Biological and engineering impacts of climate on slopes (BIONICS): The first 18 months

STEPHANIE GLENDINNING[1], MOHAMMED ROUAINIA[2], PAUL HUGHES[3] & OWEN DAVIES[4]

[1] University of Newcastle. (e-mail: stephanie.glendinning@ncl.ac.uk)
[2] University of Newcastle. (e-mail: m.rouainia@ncl.ac.uk)
[3] University of Newcastle. (e-mail: p.n.hughes@ncl.ac.uk)
[4] University of Newcastle. (e-mail: O.Davies@ncl.ac.uk)

Abstract: Climate change is likely to have a serious detrimental effect on huge parts of our infrastructure. Slopes make up a large proportion of this infrastructure. (£20B of the estimated £60B asset value of major highway infrastructure is earthworks). Major (ultimate limit state) failure of these slopes causes disruption to network operation and frustration to the public. Minor (serviceability state) failure of rail slopes causes speed restrictions and daily commuter misery due to delays. Continuous maintenance of these slopes is essential and cost an estimated £50 million in the year 1998/9 for embankments alone. However, the cost of emergency repair is ten times greater than the cost of planned maintenance works so the ability to predict the future effects of climate on the infrastructure would be of significant financial benefit.

Therefore, it is anticipated that climate change could have a major impact on transport operation in and around cities if the relevant authorities do not take it into account within their future maintenance strategies. The BIONICS project aims to enable these authorities to develop pro-active maintenance techniques to deal with the potential effects of climate change on the geotechnical asset. The specific outcomes are predicted to be:

- A full-scale, fully instrumented embankment representative of UK infrastructure (due for construction in Summer 2005), planted with representative vegetation with the facility to control climate over half of its length;
- A validated hybrid computer model capable of predicting embankment performance under predicted future climates
- A methodology for identifying parts of the UK infrastructure that require further investigation
- A medium to long term research strategy, including some specific needs-based 'spin-off' projects

In the longer term, advanced procedures for maintaining serviceability and safety of strategic embankments and cuttings will be developed, in addition to advancing the science base. This paper will report on the first 18 months work on the project.

Résumé: Le changement du climat va probablement causer des effets nuisibles à notre infrastructure. Les pentes forment une grande proportion de cette infrastructure. La rupture principale (état limite ultime) de ses pentes provoque des perturbations aux réseaux et la frustration du public. La rupture secondaire (état de service) provoque la réduction de la vitesse dans le cas des trains et les retards qui en découlent. Une maintenance périodique est essentielle. Cette opération à couter par exemple environ £50 million pendant l'année 1998/9 et ceci rien que pour les talus. Cependant, le cout de réparation d'urgence est dix fois plus élevé que le cout de la maintenance fonctionnelle d'où la nécessité de pouvoir prédire les effets du climat avenir ce qui réduirait le coût financier.

Il est attendu que le changement du climat pourrait avoir un impact majeur sur l'infrastructure de transport dans et autour des cités à moins que les autorités le prennent en compte dans leur stratégie. Le projet BIONICS permet au ces autorités de développer une maintenance proactive dans la gestion des effets du changement du climat sur les ouvrages de géotechnique. Les résultats prévus sont:

– Un remblai instrumenté à échelle réelle, représentatif de l'infrastructure Britannique, avec une végétation représentative et un système de contrôle du climat sur sa demi-largeur;
– Un model validé capable de prédire la performance du remblai sous les effets du climat avenir;
– Une méthodologie qui permet d'identifier les parties dans l'infrastructure britannique qui nécessitent des investigations complémentaires;
– Une stratégie de recherche à moyen et long terme, y compris des projets de retombée favorable.

A long terme, des procédures avancées de la maintenance et la sécurité des remblais stratégiques seront développées. Cet article décrit les 18 premiers mois de travail sur ce projet.

Keywords: climate change, embankments, geotechnical engineering, infrastructure, models, slope stability

INTRODUCTION

Slopes make up a large proportion of UK transport networks (£20B of the estimated £60B asset value of major highway infrastructure is earthworks). Major (*ultimate limit state*) failure of these slopes causes disruption to network operation and frustration to the public. Minor (*serviceability state*) failure of rail slopes causes speed restrictions and daily commuter misery due to delays. Continuous maintenance of these slopes is essential and, according to Perry, Pedley & Reid (2001), cost £50 million in the year 1998/9 for embankments alone. However, the cost of emergency repair is ten times greater than the cost of planned maintenance works (O'Brien, 2001) so the ability to predict the future effects of climate on the infrastructure would be of significant financial benefit. There is evidence that the scenario of more intense rainfall is already having an impact on the national transport infrastructure, including major landslides in Scotland (e.g. Stromeferry) and, in the winter of 2000/1, which was documented the wettest on record, over 100 slope failures in the Southern Region of Railtrack alone (O'Brien, 2001).

The strength of the materials from which slopes are created and the status of the water held within the pore spaces are key factors controlling the stability of slopes (Leroueil, 2001; Vaughan, Soda & Walbancke, 1978). Changes to the water content of clay materials cause volume changes, leading to areas of reduced strength which can initiate ultimate limit state failure. Embankments created from, and cuttings within, the overconsolidated clays prevalent throughout the UK experience high negative pore water pressures that last for approximately 10-15 years on average after construction providing apparent stability to the slope (Potts, Kovacevic & Vaughan, 1997). With time, these pore water pressures increase, leading to potential instability. The action of successive shrink-swell cycles can lead to surface cracking, allowing water into the embankment and so accelerating the process. These cycles have been observed on old railway embankments constructed of London Clay. A diagnostic study by Kovacevic, Potts & Vaughan (2001) has coupled the strain softening behaviour of the progressive collapse model with shrinkage and swelling cycles. The analysis concluded that embankments of plastic clay may suffer from progressive collapse triggered by seasonal changes of effective stress. The most critical time may be when very heavy rainfall follows a period of very dry weather. While existing embankments may have reached equilibrium, the scenario of hotter drier summers, followed by periods of more intense rainfall will change equilibrium conditions and have a major influence on the rate of degradation of the engineering condition of infrastructure slopes. Alonso, Gens & Delahaye (2003) developed a coupled hydromechanical model to simulate the deformations and evaluated the variation of safety over time for a natural slope. This model involved the input of climatic data and simulated the response of pore (air amd water) pressures within the slope paying particular attention to the unsaturated conditions above the water table.

