# Influence of climate and vegetation on railway embankments
## L'influence du climat et de la végétation sur les remblais de chemin de fer

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## ABSTRACT

The serviceability and stability of old railway embankments formed from end tipped high plasticity clay fill is controlled by the seasonal variation of pore pressures within the slope, which is directly dependant on the climatic conditions and the vegetation present. This paper uses long term monitoring data and observations of real behaviour to explore the critical factors for embankment performance within this framework. Numerical modelling provides insight into both the governing parameters for changes in pore water pressures and the development of progressive failure due to strain softening of the fill subject to seasonal cycles.

## RÉSUMÉ

L'aptitude à l'usage et la stabilité des remblais de chemin de fer anciens construits par le dépôt sans compaction de l'argile à haute plasticité sont gouvernés par la variation saisonnière des pressions pores à l'intérieur de la pente, ce qui dépend directement sur les conditions climatiques et sur la végétation qui est présent. Cette note emploie les données pris de surveillance à long terme et les observations du comportement réel des pentes pour étudier les facteurs critiques ayant une action sur le fonctionnement des remblais dans ce cadre. La modélisation numérique fournie l'aperçu des paramètres qui gouverne la variation des pressions pores et de la rupture progressive occasionné par l'adoucissement mécanique du remblai porté aux cycles saisonniers.

Keywords: railway embankments, seasonal shrink swell, progressive failure, vegetation, climate

## 1 INTRODUCTION

### 1.1 *Effect of earthworks on railway performance*

In the United Kingdom there are approximately 5000km of embankment, which support the country's railway infrastructure. Typically in the South of England many of the rail embankments were constructed in the 19th century from end tipping high plasticity clay fill (such as London Clay, Gault Clay, etc), as described by Skempton (1996). Depending on the vegetation present these embankments have experienced seasonal deformation, (Andrei, 2000) and wet periods have triggered deep seated instability, McGinnity (1998). The owners and operators of the infrastructure are increasingly concerned about these assets as they are financially penalized if they fail to achieve a prescribed level of performance.

The seasonal variation of pore pressures within an embankment slope is controlled by the climatic conditions and is exaggerated by the effects of the vegetation present. Figure 1 illustrates how seasonal and climatic variations can induce various slope deformation mechanisms which in turn can affect the performance of a railway embankment.

This paper will focus on the seasonal deformation associated with the seasonal variation in pore pressures between the summer and winter months. During the summer the vegetation is active, causing a pore pressure reduction resulting in a downward movement of the slope surface; whereas in the winter months the vegetation is dormant resulting in rehydration of the soil thereby causing swelling. In addition the tendency for localisation of strains in the clay fill results in net downwards and outwards movement on preferred shear surfaces. This can lead to the development of a "progressive failure mechanism" and eventual deep seated failure.

This paper initially describes the key results of a network scale study and then the observed field behaviour of a particular rail embankment, which was monitored for over two years. It then describes hydrogeological modelling used to understand the key parameters which govern the seasonal variation of porewater pressures within the embankment. Finally it describes a series of FLAC numerical models used to replicate the observed seasonal ground movements and assess the potential of progressive failure.

