometry, material parameters, loading, etc.

Preliminary Analytical Modelling (Task 3 Sub-task (iv))

- consideration of the main requirements (inputs/outputs/functionality) of practical analytical models (at both strategic and tactical levels), and

- development of practical analytical tools at both strategic and tactical levels.

This report should be read in conjunction with the following sub-task reports (see Table 1.1):

- Literature review (267641/TPN/FNG/001);
- Instrumentation design (267641/TPN/FNG/002);
- Embankment failure review (267641/TPN/FNG/003);
- Changes in heavy traffic (267641/TPN/FNG/004), and
- Embankment vulnerability to traffic damage (267641/TPN/FNG/005).

2. Background

2.1 Modes of Failure

Railway embankments in the UK are typically over 100 years old and of end-tipped construction,. That is, they were uncompacted at the time of construction, potentially resulting in a clod-and matrix structure (O'Brien et al, 2004, O'Brien, 2007) as shown in Figure 2.1. This embankment fill structure, not necessarily visible to the naked eye, has recently been verified by Computerised Tomography (CT) scanning (Figure 2.2a). The structure is best identified by differences in density of the component materials.

During the Victorian era, when the majority of the current UK railway network was constructed, embankments were usually constructed using material from adjacent cuttings (Skempton, 1996), borrow pits adjacent to the lines, and other local sources. Near surface natural materials, including weathered and soliflucted materials are commonly found at the base of these embankments as the material from cuttings was excavated straight to fill areas. In addition to this, many embankments have been widened in the intervening period (to carry four rather than two tracks) and this may mean that the shoulders and embankment core are comprised of different materials.

Settlement of embankments has usually occurred in service. Occasionally, large scale shear failures occurred soon after construction; restoration of the embankment level was achieved by tipping ash and adding more ballast. Consequently some embankments have increased thicknesses of ash and ballast at the crest; the boundary between these materials has often become blurred due to ongoing movements and trackbed deformations.

As a result of the complex construction history described above, old railway embankments often differ significantly from natural materials or more recent well-compacted materials. Undisturbed testing is required in order to be able to realistically investigate their deformation behaviour and this is rare. O'Brien et al. (2004) investigated the strength and stiffness characteristics of London Clay fills. They found that the original London Clay clods have a strong influence on the material compressibility, but that the shear strength is controlled more strongly by the matrix. Subsequent testing of Gault Clay fill (Mott MacDonald, 2008) showed that the clods have a greater influence on strength, perhaps reflecting the greater geological age of these particular materials. No cyclic load testing is known to have been carried out on old railway embankment fill.

Figure 2.1: Conceptual Model of Railway Embankment Fill.

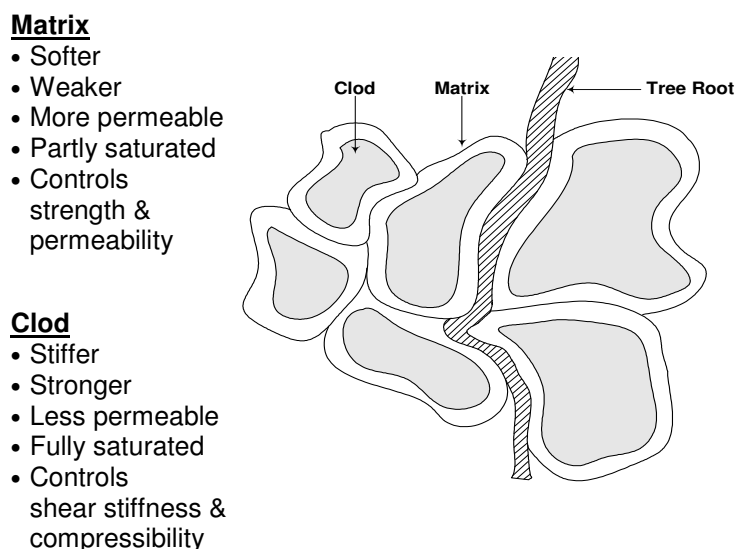
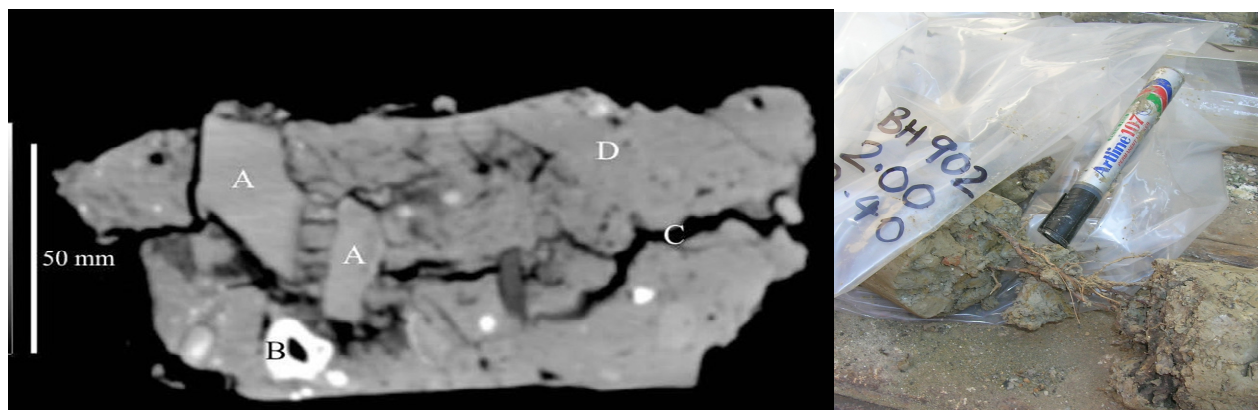


Figure 2.2: Observed Railway Embankment Fill Features (after O'Brien, 2007).



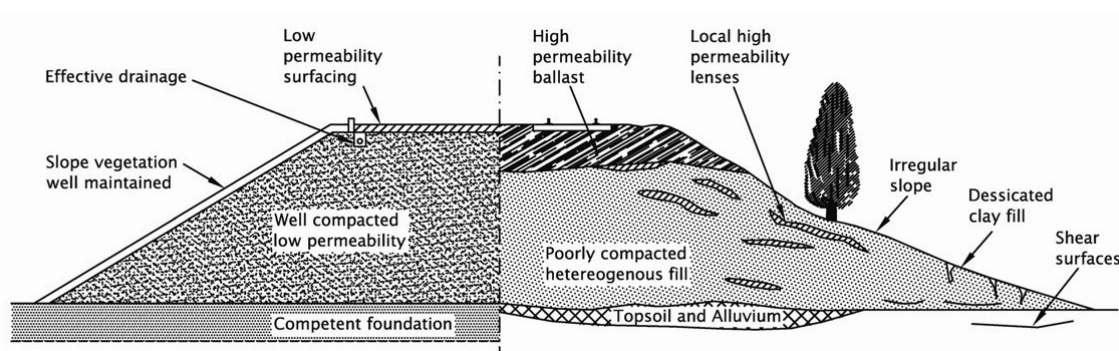
a) CT Scan of Railway Embankment Fill;

b) Roots observed between clods at depth.

Vegetation has grown readily upon railway embankments, and the softer matrix between the clods provides an ideal pathway for tree roots (e.g. Figure 2.2b). While vegetation was well maintained in the age of steam, since electrification it has largely been left to grow unchecked, with maintenance focusing on maintaining sighting distances and controlling leaf fall. Most slopes are now vegetated with anything from grass/shrubs to mature high water demand trees. High water demand trees cause considerable annual cyclic variations in moisture content and, potentially, pore water pressure. These cause cycles of shrinking and swelling that can affect track level quite severely (e.g. Scott et al., 2007; Glendinning et al., 2009). As observed by Scott et al., the type of vegetation strongly affects embankment and track deformation; the deformations caused by high water demand trees can be an order of magnitude larger than that caused by grassed slopes. The potential interaction between train loading and stress changes associated with seasonal changes in moisture content is the subject of ongoing research (for example Dykes, PhD in progress, University of Southampton).

Railway embankment slopes are also rarely well protected from water ingress, as shown in Figure 2.3. Highway embankments have well maintained road and toe drainage, combined with a largely impermeable surface, whereas railway embankments have a permeable ballast surface and often poorly maintained drainage (O'Brien, 2007). These characteristics combine with variations in vegetation and climate, to influence the seasonal deformation behaviour. In addition, where track problems and progressive deformation of the subgrade are ongoing, track drainage can be further impeded and lead to concentrations of water and exacerbation of trackbed problems (Selig & Waters, 1994).

Figure 2.3: Differences between Highway and Railway Embankments.



2.2 Limit States

In common with the design of other geotechnical structures, potential failure of a railway embankment can be classified as either an Ultimate or a Serviceability Limit State. The Ultimate Limit State (ULS) would involve the collapse of the embankment whereas the Serviceability Limit State (SLS) involves excessive deformation.

Within these limit states, there are a range of failure mechanisms which would have different impacts on the railway, for example from catastrophic ULS failure of the embankment to SLS failure of the track. The likely influence of train loading on these different failure modes varies. Failures which are directly attributable to train loading exhibit a fatigue-type of mechanism; a prolonged period of time would need to elapse before obvious signs of deterioration become apparent. Such failures would typically involve local track settlement and generally lead to increased track maintenance. The infrastructure supported by the embankment (the railway) is potentially particularly sensitive to small changes in line and level caused by such embankment movements that would not in other situations be significant.

Some common failure and deformation mechanisms are summarised in Table 2.1 and in Figure 2.4.

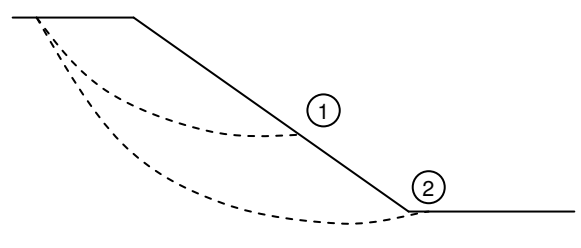
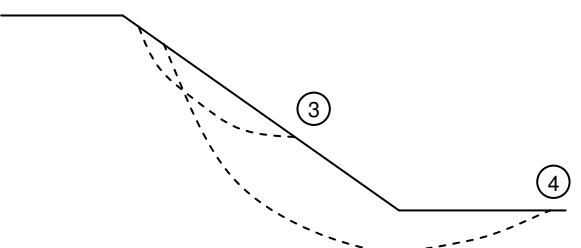
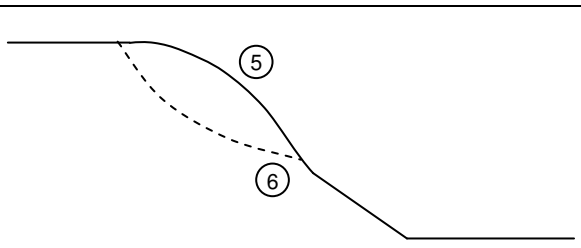
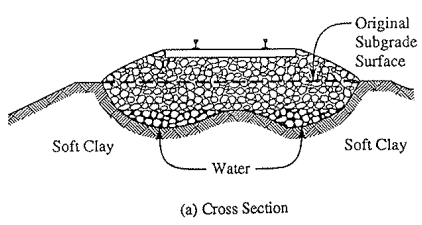
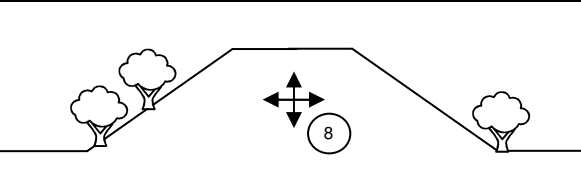
Table 2.1: Summary of Common Failure Mechanisms.

<u>Failure Mechanism</u> ¹	<u>Geometry (Size) of Failure</u>	<u>Impact on Track</u>	<u>Influence of Railway Traffic Loading</u> ^{2,3}	<u>Likely Triggers</u>
Deep -seated failure, through/beneath toe (2)	Failure daylights adjacent to track (Large)	Catastrophic	Small	Loss of shear strength. High pore water pressure.
Deep-seated failure, through/beneath toe (4)	Failure daylights on slope (Large to Medium)	Small lateral/vertical deformation, due to loss of lateral support.	Small	Loss of shear strength. High pore water pressure.
Unravelling of ballast/ash (5), (6)	Irregular undermining of track (Small)	Excessive Deformation	Large (?)	Vibration. Dry Summer.
Shear Failure through fill below ballast (1)	Local subsidence (Small to Medium)	Small to Catastrophic	Large	Heavy traffic. High pore water pressure.
Plastic deformation of fill below ballast (7)	Local Subsidence (Small)	Small to Medium	Large	Heavy traffic. High pore water pressure.
Subgrade failure (for example Ballast Pumping (7)	Irregular, loss of support to track (Small)	Excessive Deformation	Large	Heavy traffic. More frequent traffic. High pore water pressure
Seasonal Deformation due to High Water Demand trees (8)	Local subsidence (Small to Medium)	Small to Medium	Small	Dry Summer. Seasonal deformation.
Shallow slips (3)	Failure daylights close to crest (Small to Medium)	Small to Medium loss of lateral support to track	Small to Medium	Tension cracks. Seasonal deformation. High pore water pressure.
Wash-out	Removal of embankment fill, including loss of track support (Small to Medium)	Small to Catastrophic	Small	Surface water flows, erosion channels on/through fill.

Notes:

- (1) The number in brackets after the failure mechanism relates to the number in Figure 2.4 for the limit state failure mode.
- (2) If traffic loading leads to damage to track or embankment drainage then all failure mechanisms will have greater impact.
- (3) Traffic loading may also lead to damage to adjacent track infrastructure (such as signalling) which could impact on railway operations.

Figure 2.4: Summary of Common Failure Mechanisms.

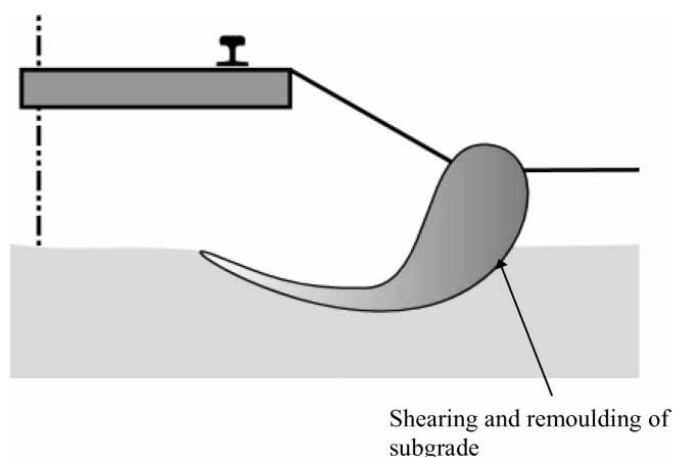
Ultimate Limit State Failure	
	<p><u>Failure through the crest</u></p> <ol style="list-style-type: none"> 1. Deep seated failure day-lighting through the slope. 2. Deep seated failure day-lighting through the toe.
	<p><u>Failure through the slope</u></p> <ol style="list-style-type: none"> 3. Shallow translational failure (thickness of slip $\sim < 2\text{m}$) 4. Deep seated failure day-lighting through the toe.
	<p><u>Failure of the shoulder</u></p> <ol style="list-style-type: none"> 5. Local ravelling due to over-steepening at the crest 6. Local crest instability
 <p>(a) Cross Section</p> <p><i>(Evaluation of Railway Subgrade Problems, Li & Selig, 1995)</i></p>	<p><u>Track bed failure</u></p> <ol style="list-style-type: none"> 7. Mud pumping and ballast settlement.
Serviceability Limit State Failure	
	<ol style="list-style-type: none"> 8. Seasonal shrink-swell movements

Particular problems associated with railway subgrade performance have been described by Li & Selig (1995). Although not specifically relating to embankments, these would apply equally to embankment fill or natural ground subgrades. The two most important subgrade failure mechanisms related to repeated train loading are:

- progressive shear failure and
- excessive plastic deformation.

During progressive shear failure (Figure 2.5) plastic flow of the subgrade occurs as a result of overstressing by repeated loading cycles. The subgrade material then squeezes out and upwards where there is least overburden/resistance. This type of failure has been observed in fine soils with a high clay content causing a reduction in track levels. The track can be lifted and reballasted, but a depression may be left in the subgrade surface which may lead to ponding of water, i.e. the formation of a ballast pocket. This could then lead to larger scale failure at a later date. Irregularity of level on the cess may also result, which will have a detrimental effect on the operation of the track drainage.

Figure 2.5: Progressive Shear Failure.



Excessive plastic deformations (Common Failure Mechanism 7 in Figure 2.4) can also develop as a result of repeated loading. As the train loading distribution will never be uniform due to irregularities in the structure and non-homogeneous subgrade soils, depressions will develop in the subgrade. These depressions can attract water which will exacerbate the problem and lead to more differential movements. As with progressive shear failure, track quality deteriorates. Although this can be temporarily maintained by re-ballasting; with water still present in the subgrade, deterioration will continue. Again, the deformation may adversely affect track drainage.

Both these failure mechanisms will cause changes to the line and level of the track, potentially resulting in the imposition of speed restrictions and increased maintenance frequencies. Earthworks movements should therefore be small enough (typically within 5 to 10mm depending on the train speed and wavelength of the defects) to ensure that the tolerances for track geometry laid down in current railway standards are maintained.

3. Literature Review

The literature review undertaken as part of this research project has highlighted a number of knowledge gaps, summarised in Table 3.1, with respect to how dynamic train loading may influence the degradation of embankments. Most research on such effects has considered straight track and at grade conditions; few studies have specifically covered embankment scenarios. In particular the literature review concluded that greater consideration is required of:

- The specific effect of embankment geometry, including embankment height, width and shoulder/cess width, ballast depth and railway/embankment alignment, on the distribution of train loadings within the ballast and subgrade, i.e. the depth of influence.
- The effect of embankment-structure transitions. Evidence from maintenance programmes clearly shows this to be an important area with significantly increased track defects. However, despite this, surprisingly little research appears to have been carried out in this field.
- The effects of track defects on the development of permanent deformations.
- The effects of track geometry on the development of permanent deformations.
- The influence of embankment material on response and behaviour.
- The effects of train speed (i.e. dynamic effects, acceleration/deceleration rates), number of load cycles, and train configuration (i.e. number of wagons).
- Confirmation of the point at which dynamic analysis is required rather than pseudo-static approaches.
- Testing of materials representative of existing embankment fills present in the UK rail network.
- Long term monitoring to allow comparison of design methods against actual permanent deformations over large numbers of cycles.

The aspects identified above are to be considered as part of the sub-tasks to be undertaken during this and subsequent stages of the research project. The effect of embankment geometry on the distribution of train loadings within the ballast and subgrade shall be considered through the application of numerical analysis supported by laboratory testing. The research project shall aim to use clay fill obtained from existing UK railway embankments in the laboratory testing thus ensuring that the materials used are representative of those encountered in the field. In conjunction with these activities, representative sites shall be identified and instrumented as part of the research project; monitoring shall continue into the medium term.

Further details of the literature review are contained in document 267641/TPN/FNG/001.

Table 3.1: Summary of Understanding and Knowledge Gaps.

Knowledge Area	Level of Understanding	Comments	Ongoing Research
Embankment geometry and effect of depth on influence of load	Poor	Although theoretically of little influence, no studies have been undertaken.	None
Importance of embankment materials.	Moderate	Lots of cyclic triaxial testing on fine grained soils is available, but little more sophisticated testing with principal stress rotation. No known testing of old embankment fills.	Continued development of hollow cylinder and resonant column testing. No relevant testing on old embankment fills.
Geometrical properties: - track geometry and defects - transitions	Poor to moderate Poor to moderate	Some theoretical studies but little field data. Some limited field data.	Not a topic of sustained research. Some research ongoing.
Train loading: - axle load (static loads) - train speeds (dynamic loads)	Good Moderate	Increased deformation under increased static load well understood. Conceptual understanding of critical velocities. Better understanding required of interactions with geometrical properties and non ideal conditions.	Not aware of any currently in progress. Some research ongoing.
State-of-the-art models	Good	A number of different models available to consider static or dynamic loads that are calibrated against field data.	Research ongoing
Testing techniques - laboratory - large scale	Moderate to good Poor to Moderate	More sophisticated testing to reflect realistic stress paths limited to a few universities. Test facilities available, but generally utilised for other trackbed rather than subgrade problems	Research ongoing None / other problems

4. Embankment Failure Review

In this sub-task a detailed review was undertaken of embankment failures occurring on the UK rail network, for which details have been made available, between August 2003 and December 2009. The review included consideration of the type and mode, as well as the consequence of failure, particularly in terms of the track operation, and the key factors affecting failure. The following aspects have been addressed:

- The geographical and temporal distribution of the failures;
- The underlying geology and slope composition;
- The prevailing weather conditions;
- The vegetation at the failure sites;
- Embankment cross-section and track alignment;
- The impact of the failures on train operation, and
- Characterisation of the failure modes reported to date.

A total of 177 incidents of embankment failure have been reviewed; their geographic distribution is shown in drawing no. 267641/001, which is reproduced in Appendix A. Drawings, showing the corresponding annual distribution of failures over the period under consideration, are presented in the sub-task report and have not been reproduced here. In the first instance, those incidents caused by concentrated surface water flow, washout or scour (64 No.) for example, were excluded from further consideration, as railway traffic loading is not considered likely to have contributed significantly to these failures. The remaining dataset comprised 113 embankment failures, for 38 of which a corresponding Safety-Related Event report (WI CIV 028), containing further information regarding the failure, was available. The analysis of embankment failures has focussed on this dataset (113); they are plotted spatially in terms of the underlying railway line geology in drawing no. 267641/002, which is also reproduced in Appendix A.

Three concentrations of failures were evident from the data:

- The Western Territory along the Great Western Mainline route corridor;
- Adjacent to Felixstowe;
- South of London.

Embankment failures were recorded in each year data was collected within the Great Western Mainline route corridor. Adjacent to Felixstowe, embankment failures were recorded in 2004, 2005 and 2006 only. Embankment failures were recorded to the south of London in 2006, 2007, 2008 and 2009. There is little evidence of embankment failure in the Scottish Territory. The two incidents for which more detailed information is available are considered unlikely to be the result of increased railway traffic loading.

The dataset was divided into ULS and SLS failures (see Section 2.2); the data indicates a Winter peak in ULS failure activity and a late Summer peak in SLS failure activity. The former peak is consistent with the expectation that a high soil moisture content caused by increased rainfall will trigger embankment slips.

The number of annual failures was also investigated to assess whether there is evidence of an increasing failure rate. The data does not suggest a trend of increasing embankment failure rather the failure rate appears to be approximately constant for 6 out of the 7 years considered. The failure rate in 2003 was particularly high, especially given that the dataset was not for the full year, and for failures occurring in only three of Network Rail's five territories. The large number of failures is attributed to the particularly hot and dry summer of that year; approximately half the failures recorded in 2003 occurred in August and September in Network Rail's Southern and Western Territories (these were probably SLS rather than ULS failures). In addition, the 2009 dataset appears to be a partial one as it does not include any failures from the LNW Territory; there may also be failure reports for the final part of the year which were not included in the database reviewed during the completion of this sub-task. In summary, the data remains inconclusive with regard to an overall trend of increasing failure rate with time.

In general, embankment failures occur predominantly within medium to high plasticity ground conditions. However, there does appear to be a reducing trend in failures involving high plasticity sites more recently. In contrast, in the years 2003 and 2007, there were significantly more failures involving medium to high plasticity sites. This is attributed to the prevailing weather conditions in these years.

The majority of failures occur in embankments of between 3 and 6m in height and with a slope angle of greater than 25 degrees (i.e. an approximately 1 in 2 side slope or greater). Embankment height and slope angle were obtained from the RT/CE/S/065, Examination of Earthworks inspection reports; the height was defined using four classifications as opposed to the three used in the RT/CE/S/065, Examination of Earthworks inspection reports:

- <3m,
- 3m to 6m,
- 6m to 10m
- and >10m.

Approximately similar numbers of failures occurred for embankments with a slope angle of between 25 and 35 degrees, and with a slope angle in excess of 35 degrees. This correlation is unlikely to be significant and probably just reflects the preponderance of embankments within this geometry range on the UK rail network.

Information concerning the slope composition at the crest and toe of embankments, where failures have occurred, was also gathered from the RT/CE/S/065, Examination of Earthworks inspection reports. This information was not available for approximately one third of the assets under consideration. Considering the dataset as a whole, there does not seem to be a tendency for embankments composed of any particular material at the crest or toe to fail. Rather, there is a tendency for embankments having Fine Granular/Ash material at the crest, or "Cohesive, low - intermediate plasticity" at the toe, to be susceptible to failure. However, it is difficult to say, from looking at the whole dataset, whether this is merely a reflection of the most common embankment construction materials across the network or not. It is important to note that the observations of surface slope composition may not, and probably do not, reflect the composition of the embankment fill below the track (which is most vulnerable to a change in railway traffic loading).

The majority of embankment failures occurred on 'straight' lengths of railway; only 20% of the recorded failures took place on 'curved' sections of track where the effect of the loading imposed is likely to be greater due to the centripetal forces associated with the movement of a train around a curve.

The prevailing weather conditions, at the time of failure, were noted as a potential contributory factor in almost half of the failures (excluding those due to scour and washout); some 35 mentioned wet weather occurring immediately before failure while a further 13 made note of dry weather conditions. The influence of vegetation on embankment slopes at the time of failure was noted in a small number of cases associated with seasonal shrink-swell effects.

The consequences of the failures, in terms of the immediate effect of the incident on train operation, were also reviewed. The failures were separated into:

- those resulting in derailment or line closure,
- those where the imposition of emergency/temporary speed restrictions was necessary,
- those having no effect on train operation.

Failures where no mention of a speed restriction is made and, those explicitly stating that there was no effect on train operation, have been designated "No effect on train operation". The data indicates one failure caused a train derailment, 10 No. failures resulted in a line closure, 36 No. failures resulted in the imposition of an emergency speed restriction, and 10 No. in the imposition of a temporary speed restriction. The remaining 56 No. failures were classed as having "No effect on train operation". It should be noted that different NR Territories adopt different approaches to dealing with the impact of failures on the rail network; the approach adopted is largely based on the line speed and thus the relative importance of the railway line. For example in the Western Territory where a large number of the failures have occurred on the main Paddington-Bristol-Penzance line, the imposition of Emergency Speed Restrictions is preferred given the importance of this rail route and financial consequences of temporary speed restrictions. The geographic distribution of these impacts are presented in drawing 267641/010 and reproduced in Appendix A.

Most of the reported ULS failures were deep-seated slips and these failures had the most significant impact on subsequent train operations. These failures were often associated with wet weather. About 70% of the embankment failures (excluding those due to scour or washout) were located in NR's Southern and Western Territories.

As noted in the sub-task report there are many different types of potential failure mechanism and the likely influence of train loading on these different failure modes varies. It is considered that the SLS 'failures' which are directly attributable to train loading, are attributable to a fatigue type of mechanism, which would not be reported under the current NR reporting system, where the emphasis is on the recording of classical ULS embankment failures. Furthermore, a prolonged time period would need to elapse before obvious signs of deterioration become apparent. Such SLS failures would typically manifest themselves as local track settlement and generally lead to the need for increased track maintenance. In order to assess the impact of such failures on the rail network it is recommended that a detailed analysis of track maintenance records is carried out.

Further details of the Embankment Failure Review, including the limitations in the data/information made available for this study, are contained in document 267641/TPN/FNG/003.

5. Changes in Heavy Traffic

In this sub-task a detailed review of historic, current and future railway traffic loading was undertaken for selected lengths of the rail network. The work report comprised a detailed review of railway traffic loading data across the UK rail network for the period 2006 – 2010; site specific plots of the change in railway traffic loading over this period are presented in document 267641/TPN/FNG/004, Changes in Heavy Traffic, and are not reproduced herein. The review included consideration of the incidence of embankment failure noted in Task 1, sub-task (ii) – Embankment Failure review (factors/causes/types/consequences). The following key issues were addressed:

- Potential correlations between changes in railway traffic loading and the large scale embankment failures reviewed under Task 1 Sub-task (ii) (See Section 4).
- Potential correlations between changes in railway traffic loading and potential embankment monitoring sites, which were identified following preliminary discussions with Network Rail's Route Geotechnical Engineers.
- Potential correlations between changes in railway traffic loading and embankments identified as vulnerable to damage from railway traffic loading under Task 1 Sub-task (i) (See Section 6) both in terms of potential monitoring sites and those subject to increased levels of maintenance and/or poor trackbed performance.

With regard to a potential correlation between the incidence of large scale catastrophic embankment failure and a change in railway traffic loading, no such correlation is evident on the basis of the data reviewed in the completion of this sub-task. This corroborates the conclusions of the Embankment Failure Review (267641/TPN/FNG/003) that, the failures recorded under current NR reporting procedures are predominantly classical geotechnical "slip circle" type failures, rather than the fatigue type failure mechanism which would be directly induced by train loading. Fatigue failure would manifest itself through increased maintenance and poor trackbed performance.

Following discussions with the NR Route Geotechnical Engineers, several sites were identified as being potentially suitable for instrumentation and monitoring. However, on subsequent review of the corresponding railway traffic loading data, together with the anticipated site geology, it is concluded that there are other sites which are potentially more suitable for instrumentation and monitoring.