A key influence on the water within slopes, and hence their engineering behaviour, is vegetation, with beneficial effects including root reinforcement, prevention of pore water pressure build up and surcharging at the base of the slope. However, serious detrimental effects include loading the upper part of the slope, uprooting or overturning. The changing seasonal demand for water causes fluctuations in soil water content, exacerbating the problems associated with shrinking and swelling. Management of the vegetation on slopes is therefore a key issue to their owners and is an inherent part of London Underground Limited's pro-active management strategy (Gellatney *et al.,* 1995). Plants respond to small changes in environment, so a temperature difference of 1-2 ^{o}C, or drought, will alter the composition of the plant community, its water use and rooting characteristics. Quite apart from their function as engineering structures, transport corridors provide valuable habitats for many plants and animals, acting as linear corridors for movement of species, so are of great value in terms of conservation. Climate change is predicted to cause migration of many species but the availability of continuous stretches of habitat will be a severe limitation, so transport corridors will play an even more important ecological role in future.

BIONICS (BIOlogical and eNgineering Impacts of Climate on Slopes) is a research project funded by the UK Engineering and Physical Sciences Research Council. The aim of BIONICS is to establish a unique facility for engineering and biological research to improve the fundamental understanding of the effects of climate change on slopes. It is also to extend modelling capability to examine the long-term effects of climate change on serviceability limits of embankments. The specific outcomes are predicted to be:

- - A full-scale, fully instrumented embankment representative of UK infrastructure, planted with representative vegetation with the facility to control climate over half of its length;
- - A validated hybrid computer model capable of predicting embankment performance under predicted future climates
- - A methodology for identifying parts of the UK infrastructure that require further investigation
- - A medium to long term research strategy, including some specific needs-based 'spin-off' projects

In the longer term, advanced procedures for maintaining serviceability and safety of strategic embankments and cuttings will be developed, in addition to advancing the science base. This paper will report on the progress towards meeting these outcomes during the first 18 months work on the project.

MODELLING AND SIMULATION

The initial aim of the computer modelling was to produce a robust design for the BIONICS embankment, subjected to a range of future climate scenarios. The approach was to couple SHETRAN (a physically-based 2-D model, allowing the simulation of changes in soil pore water pressure in response to rainfall events, Ewen, Parkin & O'Connell, 2000; Birkenshaw & Ewen, 2004) with FLAC (A 2-D Finite Difference (FD) model for soil). The hydrological data sets from SHETRAN simulations were exported to the FLAC code and used to determine deformations over the design life of the embankment. The product of the staggered coupling of the two environments, SHETRAN-FLAC was used to investigate a range of material characteristics, pore water pressure distributions, foundation and drainage regimes in order to contribute to the detailed design of the embankment. The simulations of the final embankment design will be presented herein.

Embankment profile

The specification for the embankment was derived from the literature to be 6m high with side slopes of 1 in 2 and a 5m width crest. This represents a steep, but relatively low embankment. There are four 18m wide test plots on each face, with two, 4m wide test plots at each end to provide for the duplication required for biological research. The central section has been constructed using good compaction control to simulate a newly constructed highway embankment. The outer test plots will have a 'designed' heterogeneous structure, less well compacted to simulate an older embankment. Each test plot is divided from the adjacent section vertically using an impermeable barrier. The embankment is founded directly onto the underlying ground in order to best simulate current practice. A drainage channel will be placed around the toe of the slope to collect overland flow.

This profile formed the basis for the initial modelling and is illustrated in Figure 1.

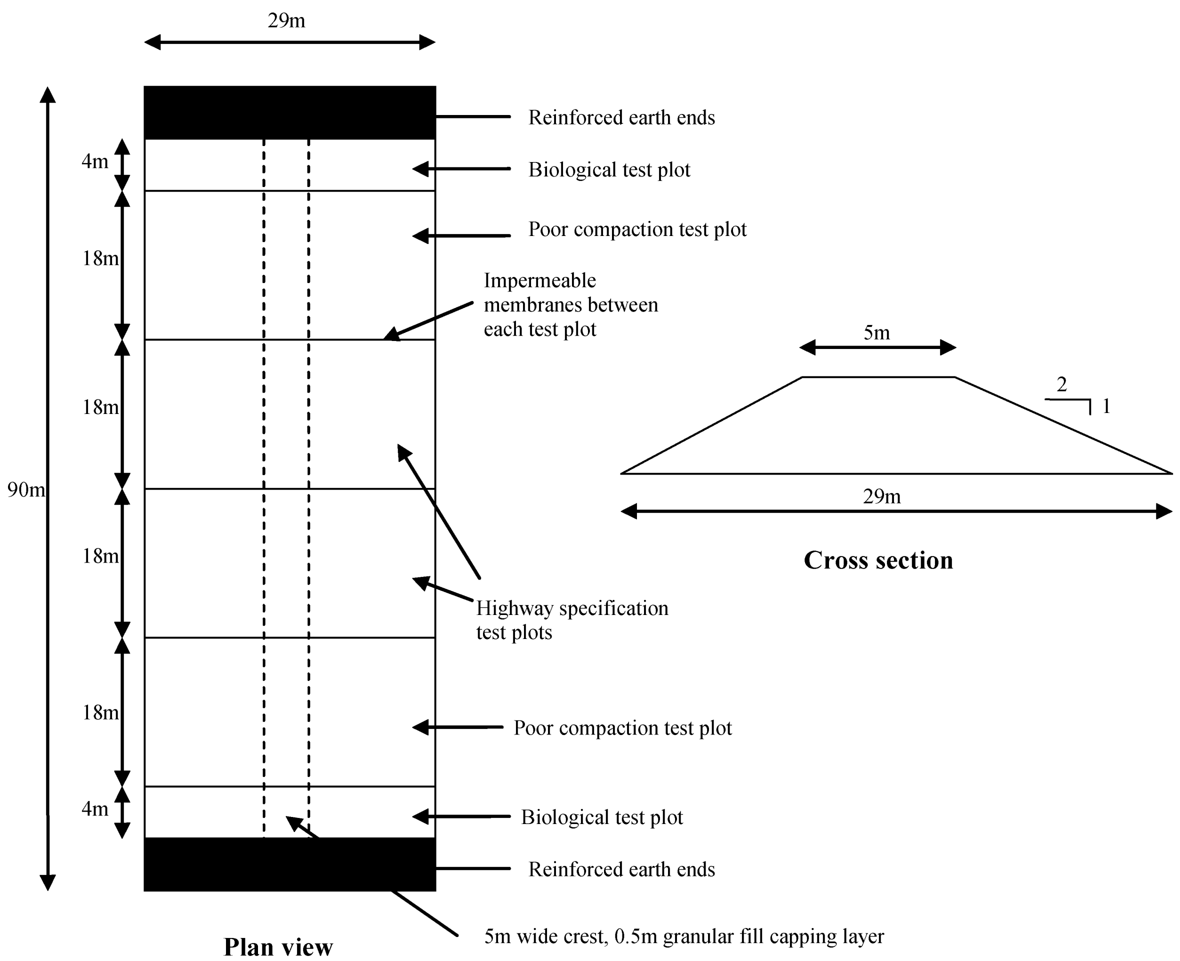


Figure 1. Plan of the BIONICS embankment

For the short-term conditions critical to the initial performance of the embankment situations with either no vegetation, or short, immature vegetation have been examined. In considering the top boundary surface, it was thought probable that the drying and heating effect produced by the proposed cover system would produce cracking in the surface layers of the soil if it was left entirely unsurfaced. This would lead to uncontrolled boundary conditions at the crest, making model validation impossible. Therefore it was decided to provide a 0.5m thick layer of non-cohesive fill on the crest in order to avoid this situation.