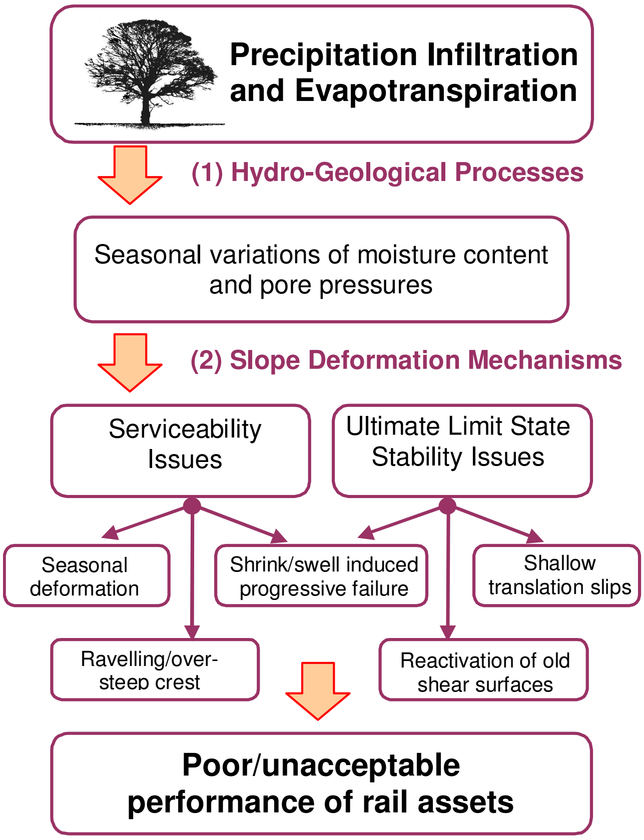


Figure 1. Influence of Climate/Vegetation on Embankment Performance

### 1.2 *Network Rail asset performance data*

The UK rail network is owned and maintained by the company Network Rail. In order to compensate Train Operating Companies for train delays resulting from the condition of the network, all incidents that cause delays are recorded, along with a cause. By studying the timing and distribution of incidents attributed to geotechnical causes it is possible to make inferences about the performance of the earthwork assets. NR have estimated that over the period 2000-2003 "Delay Minutes", as a result of geotechnical causes, totalled 400,000 at a cost of £26m.

Such studies have determined that there is a strong correlation (coefficient of determination, $R^2 > 0.8$) between occurrence of incidents and associated delay minutes and the plasticity of the local geology (Mott MacDonald, 2005). In this relationship the British Geological Survey Geosure geohazard ranking scheme (BGS, 2003) has been used as an indicator of plasticity and the incidents and delays minutes have been normalized by the amount of the network underlain by that geohazard ranking category. Hence high plasticity sites are confirmed as more problematic for the network than low plasticity sites.

This relationship is a reflection of the impact of plasticity in the development of seasonal deformations from cyclic shrink-swell behaviour, as well as the greater susceptibility of high plasticity materials to ultimate deep seated failure.

It was also observed that 5 times as many geotechnical incidents occur in the winter than the summer, and that these incidents cause approximately 10 times the amount of delay minutes (Mott MacDonald, 2006).

## 2 OBSERVED BEHAVIOUR

To gain a better understanding of the effects of vegetation a "grass" covered slope and a "tree" covered slope of a London Underground Ltd (LUL) embankment has been monitored for over two years. The automated instrumentation installed in July 2004 is described by Scott (2006). The embankment is up to 5m high with an average slope angle of 1:3. It was constructed in 1929 from ending tipping London Clay and is capped with 1-2m of ash. The fill has a plasticity index of 50% hence has a high potential for volume change according to the BRE Digest 240.

Historically the embankment has suffered from instability and currently requires significant track maintenance particularly in the summer. The LUL assessment Standard E3321 suggests for a mature tree covered slope lower pore water pressures will be present compared to a grassed slope. Hence a simple limit equilibrium stability assessment gave a factor of safety (FoS) of 1.1 for the grass slope whereas the tree covered slope had a FoS of 1.2-1.3.

### 2.1 *Desiccation induced by vegetation*

In the vicinity of the tree covered section there are two 20m high oak trees, approximately 2m from the nearest instrument. In accordance with National House Building Council (NHBC, 2003) oak trees have a high water demand. Figure 2 illustrates that in the summer of 2004 the trees caused desiccation down to 4-5mbgl, which is consistent with Driscol (2000). When plotted on a soil moisture suction curve the observed moisture contents indicate an order of magnitude difference between the suctions present for the "grass" area 10-20kPa compare to the "tree" area 50-250kPa.

### 2.2 *Porewater pressures*

The piezometers confirmed the suggested difference in suction between the two areas as illustrated by Figure 3. In the "grass" area suctions of up to 8kPa were observed and the seasonal variation was moderate compared to the "tree" area were a suction in excess of 90kPa (restricted by range of instrument) was observed. The seasonal variation of the pore pressure followed the expected seasonal trend with the largest suctions (negative pore water pressures) developing at the end of the summer and the largest positive porewater pressures developing at the end of the winter. For the “grass” area suctions dissipated in the winter, whereas for the “tree” covered area a residual suction was maintained at depth. However, relatively high near surface pore pressures developed in both cases during the winter, possibly due to the dry summer causing desiccation of the upper layer thereby increasing its permeability.