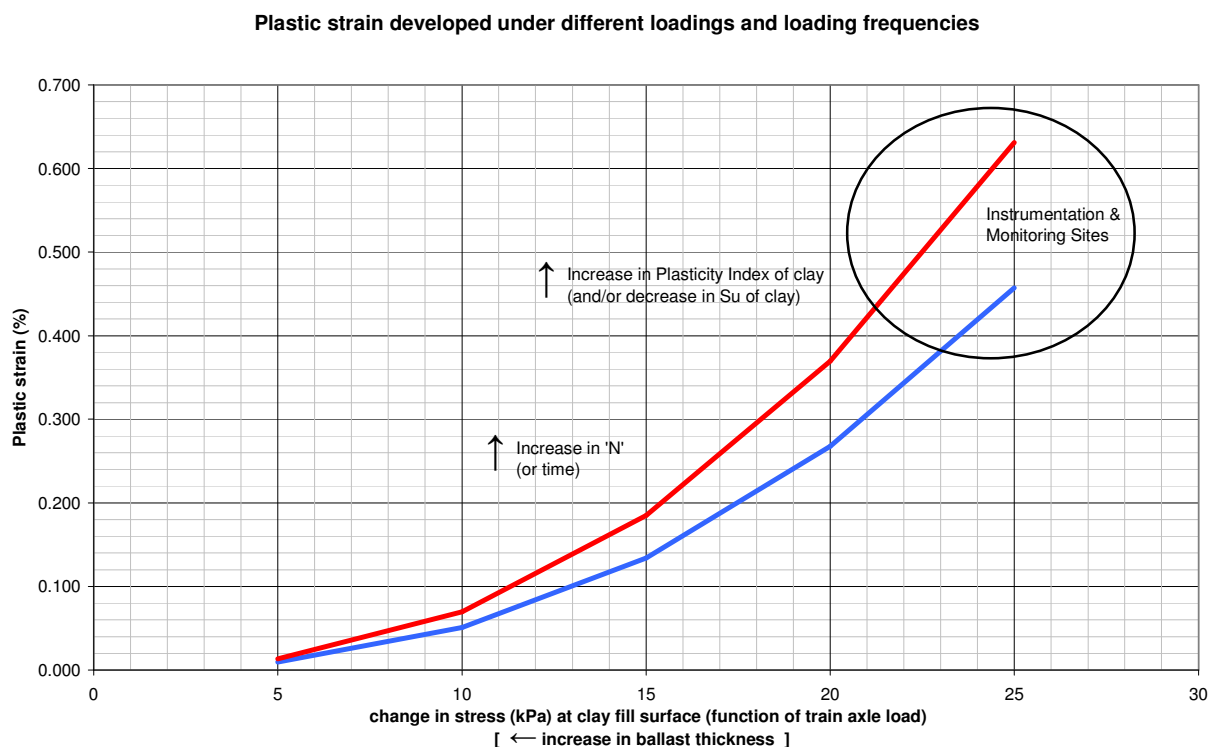
As part of this sub-task the railway traffic loading data was also studied on a much wider basis, taking account of embankments across the entire UK NR network. The purpose of this study was two-fold: to identify those potential sites worthy of further investigation in relation to recent levels of necessary maintenance as well as to identify potential sites for subsequent instrumentation and monitoring. Two different sets of criteria were applied in these studies. In identifying sites where, on the basis of the available records of railway traffic loading, maintenance may be a particular issue, the following criteria were applied:

1. The freight traffic loading is progressively increasing year-on-year.
2. The magnitude of the freight traffic loading on the railway line under consideration is significantly greater than the corresponding magnitude of passenger traffic loading, i.e. equal to at least twice that due to passenger traffic loading.

To provide a meaningful contribution to the research project, the sites selected for instrumentation and monitoring should measure a significant amount of movement, typically more than 10mm, over the 12 to 18 months monitoring period envisaged. The information presented in Figure 5.1, which is based on the work of Li & Selig (1996), summarises the key variables to be considered in the selection of sites for instrumentation and monitoring. The ideal levels of stress change and plastic strain experienced at sites suitable for instrumentation and monitoring, is also shown on this figure, that is towards the upper end in terms of train axle load, number of train passes/time, and plasticity index of embankment fill (i.e. medium to high plasticity) thus resulting in greater plastic strains. On this basis, the following criteria were adopted, in relation to the railway traffic loading, when considering a site's potential for instrumentation:

1. The freight traffic loading is greater than 1.0 MGT per year.
2. For twin track alignments, consideration is given to an out-of-balance embankment loading, i.e. the freight railway traffic loading on the Up Line is at least 1.0 MGT greater than that on the corresponding Down Line or vice versa.
3. The embankment fill is to be composed predominantly of medium to high plasticity clay.
4. The absolute railway traffic loading (passenger and freight), in terms of MGT, is also to be a maximum in relation to the foregoing criteria.

Figure 5.1: Plastic Strain Development.



This wider assessment of the UK rail network considering correlations between changes in railway traffic loading and, embankments identified as vulnerable to damage from railway traffic loading, has revealed several other potential sites which may be suitable for instrumentation and monitoring. These sites are in

267641/TPN/FNG/006/1 25 March 2011

addition to those considered to be worthy of further investigation in relation to recent levels of necessary maintenance and/or poor trackbed performance. Two short lists have been compiled and are presented in Tables 5.1 and 5.2 below. The suitability of these sites for further study will have to be discussed with NR and, in particular, NRs Maintenance Engineers; a review of the maintenance records for each potential instrumentation and monitoring site should be undertaken before any final decision is made concerning the sites. Site access will also be an important factor to consider in the selection of sites for instrumentation and monitoring.

Table 5.1: Short List for Potential Trackbed Maintenance Sites.

Engineers Line Reference	2010 Railway Traffic Loading (MGT)						Nature of Predominant Embankment Clay Fill
	Passenger			Freight			
	Up	Down	Bias	Up	Down	Bias	
ESK	0.7	0.8	0.1	7.9	8.5	0.6	Medium-High Plasticity
TAH1	2.2	2.3	0.1	5.9	6.2	0.3	High Plasticity
HNL1	1.5	1.4	0.1	2.7	1.3	1.4	Low-Medium Plasticity
SHL	1.3	1.3	0.0	2.6	1.0	1.6	Low-Medium Plasticity
HNR	4.4	4.4	0.0	7.9	7.3	0.6	Medium Plasticity

Table 5.2: Short List for Potential Instrumentation and Monitoring Sites where Traffic Loading is Significant.

Engineers Line Reference	2010 Railway Traffic Loading (MGT)						Nature of Predominant Embankment Clay Fill
	Passenger			Freight			
	Up	Down	Bias	Up	Down	Bias	
DOW	0.7	0.7	0.0	6.6	18.6	12.0	Medium Plasticity
SWY	3.0	3.1	0.1	5.5	2.0	3.5	Medium-High Plasticity
WEY	3.4	3.5	0.1	6.9	2.5	4.4	Medium-High Plasticity
FRA	2.7	2.8	0.1	4.4	1.6	2.8	Medium-High Plasticity
NOB3	0.1	0.1	0.0	2.5	6.1	3.6	Medium-High Plasticity
ECM2	7.9	7.9	0.0	4.9	8.8	3.9	Medium Plasticity

It should be noted that an assumption implicit when undertaking this sub-task is that there are lengths of embankment within the lengths of railway line reviewed. This is considered to be a reasonable assumption given that the lengths of railway line under consideration extend for several miles and, given the shallow gradients generally adopted for railway vertical alignments, it is highly likely that embankments occur over such long lengths of the railway. The nature of clay fill type given in Tables 5.1 and 5.2 is based on NRs geological mapping. Confirmation of clay fill plasticity would be appropriate prior to finalisation of site selection for monitoring; this could be based on discussions with NR Route Geotechnical Engineers, review of NR records and/or site specific investigation.

Further details of the Railway Traffic Loading Data Review, including the limitations of the data/information made available for this study, are contained in document 267641/TPN/FNG/004.

6. Embankment Vulnerability to Traffic Damage

In this sub-task the preliminary extent of embankment on the NR railway network that is vulnerable to damage from railway traffic loading was established. The following key issues were addressed:

- Identification of the key factors affecting embankment vulnerability to fatigue-type failure.
- A preliminary assessment of the distribution of potentially load-sensitive embankments across the UK NR railway network.

Owing to their complex construction history, together with a lack of understanding of their mechanical behaviour, UK railway embankments have inherited several factors which render them vulnerable to damage from railway traffic loading. These factors include embankment fill type, overlying materials (i.e. ballast/ash thickness), track drainage, embankment geometry and slope vegetation.

The work of this sub-task (Task 1 Sub-task (i)), involved a detailed investigation of the factors influencing embankment vulnerability to serviceability limit state type damage due to railway traffic loading. Such damage/failures would manifest themselves through increased maintenance and poor trackbed performance. It is recognised that poor track drainage will weaken the performance of a railway embankment; for the purpose of this study, a well-drained railway embankment was assumed. Following an extensive investigation of the causes of railway embankment serviceability limit state type damage, three principal factors have been identified, namely:

- Train axle load;
- Embankment Clay Fill Plasticity, and
- Trackbed configuration.

Track alignment (i.e. straight or curved), embankment height, embankment side slope angle and embankment shoulder width, are regarded as lesser contributory factors.

6.1 Train Axle Load

The passage of an individual train over a railway embankment will induce both elastic and plastic deformations within the earthwork. Although the embankment deformation is largely elastic and fully recoverable, irrecoverable plastic strains will accumulate gradually over a large number of cycles. As one would expect, the magnitude of permanent deformation increases with train axle load. This phenomenon was observed by Selig & Sluz (1978) and Yoo & Selig (1979) following a comprehensive full scale testing programme.

Subsequent to this work and following comparison with measurements taken from a test track on cohesive subgrade, Li & Selig (1996) proposed a relationship for estimating the accumulation of permanent plastic deformations in fine grained soils under repeated railway traffic loading.

The influence of train axle load on the resulting plastic strain accumulation, is demonstrated in Figure 6.1, using the average values for high plasticity clay (CH) proposed by Li & Selig (1996) and assuming a soil static strength of 100kPa. Plotted in the figure are cumulative plastic strains after 1 year and 5 years for

varying train axle loads and number of cycles. In general, axle loads of between 10 and 15 tonnes relate to passenger trains; whereas axle loads for freight trains are in the range 20 to 25 tonnes.

Figure 6.1: Plastic Strain Accumulation from Railway Traffic Loading.

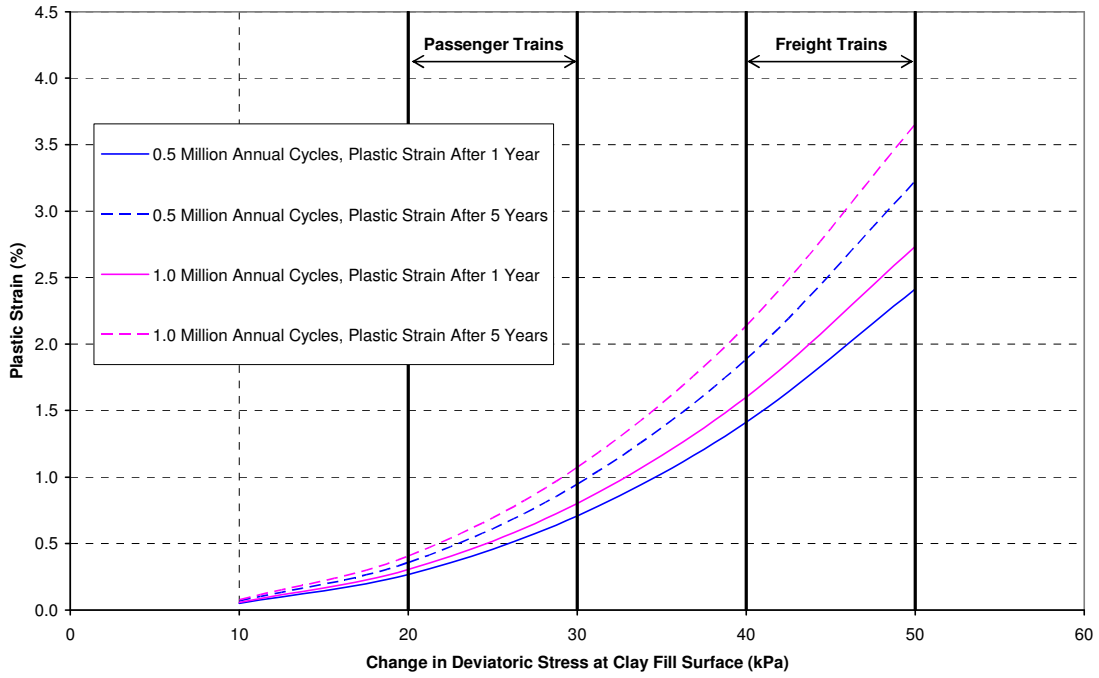
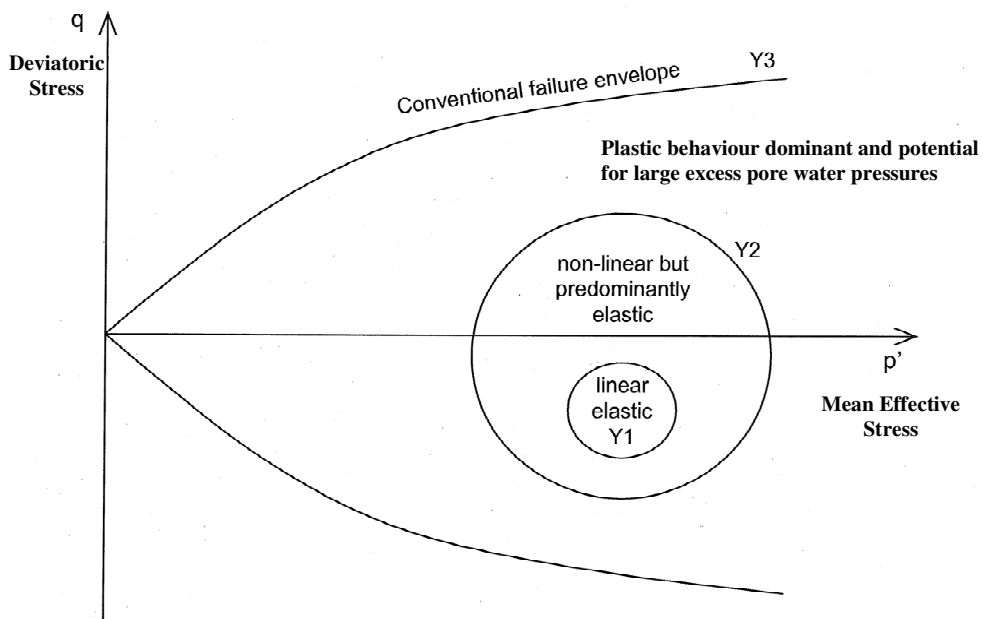


Figure 6.2: Y1, Y2 and Y3 Yield Surfaces.



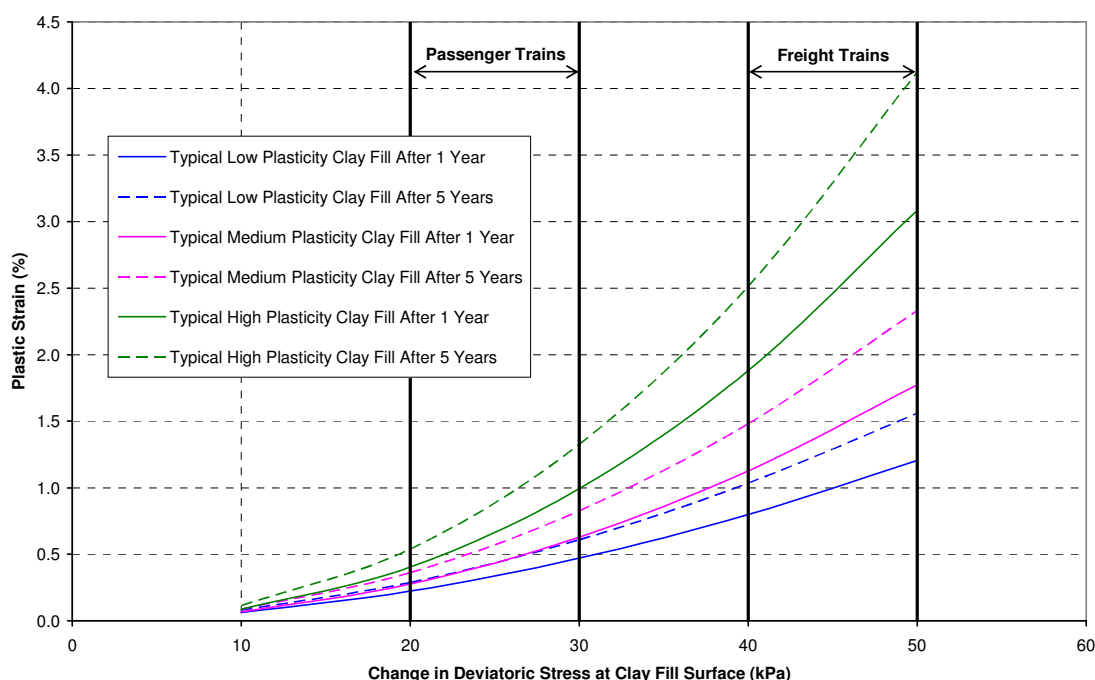
It can be seen in Figure 6.1, that the cumulative plastic strain increases exponentially as the train axle load increases. This reflects the power relationship proposed by Li & Selig (1996) and highlights the role of train axle loading in the prediction of embankment vulnerability. Figure 6.1 suggests that for 1 million loading cycles per year, the plastic strain developed as a result of 25-tonne freight train loading in the first year is approximately 2.7%, which is approximately 3.5 times that of a 15-tonne passenger train.

The incidence of larger plastic strain per loading cycle, observed for higher train axle loads, can be explained by the non-linear nature of soil. Advanced fundamental soil mechanics research, has identified 3 separate zones of soil behaviour known as the Y1, Y2 and Y3 yield surfaces (Figure 6.2). Under monotonic loading, soil behaviour within the Y1 zone is truly elastic with negligible plastic strains. As the loading enters the Y2 zone, soil behaviour becomes non-linear with the plastic strains becoming more noticeable. Traversing through the Y2 zone, plastic soil behaviour becomes progressively more dominant until failure occurs at the limit of the Y3 zone. Under cyclic loading, soil subjected to larger load amplitudes will experience higher magnitude plastic strains per cycle which will accumulate over time until instability develops.

6.2 Embankment Clay Fill Plasticity

Soil plasticity can aid assessment of the vulnerability of an embankment subject to repeated railway traffic loading. To facilitate an understanding of the role of embankment clay fill plasticity in plastic strain accumulation, a comparison of predicted plastic strains for low, medium and high plasticity clay fills, has been made; the results are illustrated in Figure 6.3. Undrained shear strengths of 40kPa, 50kPa and 60kPa were assumed for low, medium and high plasticity clay fills respectively. The average values for the soil parameters recommended by Li & Selig (1996) were used in this study. In addition, to further emphasise the impact of high train axle loads, the total load applied (the number of loading cycles x train axle load) has been kept constant at 2.5 Million Gross Tonnes (MGT), by reducing the number of loading cycles as the axle load increases. In other words, the work done in each load case is identical.

Figure 6.3: Effects of Embankment Clay Fill Type and Train Axle Load.

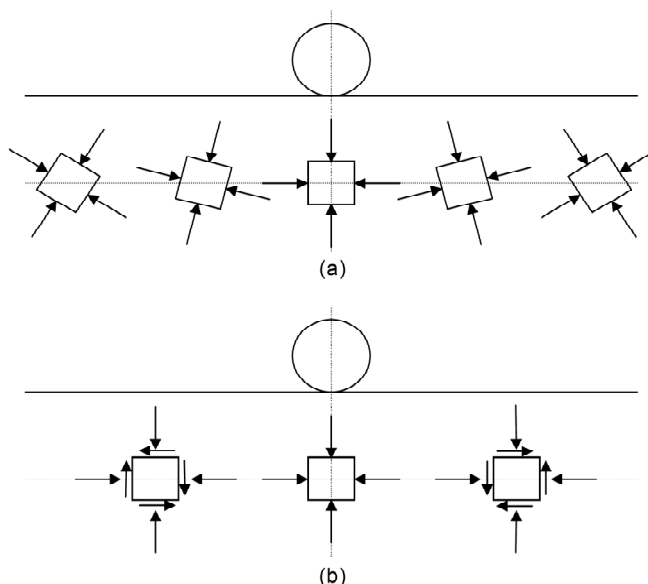


At low tonnage or small stress change (for example cause by increased depth of ash/ballast) within the embankment, the influence of the intrinsic soil properties is insignificant; all 6 lines in Figure 6.3 converge at a change in stress of 5kPa. These lines diverge with increasing train axle load; more significant divergence is evident for higher plasticity clay fill. For a stress change of 50kPa within a high plasticity clay fill, the plastic strain induced in the first year of loading is about 3.1%, more than double that for the corresponding low plasticity clay. Due to the exponential nature of the plastic strain curves, embankments composed of medium to high plasticity clay fill will undoubtedly suffer greater plastic deformation and require more frequent maintenance. As a result, for the purposes of identifying potentially vulnerable embankments, emphasis should be given to those formed predominantly of medium to high plasticity clay fill and situated on major freight routes.

6.3 Trackbed Configuration

As illustrated in Figure 6.4, stress changes induced within embankment clay fills as a result of railway traffic loading, are complex and involve a rotation in the direction of the major principal stresses, as the train approaches, passes and moves on. The magnitudes of these stress changes, are greatly influenced by the design of the overlying trackbed, which includes ballast, sub-ballast and sleepers. When the ballast thickness was increased from 150mm to 600mm, Stewart & Selig (1982) and Selig & Waters (1994), reported a reduction in vertical stress at the subgrade by approximately one half. A better load spreading capability could also be achieved by reducing the spacing of the sleepers.

Figure 6.4: Stresses on an Embankment Element during the Passage of a Wheel: (a) Principal Stress Rotation; (b) Shear Stress Reversal on Horizontal and Vertical Planes.



Source: After Brown (1996).

Therefore, both sleeper spacing and ballast (and sub-ballast) thickness should be taken into account, when determining embankment vulnerability to repeated railway traffic loading. Sleepers are visible from the ground surface and therefore the spacing could be determined without too much difficulty. Determination of ballast thickness, on the other hand, requires more effort. Ground Penetrating Radar (GPR), could be utilised to establish the depth of the ballast layer. GPR works by sending a pulse of energy into a material and recording the strength and the time required for the return of any reflected signal. GPR is being increasingly applied by NR to map the thickness of the trackbed layers.

It is anticipated that the sleeper spacing is, in general, constant over a section of railway track. However, the thickness of the ballast layer could vary considerably over the same length of embankment, as a result of deformations, the formation of ballast pockets and associated maintenance works carried out over the years.

6.4 Embankment Vulnerability Assessment

A preliminary assessment of the distribution of potentially load-sensitive embankments across the UK NR railway network, was conducted on the basis of embankment fill properties and the results presented geographically for each of the five Network Rail Territories. It should be noted that the nature of the clay fill type assumed on these drawings is based on geological mapping by NR. For identification of railway embankment vulnerability, on the basis of the influence of its fill type, the following embankment fill criteria were applied over the length of railway line under consideration:

Low vulnerability (Green): high plasticity clay fills < 10%

Moderate vulnerability (Yellow): $10\% \leq$ high plasticity clay fills < 40%

High vulnerability (Amber): $40\% \leq$ high plasticity clay fills < 90%

Very high vulnerability (Red): high plasticity clay fills $\geq 90\%$

The results of this railway embankment vulnerability classification are presented graphically for each of the five Network Rail Territories, together with an enlargement of the London area, in drawing nos. 267641/023 to 028, which are reproduced in Appendix B. The corresponding percentages for each vulnerability class are tabulated in Tables 6.1 to 6.5.

In addition, it should be emphasised that the corresponding preliminary vulnerability classification to railway traffic loading is based solely on the anticipated clay fill plasticity index. Additional factors also need to be considered, such as axle loading, ballast thickness, track geometry, drainage, clay fill strength and local structural features (adjacent/underlying "hard spots", such as culverts, retaining walls, which may act as stress concentrators), in order to assess the overall risk of damage due to changes in railway traffic loading. Nevertheless, the preliminary vulnerability classification adopted during the completion of this sub-task provides an initial basis for planning purposes.

With regard to assessing the causes of serviceability limit state damage to embankments as a result of railway traffic loading, the following factors were identified as being of most importance:

- Train axle load.
- Embankment fill type (i.e. low, medium or high plasticity clay).
- Overlying material (i.e. type and thickness of ash/ballast).

These should be taken into consideration when selecting sites for instrumentation and monitoring in the future. The importance of train axle load and plasticity has been highlighted through reference to the work of Li & Selig (1996) as has the depth of ash/ballast cover. Confirmation of clay fill plasticity would be necessary prior to finalisation of site selection for instrumentation and monitoring; this would be based on

discussions with NR Route Geotechnical Engineers, review of NR maintenance records and site specific ground investigation data.

Further details of the Embankment Vulnerability to Traffic Damage review, including the limitations of the data/information made available for this study, are contained in document 267641/TPN/FNG/005.

Table 6.1: Proportion of Potential Vulnerability in Scotland Territory.

Vulnerability	Track Length (km)	Percentage (%)
Low	2752	100.0
Moderate	0	0.0
High	0	0.0
Very High	0	0.0
Total	2752	100.0

Table 6.2: Proportion of Potential Vulnerability in London North East Territory.

Vulnerability	Track Length (km)	Percentage (%)
Low	3005	78.4
Moderate	560	14.6
High	164	4.3
Very High	101	2.6
Total	3831	100.0

Table 6.3: Proportion of Potential Vulnerability in London North West Territory.

Vulnerability	Track Length (km)	Percentage (%)
Low	2995	87.8
Moderate	289	8.5
High	42	1.2
Very High	85	2.5
Total	3410	100.0

Table 6.4: Proportion of Potential Vulnerability in Western Territory.

Vulnerability	Track Length (km)	Percentage (%)
Low	2287	74.7
Moderate	588	19.2
High	148	4.8
Very High	38	1.2
Total	3061	100.0

Table 6.5: Proportion of Potential Vulnerability in South East Area Territory.

Vulnerability	Track Length (km)	Percentage (%)
Low	1251	34.6
Moderate	1200	33.2
High	763	21.1
Very High	404	11.2
Total	3619	100.0

7. Instrumentation Design

As part of this sub-task a detailed review was undertaken of the various instrumentation available, to monitor both dynamic load effects associated with railway traffic loading and, the more conventional types of instrumentation that is capable of assessing global deformation effects, such as seasonal-shrink swell, which are independent of traffic loading effects. Experience from existing instrumented sites was also presented. The following key issues were addressed:

- the practical aspects of instrument installation;
- site access and rail safety requirements, both during installation and ongoing monitoring;
- data logging, storage and management, and
- data analysis and post-processing.

The advantages/disadvantages and relative costs of the various instrumentation types, together with details of measurement range/quality and reading frequency, were outlined; the tables summarising this information are reproduced in Appendix C. This information was used to inform an outline instrumentation layout to measure both global slope movements/deformations and subgrade displacements/dynamic effects on a typical embankment; the layout includes sub-surface horizontal arrays of geophones with verification using video monitoring. The schematic plan and cross-section outlining the proposed instrumentation layout for a generic embankment is reproduced in Appendix C.

At this stage of the research project, the instrumentation sites have not yet been finalised, and as such, the proposed outline scheme is designed to be flexible.

Although not formally approved for sub-surface use on the UK rail network it is considered that sub-surface geophones are likely to have no greater impact on the rail signalling equipment, through potential electromagnetic signal interference, than the equivalent surface layout (which is approved by NR for use on the rail network); sub-surface, the ballast/ash/embankment fill will shield the signalling equipment from the geophone.

Further details of the proposed instrumentation are contained in document 267641/TPN/FNG/001.

8. Preliminary Modelling

In this section the results of the preliminary work carried out in the development of both numerical and analytical models are presented. Past experience indicates that preliminary numerical modelling (because of the rigour that this requires) can be useful in highlighting key variables and potential pitfalls/problems at an early stage with conceptual models of behaviour. It should be noted, that at this stage in the research project, these models are inevitably relatively crude and are to be subject to refinement in the future when the laboratory test results and monitoring data become available.

8.1 Numerical

With the advent of cheap and powerful computers in the last two decades, the use of numerical modelling to aid the design and verification processes has become increasingly popular. In this research project, the importance of numerical modelling is threefold:

- To highlight key variables and potential pitfalls/problems at an early stage (i.e. prior to carrying out laboratory tests and field monitoring) with the conceptual models being formulated;
- To assess the likely optimum locations for installation of monitoring equipment;
- To facilitate parametric studies of the behaviour of a typical embankment under railway traffic loading.