Climate

As this exercise was looking specifically at the design of the embankment, with timescales for examination of the critical issues in the short term, climate data representing the present were used. Additionally, a future climate scenario incorporating a higher seasonal variability was examined. A more detailed account of the meteorological data used is included in the section relating to the SHETRAN modelling.

Modelling procedure

The following procedural approach was adopted for coupling SHETRAN and FLAC and to investigate the embankment design issues:

1. A representative model of the embankment was built in both SHETRAN and FLAC.
2. Variation of pore water pressure with respect to climate data was then modelled within SHETRAN.

3. 10 'snapshots' of the pore water pressure for the wettest part of each of a 10 year anticipated lifetime were then imported into the FLAC grid.
4. Models were then run in FLAC with the maximum geotechnical strength properties.
5. The strength properties were then reduced towards residual values (see discussion on FLAC simulation) for the worst case scenario pore water pressure distribution (highest saturation) to evaluate the overall safety of the slope.

The principle of the approach was to allow SHETRAN to simulate pore water pressures related to infiltration and permeability and then to examine the effect of these pore water pressures on movement, whilst also considering a potential reduction in strength. This was carried out in order to capture the effects of climate and differs from previous approaches that have generated pore water pressures from the consolidation and/or swelling behaviour of the clay (Kovacevic *et al.,* 2001).

The main limitations of this approach are the uncoupled nature of the SHETRAN-FLAC modelling, with 'snapshots' of pore water pressure passed from SHETRAN to FLAC. Fully coupling the water flow with a geotechnical model would allow feedbacks between the two to be simulated. Suggestions for improved coupling between the two models are made later in the paper. The effects of these limitations will be highlighted as the results from the modelling are presented.

SHETRAN simulations

The soil properties used in the SHETRAN simulation can be seen in Table 1. These correspond to layers that can be seen in Figure 2. Porosity, residual water content and van Genuchten parameters are typical values for the soil type used (van Genuchten, 1980) but the porosity is reduced in the lower layers due to the anticipated effects of compaction. Permeability values were selected from Anderson & Kneale (1980). They measured a reduction of permeability with depth into an embankment. As Anderson & Kneale suggested, the effective permeability values used here are greater than the laboratory measurements, which may be attributable to several factors, including surface cracking, and zoning induced by compaction methods.

Table 1. Soil properties used in the SHETRAN simulations

Soil Type	Porosity	Residual Water Content	Permeability (m/s)	vanGenuchten-alpha (cm^{-1})	vanGenuchten-n
Gravel top of embankment	0.45	0.05	6.0×10^{-5}	0.05	2.0
Embankment – layer1	0.50	0.15	2.0×10^{-7}	0.01	1.2
Embankment – layer2	0.48	0.15	8.1×10^{-8}	0.01	1.2
Embankment – layer3	0.46	0.15	2.0×10^{-8}	0.01	1.2
Embankment – layer4	0.45	0.15	8.1×10^{-9}	0.01	1.2
Foundation	0.45	0.15	1.5×10^{-10}	0.01	1.2

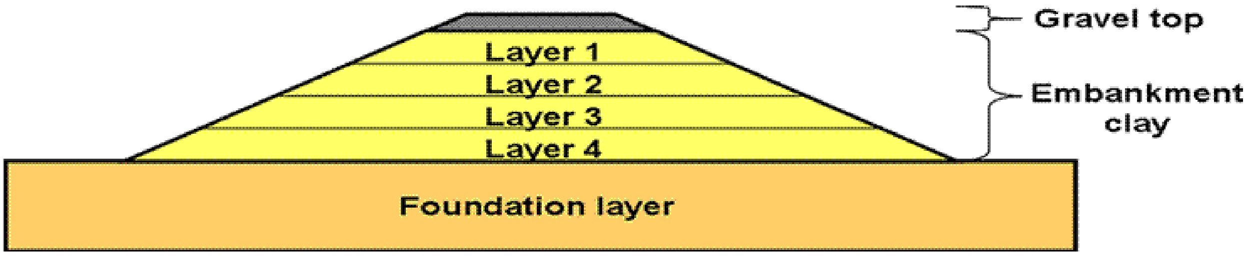


Figure 2. Soil layers using in the SHETRAN simulations

These values may be rather high, especially when the partially saturated nature of the fill is considered. Hence the infiltration rates, and the rate of increase in pore water pressure may be over predicted.

The top of the embankment had ground bare of vegetation, whilst the rest of the embankment was grassed over. The vegetation properties used in these simulations are given in Table 2. Values for the vegetation come from typical values measured in the field and previous SHETRAN simulations (Dunn & Mackay, 1995; Bathurst et al. 2004; Birkinshaw & Ewen, 2004)

Table 2. Vegetation properties used in the SHETRAN simulations

Parameter	Grassland	Bare Ground
Evapotranspiration reduction factor at –3.3m head	0.4	0.4
Canopy storage capacity	1×10^{-4} m	0 m
Maximum canopy drainage rate	14×10^{-9} m/s	-
Fractional rate of change of canopy drainage storage water	5.1×10^{3} m^{-1}	-
Canopy resistance factor	100 s/m	0 s/m
Vegetation height	0.3 m	0 m
Leaf area index	1	0
Fraction of energy absorbed by the canopy	0.9	0.0
Maximum rooting depth	0.3 m	0 m

The boundary conditions for the SHETRAN simulation was a head boundary set at the edge of the embankment. This was set so that the water table was 2m below ground. It was assumed that the embankment was built dry, with the initial water table throughout the embankment also set at 2m below ground and a hydrostatic head above. This means that at the embankment crest there was an initial suction of 8m (80kPa). Evidence from the literature (Ridley & Perz-Romero, 1998), suggested that this may be an underestimation of the initial compaction- induced suctions and therefore represents a conservative approach.

10 years of hourly precipitation data was required for the simulation. The nearest suitable data for the site proposed for the embankment in Northumberland, UK, was from Leeming in North Yorkshire. 10 years of potential evaporation data was also obtained. The precipitation data for the future climate used 10 years of UKCIP02 (Hulme *et al.,* 2002) high forecasted precipitation data from Leeming, North Yorkshire. The potential evaporation data was the same as for the current climate.

The annual precipitation for the future climate was similar to the current climate, however, there was a major seasonal difference incorporated to account for potential extremes. Precipitation in the future climate is higher in the winter and lower in the summer compared to the current climate.