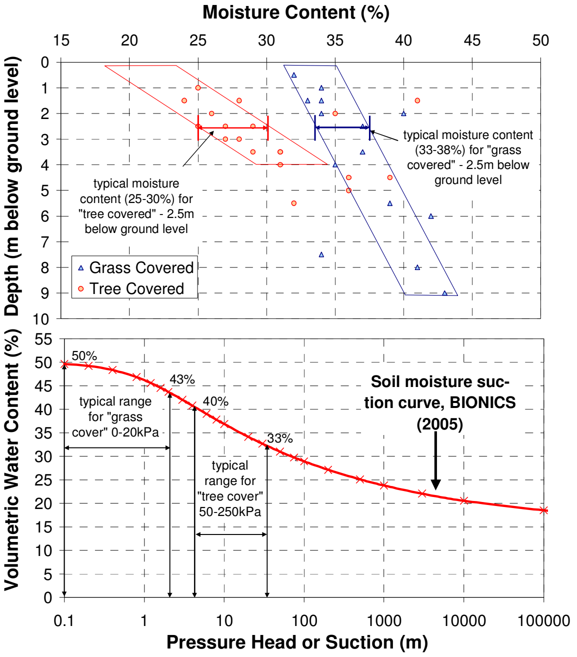


Figure 2. Desiccation induced by high water demand oak trees (July 2004)

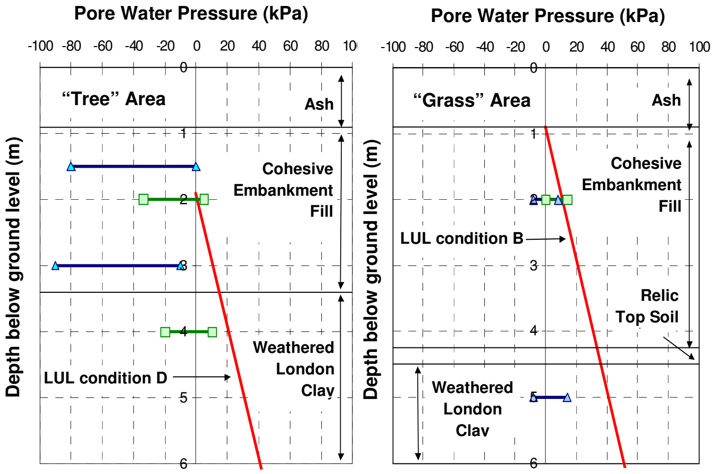


Figure 3. Pore pressure variation with depth (a) “tree” covered and (b) “grass” covered

## 2.3 *Vertical ground movements*

Figure 4 illustrates that for the “tree” and “grass” covered area settlement was observed in the summer months followed by heave over the late autumn/winter months. However, the amplitude of the “tree” area shrink-swell cycle (50-55mm) was an order of magnitude greater than for the “grass” area (5-8mm), which compares well with Andrei (2000). There is a strong correlation between the variation in the soil moisture deficit (SMD) and the vertical ground movement. Hence as the SMD reduced heave occurred and as the SMD increased settlement was observed. To date over the two seasons there has been a net downwards movement for the “tree” covered slope, but further monitoring is require to confirm this trend.