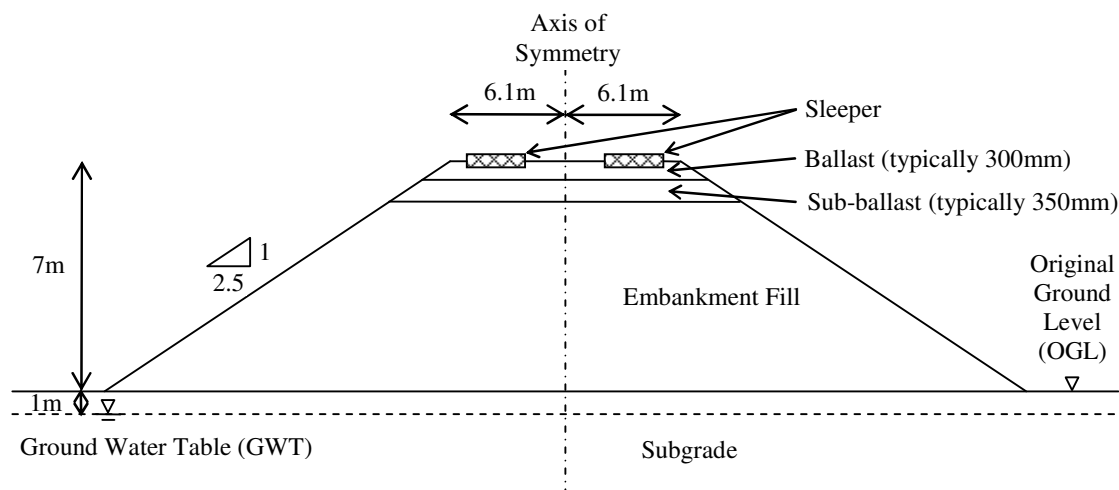
8.1.1 Numerical Model

The railway embankments across the UK NR network vary both in height and slope angle. For instance, the embankment at Charing is relatively high (>8m) but of shallow slope angle (16 to 18 degrees) (Mott MacDonald, 2008); a smaller (<5m in height) and steeper (29 degrees) embankment can be found at Pound Green (Mott MacDonald, 2009). The embankment considered in this numerical study is as shown in Figure 8.1. The embankment is 7m high, being 12.2m wide at its top with side slopes of 1 in 2.5 (approximately 22 degrees). On the basis of the information reviewed to date, this configuration would seem to represent a typical embankment on the UK NR network (Mott MacDonald, 2010). The groundwater table (GWT) was assumed to be located 1m below the original (i.e. pre-embankment) ground level (OGL). A hydrostatic pore water pressure distribution with depth was assumed; zero pore water pressure was assumed above the GWT.

The numerical modelling was undertaken using the finite difference program FLAC (Fast Lagrangian Analysis of Continua). A transverse plane strain model was adopted and through the use of symmetry, only half of the embankment was modelled. The underlying subgrade was made sufficiently wide and deep to avoid the boundary effects that can be associated with numerical models and thus misleading results.

The main objective of the preliminary numerical modelling was to understand the behaviour of a typical railway embankment under monotonic loading, in particular the stress changes within the embankment fill and the resulting displacements. An in-house advanced non-linear soil constitutive model, namely the A* model, was used to model the response of the embankment fill to loading. A short description of the A* model and its basis is included in Appendix D. Simple linear elastic-perfectly-plastic models obeying the Mohr-Coulomb failure criteria were adopted for the other materials of the embankment (i.e. the ballast, sub-ballast and subgrade); the sleeper was modelled as an elastic material.

Figure 8.1: Schematic Illustration of a Typical Railway Embankment.



8.1.2 Input Parameters

There are two main groups of input parameters:

- Railway traffic loading; and
- Embankment (i.e. ballast, sub-ballast, embankment clay fill and subgrade) strength and stiffness.

8.1.2.1 Railway Traffic Loading

A running train imposes loads on the track mainly through its axles. Esveld (2001) provides nominal axle loads applied to the railway track for various types of rolling stock. These axle loads are presented in Table 8.1. In addition, BS EN 15528:2008 classifies load in relation to rolling stock type and line speed, providing an equivalent uniformly distributed load for the track. This information is summarised in Table 8.2. In addition to the axle load, which is a static value, the dynamic component of the train loading, which is dependent on the train speed and track alignment, should also be considered. For simplicity, the preliminary modelling considered only the static component of the railway traffic loading – a value of 40kN/m per track was adopted in the plane strain model simulations. As noted in the literature review, for moderate train speeds the dynamic component of railway traffic loading is negligible. This magnitude of loading is equivalent to that of a freight train – with axle loads of approximately 225kN.

Table 8.1: Nominal Axle Loads Applied to the Track.

Rolling Stock	Number of Axles	Empty (kN)	Loaded (kN)
Trams	4	50	70
Light-rail	4	80	100
Passenger Coach	4	100	120
Passenger Motor Coach	4	150	170
Locomotive	4 or 6	215	-
Freight Wagon	2	120	225
Heavy Haul (USA, Australia)	2	120	250-350

Source: Esveld, 2001

Table 8.2: Load Classification.

Reference Wagon	Axle Load P(t)	Mass per unit length p (t/m)
A	16.0	5.0
B1	18.0	5.0
B2	18.0	6.4
C1	20.0	6.4
C3	20.0	7.2
C4	20.0	8.0
D4	22.5	8.0

Source: BS EN 15528:2008

8.1.2.2 Embankment Strength and Stiffness

The embankment fill properties were derived on the basis of the results of ground investigation at the Charing Embankment, reported in Mott MacDonald (2008) as part of a portfolio of Six Sigma workstreams arising from Network Rail’s Weather and Seasonal Preparedness Action Plan. Charing Embankment is situated on the SBJ (Swanley and Ashford B Junction) between Charing and Ashford stations in Kent. The embankment is approximately 590m in length, with a maximum height of 8.5m. Typical slope angles are between 16° and 25° but are locally as shallow as 12.5°. The embankment is believed to have been constructed in 1874.

The embankment is composed primarily of reworked Gault Clay. The reworked clay fill was typically encountered between 1m to 4.5m below the embankment crest level and has a maximum thickness of 9m. This material was described as a generally firm to stiff, locally very stiff, dark green and grey, slightly sandy, gravelly clay. A typical description is firm to stiff, light green and grey mottled brown, slightly gravelly, CLAY, with clods of stiff clay up to 20mm. The gravel is fine to medium, subangular to subrounded, flint, coal, brick fragments and occasional chalk. The material is variable in composition and this is reflected in the laboratory testing results.

Table 8.3: Soil Parameters.

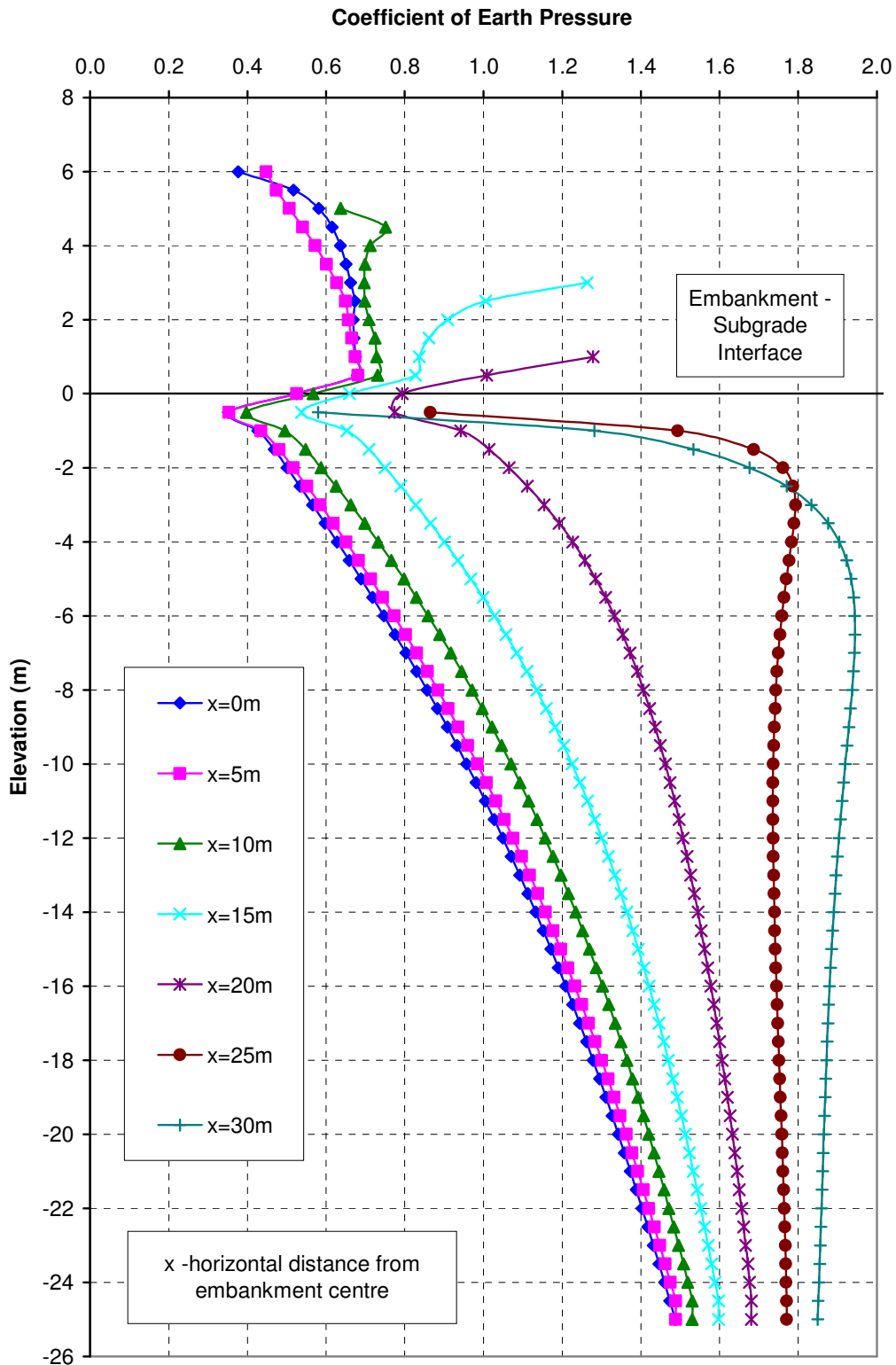
Material	Friction Angle (°)	Undrained Shear Strength (kPa)	Stiffness (MPa)	Poisson's Ratio
Ballast	40	n/a	200	0.3
Sub-ballast	30	n/a	100	0.3
Embankment Clay Fill	n/a	30, 50, 100	A* Model	0.1
Subgrade	n/a	$50+8z^1$	60	0.1

Note: ¹ - z is depth below top of subgrade.

The concrete sleeper was allowed to behave in an elastic manner with a Young's modulus of 30GPa. The material properties for ballast, sub-ballast and subgrade are given in Table 8.3.

A simple stress history analysis was carried out to compute the stress states within the embankment. Initially, only the natural clay (i.e. subgrade) was modelled and its stress state was defined by the total horizontal stresses based on an earth pressure coefficient of 2. Subsequently, the embankment was modelled and the model was allowed to run until equilibrium was reached. The resulting distribution with depth of the coefficient of earth pressure in the embankment and subgrade is shown in Figure 8.2 for a number of positions relative to the centre of the embankment. This figure indicates that the earth pressure coefficient for the embankment core was approximately 0.65 and that for the underlying subgrade varied from about 0.35 to approximately 1.95.

Figure 8.2: Profiles of Earth Pressure Coefficient.



8.1.3 Preliminary Numerical Modelling

A total of 10 analyses were carried out during this preliminary numerical modelling phase. These analyses are summarised in Table 8.4. The main objectives of these analyses were to investigate the effects of:

- Embankment clay fill properties on the stresses and displacements within a railway embankment (Analyses 1, 2 and 3);
- Embankment shoulder width on the stresses and displacements within a railway embankment (Analyses 1, 4 and 5);
- Trackbed thickness (ballast + sub-ballast) on the stresses and displacements within a railway embankment (Analyses 1, 6, 7 and 8); and
- The embankment itself on the stresses and displacements underneath the loaded sleeper (Analyses 1 and 9).

Analysis 10 was undertaken for comparative purposes with the preliminary analytical modelling, which is discussed in detail in Section 8.3. The contour plots of vertical stress increment and vertical displacement for Analyses 1 to 9 are presented in Appendix D.

Table 8.4: Description of Numerical Analysis.

Analysis Number	Embankment Included	Shoulder Width (mm)	Ballast Thickness (mm)	Sub-ballast Thickness (mm)	Clay Fill Undrained Shear Strength (kPa)
1 (base case)	Yes	600	250	350	50
2	Yes	600	250	350	30
3	Yes	600	250	350	100
4	Yes	300	250	350	50
5	Yes	900	250	350	50
6	Yes	600	250	100	50
7	Yes	600	500	100	50
8	Yes	600	250	750	50
9	No	600	250	350	50
10	No	n/a	n/a	n/a	50

For consistency when comparing the results of all the preliminary modelling, a reference level of 1.0m below the top of the trackbed was selected for results comparison.

Figure 8.3 shows the increase in vertical stress and corresponding vertical displacement across the section of embankment modelled in Analyses 1, 2 and 3 due to vertical loading of 40kN/m on each track. Three values of clay fill undrained shear strength were investigated – 50kPa, 30kPa and 100kPa. The increase in stiffness evident for a higher strength embankment clay fill was taken into account through the A* model, i.e. the stiffness of the embankment clay fill was greatest in Analysis 3 and least in Analysis 2. Figure 8.3a indicates that the resulting vertical stress increment within a railway embankment increases as the stiffness (and strength) of the clay fill increases. This observation is in line with the general perception that a stiffer material will attract more load. The ‘kink’ in the vertical stress increment profile for Analysis 2 was a result of the low clay fill strength adopted in the analysis (i.e. the clay fill yielded under the loading). The

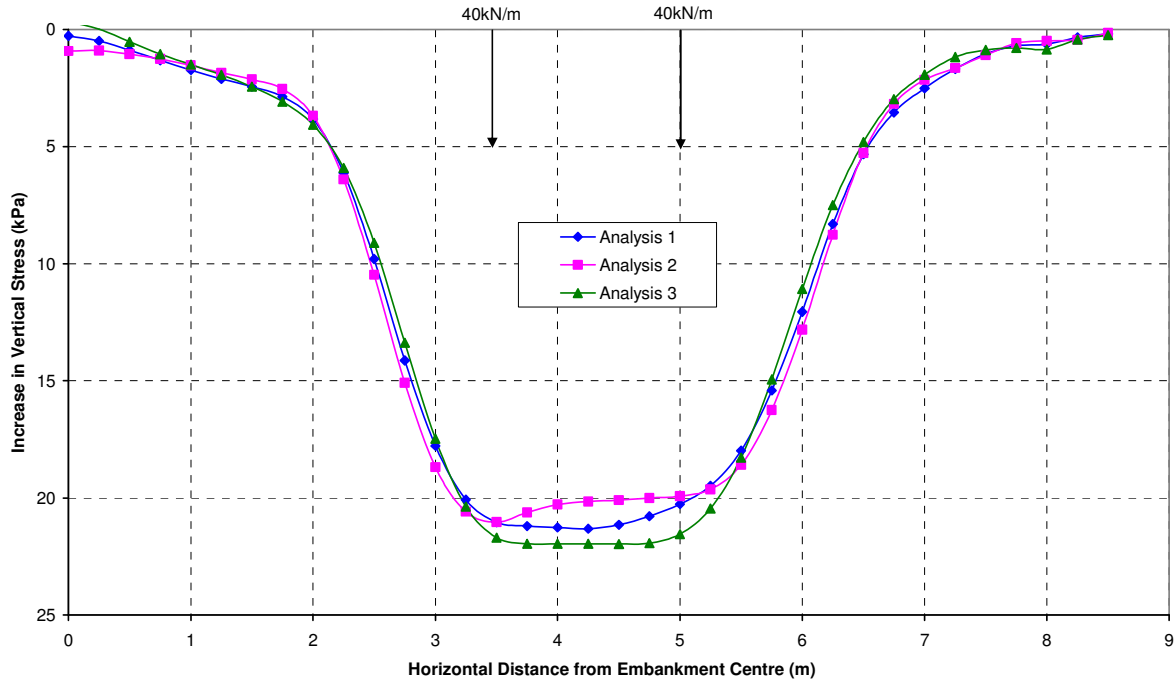
corresponding vertical displacements are plotted in Figure 8.3b; the effect of the embankment clay fill properties, in the prediction of the deformation of a railway embankment, is clearly demonstrated. Comparing Analyses 2 and 3, the resulting maximum vertical displacement increases from approximately 1.4mm (Analysis 3) to about 3.9mm (Analysis 2); a nearly 3-fold increase in vertical displacement despite the corresponding vertical stress increment for Analysis 3 being about 10% larger (Figure 8.3a).

The results of the analysis investigating the impact of the width of the embankment shoulder (defined for the purposes of this study as the horizontal distance between the top edge of the railway embankment and the nearest sleeper) on the stresses and displacements induced within a railway embankment (Analyses 1, 4 and 5) are illustrated in Figure 8.4. Three values of railway embankment width were investigated – 600mm, 300mm and 900mm in Analyses 1, 4 and 5 respectively. It can be seen from Figures 8.4a and 8.4b that railway embankment widths of 600mm and 900mm yield similar magnitudes of vertical stress increment and vertical displacement respectively. For the case of a 300mm wide railway embankment shoulder (Analysis 4) there was an approximately 5% maximum increase in both the vertical stress increment and corresponding vertical displacement. This additional deformation will accumulate over time and eventually affect the track alignment. As a result, it may be concluded from this numerical investigation that to reduce the deformation caused by railway traffic an embankment shoulder width of less than 600mm should be avoided. Embankment shoulder widths greater than 600mm are unlikely to significantly influence track behaviour. Embankment widths on the UK NR network are typically 600mm or greater.

A total of four analyses, namely Analyses 1, 6, 7 and 8, were performed to examine the effect of the trackbed thickness and composition (i.e. ballast + sub-ballast) on the stresses and displacements induced within a railway embankment. The combinations of ballast and sub-ballast layer thicknesses used in these analyses are summarised in Table 8.4. The results of these analyses are plotted in Figure 8.5. As shown in Figures 8.5a and 8.5b for vertical stress increment and vertical displacement respectively, the predicted values for analyses with sub-ballast layer thickness of 350mm and 750mm (Analyses 1 and 8) are broadly similar; whereas greater deformation was predicted for the analysis with a thinner sub-ballast layer (100mm in Analysis 6). This suggests that the performance of a railway embankment is not sensitive to the thickness of the sub-ballast layer when that layer is thicker than 350mm provided that an appropriate thickness of ballast layer is utilised (250mm in this case). Both Analyses 1 and 7 have total ballast and sub-ballast thickness of 600mm. However, the ballast layer thickness in Analysis 7 is twice that in Analysis 1; thus comparing these two analyses will provide an insight into the effect of the ballast layer thickness. It can be concluded from Figure 8.5 that a thicker ballast layer is more efficient in distributing the loading to the underlying layers, resulting in reduced magnitudes of vertical stress increment (Figure 8.5a) and vertical displacement (Figure 8.5b). However, the differences between the results for the various analyses are, for practical purposes, relatively small.

The final numerical investigation examined the effect of the railway embankment itself (i.e. the case of a trackbed on an embankment, Analysis 1, was compared to an at-grade trackbed configuration, Analysis 9). The corresponding vertical stress increments and vertical displacements for these analyses are shown in Figures 8.6a and 8.6b respectively. It can be seen from Figure 8.6b that the maximum vertical displacement for the case with an embankment (Analysis 1) is approximately 2.3mm, about 3 times that for the at-grade case (Analysis 9); in contrast the vertical stress increment for Analysis 1 is a mere 5% more than that for Analysis 9, as shown in Figure 8.6a. The difference in displacement is considered to be due largely to the different values assumed for the coefficient of earth pressure at rest, K_0 , namely 0.65 in Analysis 1 and 1.5 in Analysis 9.

Figure 8.3: Effect of Embankment Clay Fill Properties: (a) Vertical Stress Increment;



(b) Vertical Displacement.

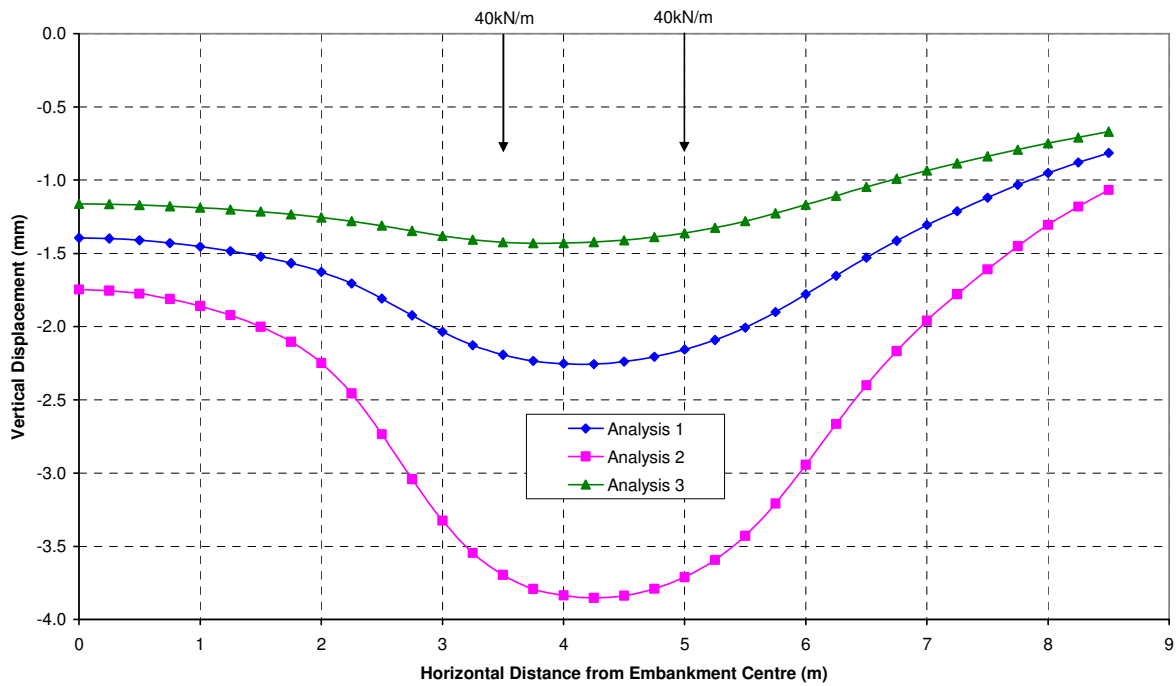
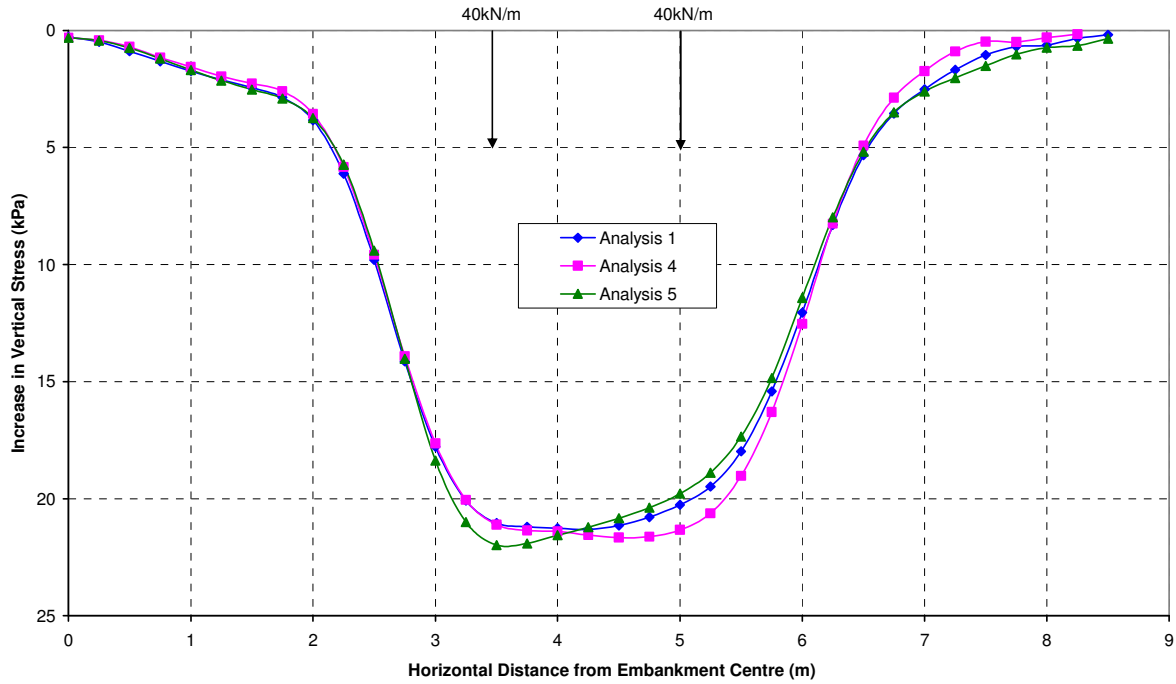


Figure 8.4: Effect of Embankment Shoulder Width: (a) Vertical Stress Increment;



(b) Vertical Displacement.

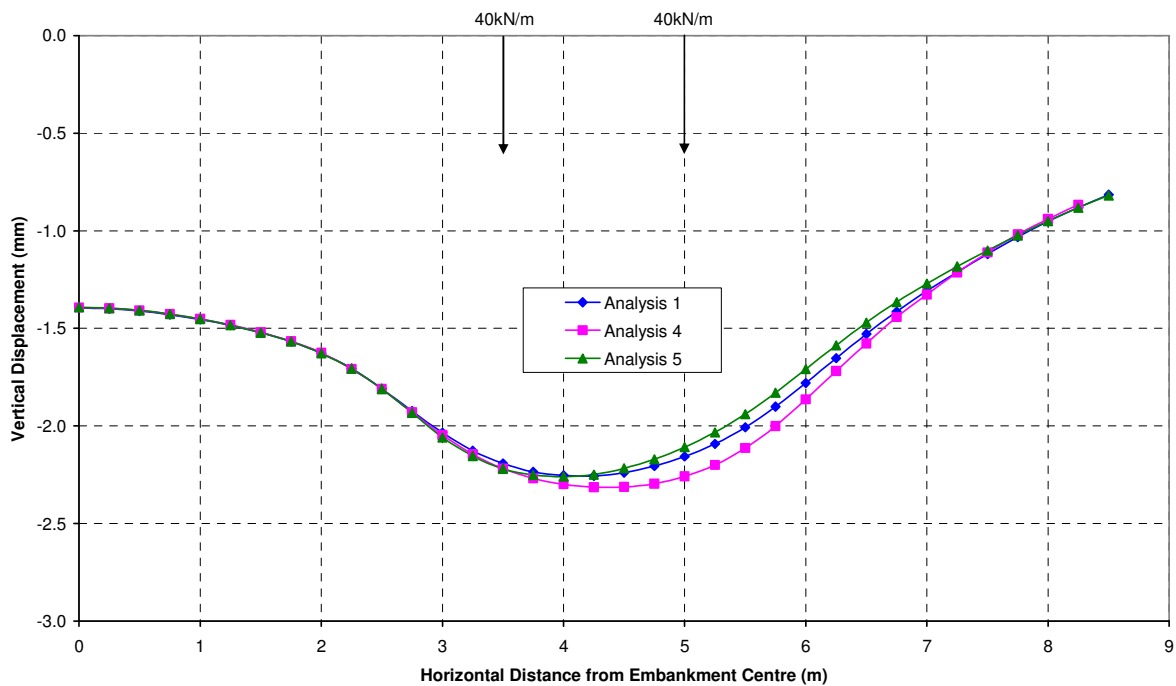
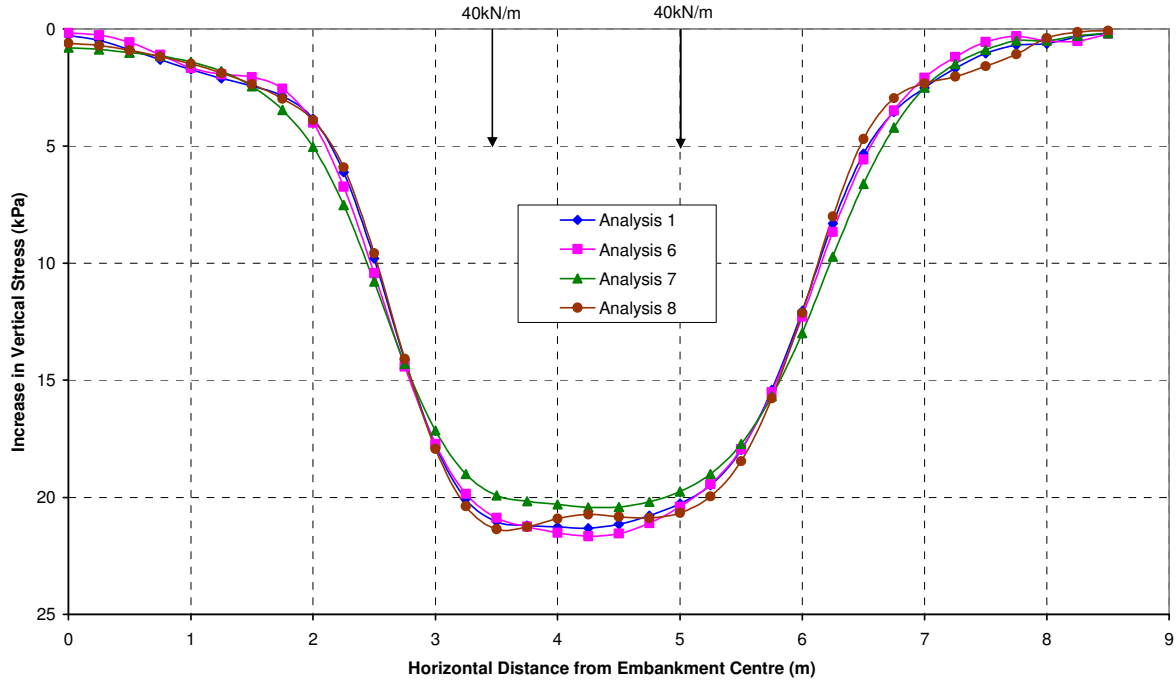


Figure 8.5: Effect of Trackbed Thickness/Composition: (a) Vertical Stress Increment;



(b) Vertical Displacement.