Assessment of Pore Water Pressure Profiles

Figure 3 illustrates the SHETRAN finite difference grid for the embankment.

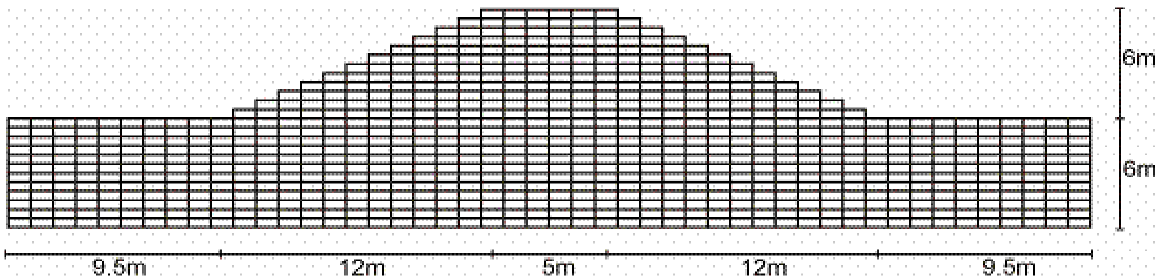


Figure 3. SHETRAN finite difference grid for the embankment

The results for the worst case scenario with bare soil and a future climate will be illustrated here. It should be noted that there is a build up of water within the embankment and water flows out of the side of the embankment as overland flow as a result of the lack of drainage beneath the embankment. This leads to relatively high evapotranspiration (Table 3) due to the wet surface of the soil, and relatively high mean annual water flows on the side of the embankment. Profiles of the pore water pressures (Figure 4) show the embankment is relatively wet. There is the expected increase in pore water pressures with depth and generally higher pore water pressures in the winter than in summer. There is a slight change in the smooth profile in winter at the boundary between the embankment and foundation, which shows the wetting front moving down the profile. In Figure 5 the time series of pore water pressures can be seen for three points in the embankment. The flat lines in winter at 'pore pressure 3' show when the water table has reached the ground surface directly above this point.