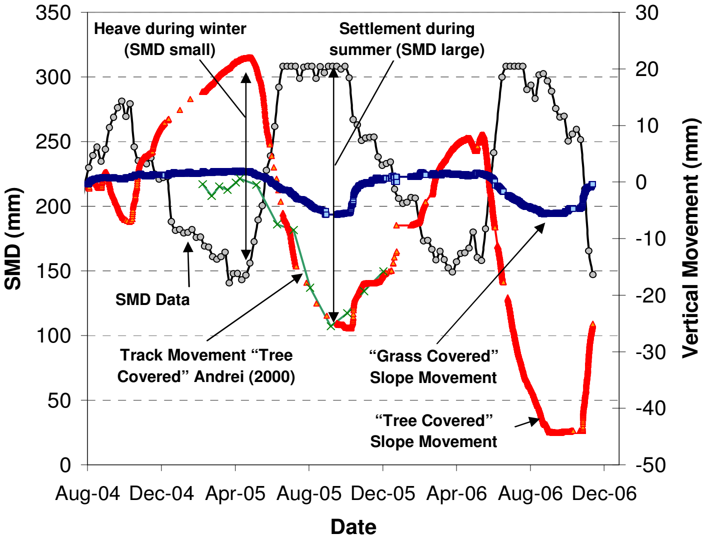


Figure 4. Vertical ground movements, July 2004 to Dec 2006 compared to SMD

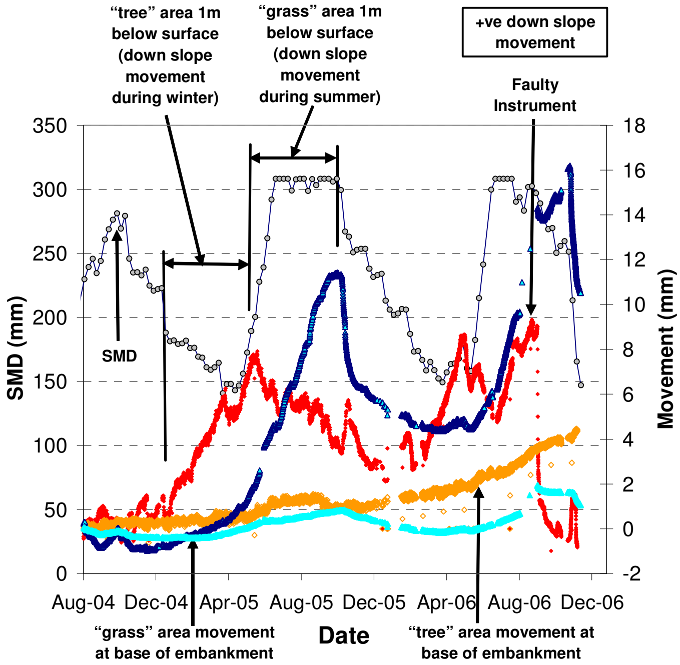


Figure 5. Lateral ground movements, July 2004 to Dec 2006 compared to SMD

## 2.4 *Lateral ground movements*

The lateral movements at the crest have fluctuated over the two years as shown by Figure 5, but the “grass” and “tree” covered slope have different seasonal trends. For the “tree” covered slope down slope movements tended to occur during the winter as the embankment swelled and conversely up slope movements occurred during the summer as the embankment dried out. The opposite was true for “grass” area as the down slope movement occurred during the summer as the SMD increased with subsequent upslope movement during the winter. As suggested by Perry et al (2003) this is believed to be due to the ash drying during the summer and conversely becoming more stable in the wetter winter months due to a capillary menisci developing between the ash particles resulting in an apparent cohesion. At depth there is not a seasonal trend for the “grass” covered slope, however for the “tree” covered slope there has been continual outward movement at the base of the embankment albeit very small (3mm) which may be indicative of gradual creep/progressive deep seated movement.

## 3 HYDROLOGICAL MODELLING

Changes in pore pressures in embankments are controlled by two factors, the rate and duration of infiltration and the permeability and permeability contrasts within the embankment fill. In order to better understand the process of seasonal porepressure changes a hydrogeological model of the embankment described above has been produced using the software CHASM (eg Wilkinson et al, 2002).

CHASM allows rainfall to infiltrate the surface of a slope, whereby vertical flow in the unsaturated zone is governed by Richards Equation (Richards, 1931) and flow in the saturated zone is governed by Darcy’s law (Darcy, 1856). CHASM was designed for use with tropical soils and climate. Consequently there are a number of limitations with its use for long duration models which are required to simulate the winter wetting up of embankments over a number of months. These limitations have been described by Manning et al (2007), and include the applicability of the evaporation model. For this reason the embankment has been modeled based on an assumed end of summer condition and considers only the winter period when evaporation can be assumed to be negligible. Assumed initial conditions for the modelling are summarised in Table 1 and Figure 6.