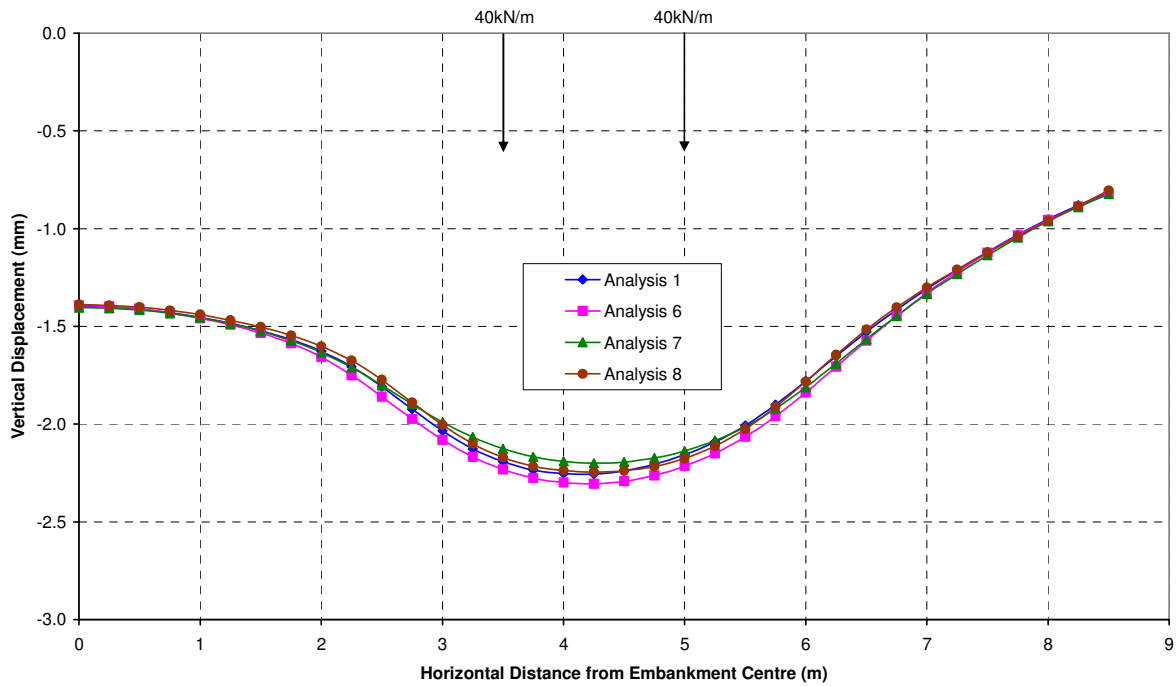
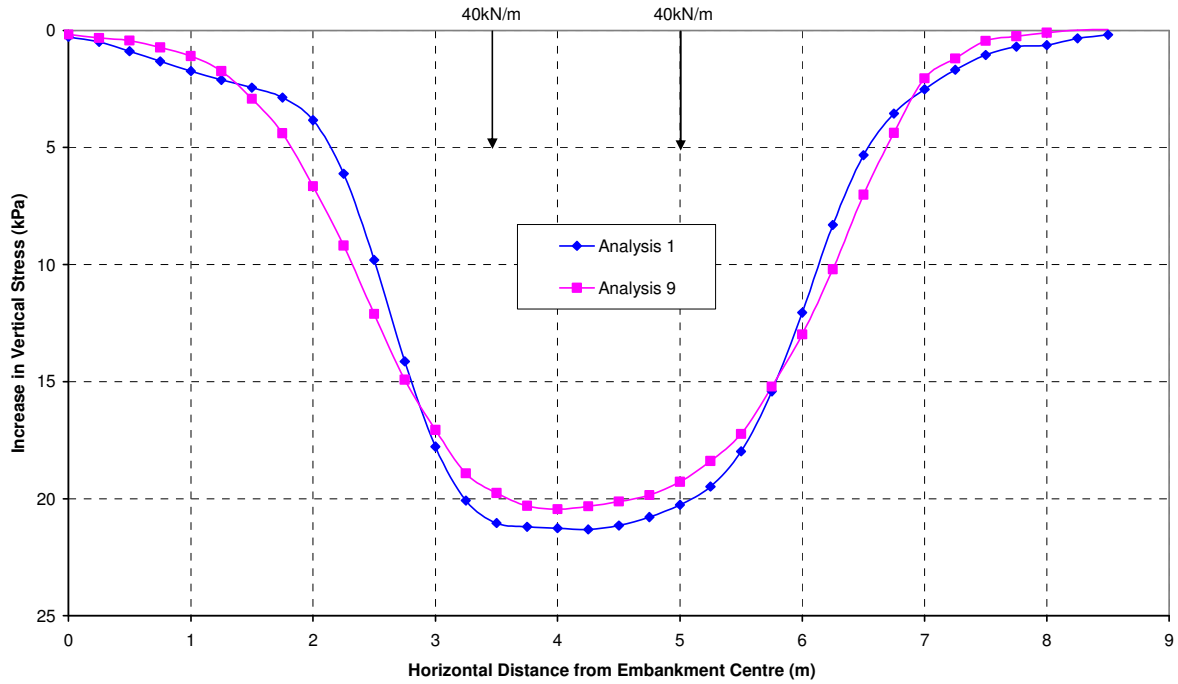
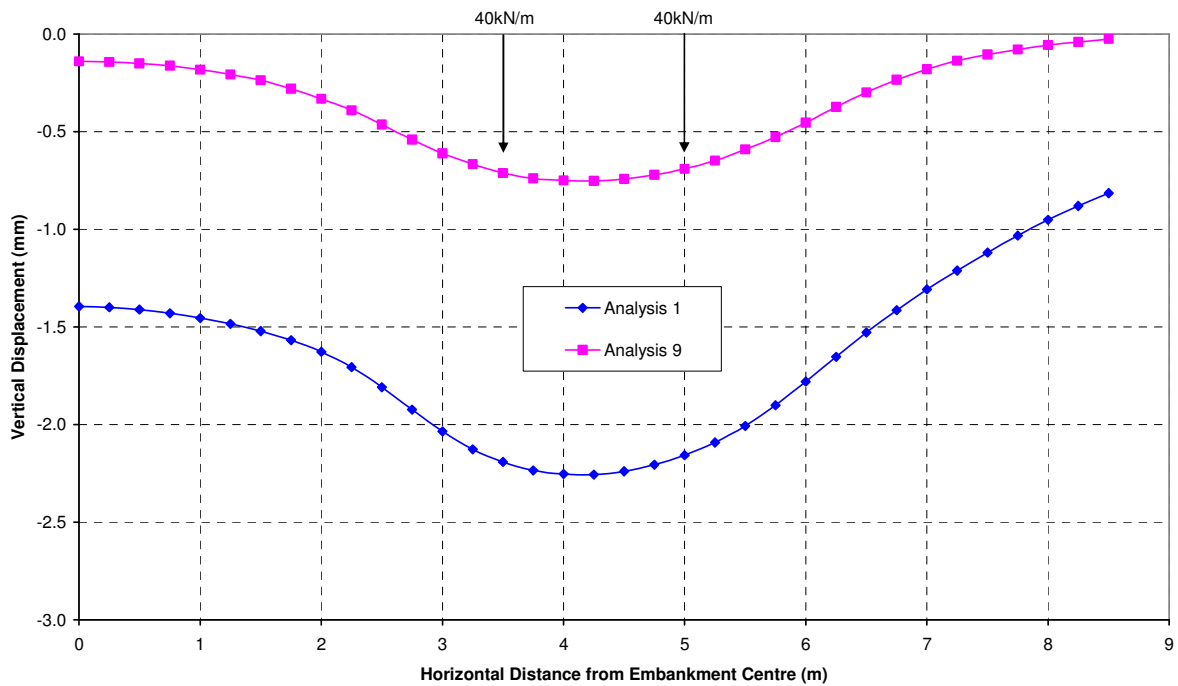


Figure 8.6: Effect of Embankment: (a) Vertical Stress Increment;



(b) Vertical Displacement.



8.2 Analytical

As part of this research project, practical analytical models for application, at both the strategic and tactical levels, are to be developed for the assessment of damage to railway embankments subject to increased train loading. The models are intended to be used as tools for the development of the business cases necessary to support proposals for renewal works, where embankment damage is predicted for increased railway traffic load. This will enable the budget for renewal works to be identified and targeted at improvement schemes where utilisation of the railway network can be maximised for increased traffic at a reasonable cost.

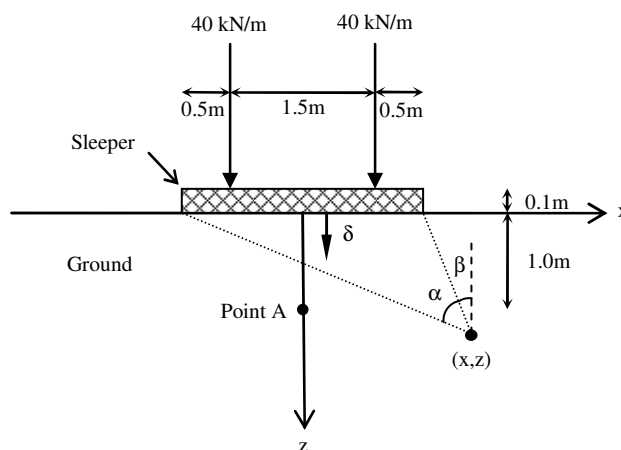
8.2.1 Analytical Model

The analytical model is intended for use by NR Maintenance Engineers, NR Permanent Way Engineers and NR Route Geotechnical Engineers (and their Consultants) as a simple strategic and tactical tool for use in design and decision-making. For this reason, the analytical model is required to be uncomplicated, yet robust, despite the complexities of the problem in reality.

The proposed preliminary analytical model is a modification of the Mobilisable Strength Design (MSD) method reported in Osman & Bolton (2005). The MSD method links the soil strength needed to maintain the stability of the soil structure to its displacement, by means of an appropriate stress-strain curve and a suitable deformation mechanism. It was first introduced for embedded retaining walls by Bolton & Powrie (1988) and subsequently developed for other structures by O'Rourke (1993) and Osman & Bolton (2005). Further details of the MSD method are contained in document 267641/TPN/FNG/001.

At this early stage of the research project, the preliminary analytical model considered two infinite vertical line loads on the surface of a semi-infinite soil mass, as illustrated in Figure 8.7. The railway embankment itself was excluded at this stage for both simplicity and ease of evaluation. The two infinite vertical line loads represent the rails; 40kN/m is equivalent to a 225kN axle loading. Although in reality the soil mass consists of ballast, sub-ballast, clay fill and subgrade which are non-elastic, non-homogeneous and non-isotropic; the semi-infinite soil mass assumed an elastic, homogeneous and isotropic medium to allow the use of the Boussinesq solution for calculating stresses within the soil. The calculated stress is then used to compute the resulting displacement of the soil mass with the help of a soil stress-strain curve from an undrained triaxial compression test on an appropriate sample of embankment clay fill.

Figure 8.7: Schematic Illustration of Preliminary Analytical Model.

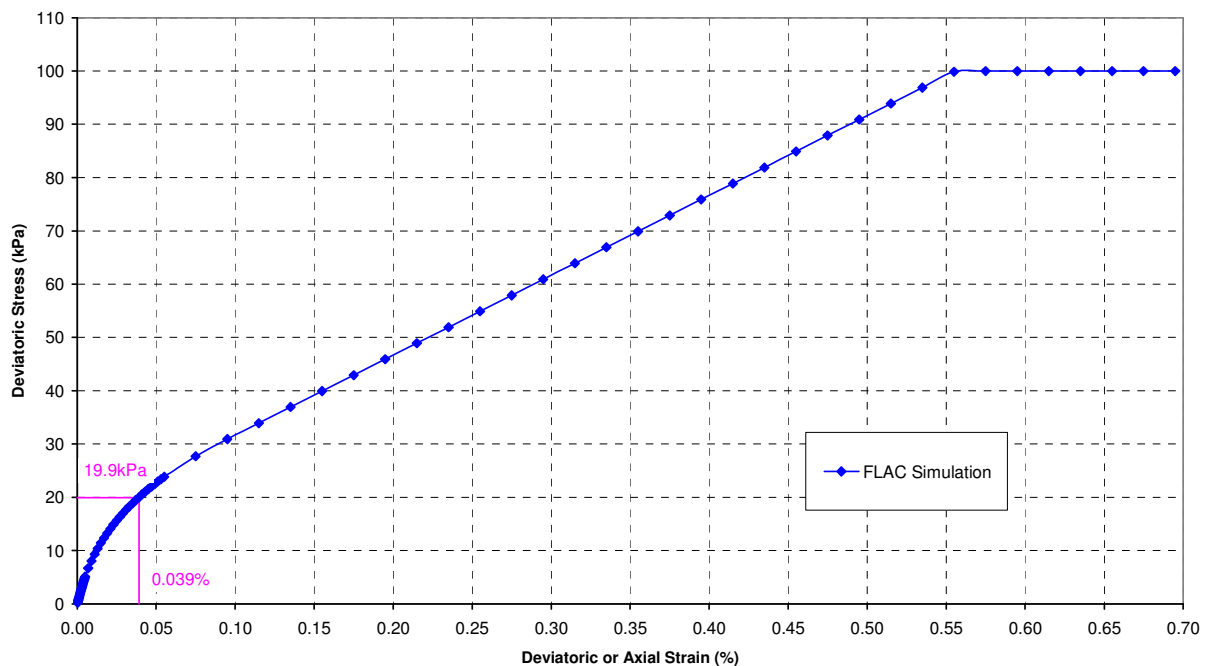


8.2.2 Input Parameters

Owing to the assumptions and simplifications made in the simulation of the problem, the input parameters are straightforward and easily obtained:

- Railway traffic loading (assumed to be 40kN/m per track, see Section 8.1.2.1);
- Distance between the rails (assumed to be 1.5m);
- Sleeper dimensions (assumed to be 2.5m long and 0.1m thick);
- Depth of interest (assumed to be 1.0m below the sleeper, consistent with numerical modelling); and
- Stress-strain curve from numerical simulation of an undrained triaxial test for embankment clay fill (see Figure 8.8 for FLAC simulation of Charing Embankment clay fill sample).

Figure 8.8: FLAC Undrained Triaxial Test Simulation (Charing Embankment Clay Fill Sample).



8.2.3 Preliminary Analytical Modelling

The increase in both horizontal and vertical stresses due to two vertical line loads at Point A in Figure 8.7 can be calculated using the Boussinesq equations for distributed loading on an infinite strip:

$$\sigma_x = p/\pi[\alpha - \sin \alpha \cos(\alpha + 2\beta)] \quad (8.1)$$

$$\sigma_z = p/\pi[\alpha + \sin \alpha \cos(\alpha + 2\beta)] \quad (8.2)$$

where σ_x is the increase in horizontal stress;

σ_z is the increase in vertical stress;

p is the vertical load in kN/m^2 ; and

α, β are defined in Figure 8.7.

The assumption of a sleeper length of 2.5m gives $p=32\text{kN/m}^2$ (i.e. $2 \times 40 / 2.5$); substituting this value into Equations (8.1) and (8.2) above produces $\sigma_x=8.3\text{kPa}$ and $\sigma_z=28.2\text{kPa}$ at Point A. For simplicity, it is assumed that σ_x and σ_z represent the minor and major principal stresses respectively. This simplification allows the deviatoric stress at Point A to be easily determined by calculating the difference between the values of σ_x and σ_z . Thus, the deviatoric stress at Point A is 19.9kPa and from the soil stress-strain curve in Figure 8.8, the corresponding axial strain is 0.039%. The calculated deviatoric stress will be compared with the prediction from the numerical model in the following sub-section.

The MSD method proposed by Osman & Bolton (2005) is for use in the prediction of undrained settlement of shallow circular foundations on clay. They proposed the following relationship for calculating the settlement of a circular footing:

$$\delta = \varepsilon_s D / 1.35 \quad (8.3)$$

where δ is the footing settlement;

ε_s is the engineering shear strain which is equal to 1.5 times the axial strain; and

D is the diameter of the circular footing.

In order to use Equation (8.3) for the railway sleeper, first determine an equivalent diameter, D_e , assuming a circular shape for the sleeper:

$$\pi/4 D_e^2 = l \times w \quad (8.4)$$

where D_e is the equivalent diameter;

l is sleeper length (assumed to be 2.5m); and

w is the width of the sleeper (unit length to be consistent with line load).

For the case under consideration, the equivalent diameter is 1784mm. Substituting $D = 1784\text{mm}$ and $\varepsilon_s = 1.5 \times 0.00039$ into Equation (8.3) yields a sleeper settlement of 0.77mm. This settlement magnitude will be compared with the prediction from the numerical model in the following sub-section.

8.3 Comparison between Numerical and Analytical Modelling

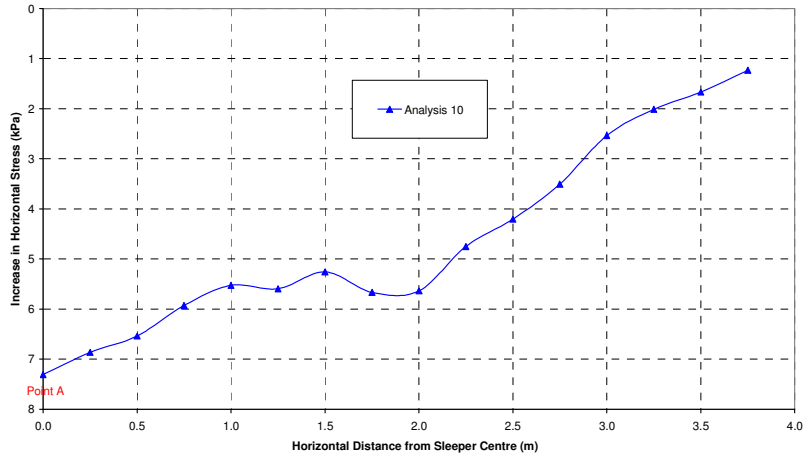
A numerical analysis, namely Analysis 10 (see Table 8.4), was undertaken to evaluate the preliminary analytical modelling by comparing the predictions between the two models. The configuration shown in Figure 8.7 was modelled in Analysis 10 with a uniformly distributed load of 32kN/m^2 instead of the two line loads of 40kN/m each, in accordance with the assumption made in the use of the Boussinesq equations

above. It should be noted that only half of the model was considered due to the symmetry of the loading condition.

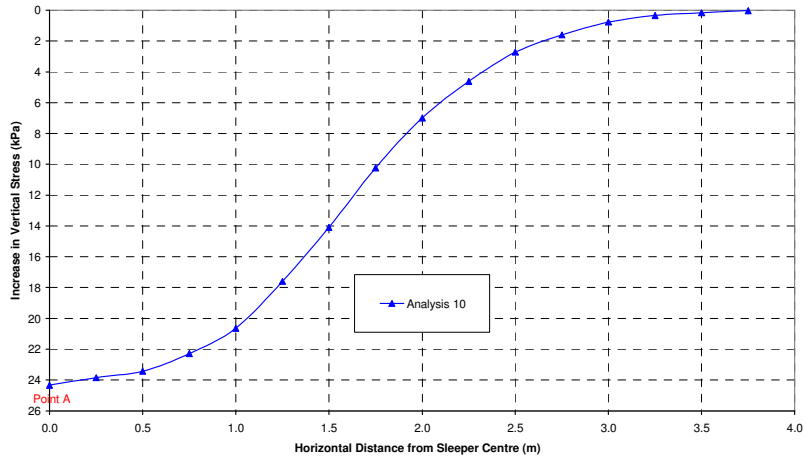
The results of Analysis 10, at 1.0m below the sleeper, are presented in Figure 8.9. As shown in Figures 8.9a and 8.9b for the increase in horizontal and vertical stresses respectively, stresses of 7.3kPa and 24.3kPa were predicted by the numerical model for the horizontal and vertical components respectively. In comparison with the stresses calculated using the Boussinesq equations in Section 8.2 above, the numerical model predictions were, unsurprisingly, of smaller magnitude due to load spread through the ballast, in particular the vertical component. Under the 40kN/m railway traffic loading, the sleeper was predicted by the numerical model to settle by 0.71mm, as shown in Figure 8.9c, compared with settlement of 0.77mm calculated by the analytical model in Section 8.2 above.

It should be noted that at this stage in the research project both the analytical and numerical models are preliminary in nature and are therefore inevitably relatively crude. These models are to be subject to refinement in the future when the laboratory test results and monitoring data become available. Nonetheless, the proposed preliminary analytical model has been shown to possess good potential for future development, in particular it has been demonstrated that the MSD method is capable of reproducing the sleeper settlement predicted by the numerical model with reasonable accuracy.

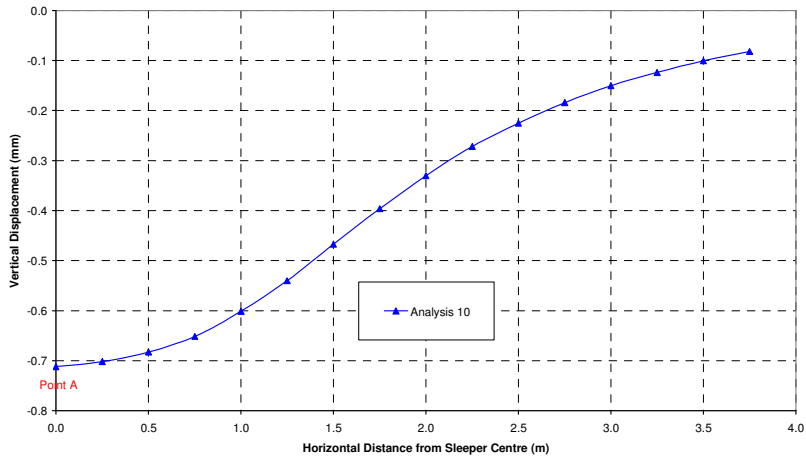
Figure 8.9: Railway Sleeper on Flat Ground (Analysis 10): (a) Horizontal Stress Increment;



(b) Vertical Stress Increment;



(c) Vertical Displacement.



9. Practical Analytical Tools

As part of this research project practical analytical models at both strategic and tactical levels are to be defined. Different parts of NR will require different types of output from such models, varying from strategic level prioritisation data, through to site-specific tactical level calculations. These models will be developed in the context of technical rigour and practicality for asset management.

The models will provide tools for the development of the business cases necessary to support proposals for renewal works, where embankment damage is predicted for increased railway traffic load. This will enable budgets for renewal works to be identified and targeted at improvement schemes where utilisation of the rail network can be maximised for increased traffic at a reasonable cost.

9.1 Strategic Level Model

A strategic level model, by its very nature, would be broad-based, relying on only two or three key input parameters, for example line speed, railway traffic loading and the plasticity of the embankment fill, with a damage classification related to the corresponding number of passes of a typical train configuration.

In the investigations to date, three principal factors have been identified as the causes of railway embankment serviceability limit state type damage, namely:

- Train axle load;
- Embankment clay fill plasticity, and
- Trackbed configuration.

Track alignment (i.e. whether the section of the railway line is straight or curved), embankment height, embankment side slope angle and embankment shoulder width, are regarded as lesser contributory factors. It is recognised that poor track drainage will weaken the performance of a railway embankment and high line speed may also lead to increased damage. The influence of these factors will need to be considered during the later stages of the project.

At this stage in the research project, only a very general strategic level model can be defined, based on the plasticity of the embankment fill, as highlighted in the Embankment Vulnerability Report. A risk ranking model based on simple input parameters related to the plasticity of the clay fill, should be tested for reliability and future scope of application, during subsequent stages of the research project.

In identifying railway embankment vulnerability, on the basis of the influence of the fill type, the following criteria were applied:

Low vulnerability (Green): high plasticity clay fills < 10% of route length;

Moderate vulnerability (Yellow): $10\% \leq$ high plasticity clay fills < 40% of route length;

High vulnerability (Amber): $40\% \leq$ high plasticity clay fills < 90% of route length;

Very high vulnerability (Red): high plasticity clay fills \geq 90% of route length.

The results of the railway embankment vulnerability classification according to this criteria, are presented graphically for each of the five Network Rail Territories, together with an enlargement of the London area, in drawing nos. 267641/023 to 028, which are reproduced in Appendix B.

9.2 Tactical Level Model

A tactical level model will be a site-specific model based on, amongst other factors, the pre-existing ground conditions at the site, and the proposed train axle loading.

Some initial calculations have been presented employing the Mobilisable Strength Design method (see Section 8.2). This simple model has been compared to the non-linear numerical model employed in Section 8.1; relatively good agreement is noted between the different model predictions.

However, this model on its own, will not be sufficient as a tactical level tool; consideration will have to be given to the development of, amongst other things, shape factors for incorporation in the model. In addition, it is proposed to investigate integration of this model with the empirical model previously proposed by Li & Selig (1996).

Further development through consideration of the impact of the ballast thickness, track alignment and hard/soft spots, will be required in subsequent phases of the research project.

10. Conclusions

This report summarises the work carried out under this stage of the research project RSSB1386 (revised), The effects of railway traffic loading on embankment stability, as amended by the Alternative Strategy proposal and addresses the following key tasks:

Literature Review (Task 1 Sub-task (vii) and Task 3 Sub-task (i))

The literature review provides an overview of ground behaviour during dynamic loading induced by the passage of a train. It has highlighted a number of knowledge gaps with respect to how dynamic train loading may influence the degradation of embankments, which are summarised in Table 3.1. Most research on the effects of train loading has considered straight track and at grade conditions; few studies have specifically covered embankment scenarios. In particular greater consideration is required of:

- The specific effect of embankment geometry on the distribution of train loadings within the ballast and subgrade.
- Greater consideration of the effects of track defects on the development of permanent deformations.
- Greater consideration of the effects of track geometry on the development of permanent deformations.
- Confirmation of the point at which dynamic analysis is required rather than pseudo-static approaches.
- Testing of materials representative of existing embankment fills present in this country.
- More detailed study of the effect of embankment-structure transitions. Evidence from maintenance programmes clearly shows this to be an important area with significantly increased track defects. However, despite this, there is surprisingly little research in this field.
- Long term monitoring to allow comparison of design methods against actual permanent deformations over large numbers of cycles.

The effect of embankment geometry on the distribution of train loadings within the ballast and subgrade, including the influence of embankment-structure transitions, should be considered through the application of numerical analysis in the first instance, subsequently supported by field monitoring. This project should aim to use clay fill obtained from existing UK railway embankments for laboratory testing, thus ensuring that the materials tested are representative of those encountered in the field. In conjunction with these activities, representative sites should be identified for instrumentation once the laboratory testing is complete; monitoring should continue into the medium term.

Embankment Failure Review (Task 1 Sub-task (ii)):

A review of embankment failures occurring across the NR network between August 2003 and December 2009 was carried out. The review considered the following aspects:

- Failure occurrence (both geographical and temporal);
- Underlying geology of the embankment and the composition of the slope;

- Embankment cross-section and track alignment;
- Weather and vegetation;
- Consequence of failure in terms of the impact on train operations, and
- Failure classification.

Three concentrations of failures are evident from the data: in the Western Territory along the Great Western Mainline route corridor; adjacent to Felixstowe, and to the south of London. Embankment failures were recorded in each year data was collected within the Great Western Mainline route corridor; adjacent to Felixstowe embankment failures were recorded in 2004, 2005 and 2006 only while failures were recorded to the south of London in 2006, 2007, 2008 and 2009.

The dataset was divided into ULS and SLS failures. The data indicates:

- a Winter peak in ULS failure activity
- a late Summer peak in SLS failure activity.

The Winter peak is consistent with the expectation that a high soil moisture content caused by increased rainfall will trigger embankment slips. The Summer peak is associated with desiccation due to drying in higher temperature conditions.

The number of annual failures was also investigated, to assess whether there is evidence of an increasing failure rate; the data remains inconclusive with regard to an overall trend of increasing failure rate with time. In general embankment failures occur predominantly within medium to high plasticity ground conditions.

As noted in the sub-task report there are many different types of potential failure mechanism and the likely influence of deformation as a result of train loading on these different failure mechanisms varies. It is considered that the 'failures' which are directly attributable to train loading (a fatigue type of mechanism) would not be reported in the current NR reporting system, where the emphasis is on the recording of classical ULS embankment failures. Furthermore, a prolonged time period would need to elapse before obvious signs of deterioration become apparent. Such SLS failures would typically manifest themselves as local track settlement and generally lead to the need for increased track maintenance. In order to assess the impact of such failures on the rail network, it is recommended that a detailed analysis of track maintenance records is carried out.

Changes in Heavy Traffic (Task 1 Sub-task (iii)):

This report presents the results of a review of railway traffic loading between 2006 and 2010 across the GB rail network.