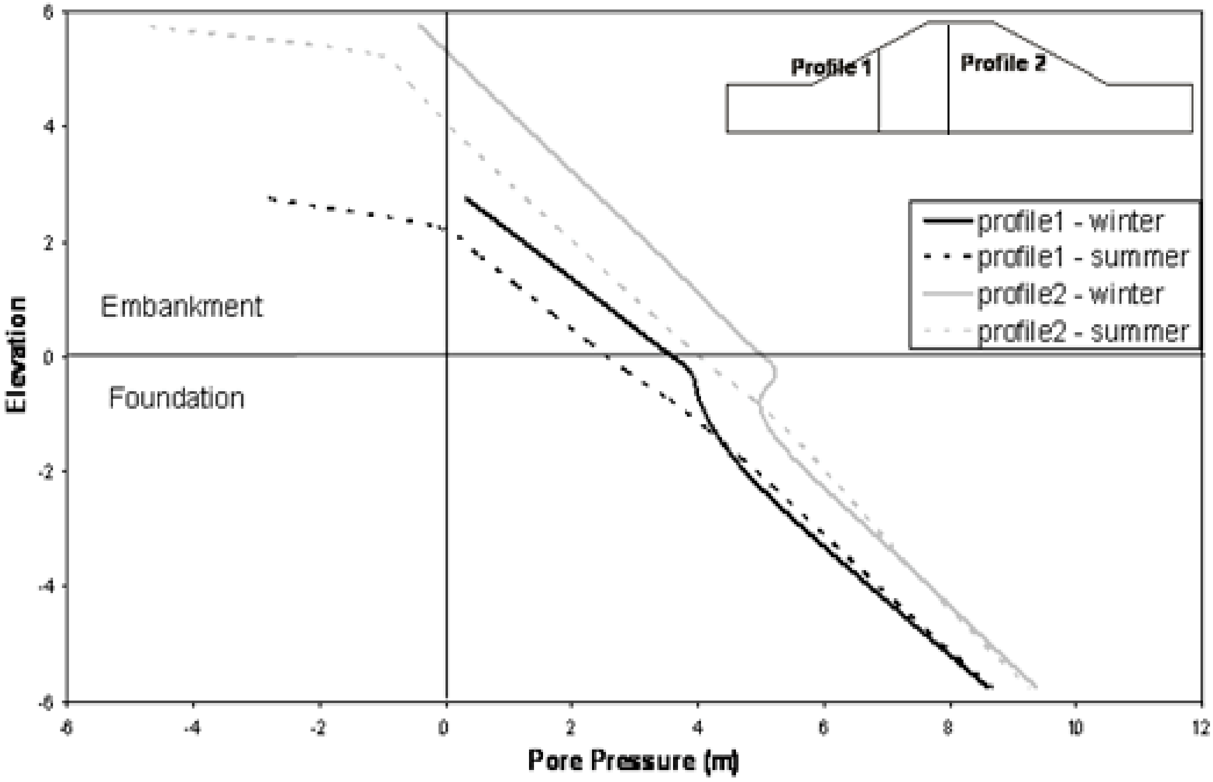


Figure 4. Embankment profiles the no underdrainage simulation

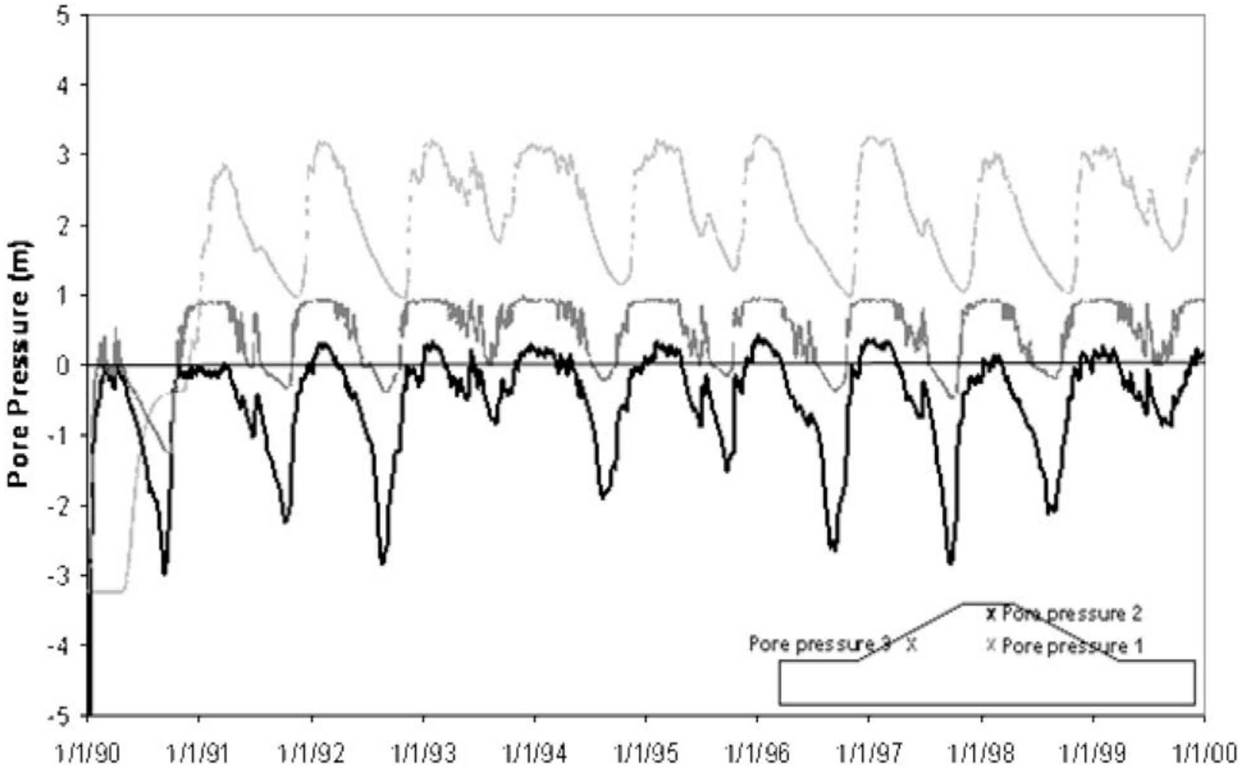


Figure 5. Pore water pressures in the embankment for the no underdrainage simulation

FLAC simulations

The properties for the materials used to construct the embankment have been derived from a variety of sources, including data provided by the BIONICS Steering Committee. However, the key source of data was Potts & Zdravkovic, 2001. A summary of the values used is shown in Table 3. No gradation of soil properties has been assumed unlike the SHETRAN modelling.

Table 3. Geotechnical properties of construction materials

Property	Foundation (in-situ London clay)	Embankment (compacted London Clay)
Bulk unit weight (kN/m^3)	18.8	18.8
Effective Cohesion c' (kPa)	Maximum 7 (assumed from peak strength for bulk material) Minimum 2 (assumed from residual strength)	Maximum 12 (assumed from peak strength) Minimum 2 (assumed from residual strength)
Effective angle of internal friction Φ' (degrees)	Maximum 20 (assumed from peak strength) Minimum 13 (assumed from residual strength)	Maximum 20 (assumed from peak strength) Minimum 13 (assumed from residual strength)
Property	Foundation (in-situ London clay)	Embankment (compacted London Clay)
Young's modulus (kPa)	4000 Calculated from foundation mean effective stress (minimum default value used)	2000 Calculated from embankment mean effective stress (minimum default value used)
Poisons ratio	0.2	0.3

A Mohr coulomb model has been used for all materials. This standard soil model was considered to be sufficient for the design stage of the project as the exact material properties were unknown at the time. A more rigorous constitutive soil model will be incorporated once the material properties are established. In order to examine the longer-term performance of the embankment, failure was induced by reducing the material strength properties from maximum values to residual values as shown by Figure 6. This strength reduction was not directly related to strain as it was not possible to allow the full coupling of SHETRAN to FLAC. This is one of the limitations of the approach and is discussed further in later sections.

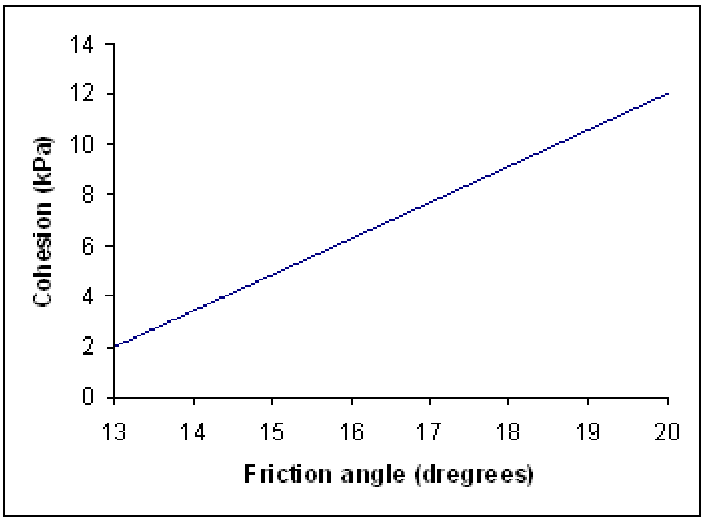


Figure 6. Strength reduction chart

The grid of the model within FLAC was built to mirror the grid within the SHETRAN model as closely as reasonably possible. As the embankment is expected to be symmetrical along its centre point only half the embankment has been modelled. The boundary along the centreline of the embankment has restricted horizontal movement. The geometry cannot be altered within this part of the simulation as the SHETRAN grid has been set and code written to transfer pore water pressure readings to the relevant gridpoints within the FLAC grid. Any changes to the FLAC grid will result in an increasingly inconsistent pore water pressure distribution.

The embankment was founded directly onto a material with the in-situ properties of London Clay. For each simulation the foundation of the model was built and solved as an elastic model under gravitational load to simulate the initial conditions. The embankments were then built instantaneously. The relevant pore water pressure snapshot was installed into the grid (generated from SHETRAN), as opposed to building the embankment in stages and allowing pore water pressures to be generated by consolidation. The models were then saved at this point, before the gravitational load was reapplied.

This procedure was repeated for all the pore water pressure snapshots. Any model could then be run under gravitational load and the material parameters reduced as detailed earlier to determine the minimum strength requirements for each pore water pressure distribution and the mode of failure.

Results

All the simulations run using the maximum strength parameters remained stable. Shear strains remained negligible (less than 5%). Within this simulation the embankment became steadily wetter throughout the course of the simulation. The worst case conditions for this simulation were produced in years 8 through to 10 and are likely to degenerate thereafter given a similar climate. The pore water pressure distribution for year 9 is shown in Figure 7.