Table 1 CHASM Initial End of Summer Conditions

| Vegetation Cover | Surface Suction | Depth to Water Table Crest / Toe |
|---|---|---|
| Tree 200 | 200kPa | 5m / 2m |
| Grass 100 | 100kPa | 2m /2m |
| Grass 20 | 20kPa | 2m / 2m |

### 3.1 *Permeability of Embankment Fill*

Whilst, in-situ parent clays may be of low permeability, for example $10^{-10}$ m/s, the end-tipped construction of the embankments mean that the derived fill is much more permeable. Average in-situ permeability measurements for London Clay fill are $3\times10^{-8}$ m/s (O’Brien et al, 2004). In addition, significant variability may exist within the embankment. Desiccation on the embankment slopes may result in increased permeability by up to three orders of magnitude. Sandy layers within the fill or past drainage measures may also result in higher permeability conduits being present.

The presence of the ballast and granular fill layers at the top of the embankment provides a high permeability cap to the structure through which rain water can easily infiltrate and then pond. This provides a sump which allows infiltration to the core of the embankment. The desiccated embankment slopes can also function in a similar way.

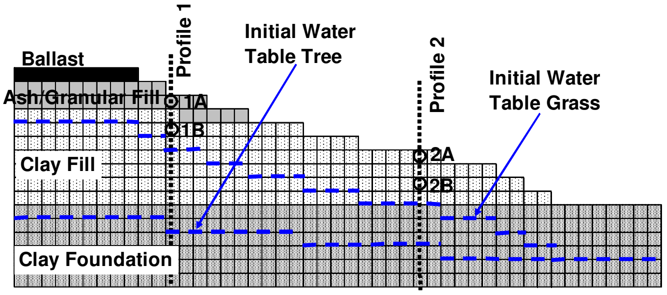


Figure 6. Geometry of CHASM Model

Table 2 CHASM soil input parameters

| | van Genuchten constants (van Genuchten, 1980) | | | | |
|---|---|---|---|---|---|
| Material | Ksat m/s | θsat | θres | α $m^{-1}$ | m |
| Ballast | $5\times10^{-3}$ | 0.45 | 0.05 | 5 | 2 |
| Ash / Granular Fill | $1\times10^{-5}$ | 0.40 | 0.06 | 1.1 | 1.5 |
| Clay Fill | $3\times10^{-8}$ | 0.5 | 0.15 | 1 | 1.2 |
| Clay Foundation | $3\times10^{-10}$ | 0.45 | 0.15 | 1 | 1.2 |

As a result of the factors described above, permeability is a key input parameter to the CHASM model. Consequently, although the model presented is highly simplified, it is designed to address the effect of two variables. Firstly the initial conditions resulting from the combined effects of summer climate and vegetation type, and secondly, the permeability of the embankment fill. Initial parameters are given in Table 2; subsequently variation in permeability was also investigated and this is discussed below.

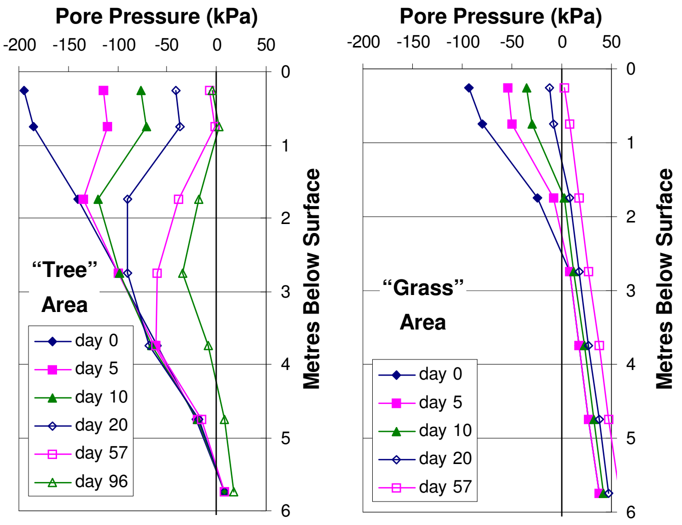


Figure 7. CHASM pore pressures at Profile 1(a) “tree” - suction 200kPa and (b) “grass” – suction 100kPa