The review concluded that there is no correlation evident between the incidence of large scale catastrophic embankment failure, and a change in railway traffic loading, on the basis of the data reviewed. This corroborates the conclusions of the Embankment Failure Review, that the failures recorded under current NR reporting procedures, are predominantly classical geotechnical "slip circle" type failures, rather than the fatigue type failure mechanism, which would be induced by train loading. Fatigue failure would manifest itself by increased maintenance and poor trackbed performance.

A wider assessment of the UK rail network, considering correlations between changes in railway traffic loading, and embankments identified as vulnerable to damage from railway traffic loading, has revealed several potential sites which may be suitable for instrumentation and monitoring, as well as those sites worthy of further investigation in relation to recent levels of necessary maintenance and/or poor trackbed performance. Two short lists have been compiled and are presented in Tables 5.1 and 5.2. The suitability of these sites for further study, will have to be discussed with NR and, in particular, NR's Maintenance Engineers. A review of the maintenance records for each potential instrumentation and monitoring site, should be undertaken before any final decision is made concerning the sites. Site access will also be an important factor to consider in the selection of sites for instrumentation and monitoring.

Embankment Vulnerability (Task 1 Sub-task (i)):

A preliminary assessment of the distribution of potentially load sensitive embankments across the UK railway network has been conducted on the basis of embankment fill properties and the results presented geographically for each of the five Network Rail Territories. On the basis of the initial vulnerability classification, about 1100km of track is classified as high, and 628km is classified as very high, with the majority (60-70%) being located in the South East Area Territory. This is consistent with expectations due to the nature of the geology across the network. It should be emphasised that this classification of vulnerability to railway traffic loading, is based solely on the anticipated clay fill plasticity index. Additional factors also need to be considered, such as axle loading, ballast thickness, track geometry, drainage, clay fill strength and local structural features (adjacent/underlying "hard spots", such as culverts and retaining walls for example, which may act as stress concentrators), in order to assess the risk of damage to railway traffic loading. Nevertheless, the above vulnerability classification provides an initial basis for planning purposes.

Instrumentation Design (Task 2 Sub-task (ii)):

A review has been carried out of:

- some of the instrumented embankment sites within the UK railway network, both in terms of earthwork movements and stability, and track and subgrade displacements/dynamic performance characteristics,
- the potential instrument types that may be used to monitor slope movements/assess stability, and track subgrade displacements/dynamic performance characteristics.

The advantages/disadvantages and relative costs of the various instrumentation options together with details of measurement range/quality and reading frequency, are tabulated in Appendix C. This information has been used to inform an outline instrumentation layout to measure both global slope movements/deformations and subgrade displacements/dynamic performance characteristics. The outline instrumentation layout includes sub-surface horizontal arrays of geophones with verification using video monitoring. It is recommended that the generic instrumentation layout proposed in Appendix C, is reviewed by NR and preliminary specific sites are selected for monitoring in later phases of the research project.

Preliminary Numerical Modelling (Task 1 Sub-tasks (iv) & (v), and Task 3 Sub-tasks (ii) & (iii))

A preliminary generic numerical model has been developed which simulates the response of the embankment fill (i.e. the changes in stress and strain) under railway traffic loading. This work has indicated that the embankment shoulder width (and hence overall embankment geometry) may not be a critical

parameter, provided the shoulder width is wider than a critical minimum value (circa 600mm); this assumption will be tested in the initial stages of the physical model testing during the next stage of the research project.

Preliminary Analytical Modelling (Task 3 Sub-task (iv))

Consideration has been given to the main requirements (inputs/outputs/functionality) of a practical analytical model, and the preliminary practical tools, which would need to be developed at both strategic and tactical levels.

General

Previous work to investigate the impact of railway traffic on earthworks, has focussed on the link between railway traffic damage, subgrade performance and the impact on track alignment. This work is also relevant to track supported by embankments.

Although the evidence of embankment failures around the UK railway network does not provide a link with failure due to increased railway traffic loading, the project has highlighted the potential mechanisms for failure. It is likely that the development of embankment failures induced by railway traffic loading will be a slow progressive process which will initially become evident through increasing frequency of track maintenance.

Without a reliable means of prediction, it is possible that works to strengthen the track sub-grade to carry increased railway traffic loading, will not address the root cause of the problem within the embankment below the track.

11. References

- Bolton, M. D. & Powrie, W. (1988). Behaviour of diaphragm walls in clay prior to collapse. *Géotechnique* 38 (2), 167-189.
- Brown, S. F. (1996). Soil mechanics in pavement engineering. *Géotechnique* 46 (3), 383-426.
- British Standard BS EN 15528:2008. Railway applications – Line categories for managing the interface between load limits of vehicles and infrastructure. 30 June 2008.
- Esveld, C. (2001). *Modern railway track*, MRT Productions, Zaltbommel, Netherlands.
- Glendinning S., Loveridge, F., Star-Keede R. E., Bransby, M. F. & Hughes, P. N. (2009). The Role of Vegetation in The Sustainability of Infrastructure Slopes *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 162 (2), 101-110.
- Jardine, R. J., Potts, D. M., Fourie, A. B. & Burland, J. B. (1986). Studies of the influence of non-linear stress-strain characteristics in soil structure interaction. *Géotechnique* 36 (3), 377-396.
- Li, D. & Selig, E. T. (1995). Evaluation of Railway Subgrade Problems, *Transportation Research Records*, 1489, 17-25.
- Li, D. & Selig, E. T. (1996). Cumulative plastic deformation for fine-grained subgrade soils. *Journal of Geotechnical Engineering*, 122(12), 1006-1013.
- Mott MacDonald (2008). *Seasonal Preparedness Earthworks (TSERV 567), Packages 3 & 4 Deep Dive Site Modelling, Charing Embankment Modelling and Monitoring Report*, 244568/01/A - December 2008.
- Mott MacDonald (2009). *Seasonal Preparedness Earthworks (TSERV 567), Packages 3 & 4 Deep Dive Site Modelling, Pound Green Embankment Modelling and Monitoring Report*, 244568/01/A - February 2009.
- Mott MacDonald (2010). *Embankment Failure Review, Unpublished report to the Rail Safety Standards Board*, 267641/TPN/FNG/003 - December 2010.
- O'Brien, A. (2007). Rehabilitation of Urban Railway Embankments-Investigation, Analysis and Stabilisation. *Proceedings of the 14th International Conference Soil Mechanics and Geotechnical Engineering, Madrid*, 1, 125-143.
- O'Brien, A. S., Ellis, E.A. & Russell, D. (2004). Old railway embankment clay fill- laboratory experiments, numerical modelling and field behaviour. *Proceedings. Advances in Geotechnical Engineering: The Skempton Conference*, London 2004, London: Thomas Telford. Vol. 2, 911-921.
- O'Rourke, T. D. (1993). Base stability and ground movement prediction for excavations in soft clay. *International Conference on Retaining Structures, Cambridge, UK*, Thomas Telford, London.
- Osman A. S. & Bolton, M. D. (2005). Simple plasticity-based prediction of the undrained settlement of shallow circular foundations on clay. *Géotechnique* 55 (6), 435-447.

Scott, J. M., Loveridge, F. & O'Brien, A.S. (2007). Influence of climate and vegetation on railway embankments. *Proceedings of the 14th International Conference Soil Mechanics and Geotechnical Engineering, Madrid, 2*, 659–664.

Selig, E. T. & Sluz, A. (1978). Ballast and subgrade response to train loads. *Transport Research Record*, 694, 53-60.

Selig, E. T. & Waters, J. M. (1994). *Track geotechnology and substructure management*, Thomas Telford, London.

Skempton, A.W. (1996). Embankments and cuttings on the early railway. *Construction History*, 11, 33-49.

Stewart, H. E. & Selig, E. T. (1982). Predicted and measured resilient response of track. *ASCE J Geotech Eng Div*, 108, 1423-1442.

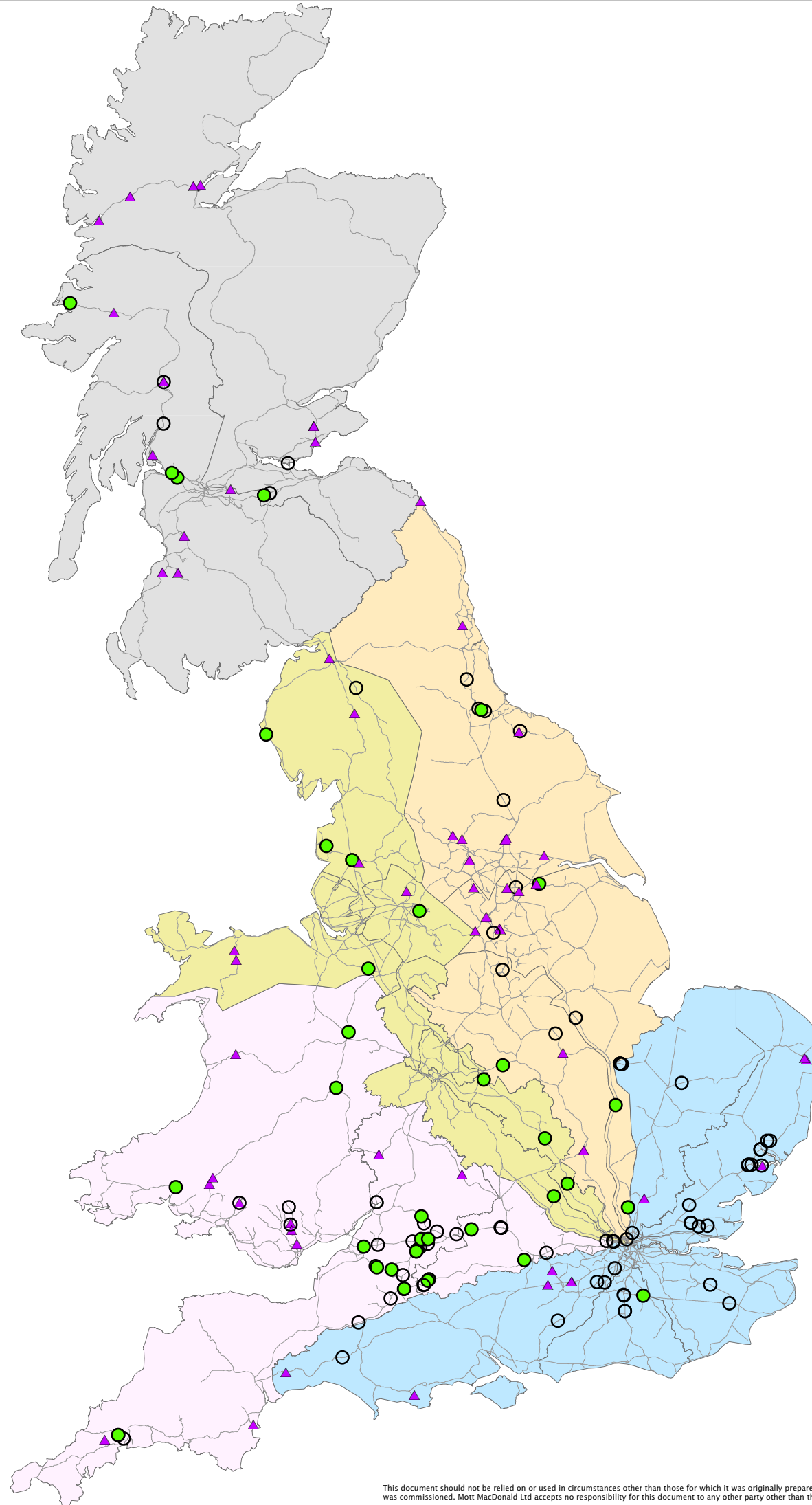
Vigianni, G. & Atkinson, J. H. (1995). Stiffness of fine-grained soil at very small strains. *Géotechnique* 45 (2), 249-265.

Yoo, T-S. & Selig, E. T (1979). Field observations of ballast and subgrade deformations in track. *Transport Research Record*, 733, 6-12.

Appendices

Appendix A. Embankment Failure Review	54
Appendix B. Embankment Vulnerability to Traffic Damage	55
Appendix C. Instrumentation Design	56
Appendix D. Preliminary Numerical Modelling	60

Appendix A. Embankment Failure Review



This document should not be relied on or used in circumstances other than those for which it was originally prepared and for which Mott MacDonald Ltd was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party other than the person by whom it was commissioned.

Notes

Key to symbols

Legend

Failure Summary

CLASSIFICATION

- Detailed failure report available
- No detailed failure report
- ▲ Scour or washout

Areas region

NAME

- London North Eastern
- London North Western
- Scotland
- South East
- Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



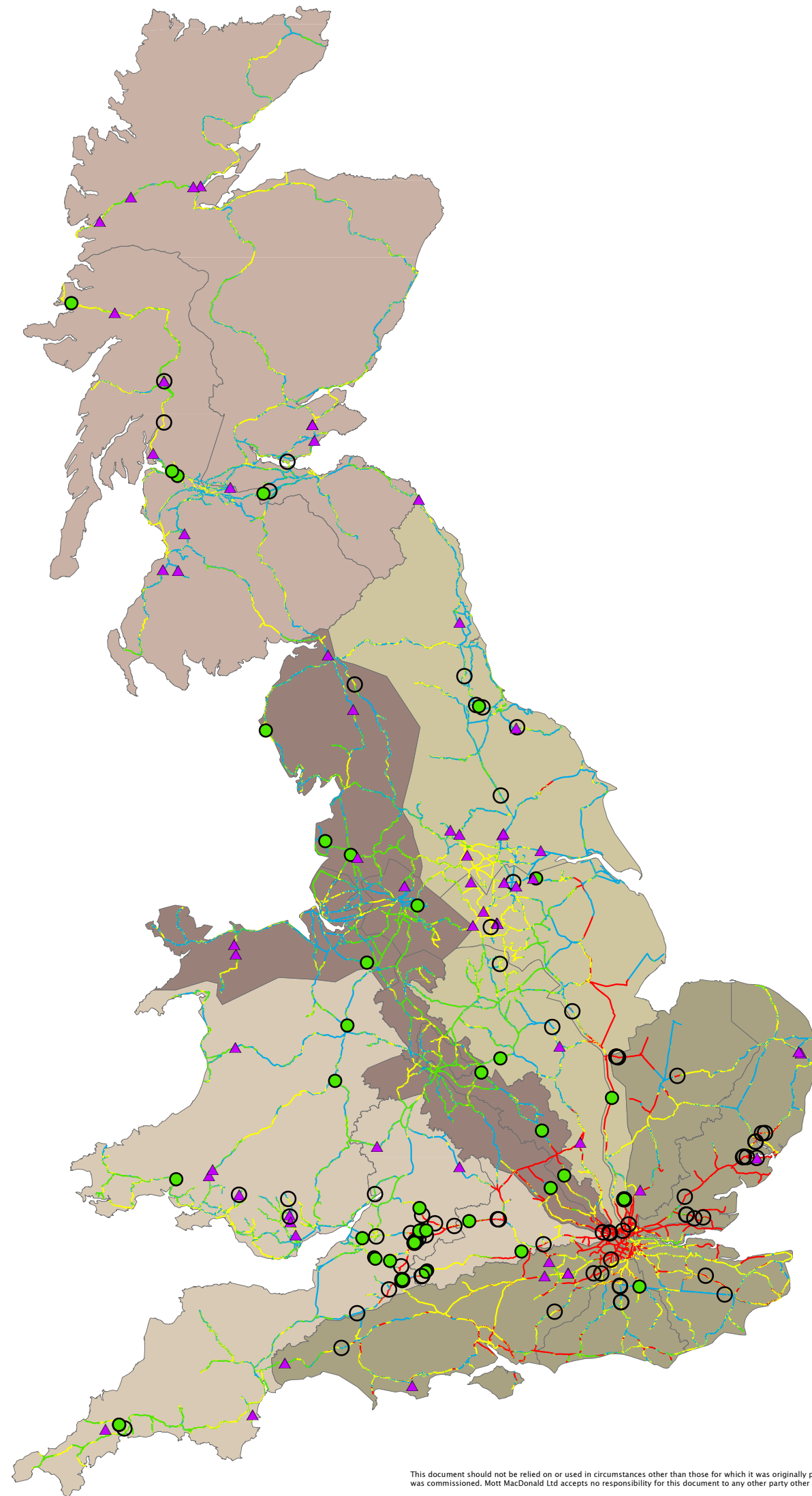
Mott MacDonald House
8-10 Sydenham Road
Croydon CR9 2EE
United Kingdom
Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

Client
Rail Safety Standards Board



Title
The effects of railway traffic on embankment stability (RSSB 1386 Revised)
Hazard Plans
Map of recorded embankment failures (2003 - 2009)

Designed	RH	Eng. Chk.	GRT
Drawn	GPR	Coordination	
Dwg. Chk.	RH	Approved	ASOB
Scale	1:3,332,942	Project	267641
		CAD file	
Drawing No	267641 / 001	Status	PRE
		Rev	P1



Notes

Key to symbols

Legend

Failure Summary

CLASSIFICATION

- Detailed failure report available
- No detailed failure report
- ▲ Scour or washout

Shrinkable Clay Soils Geo-hazard

Legend

- A Non-plastic (Granular soils and rock)
- B Low plasticity clays
- C Medium plasticity clays
- D High plasticity clays

Areas region

NAME

- London North Eastern
- London North Western
- Scotland
- South East
- Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



Mott MacDonald House
8-10 Sydenham Road
Croydon CR0 2EE
United Kingdom
Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

Client
Rail Safety Standards Board



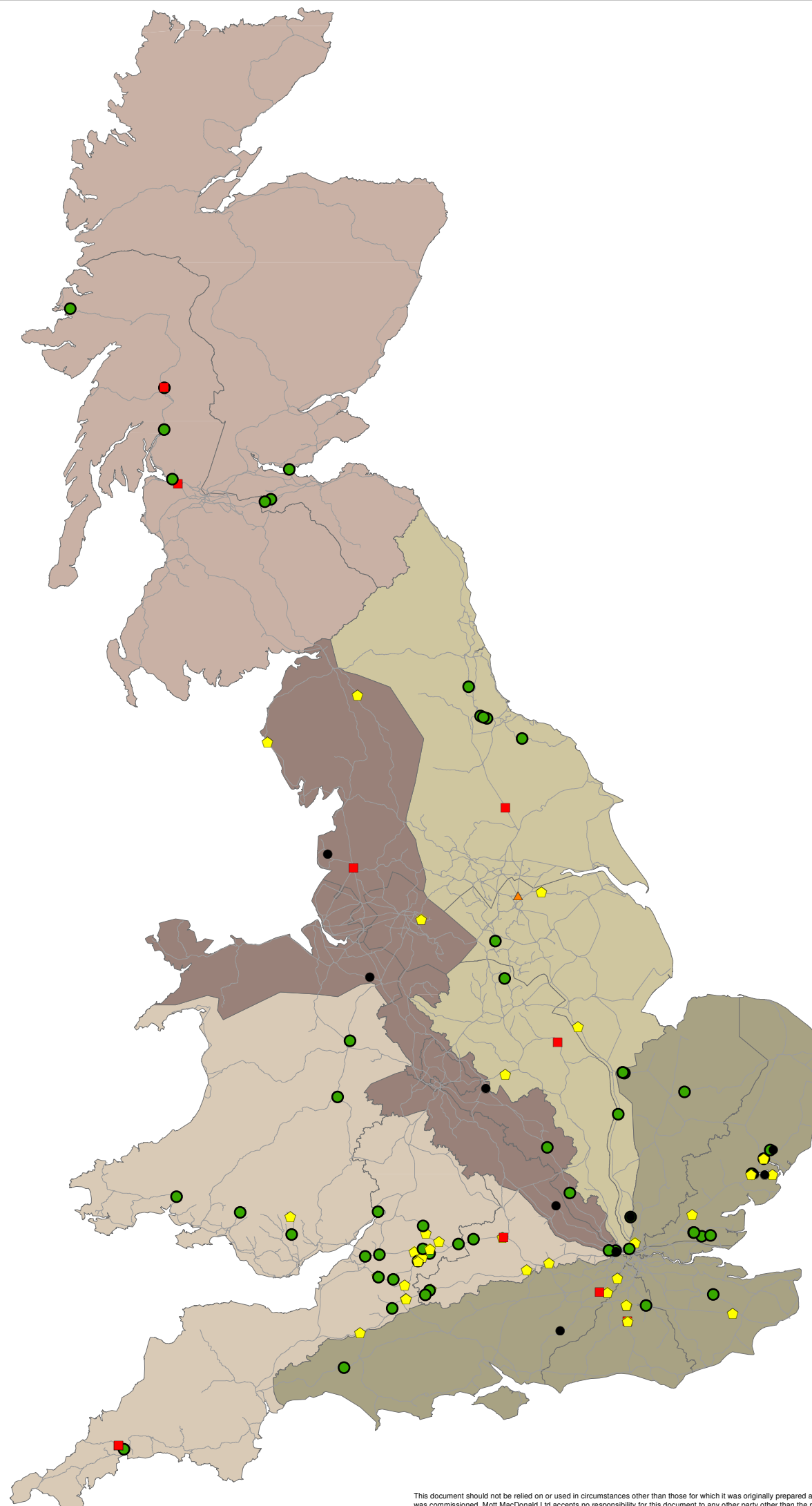
Title

The effects of railway traffic on embankment stability
(RSSB 1386 Revised)

Map of recorded embankment failures (2003-2009)
superimposed on line geology

Designed	RH	Eng. Chk.	CT
Drawn	GPR	Coordination	
Dwg. Chk.	RH	Approved	A&B
Scale	1:3,346,555	Project	267641
		CAD file	
Drawing No	267641 / 002	Status	PRE
		Rev	P1

This document should not be relied on or used in circumstances other than those for which it was originally prepared and for which Mott MacDonald Ltd was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party other than the person by whom it was commissioned.



Notes

Key to symbols

Legend

Impact on train operation

IMPACT

- Line closed
- ▲ Train derailed due to failure
- ◆ ESR - Emergency speed restriction imposed
- TSR - Temporary speed restriction imposed
- No speed restriction imposed

Areas region

NAME

- London North Eastern
- London North Western
- Scotland
- South East
- Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



Mott MacDonald House
8-10 Sydenham Road
Croydon CR9 2EE
United Kingdom
Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

Client
Rail Safety Standards Board



Title

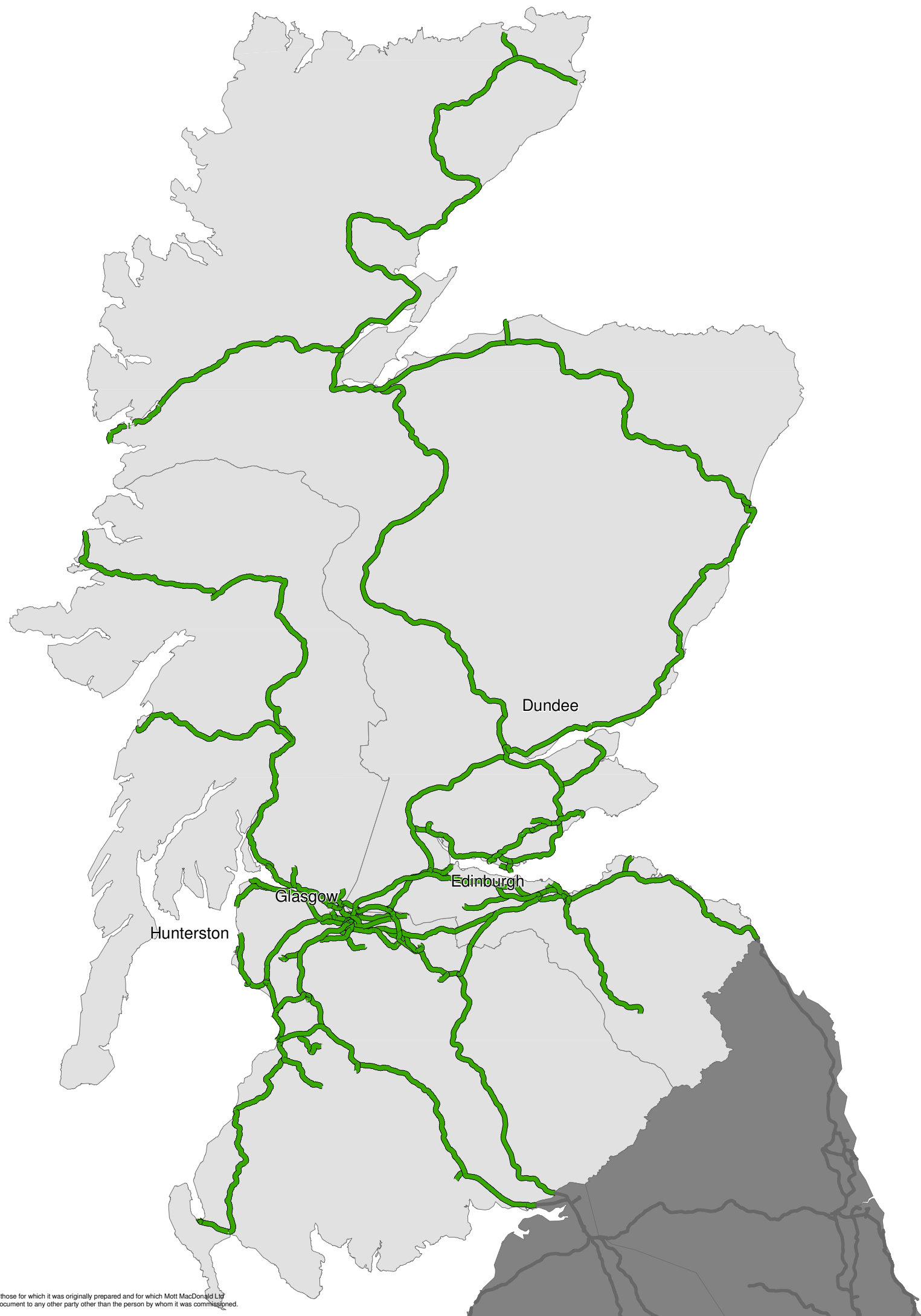
The effects of railway traffic on embankment stability
(RSSB 1386 Revised)

Map of recorded embankment failures (2003-2009)
impact on rail operation

Designed	RH	Eng. Chk.	GT
Drawn	GPR	Coordination	
Dwg. Chk.	RH	Approved	ASOB
Scale	1:3,346,555	Project	267641
		CAD file	
Drawing No	267641 / 010	Status	PRE
		Rev	P1

This document should not be relied on or used in circumstances other than those for which it was originally prepared and for which Mott MacDonald Ltd was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party other than the person by whom it was commissioned.

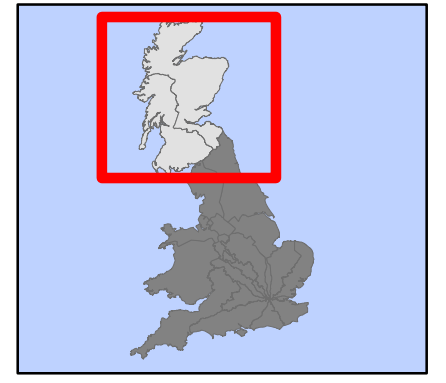
Appendix B. Embankment Vulnerability to Traffic Damage



Notes

Key to symbols

OVERVIEW MAP



Legend

- Railway Network**
- Other Regions
- Vulnerability**
- Low
 - Moderate
 - High
 - Very High
- Areas region**
- NAME**
- London North Eastern
 - London North Western
 - Scotland
 - South East
 - Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



Mott MacDonald House
8-10 Sydenham Road
Croydon CR9 2EE
United Kingdom
Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

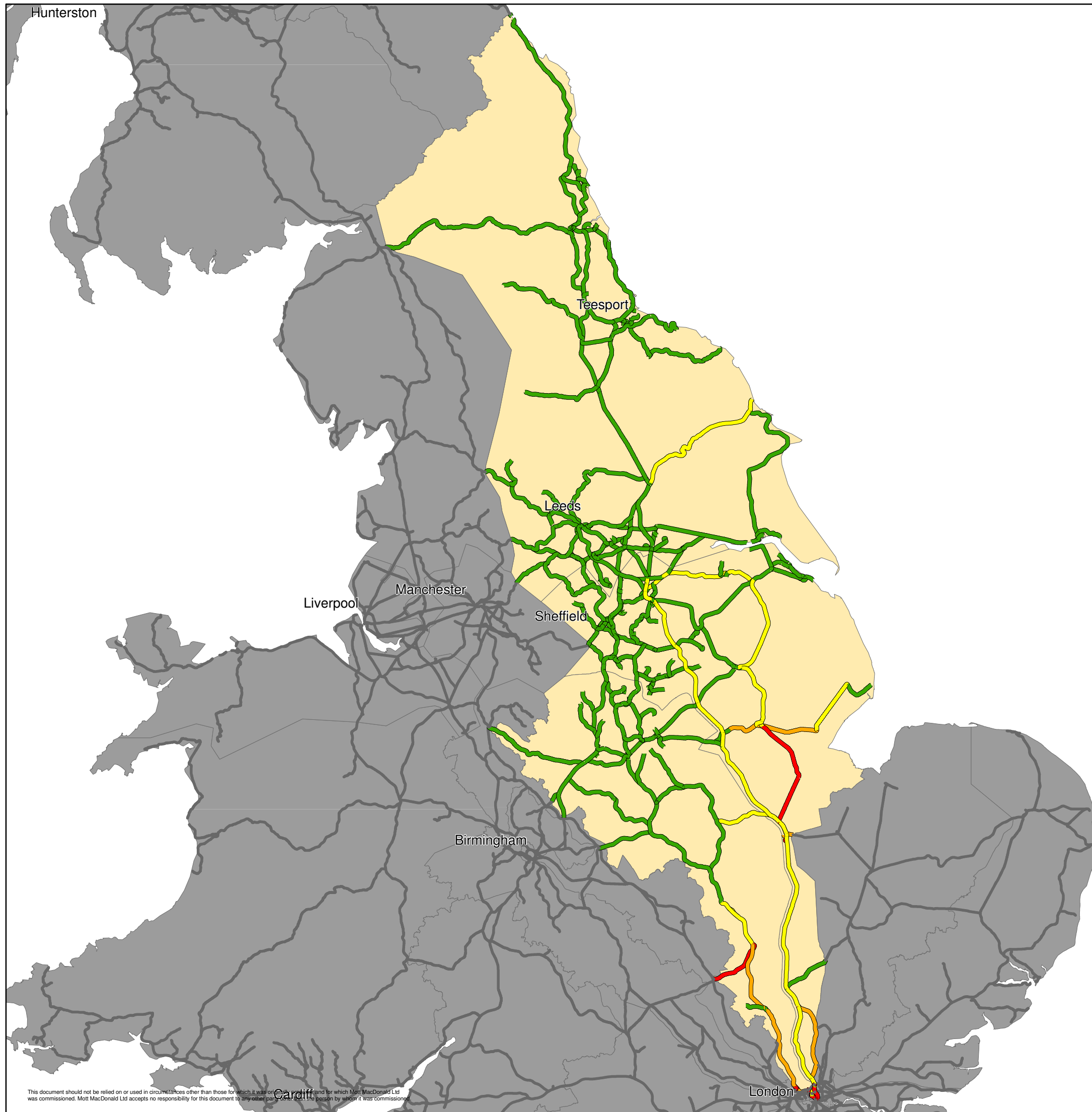
Client
Rail Safety Standards Board



Title
The effects of railway traffic on embankment stability
(RSSB 1386 Revised)
Potential Vulnerability
Scotland Territory

Designed		Eng. Chk.	GRT
Drawn	GPR	Coordination	
Dwg. Chk.	RH	Approved	GRT
Scale	Project 267641	Status	PRE
	CAD file		
Drawing No	267641 / 023	Rev	P1

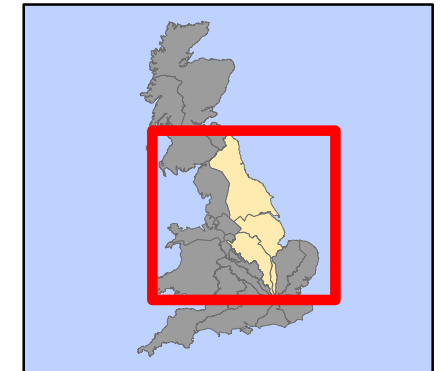
This document should not be relied on or used in circumstances other than those for which it was originally prepared and for which Mott MacDonald Ltd was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party other than the person by whom it was commissioned.