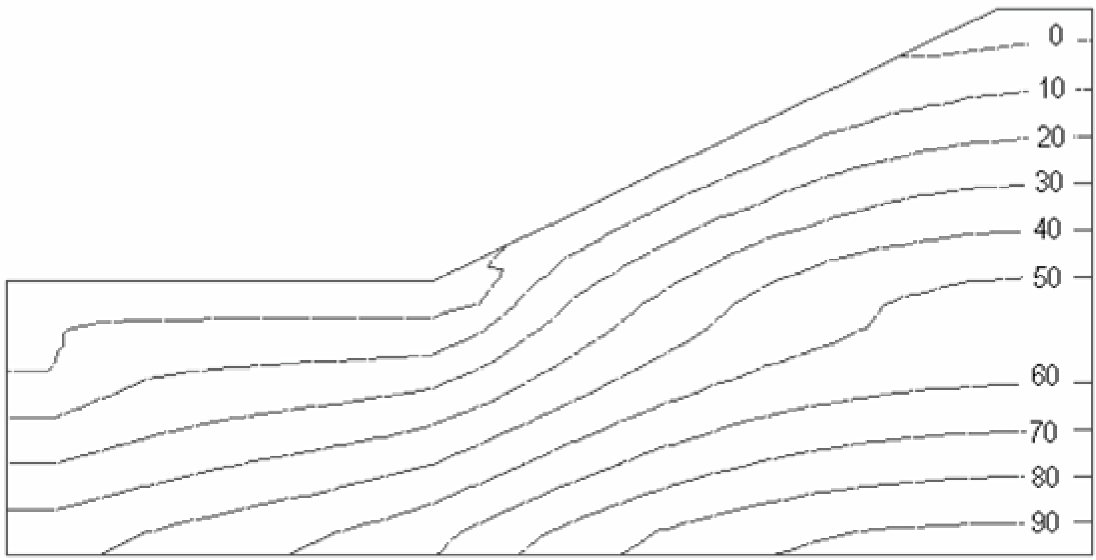


Figure 7. Pore water pressure distribution for year 9

For these models the embankment was on the verge of failure at a ϕ' value of 17° and an effective cohesion of 7.4kPa. The plot of the displacement vectors for this scenario is illustrated in Figure 8.

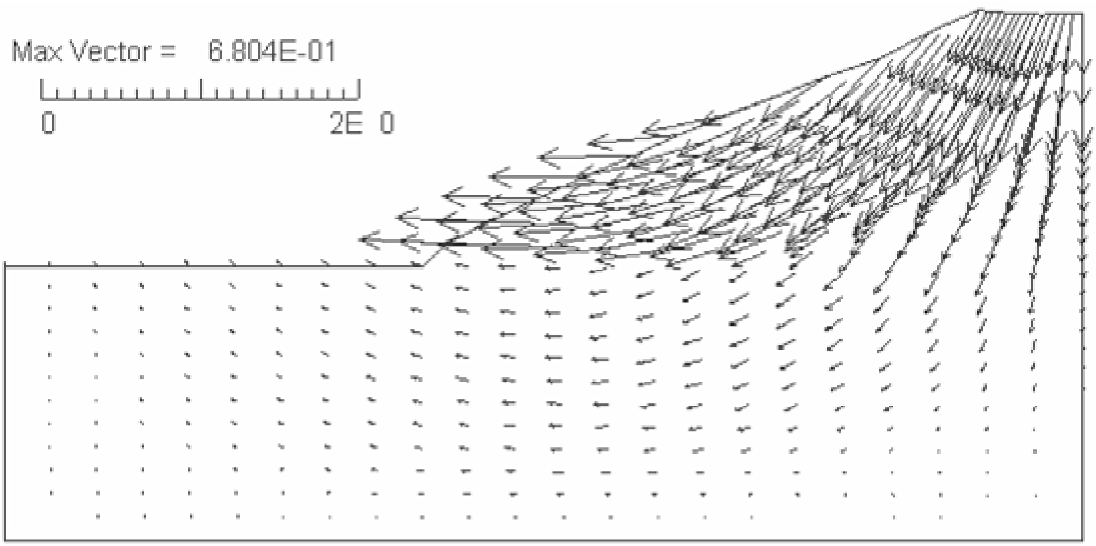
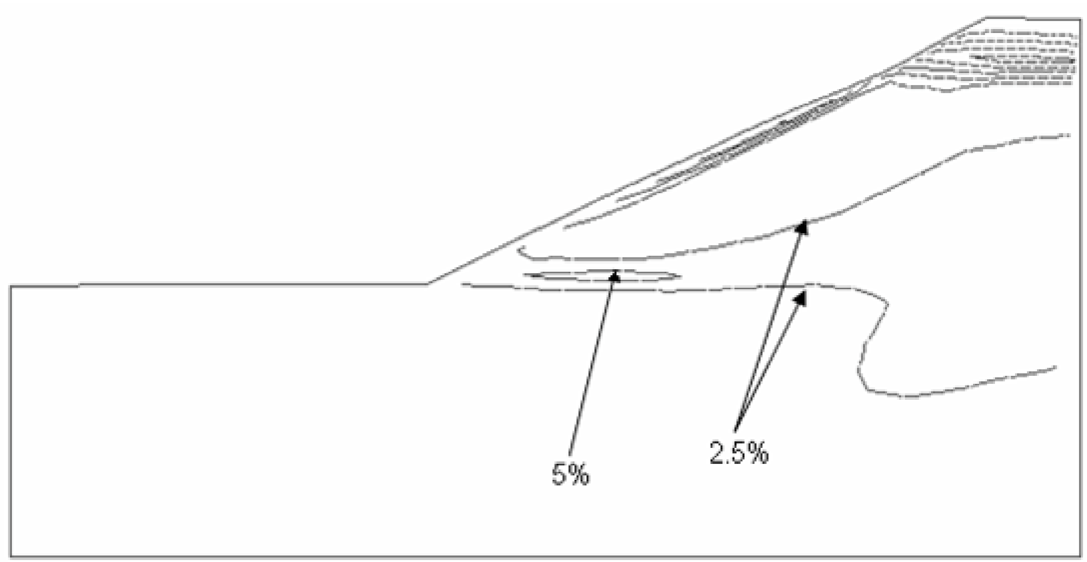
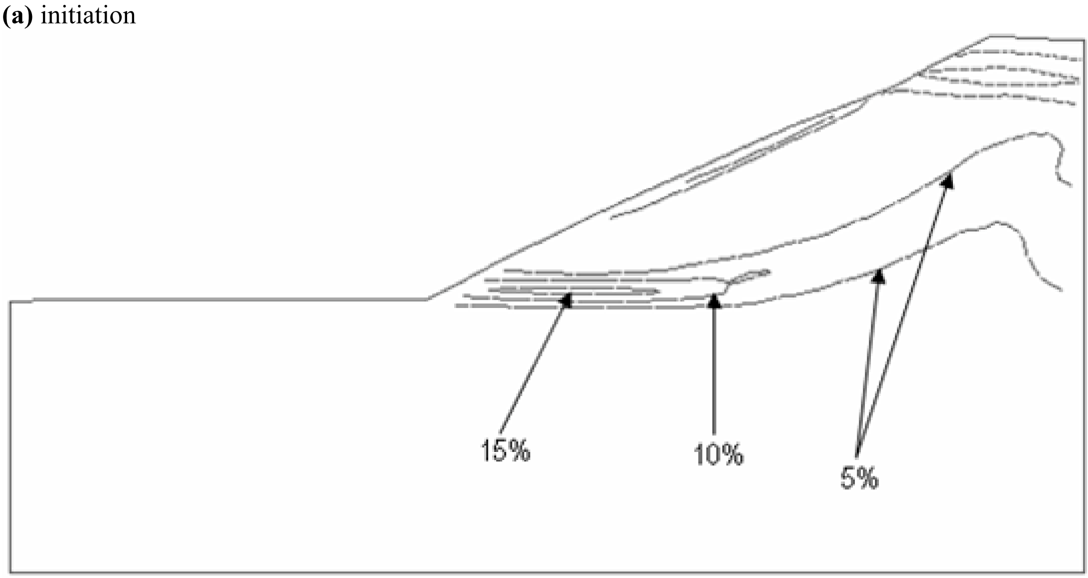