### 3.2 *Results of Modelling*

The results of the CHASM model, using the initial conditions indicated in Table 1 and subject to 34mm rainfall per week are given in Figure 7 and Figure 8. This precipitation rate is based on actual rainfall that fell in the area over a 3 month period at the start of the wet winter of 2000/2001, and therefore represents a realistic worst case scenario.

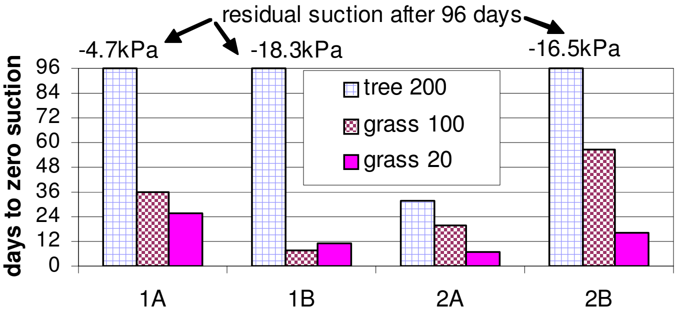


Figure 8. Dissipation of suctions with time (for location of points see Figure 6)

The results demonstrate the marked difference in behaviour between a "grass" slope and a "tree" covered slope. Whilst a "grass" slope would have dissipated suctions by 57 days, a "tree" covered slope retains residual suctions of around 35kPa at depth after 3 months.

Sensitivity to the effect of permeability of the embankment fill is shown in Figure 9. This indicates that for values of around $10^{-6}$ to $10^{-7}$ m/s this precipitation rate matches well the rate at which the soil can take up moisture. However, for lower permeability, there is a significant lag at depth, with leads to the preservation of the residual suctions.

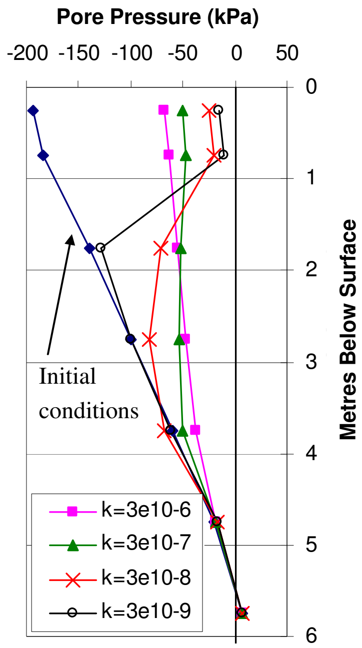


Figure 9 CHASM pore pressures at Profile 1 for tree covered slope after 30 days.

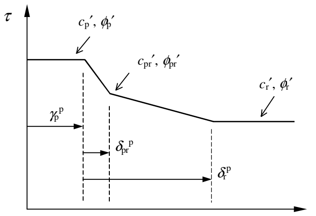
## 4 DEFORMATION/STABILITY MODELLING

### 4.1 *Basis of FLAC model*

Numerical modelling was undertaken using the finite difference program FLAC, ITASCA (1999) to identify the potential of the embankment to fail in a progressive manner and to replicate the seasonal ground movements. The modelling methodology was based on previous LUL applied research, O'Brien et al (2004), which was calibrated against research undertaken by Potts el al (1997). For the London Clay embankment fill a strain softening strength model was adopted, which defined strengths at peak, post rupture and residual states as given in Table 3. The initial embankment construction was modeled undrained. Subsequently a series of shrink-swell cycles were applied to the embankment to simulate the seasonal variation of pore pressure from an extreme "summer" to "winter" condition.