Notes

Key to symbols

OVERVIEW MAP



Legend

Railway Network

— Other regions

Vulnerability

— Low

— Moderate

— High

— Very High

Areas region

NAME

London North Eastern

London North Western

Scotland

South East

Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



Mott MacDonald House
8-10 Sydenham Road
Croydon CR9 2EE
United Kingdom
Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

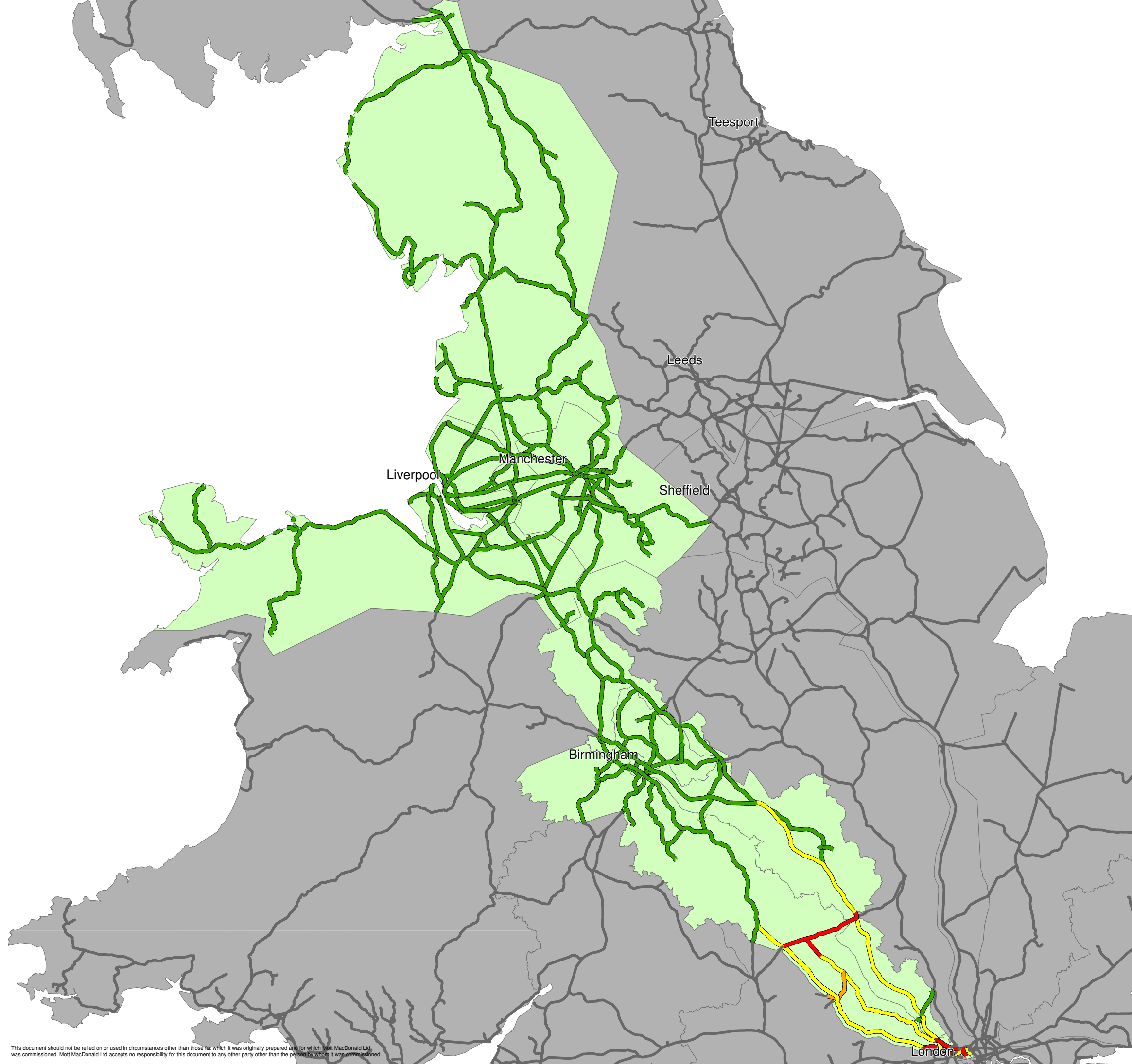
Client
Rail Safety Standards Board



Title
The effects of railway traffic on embankment stability
(RSSB 1386 Revised)
Potential vulnerability
North Eastern Territory

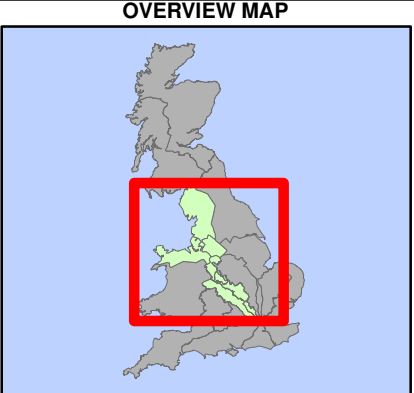
Designed		Eng. Chk.	GRT	
Drawn	GPR	Coordination		
Dwg. Chk.	RT	Approved	GRT	
Scale	Project	267641	Status	
	RT	CAD file	PRE	
Drawing No	267641 / 024	Rev	P1	

This document should not be relied on or used in circumstances other than those for which it was commissioned and for which Mott MacDonald Ltd was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party.



Notes

Key to symbols



Legend

Railway Network

— Other regions

Vulnerability

- Low
- Moderate
- High
- Very High

Areas region

- London North Eastern
- London North Western
- Scotland
- South East
- Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



Mott MacDonald House
8-10 Sydenham Road
Croydon CR9 2EE
United Kingdom
Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

Client
Rail Safety Standards Board

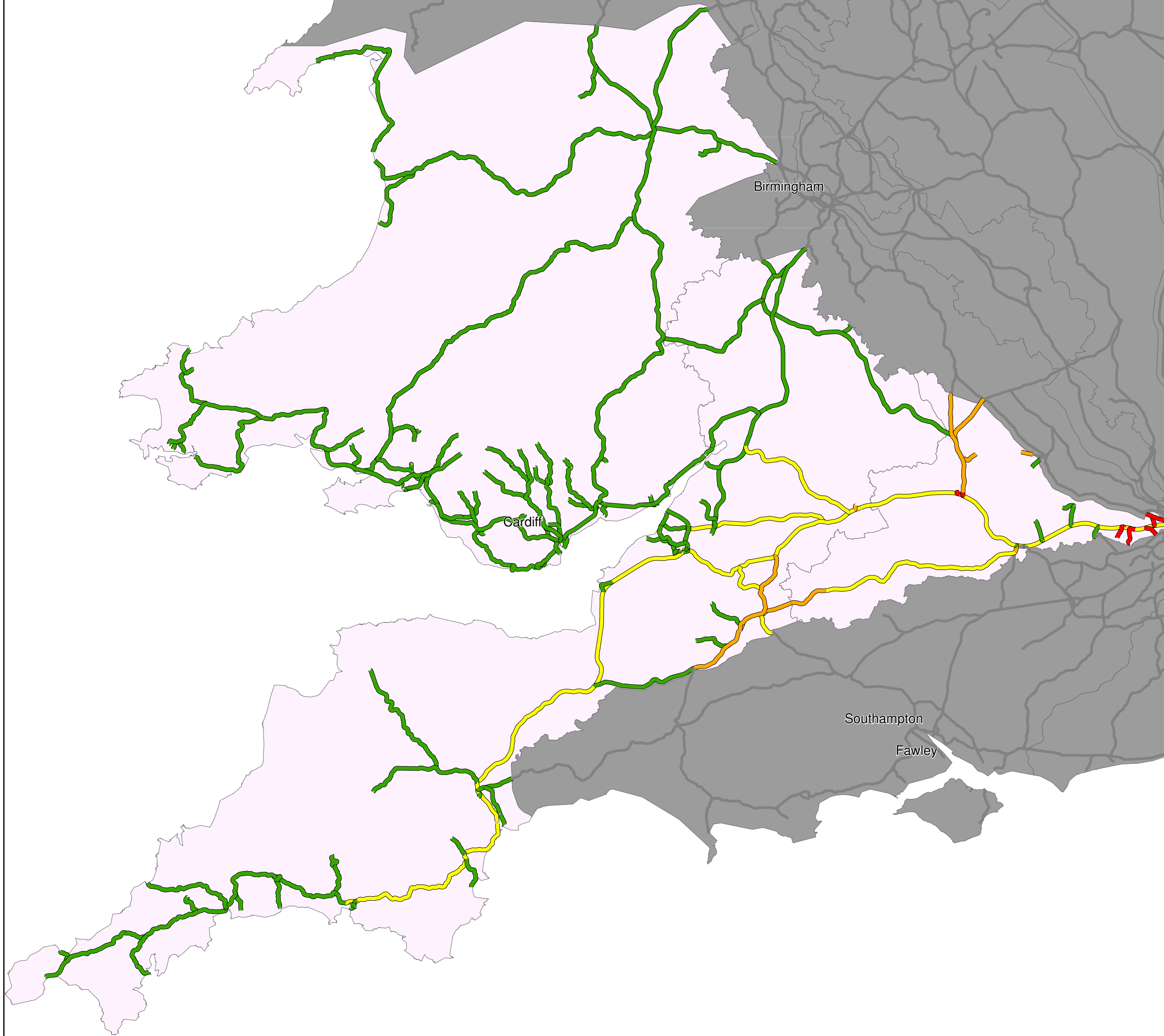


Title
The effects of railway traffic on embankment stability
(RSSB 1386 Revised)
Potential Vulnerability
North Western Territory

Designed		Eng. Chk.	GRT
Drawn	GPR	Coordination	
Dwg. Chk.	RH	Approved	GRT
Scale	Project 267641	Status	PRE
	CAD file		
Drawing No	267641 / 025	Rev	P1

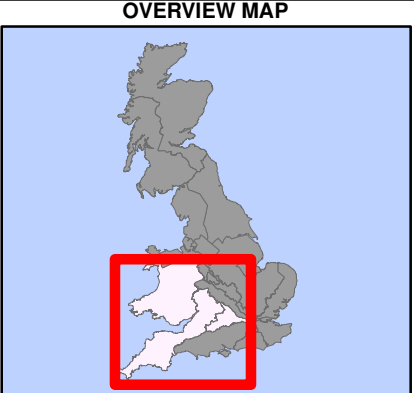
This document should not be relied on or used in circumstances other than those for which it was originally prepared and for which Mott MacDonald Ltd. was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party other than the person by whom it was commissioned.

DRAFT



Notes

Key to symbols



Legend

Railway Network

— Other Regions

Vulnerability

- Low
- Moderate
- High
- Very High

Areas region

NAME

- London North Eastern
- London North Western
- Scotland
- South East
- Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



Mott MacDonald House
8-10 Sydenham Road
Croydon CR9 2EE
United Kingdom
Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

Client
Rail Safety Standards Board

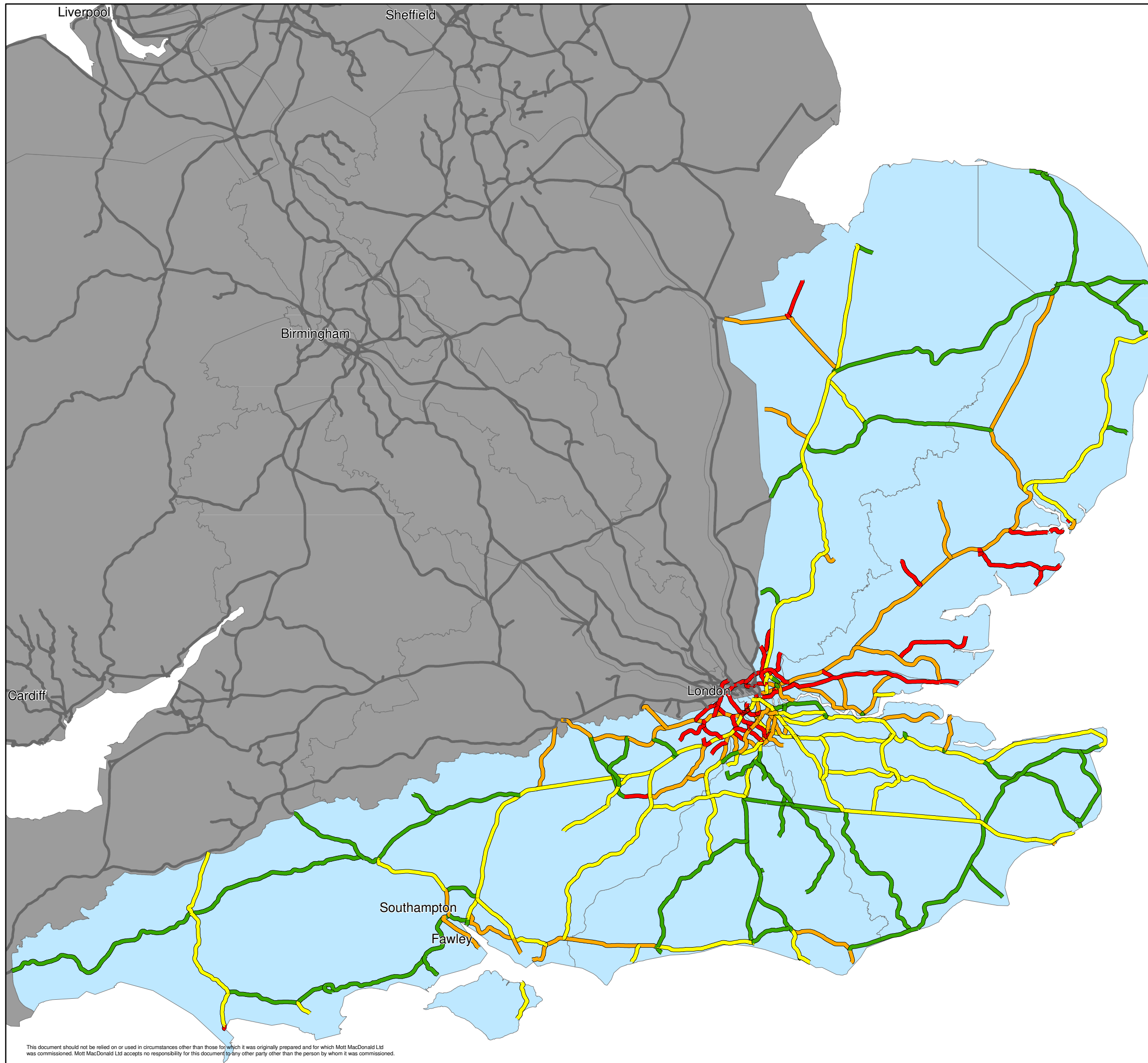


Title
The effects of railway traffic on embankment stability
(RSSB 1386 Revised)
Potential Vulnerability
Western Territory

Designed		Eng. Chk.	GRT
Drawn	GPR	Coordination	
Dwg. Chk.	RH	Approved	GRT
Scale	Project 267641	Status	PRE
	CAD file		
Drawing No	267641 / 026	Rev	P1

This document should not be relied on or used in circumstances other than those for which it was originally prepared and for which Mott MacDonald Ltd was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party other than the person by whom it was commissioned.

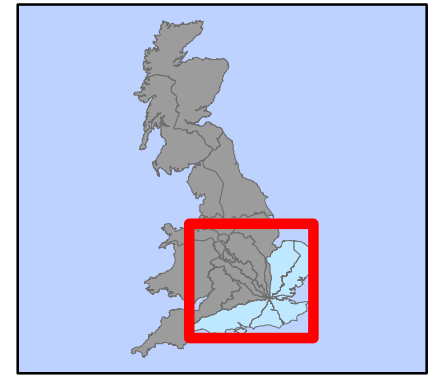
DRAFT



Notes

Key to symbols

OVERVIEW MAP



Legend

Railway Network

— Other regions

Vulnerability

- Low
- Moderate
- High
- Very High

Areas region

NAME

- London North Eastern
- London North Western
- Scotland
- South East
- Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



Mott MacDonald House
8-10 Sydenham Road
Croydon CR9 2EE
United Kingdom
Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

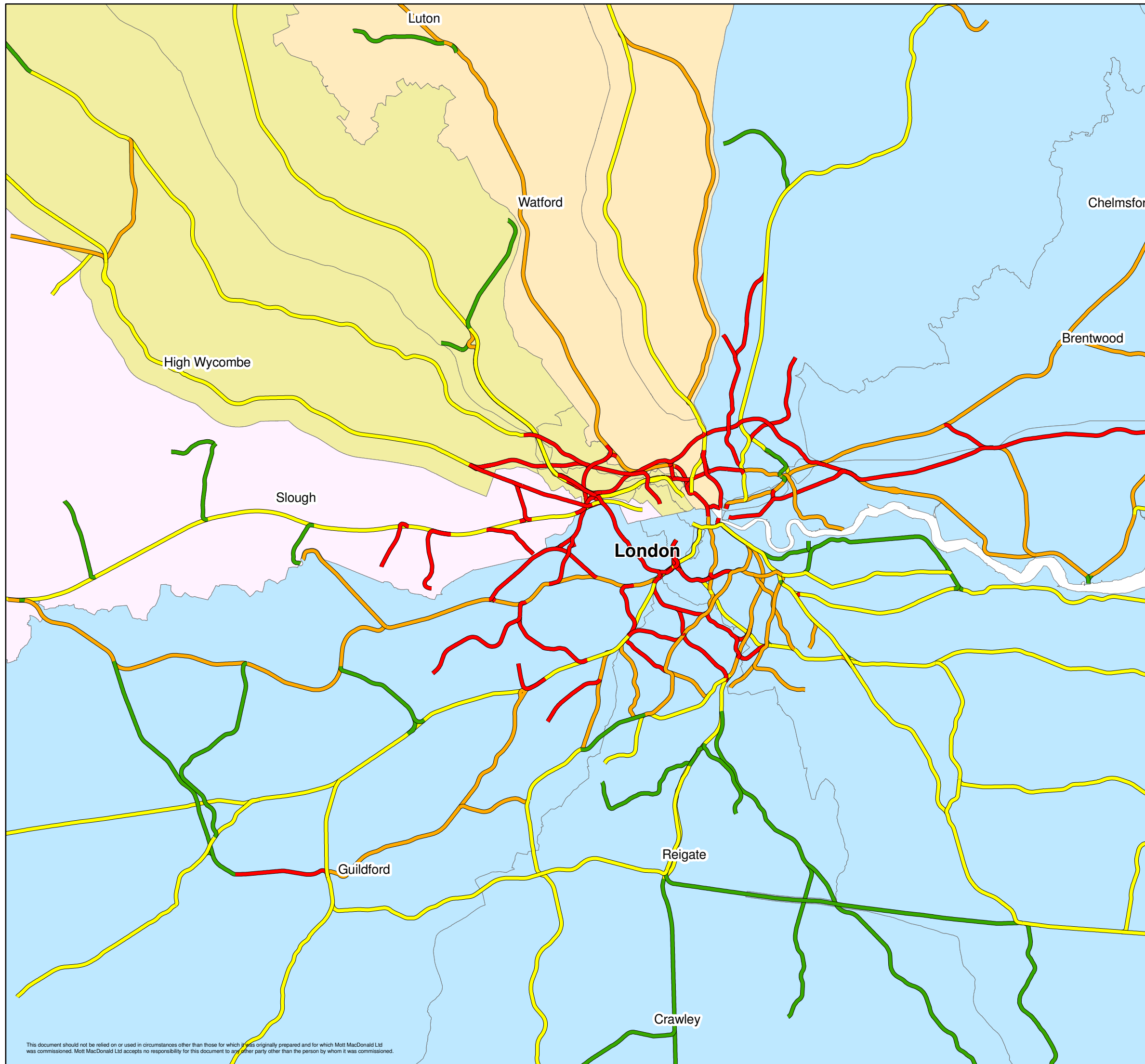
Client
Rail Safety Standards Board



Title
The effects of railway traffic on embankment stability
(RSSB 1386 Revised)
Potential Vulnerability
South Eastern Territory

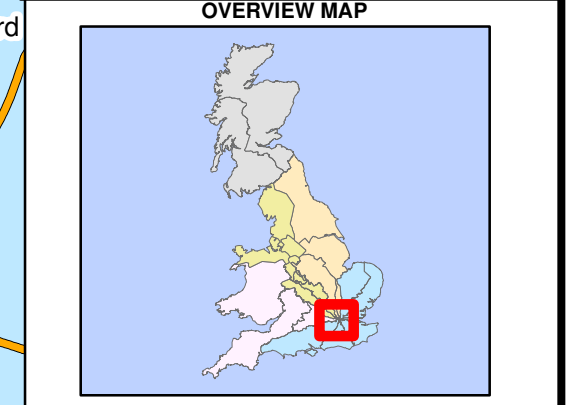
Designed		Eng. Chk.	GRT
Drawn	GPR	Coordination	
Dwg. Chk.	RH	Approved	GRT
Scale	Project 267641	Status	PRE
	CAD file		
Drawing No	267641 / 027	Rev	P1

This document should not be relied on or used in circumstances other than those for which it was originally prepared and for which Mott MacDonald Ltd was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party other than the person by whom it was commissioned.



Notes

Key to symbols



Legend

Railway Network Vulnerability

- Low
- Moderate
- High
- Very High

Areas region

NAME

- London North Eastern
- London North Western
- Scotland
- South East
- Western

Rev	Date	Drawn	Description	Ch'k'd	App'd



Mott MacDonald House
8-10 Sydenham Road
Croydon CR9 2EE
United Kingdom

Tel +44 (0)20 8774 2000
Fax +44 (0)20 8681 5706
Web www.mottmac.com

Client

Rail Safety Standards Board



Title

The effects of railway traffic on embankment stability
(RSSB 1386 Revised)

Potential Vulnerability
London

Designed		Eng. Chk.	GRT
Drawn	GPR	Coordination	
Dwg. Chk.	RH	Approved	GRT
Scale	Project 267641	Status	PRE
	CAD file		
Drawing No	267641 / 028	Rev	P1

This document should not be relied on or used in circumstances other than those for which it was originally prepared and for which Mott MacDonald Ltd was commissioned. Mott MacDonald Ltd accepts no responsibility for this document to any other party other than the person by whom it was commissioned.

Appendix C. Instrumentation Design

Table C.1: Instrumentation for Dynamic Displacement Measurement.

Probe type	Measurement (range/quality)	Reading frequency	Advantages/ disadvantages	Approved for NR use/ Supplier	Relative cost
Geophones	Direct measurement of velocity, integrated to get displacements. Accuracy of 0.07 mm at 1 Hz.	Typically 500Hz, using high speed datalogger during train passage. Datalogger connected and monitored during visits to site.	Advantages: High quality displacement traces – can be used vertically and horizontally, and buried beneath the ground. Disadvantages: do not function well at low train speeds (where axle spacing and speed give frequencies below 0.5 Hz).	University of Southampton has an established system, which is approved by NR.	Quick and easy to install onto track sleepers. Can be fairly rapidly installed into the base of vertical/horiz. holes for measurement of subgrade at depth. Requires visits by personnel to site during monitoring to operate datalogger etc.
Video displacement monitoring (Particle Imagery Velocimetry)	Direct measurement of displacement. Accuracy better than 0.1 mm at displacement frequencies of 5 Hz.	Uses high speed camera at 120 Hz. Monitored during visits to site.	Advantages: very accurate, including at low train speeds. Disadvantages: requires line of sight, remote camera needs to be set a fair distance from the targets to prevent interference from ground borne vibration.	University of Southampton. Use on High Speed 1 and West Coast Main Line.	Quick and easy to install onto track sleepers. Requires visits by personnel to site during monitoring to operate
Displacement monitoring using laser based system	Direct measurement of displacement. Confidence interval of ± 1.5 mm.	Uses high speed datalogger to log photosensors mounted on sleeper end. Monitored during visits to site.	Advantages: measures displacements at low train speeds. Disadvantages: requires line of sight, remote camera needs to be set a fair distance from the targets to prevent interference from ground borne vibration. Displacement measurement not as accurate as video monitoring above.	University of Belfast. Not aware of use on UK rail network.	Quick and easy to install onto track sleepers. Requires visits by personnel to site during monitoring to operate.
Multi-depth deflectometer	Direct measurement of displacement.	Uses high speed datalogger to log adjoined LVDT's linked to anchors attached to the wall of a vertical borehole. Displacements are measured relative to datum at depth end. Monitored during visits to site.	Advantages: accurate measurements at multiple depths in the subgrade. Can record long term, as well as dynamic displacement of the subgrade. Disadvantages: complex installation method which takes time.	Transnet (South Africa), other commercial variants are available – however not sure whether any have been used for this application. Not used on UK rail network to date.	A more complex installation, involving excavation and installation of LVDT's in stages using resin grout.

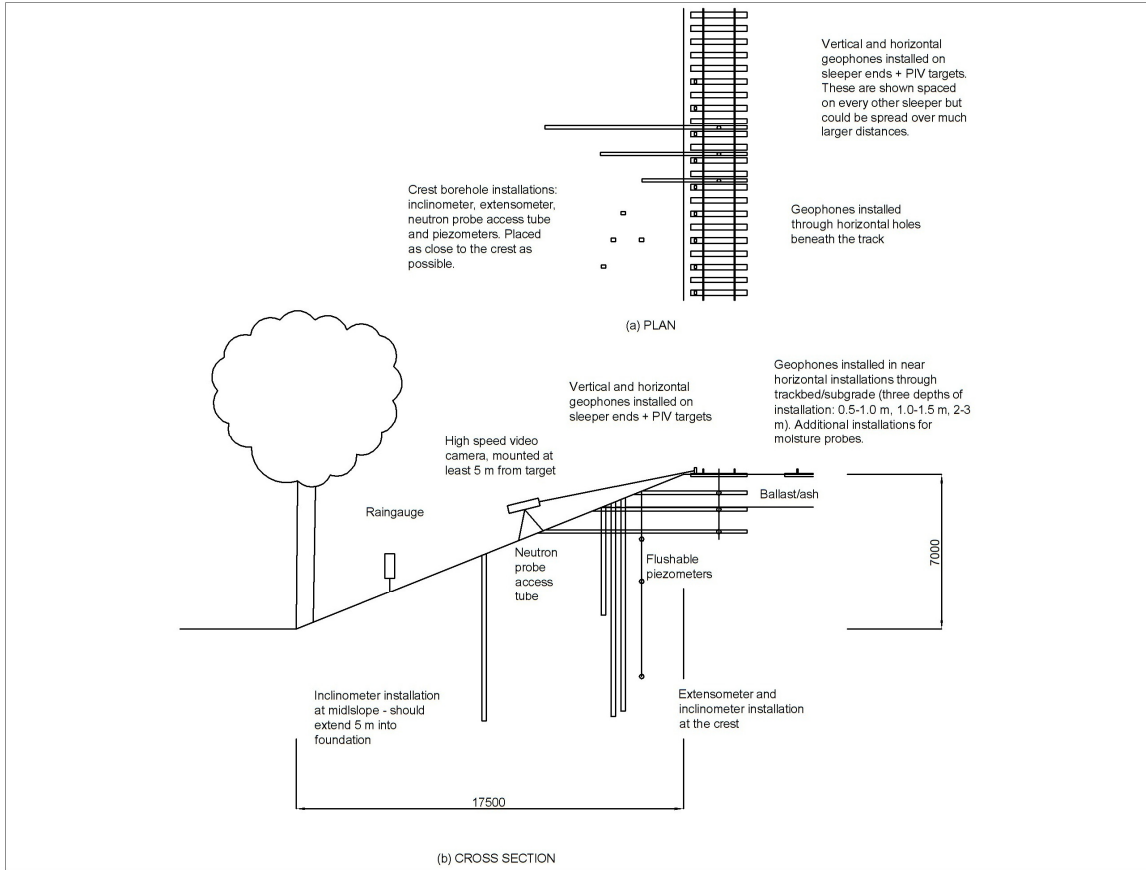
Table C.2: Instrumentation for Static Displacement Measurement.