Figure 8. Displacement vectors for 9 ϕ' 17 c' 7.4kPa

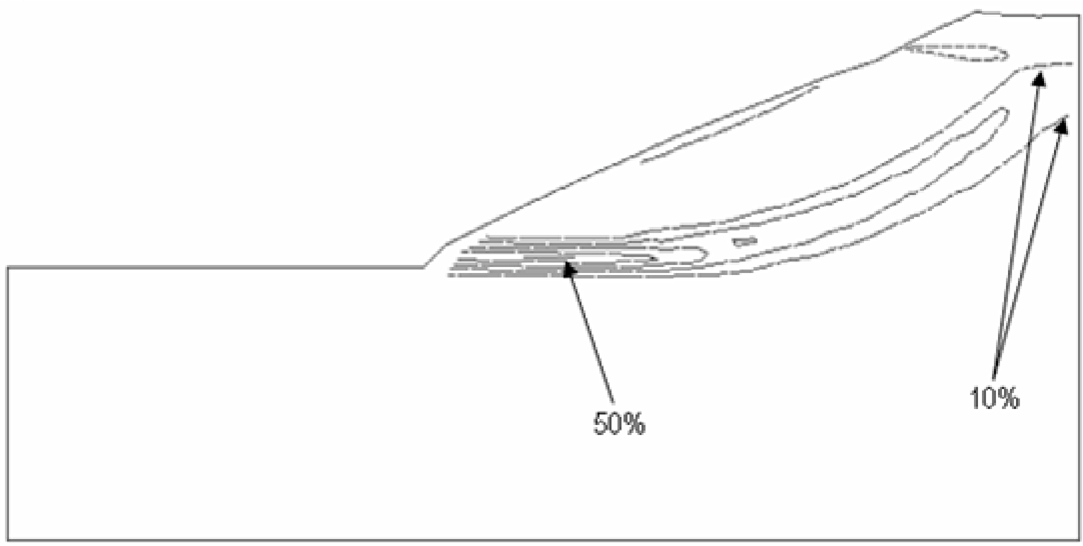
It can be seen from these plots that the slip plane forms relatively deeply within the embankment and there is some horizontal movement within the foundation. High shear strain first appears above the foundation near the toe (Figure 9 (a) which then spreads up towards the crest of the embankment ((b) and (c)). High shear strain does not appear within the higher strength rockfill at the crest of the embankment. It should be noted that, although the embankment model remains in equilibrium the high shear strains indicate the material will slip under these conditions.



(a) initiation



(b) exit at toe



(c) movement towards the crest

Figure 9. Shear strain development at year 9

The slip plane inferred from these profiles follows the line of the foundation before rising steeply towards the crest midpoint. The flatness of the slip plane at this point will be due to the change in material strengths at this boundary where the stronger foundation material shows greater resistance to shear.

The behaviour of this embankment is similar to the 10m high embankment with 1:2.5 side slopes modelled by Potts, Kovasevic & Vaughan (1993). Here, failure was predicted after 9.75 years. The pore water pressures distribution for this simulation is shown in Figure 7 and again is in qualitative agreement with that of Potts *et al.* (1993).

CONCLUSIONS

From the modelling that has been undertaken it would appear unlikely that the embankment would suffer from excessive deformation in the short term. The conditions that bring about large deformation are significantly reduced strength and several years of above average rainfall. It does, however, seem likely that there will be sufficient detectable movement in order to provide useful data for the validation of the computer models required to achieve all he aims of the BIONICS project.

Throughout the modelling exercise strength parameters have been assumed for the fill and foundation materials. As soon in-situ properties are established the critical simulations will be re-run. For the worst case scenario of bare slopes and increased future precipitation the minimum strength for the construction material is 7.4kPa and a 17° angle of friction. These properties represent a strength somewhere between peak and residual for compacted London clay. Preliminary testing of the compacted fill during construction indicates that the fill has shear strength properties significantly in excess of these.

Although the modelling approach used in this work had some significant limitations, it has produced failure modes that are comparable to Potts *et al.* (1993) who examined progressive failure in highway slopes. Similarities in the time taken from construction to failure were also found. The pore water pressure distributions of the SHETRAN simulations are also found to be in qualitative agreement with the predictions of Potts *et al.* (1993).

ONGOING WORK

The limitations of the coupling of SHETRAN and FLAC models have been identified and a revised approach is required in order to develop the model further. The FLAC two phase flow model is able to simulate water flow through the embankment fully coupled to the standard FLAC capabilities. The water flow through the embankment is simulated in a similar way to SHETRAN, however, the evapotranspiration and surface water flow processes are not simulated within the FLAC two phase flow model. It is planned to achieve this either by allowing SHETRAN to supply time series of percolation from the bottom of the rooting zone at various points along the side and top of the embankment, or to write a simple model to simulate evapotranspiration and surface water flows using the FISH model within FLAC. In both cases the FLAC two phase model will then simulate the water flow through the embankment fully coupled to the FLAC geotechnical model.

CONSTRUCTION OF THE EMBANKMENT

The site chosen for the embankment installation was Nafferton Farm, Stocksfield, Northumberland where Newcastle University School of Agriculture has on-site research facilities.

In order to achieve project aims and satisfy stakeholders fill for the embankment was specially selected. The chosen fill is of intermediate plasticity (plastic limit 17%, liquid limit 33%) sourced for BIONICS from a site 2 miles to the south of Durham city centre.

The test programme requires that the embankment be separated into 4 engineering test plots, two compacted to UK Highway specification and two to a lower standard more typical of older UK embankments. These sections were to be separated hydraulically. Achieving low compactions proved surprisingly difficult however, compaction difference was achieved by constructing the less compacted zones in 1 metre lifts with no rolling and minimal dozer tracking whilst constructing the highway specification zones in 300mm lifts, each layer then being compacted in 9 passes of a vibrating self propelled roller (Figure 10 shows the construction of the test zones). By using this technique dry densities in the well compacted zones averaged 1.7 Mg/m^3 (less than 3% air voids) whereas in the less compacted zones averaged 1.6mg/m^3 (5% air voids). Zones were separated hydraulically by placing a double layer of plastic membrane between them, achieved a vertical boundary by compacting alternate lifts against hay bails before raising the plastic membrane (see Figure 11).