Table 3 FLAC – Embankment Fill Material Parameters

| London Clay Fill | |
|---|---|
| Bulk unit weight | 18.8 kN/m3 |
| Young's modulus | 75(p′+100), min. 5000 kPa |
| Poisson's ratio | 0.2 |
| Peak strength (Bulk) | c′ = 7.0 kPa, ϕ′ = 21.0° |
| Post-rupture strength | c′ = 2.0 kPa, ϕ′ = 21.0° |
| Residual strength | c′ = 2.0 kPa, ϕ′ = 13.0° |
| Plastic strain at peak strength, $\gamma_p$ | 3 % |
| Plastic disp. to post-rupture strength, $\delta^p$ | 5 mm |
| Plastic disp. to residual strength, $\delta^p$ | 100 mm |



$\gamma^p$ = plastic shear strain

$\delta^p$ = plastic displacement

Subscripts:

p = peak; pr = post-rupture

r = residual

### 4.2 *Progressive Failure Assessment*

It was shown that the rate at which a progressive failure develops is related to the magnitude of the seasonal change in pore water pressure and the presence of a residual winter suction. On the basis of applying a summer surface suction of 100kPa and there not being a residual winter suction a progressive failure occurred after the 35th shrink swell cycle, as shown in Figure 10. The embankment was constructed in the early 1930's and there is evidence of remedial measures being implemented from the 1960's through to the 1990's. Therefore the suggested rate at which slope stability degraded (i.e. over a 35 to 50 year period) seems consistent with anecdotal evidence.

For the model representing the "tree" covered slope with a winter residual suction of 30kPa a progressive failure did not develop after 50 cycles despite applying a much large summer suction of 250kPa. This is because the residual winter suction maintained stability during the winter condition, despite significant strain softening at the toe of the slope. However, if the residual suction was not maintained during the winter (i.e. if the tree was felled) then the previous historical strain softening resulted in a deep slip.

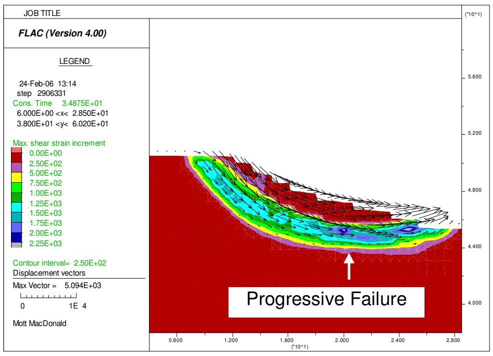


Figure 10. Failure of grass slope after 35 shrink swell cycles

### 4.3 *Seasonal deformation assessment*

To replicate the observed vertical ground movements the pore pressures were required to vary seasonal by 200kPa for the “tree” area, which was double that observed. However, the piezometers were only capable of reading suctions upto 90kPa, which is far less than the 500kPa suctions suggested by previous laboratory testing, O’Brien et al (2004). For the “grass” area the required seasonal variation in pore pressure was 30kPa, which is slightly higher, but similar to that observed in the field. In general the predicted lateral displacements did not correspond particularly well with those observed. This is in part, probably due to the FLAC model not considering the buttressing effect of the tree roots.

## 5 CONCLUSIONS

Studies of rail network performance data demonstrate that the plasticity index is a key risk factor for individual earthwork performance. Observations from an end tipped high plasticity clay embankment illustrate the relationship between performance, climate and vegetation. Ground movements exhibit a strong correlation with SMD for both “grass” and “tree” covered slopes, with significantly greater deformations occurring in the tree covered area.

Hydrogeological modelling illustrated that the grass covered areas will dissipate suctions more rapidly than the tree covered areas. It also demonstrated that permeability is an important control on the wetting up process.

In general the FLAC modelling confirmed that there is a greater potential for failure of a “grass” covered slope than a “tree” covered slope because of the higher water table during the winter condition. However, serviceability problems are more likely with a slope covered in high water demand trees. If the trees were removed the effect on the slope is two fold, firstly the residual winter suctions are unlikely to remain during the winter and the strength of the cohesive fill is likely to have been reduced due to the “ratcheting effect” previously induced by high water demand trees.

## ACKNOWLEDGEMENTS

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