Probe type	Measurement (range/quality)	Reading frequency	Advantages/ disadvantages	Approved for NR use/ Supplier	Relative cost
Inclinometer	Lateral displacement of ground with depth. Repeatability of better than ± 1.0 mm over a 15 m deep installation.	Tube installation that is read with probe during visits to site.	Advantages: good measurement accuracy if probe is used carefully.	Commonplace within geotechnical engineering – several suppliers.	Low installation cost compared with in-place below, visit to site required for manual readings.
In-place inclinometer	Lateral displacement of ground with depth.	Continuously datalogged – readings every few hours.	Advantages: continuous readings of lateral displacement. Disadvantages: high cost usually means reduced number of reading intervals with depth.	Commonplace within geotechnical engineering – several suppliers.	High installation cost compared with above, no visits to site required to read.
Magnet extensometer	Vertical displacement of the ground with depth. Depth of each magnet can be determined within 1-2 mm.	Manually read using a probe that detects depth of magnets.	Advantages: simple system, unlimited amount of vertical travel. Disadvantages: only read during visits to site.	Fairly commonplace – Geotechnical Observations have designed a system of spider magnets specifically for stiff clays.	Lower installation cost compared with multi-depth extensometer (below), visit to site required for manual readings.
Multi-depth or rod extensometer	Vertical displacement of the ground with depth. Accuracy likely to be better than magnet extensometer above.	Continuously datalogged – readings every few hours.	Advantages: continuous readings of vertical displacement. Disadvantages: typically have a limited travel of 50 mm or so, which can be exceeded by ground movements.	Commonplace within geotechnical engineering – numerous suppliers.	Higher installation cost compared with magnet extensometer above.
Precise levelling (using a digital level).	Measures vertical displacement.	Readings taken during visits to site.	Advantages: little data to process, fairly quick, can be done at night. Disadvantages: far fewer measurement points than LIDAR below, no horizontal displacements.	Commonplace within geotechnical engineering – several suppliers.	Simple, and will provide reliable data on vertical alignment of the track.
Geodetic surveying.	Uses theodolite to measure 3D position of survey points.	Readings taken during visits to site.	Advantages: will capture vertical and horizontal displacements. Disadvantages: previous experience shows that it requires a great deal of care and good quality survey points to achieve decent accuracy – track displacements may be ok but could be hard to pick up displacements of less than a few mm elsewhere.	Commonplace within geotechnical engineering – several suppliers.	Likely to be more expensive than levelling.
Terrestrial LIDAR (Light Distance And Ranging).	Laser reflects from ground surface to calculate a dense grid of three-dimensional points representing the topography.	Readings taken during visits to site. Reading accuracy ± 2 mm over shorter distances.	Advantages: captures topography over a wide area providing a lot of information. Disadvantages: relatively untried for displacement measurement of this type – more commonly used to obtain topography.	University of Southampton owns one, other suppliers. Previously used on NR (more commonly flown from a helicopter).	More specialist and likely to be more expensive than levelling. Some experimentation may be required to see if it is suitable for the application in hand.

Table C.3: Instrumentation for Measurement of Rainfall, Water Content and Pore Water Pressure.

Probe type	Measurement (range/quality)	Reading frequency	Advantages/disadvantages	Approved for NR use/Supplier	Relative cost
Raingauge.	Resolution of 0.2 mm of rainfall.	Continuously datalogged.	Advantages: provides site specific data. Disadvantages: has to be regularly maintained to get good readings.	Commonly available, including from Delta-T Devices, Cambridge.	More expensive than buying data from the Meteorological Office.
Time domain reflectometry water content sensor/ ThetaProbe.	Volumetric soil water content.	Continuously datalogged	Advantages: continuous readings. Disadvantages: small measurement zone, expensive if a large number of points are being measured.	Delta-T Devices, Cambridge.	Expensive for a large number of measurement points. Once installed, continuously datalogged.
Neutron probe.	Volumetric soil water content with depth.	Readings taken with measurement probe during visits to site.	Advantages: large measurement zone, full profile with depth can be obtained. Disadvantages: requires careful installation of access tubes. Is a fairly specialist device.	University of Southampton owns one. There are other suppliers, but these may not do rail work.	Installation of access tubes can be tricky. Visits to site required to take readings.
Basic vibrating wire flushable piezometer.	Pore water pressure/suction. Suction range depends on depth of instrument.	Continuously datalogged, although visits to site required to flush air from instruments.	Advantages: basic heavy-duty piezometer. Disadvantages: the longer the flushing tubes to the surface, the less suction can be measured.	Soil Instruments Ltd, Uckfield.	
GEO flushable piezometer.	Pore water pressure/suction. Range -90 kPa to 100 kPa pore pressure.	Continuously datalogged, although visits to site required to flush air from instruments.	Advantages: capable of reading to -90 kPa regardless of installation depth, probe can be removed from installation in the ground in the event of failure.	Geotechnical Observations Ltd, Egham, Surrey.	Slightly more expensive but technically a better product than basic vibrating wire piezometer. Now standard for clay structures where suction may be present.

Figure C.1: Typical Outline of Proposed Instrumentation for a Generic 7m High Embankment.



Appendix D. Preliminary Numerical Modelling

Most of the small strain non-linear stiffness models in the literature (e.g. Jardine et al., 1986) define the soil stiffness as a proportion of the mean effective stress at particular strain amplitudes from a range of non-linear parameters. The shape of the non-linear stiffness curve is generally derived from laboratory based advanced test data which is notoriously unreliable at small strains making the estimation of design values of small strain stiffness difficult. This, as well as the influence of sample disturbance, means that the non-linear stiffness curves derived from laboratory data, may be overly conservative. Hence, a new framework for deriving the non-linear stiffness has been developed based around the A* non-linear stiffness model (Eadington & O'Brien, in preparation).

The A* non-linear stiffness model defines the secant shear moduli, $G_{s,i\varepsilon}$, as a function of mean effective stress, p' , and axial strain, ε_a , (as measured in triaxial testing):

$$G_{s,i\varepsilon} = A^*_{i\varepsilon} p'^{0.6} \quad (D.1)$$

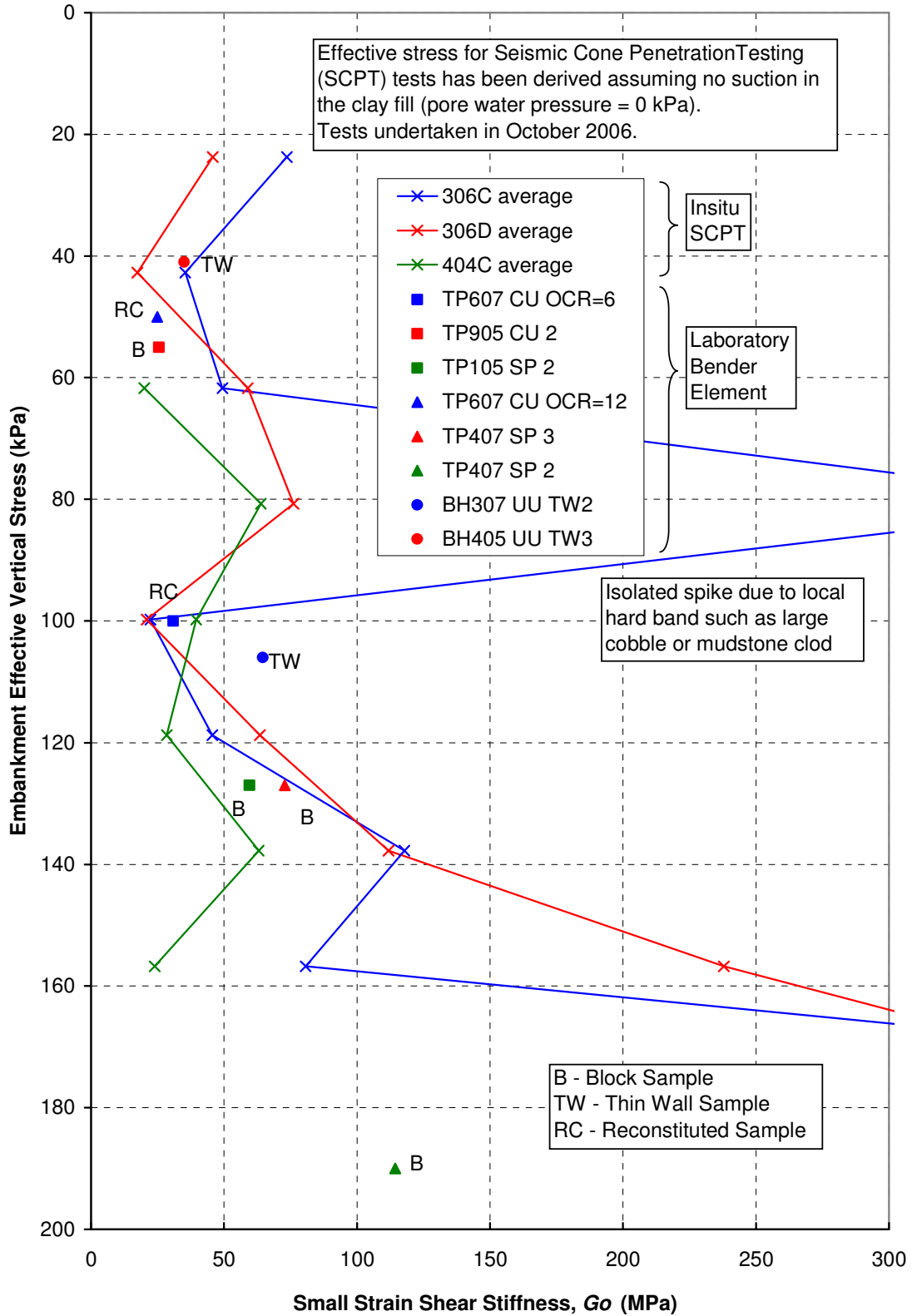
where $A^*_{i\varepsilon}$ is a function of ε_a

This equation for determining the secant shear stiffness has the advantage of being less dependent on the mean effective stress (due to raising p' to the power of 0.6) rather than the conventional equations which assume unity. The mean effective stress is difficult to predict due to problems estimating the insitu lateral earth pressure coefficient at rest, K_0 ; this uncertainty is reduced by defining the stiffness via Equation (D.1) above. The power of 0.6 is based on the work by Viggiani & Atkinson (1995); this value gives a good approximation to the test data from the Crossrail Project.

The A* methodology is based on using the soil shear stiffness at very small strains, G_o , as a reference point for assessing the variation of stiffness with depth, and variations with strain amplitude. In practice, G_o can be measured insitu in both the horizontal and vertical directions. This overcomes potential difficulties in using the laboratory data which are subject to inevitable sampling disturbance. In addition, robust empirical correlations can be used to derive the G_o values. These derived G_o values are to be compared with the G_o values measured in the laboratory (bender element tests) and in the field (self-boring pressuremeter tests) as well as the normalised non-linear stiffnesses measured in the laboratory based advanced triaxial tests.

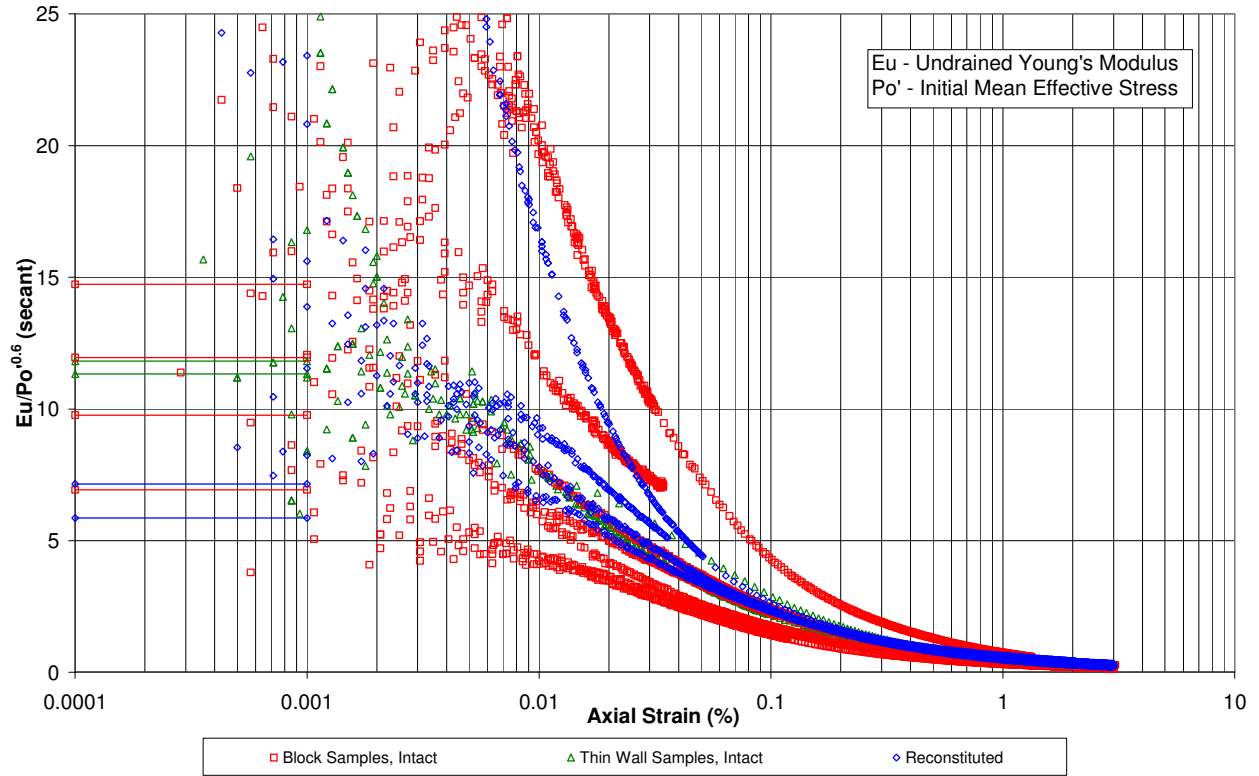
The A* parameters used in the preliminary numerical modelling were determined from the G_o values for the Charing Embankment clay fill obtained from both insitu Seismic Cone Penetration Testing and laboratory bender element testing (Mott MacDonald, 2008). The measured G_o values at various depths are shown in Figure D.1 as a function of the effective vertical stress within the embankment. In addition, the normalised non-linear stiffnesses measured in the laboratory based advanced triaxial tests presented in Figure D.2 were used in the determination of the stiffness degradation parameters.

Figure D.1: Measured Go Values of Charing Embankment Clay Fill.



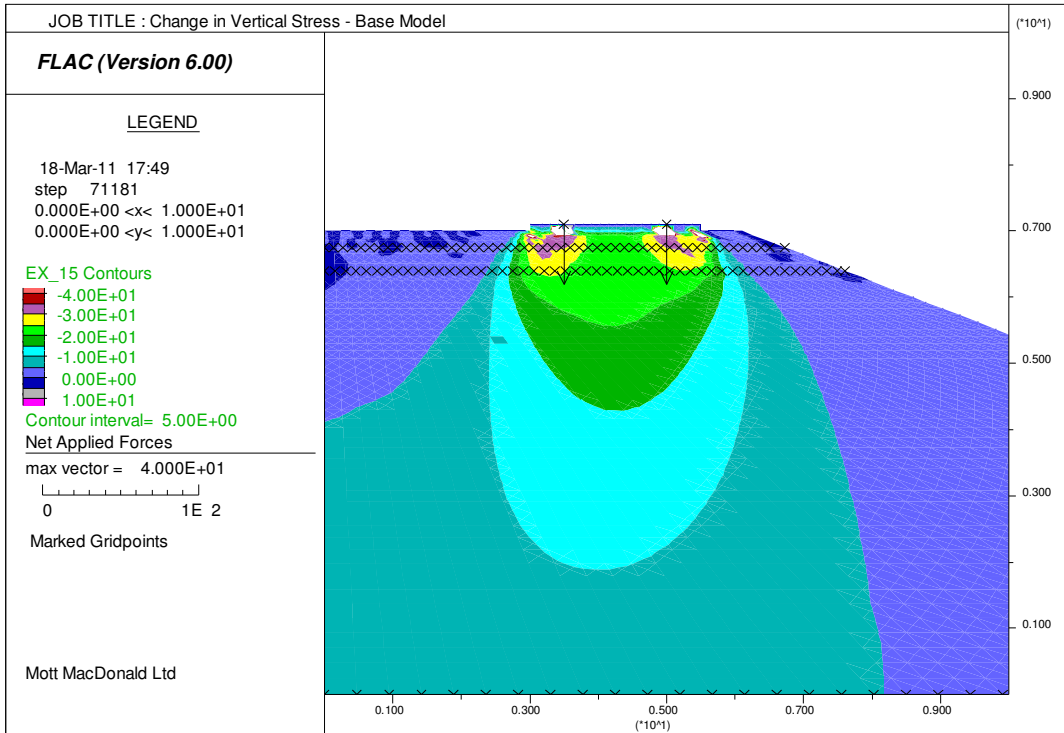
Source: After Mott MacDonald (2008)

Figure D.2: Normalised Young's Modulus Degradation Curves for Charing Embankment Clay Fill.



Source: After Mott MacDonald (2008)

Figure D.3: Numerical Analysis 1: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

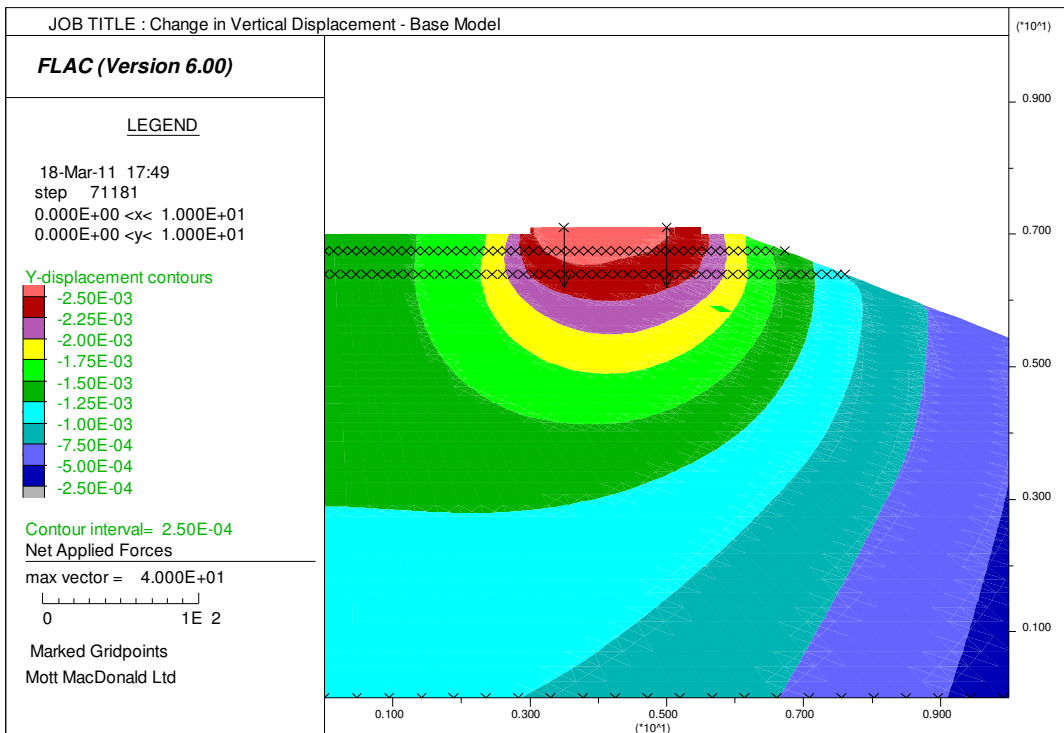
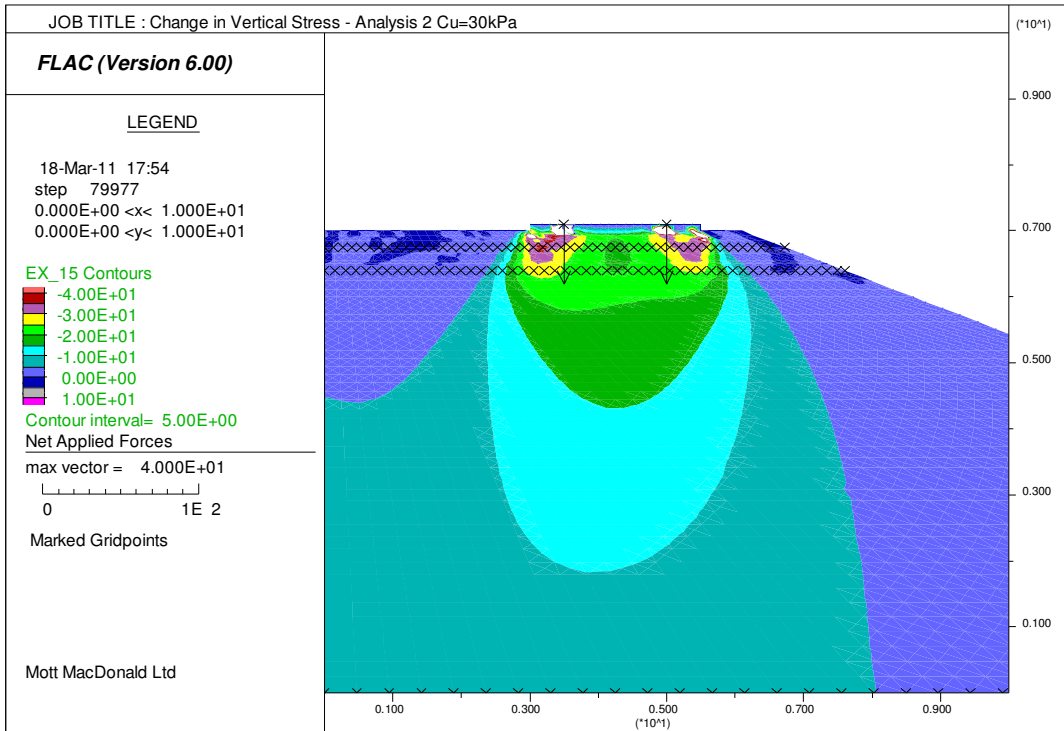


Figure D.4: Numerical Analysis 2: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

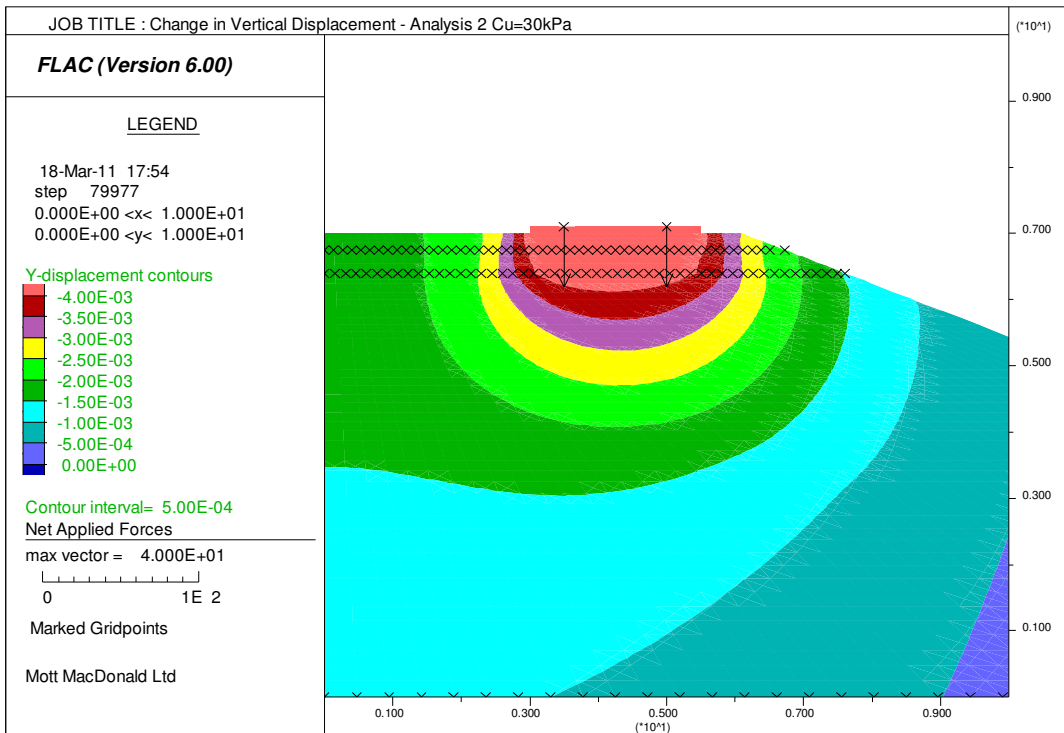
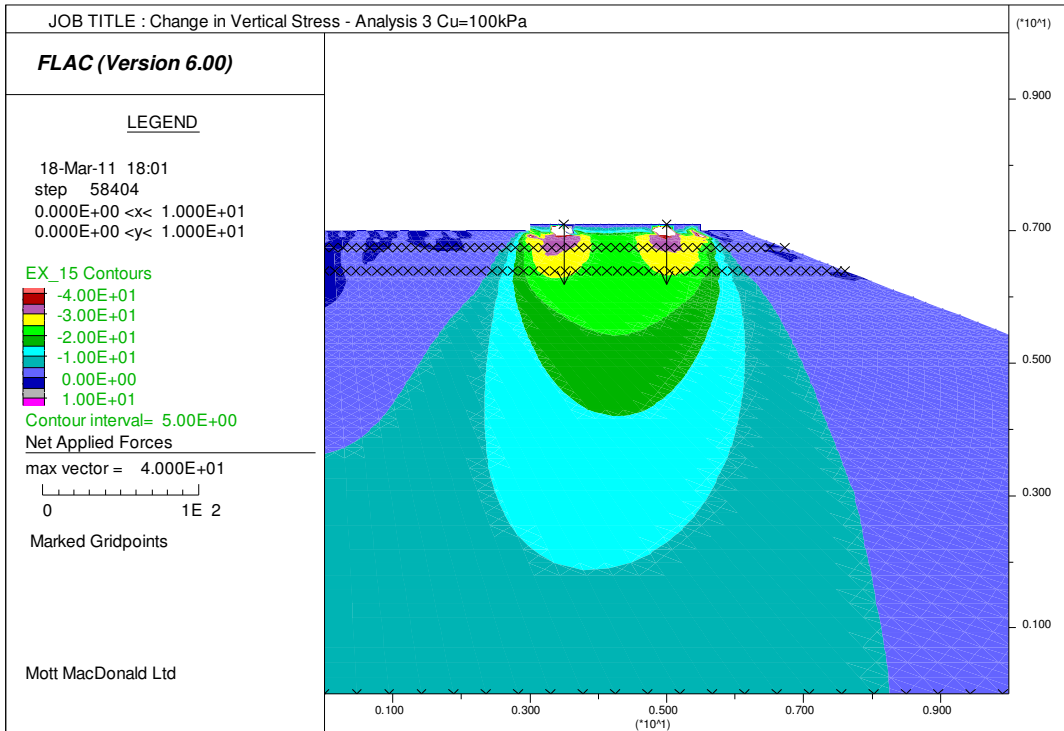


Figure D.5: Numerical Analysis 3: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