During construction core samples were taken from each layer of the embankment for density measurement (in the case of the less compacted zones the samples were taken from pits dug 0.5m into each lift), samples were also taken for on site soil suction measurements. Soil suctions in excess of -600kPa were measured in the well compacted zones, lower suctions were recorded in the less compacted zones (more than -250 kPa). In addition to the density and suction tests a hand shear vane was used to check the shear strengths. In the well compacted zones strengths were in excess of the instruments operating range (>140kPa) were measured; in the less compacted zones strengths averaged approx 80-100 kPa.

Further testing of the embankment properties will take place in November/December 2005 when drilling for geotechnical instrumentation will take place enabling in-situ testing to be conducted and undisturbed samples to be taken.

Figure 10. Construction of the test zones (well compacted in the foreground)

Figure 11. Compaction around the membrane dividers

DEVELOPMENT OF METHODOLOGY TO IDENTIFY PARTS OF UK INFRASTRUCTURE REQUIRING FURTHER INVESTIGATION

The longer-term aim of the computer modelling is to incorporate the results from testing of the fully-constructed embankment and from centrifuge modelling also being carried out as part of the BIONICS project. Subsequently, the refined model will be run using data provided by the stakeholders from a small selection of typical embankments, and the possible impacts of different climate change scenarios would then explored through model simulations.

SPIN-OFF PROJECTS

So far two further projects have been funded by EPSRC that will use the embankment. The first entitled “Remote asset inspection for transport corridor environments” (led by Jon Mills at the University of Newcastle) will develop methods for intelligent analysis in transport corridor environments using integrated remote sensing techniques (including LiDAR, multispectral imagery and photogrammetry). The overall aim of the research is to improve the reliability, safety and profitability of transport networks through the identification of existing and potential slope stability hazards using integrated remote engineering surveying techniques. As part of this project, object recognition algorithms will be developed to identify the symptoms of slope instability and/or the presence of previous failures, using the embankment as a test site. A second project (led by Neil Dixon at Loughborough University) will be developing an acoustic means of detecting slope movement: trial instruments will be installed alongside the rest of the instruments for comparison purposes.

Acknowledgements: The financial support from EPSRC, the University of Newcastle upon Tyne (via the SRIF infrastructure fund) and the rssb are gratefully received. the support of the ukcip and other bkcc projects are also acknowledged. thanks are extended to all the researchers working on the project, particularly partners in the universities of Dundee, Durham, Bristol,Loughborough and Nottingham Trent. the invaluable contributions form all the bionics steering committee are also acknowledged, without which the project would not be able to fulfil its aims, in particular Tensar Ltd. who donated the reinforcement for the ends of the embankment**.**

Corresponding author: Dr Stephanie Glendinning, University of Newcastle, School of Civil Engineering and Geosciences, Newcastle upon Tyne, Tyne and Wear, NE1 7RU, United Kingdom. Tel: +44 1912226612. Email: stephanie.glendinning@ncl.ac.uk

REFERENCES

ALONSO E.E., GENS A. & DELAHAYE C.H. 2003. Influence of rainfall on the deformation and stability of a slope in overconsolidated clays: a case study. *Hydrogeology Journal,* **11**, 174–192.

ANDERSON M.G. & KNEALE P.E. 1980. Pore Water Pressure Changes in a Road Embankment. *The Journal of the Institution of Highway Engineers*, **27**, 11-17.

BATHURST J.C., EWEN J., PARKIN G., O’CONNELL, P.E. & COOPER, J.D. 2004. Validation of catchment models for predicting land-use and climate change impacts. 3. Blind validation for internal and outlet responses *Journal of Hydrology*, **287**, 74-94

BIRKINSHAW, S.J. & EWEN, J. 2004. *SHETRAN Version 5 Evaluation Modelling for Water Flow and Nitrate Transport in the Slapton Wood Catchment.* Report

DUNN, S.M. & MACKAY, R. 1995. Spatial variation in evapotranspiration and the influence of land use on catchment hydrology. *Journal of Hydrology*, **171**, 49-73.

EWEN, J., PARKIN, G. & O'CONNELL, P.E. 2000. SHETRAN: distributed river basin flow and transport modeling system. *ASCE J. Hydrologic Eng.,* **5**, 250-258

GELLATNEY, M.J., MCGINNITY, B.T., BARKER, D.H. & RANKIN, W.J. 1995. Interaction of vegetation and LUL embankment surface railway system in Vegetation and slopes. *In: Proc. Int. Conference*, *Oxford, UK,* 60-71.

HULME, M., JENKINS, G.J., LU, X., TURNPENNY, J.R., MITCHELL, T.D., JONES,R.G., LOWE, J., MURPHY, J.M., HASSELL, D., BOORMAN, P., MCDONALD, R. & HILL, S. 2002. *Climate Change Scenarios for the United Kingdom*. The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

KOVACEVIC, K., POTTS, D.M., & VAUGHAN P.R. 2001. Progressive failure in clay embankments due to seasonal climate changes. *In: Proc. 15th International Conference on Soil Mechanics and Geotechnical Engineering, Istanbul*. Balkema, Rotterdam, 2127-2130.

LEROUEIL, S. 2001. 39th Rankine lecture: natural slopes and cuts: movement and failure mechanisms. *Geotechnique,* **51**(3), 197–243.

O'BRIEN, A. 2001. *Personal communication.*

PERRY, J, PEDLEY, M. & REID, M. 2001. *Infrastructure Embankments - condition appraisal and remedial treatment.* CIRIA publication C550.

POTTS, D. M., KOVASEVIC, N. & VAUGHAN, P. R. 1993. *The design of slopes for highway cuttings and embankments of clay*. Report to the Transport Research Laboratory for the Ministry of Transport. Contract No 5530.

POTTS, D.M. & ZDRAVKOVIC, L. 2001. *Finite element analysis in geotechnical engineering: application***.** Thomas Telford, London.

POTTS, D.M., KOVACEVIC, N., & VAUGHAN, P.R. 1997. Delayed collapse of cut slopes in stiff clay. *Geotechnique,* **47**(5), 953-982.

RIDLEY, A. & PERZ-ROMERO, J. 1998. Suction-water content relationships for a range of compacted clays. *In: Proc. 2nd International Conference on Unsaturated Soil, Beijing, China,* **1**. International Academic Publishing House 249-254.

TOMLINSON, M.J. 2001. *Foundation Design and Construction.* 7th edition. Pearson Education Ltd. Essex.

VAN GENUCHTEN, M. TH. 1980. A closed-form equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America. J.,* **44**, 892-898.

VAUGHAN, P.R., SODA, V. G. & WALBANCKE, H.J. 1978. Factors controlling the stability of clay fills in Britain. *Clay Fills*, ICE, London, 205-217.