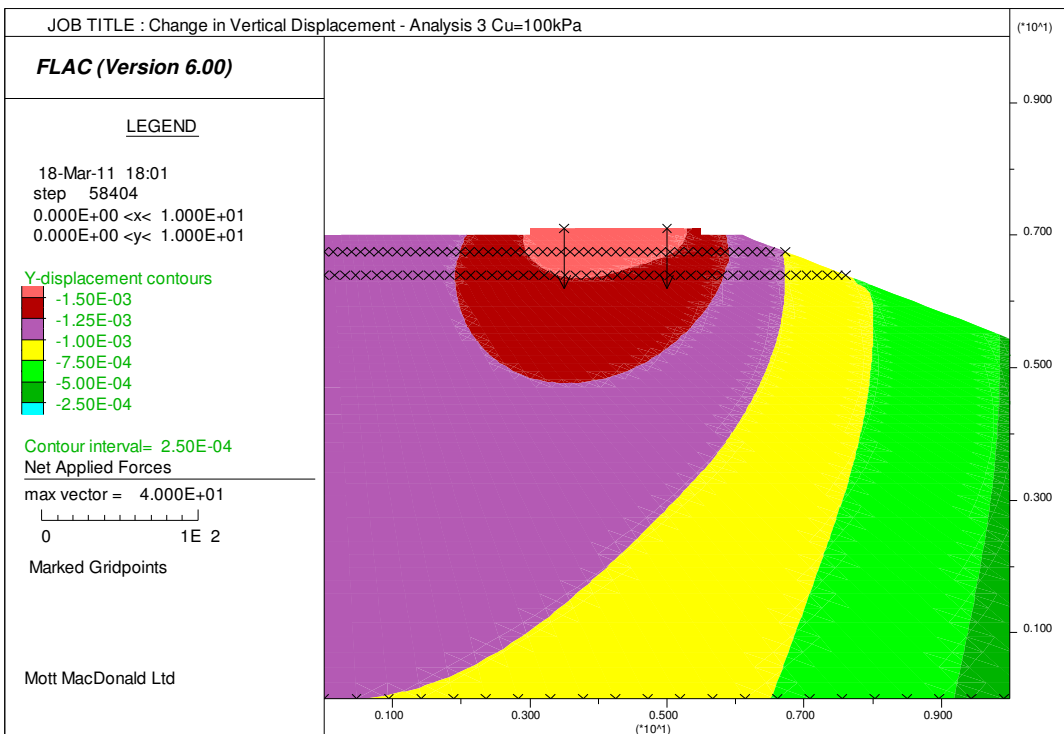
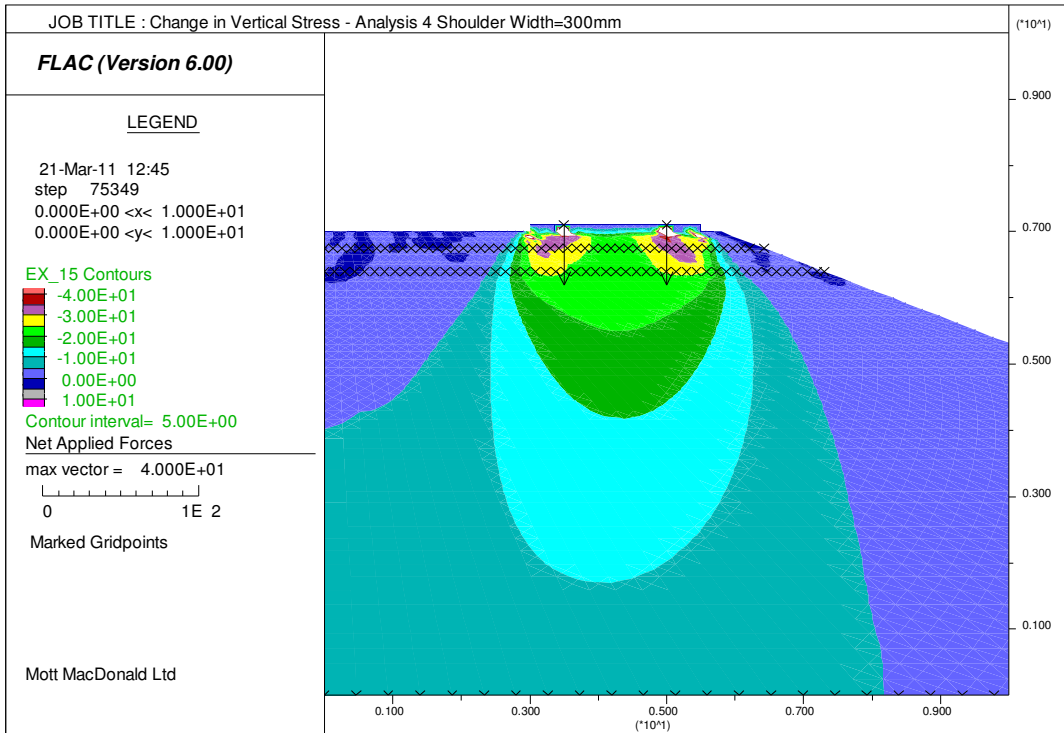


Figure D.6: Numerical Analysis 4: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

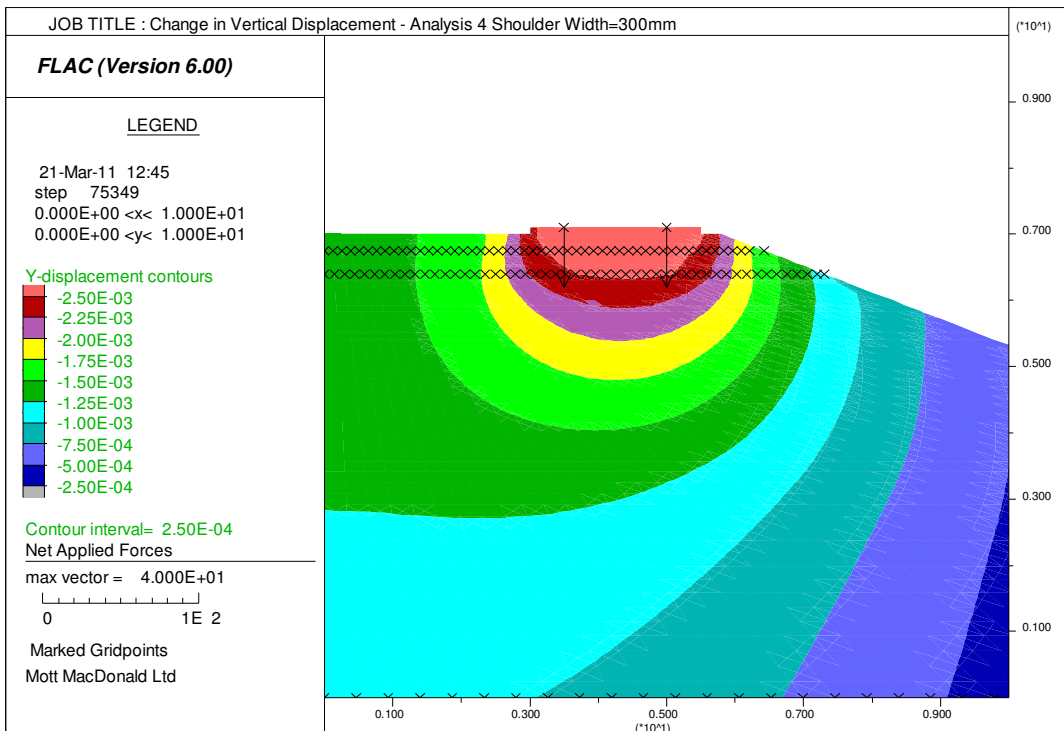
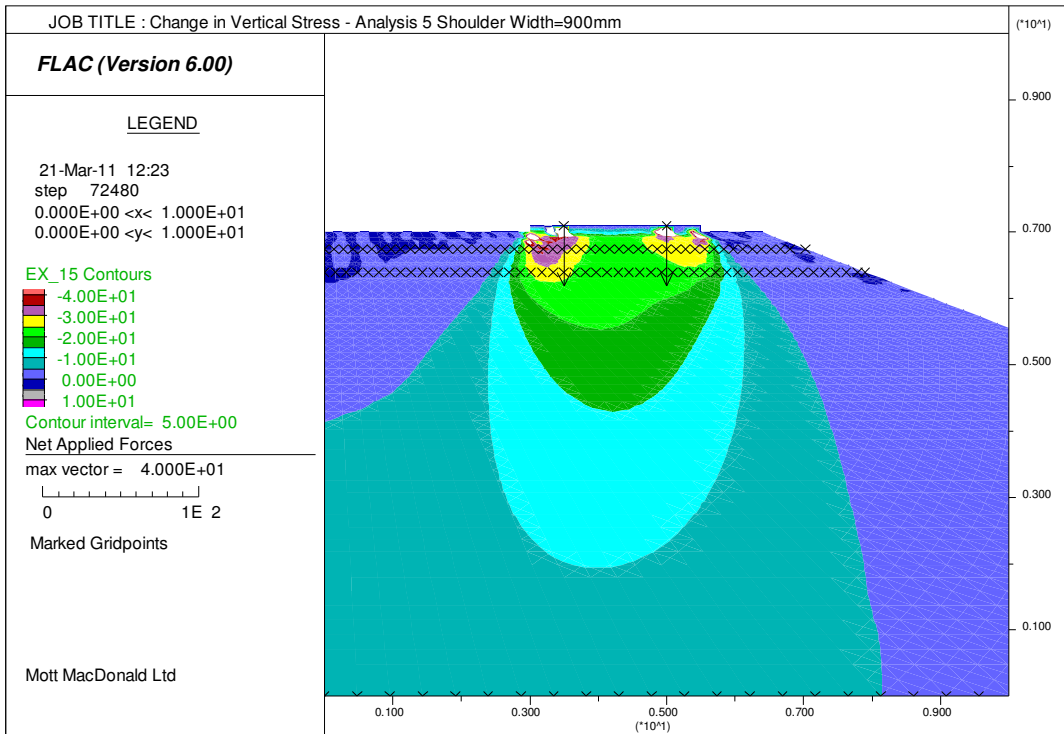


Figure D.7: Numerical Analysis 5: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

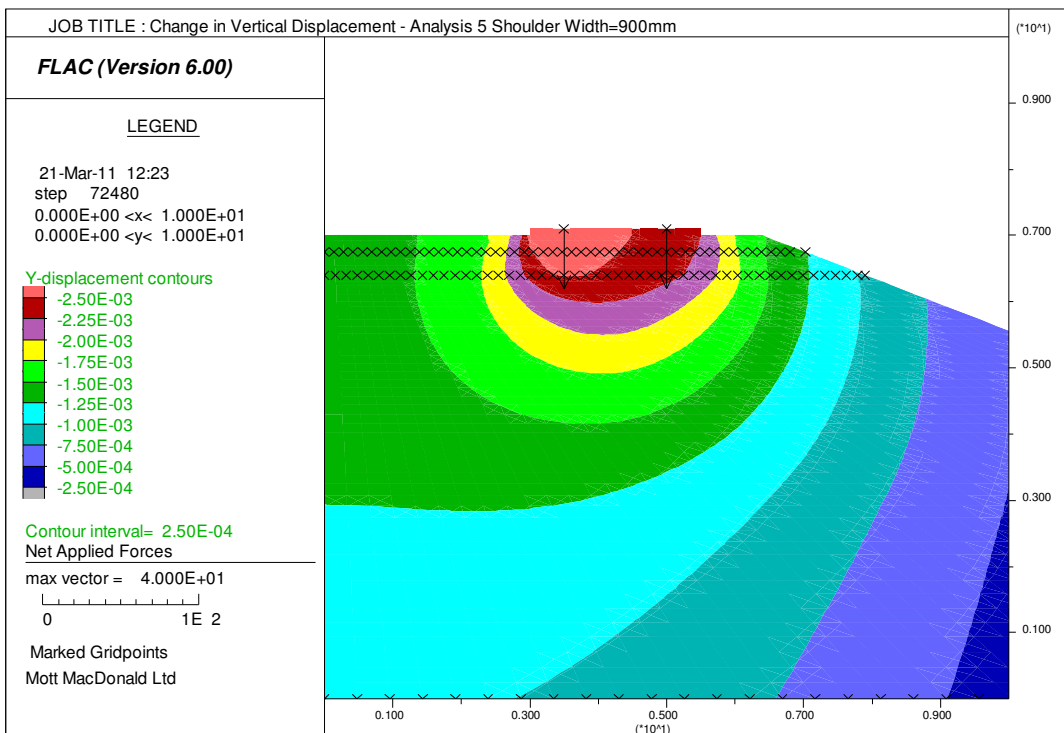
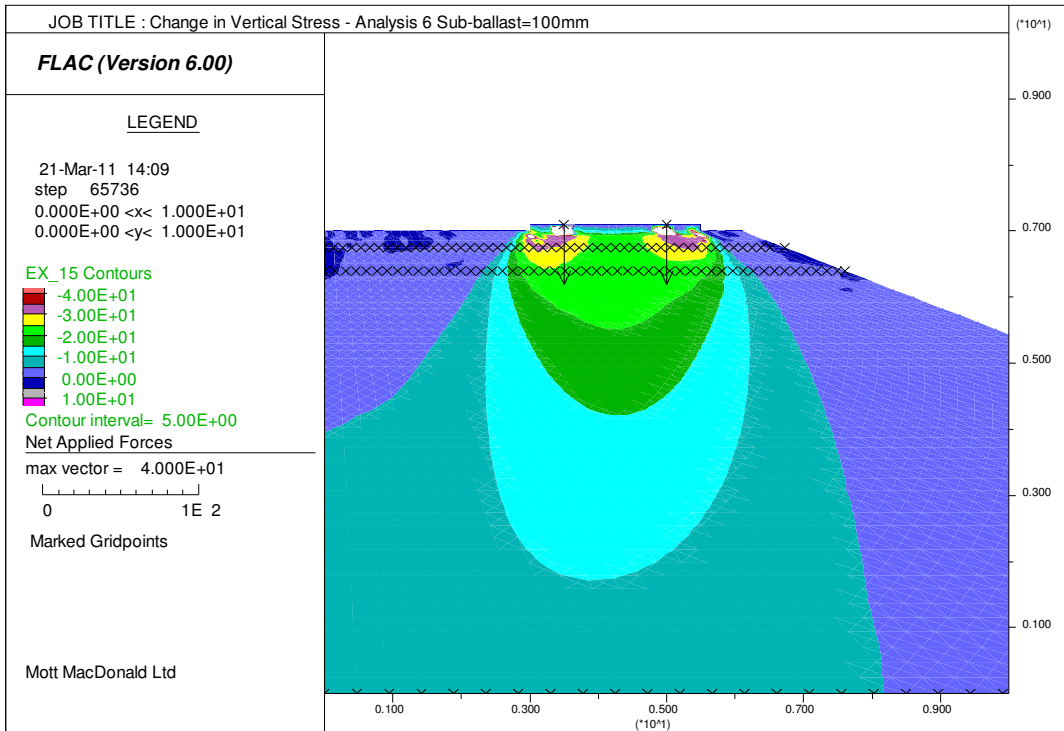


Figure D.8: Numerical Analysis 6: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

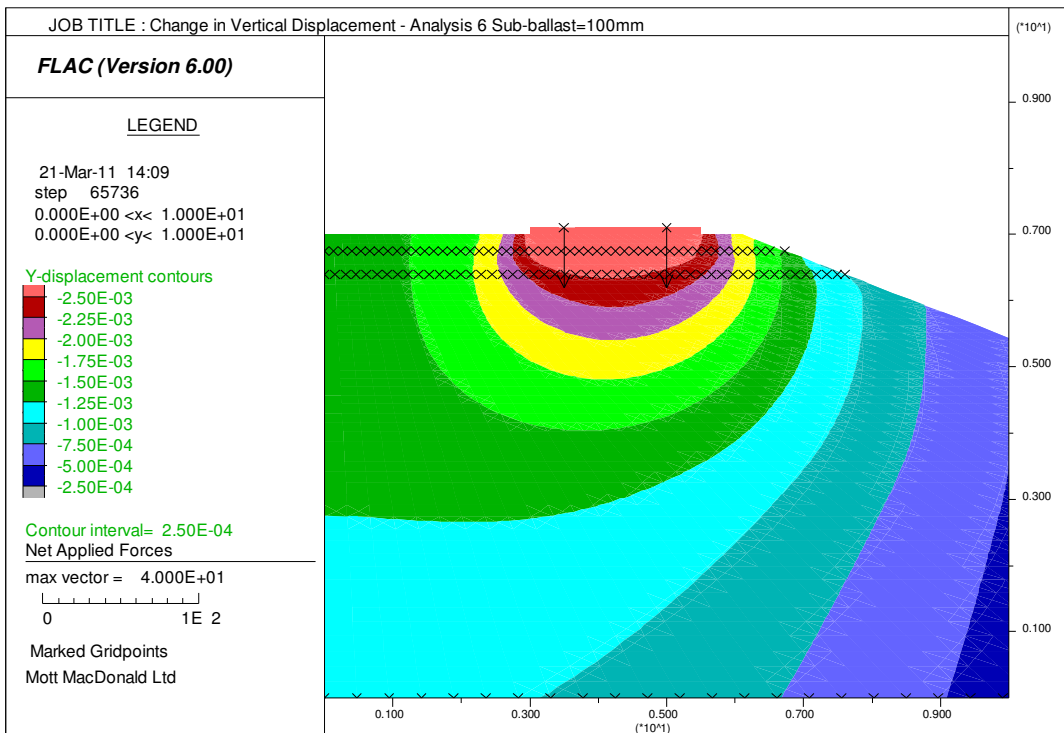
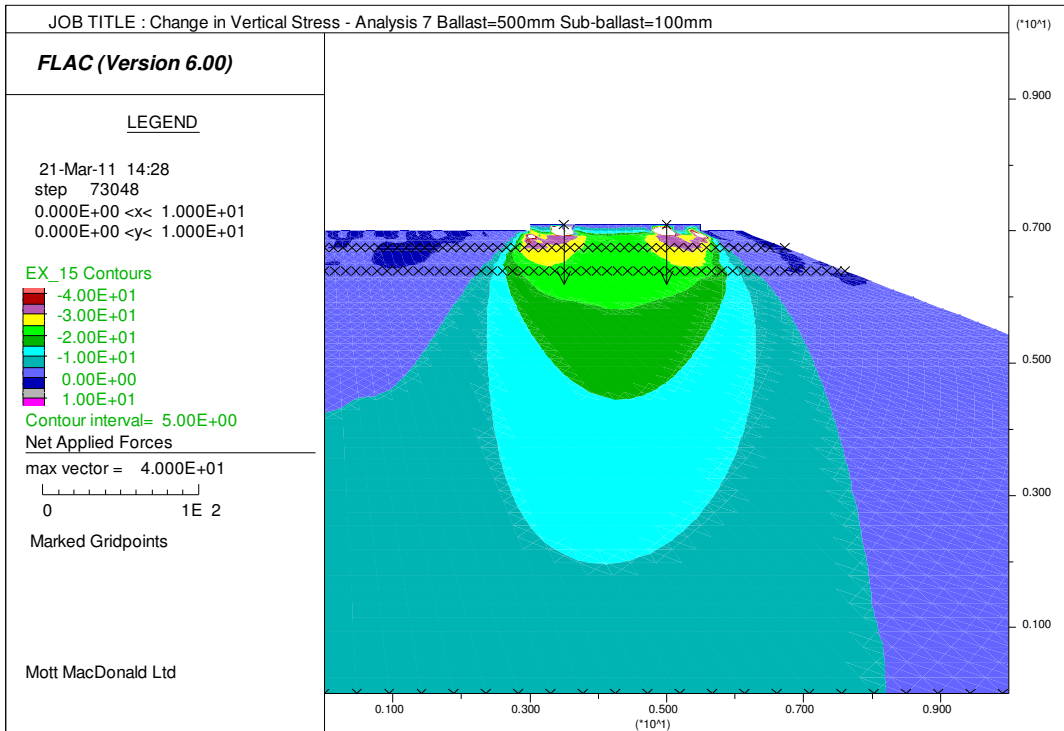


Figure D.9: Numerical Analysis 7: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

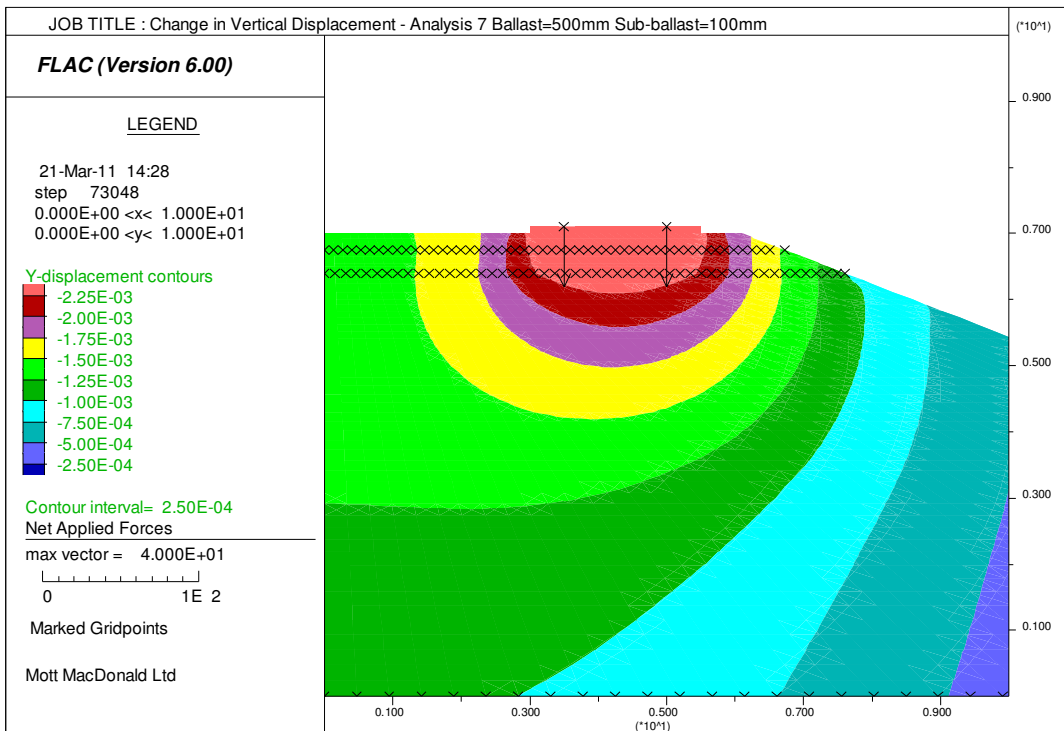
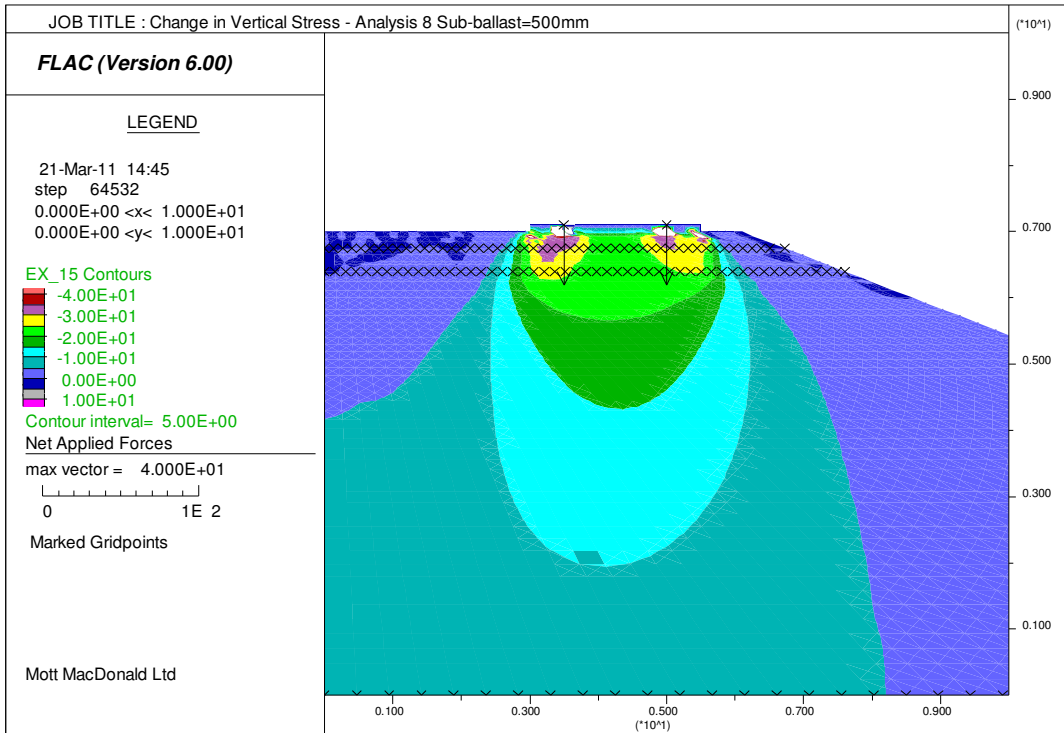


Figure D.10: Numerical Analysis 8: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

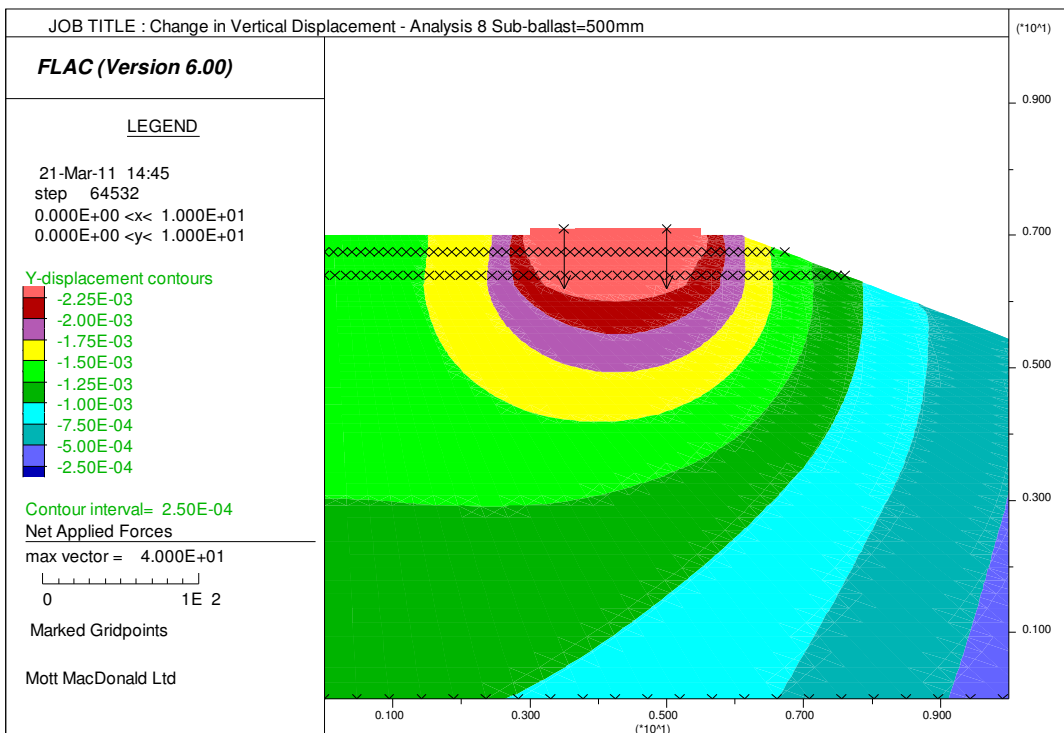
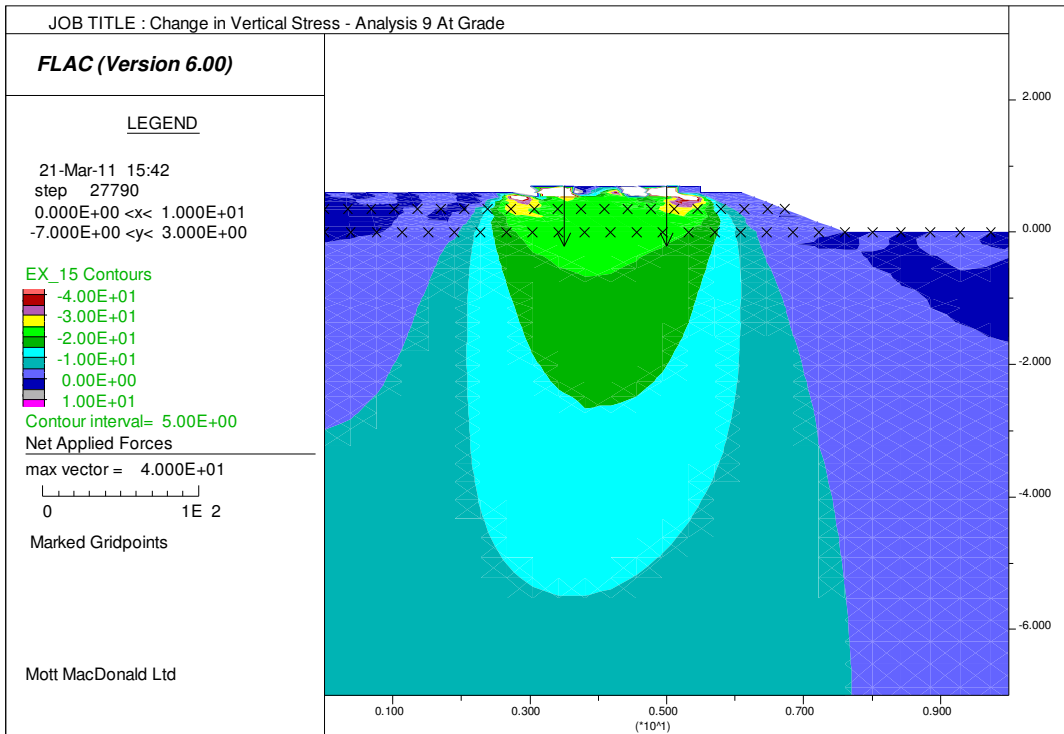


Figure D.11: Numerical Analysis 9: (a) Change in Vertical Stress;



(b) Change in Vertical Displacement.

