Climate change and slope stability – improving our forecasting capabilities



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ABSTRACT

Civil engineering infrastructure in the UK exists in many areas where marginally stable soils are found. Good design can reduce the risk of failure (both ultimate limit state and serviceability issues). Current long-term asset management is traditionally based on static/historical information, including the potential effects of climate and climate change. This is a risky approach, and planning requires better information on long-term changes in slope stability. This paper discusses collaborative research of five UK Universities who are working to better understand the influence of climate change and other environmental factors on the stability of slopes.

RÉSUMÉ

L'infrastructure de travaux publics dans le Royaume-Uni existe dans beaucoup de régions où les sols très légèrement fermes sont trouvés. Le bon design peut réduire le risque d'échec (tant état de limite ultime qu'éditions de praticabilité). La gestion d'actifs à long terme actuelle est fondée traditionnellement sur les informations statiques/historiques, en incluant les effets potentiels de climat et de changement climatique. C'est une approche risquée et la planification exige de meilleurs informations sur les changements à long terme dans la stabilité de pentes. Ce papier discute la recherche en collaboration de cinq Universités britanniques qui travaillent pour mieux comprendre l'influence de changement climatique et d'autres facteurs de l'environnement sur la stabilité de pentes.

1 INTRODUCTION

Climate change is occurring and is having an impact on the stability of slopes (CLIFFS 2008). The headline messages from current climate forecasts for the UK (UKCIP02, Hulme et al. 2002) include wetter winters, warmer and drier summers, and changes in the nature of precipitation (magnitude/frequency; Jenkins 2008, Street 2008). Current relatively extreme events are likely to become the norm in the future. For example the winter of 2000/1 was the wettest on record in some parts of the UK and rainfall caused more than 100 slope failures in the Southern Region of Railtrack alone. Heavy rainfall was also to blame for extensive slope failure in Scotland in 2001 and 2004.

Probabilistic forecasts of future climate in the UK will be delivered as part of the United Kingdom Climate Impact Programme (UKCIP08, delivery in late 2008; Jenkins 2008, Street 2008). These form a promising development in the quality of the climate data for input into slope stability models. For slopes where stability is controlled by pore water pressure, the direct and indirect consequences of climate change will be important. Failure mechanisms may change; some sites may become higher risk areas and increased seasonality may have serviceability consequences. Because of the complexity of the climate-vegetation-slope systems, it is not possible to quantify the consequences of climate change reliably to enable the prediction of the behaviour of long-term infrastructure earthworks to enable the design of appropriate solutions and efficient asset management strategies. In order to improve forecasting capabilities there is a need to concentrate on research filling in the gaps.

2 IMPROVING THE FORECASTING CAPABILITY

In the UK a concerted effort is being made to address the uncertainties in our slope models. This is, among others, reflected in the large multi-disciplinary membership of a UK-wide network focusing on Climate Impact Forecasting For Slopes (CLIFFS) based at Loughborough University. Frequent workshops served as platforms for exchanging ideas, achievements and the ways forward. This has resulted in the collaboration of several universities (Southampton, Newcastle, Durham, Loughborough and Queen's University Belfast). This paper reports on some of the outcomes from this research effort and aims to provide an insight into the work that is still needed to enable useful long-term forecasts of the stability of slopes. Due to the nature of the research of these universities, this paper is restricted to studies of infrastructure slopes in the UK.

2.1 Infrastructure earthworks and slope stability

Infrastructure slopes in the UK are generally old. Most railway embankments were constructed some 100 years or more ago using poorly compacted fill on ground surfaces that had seen little ground improvement or drainage. Highway embankments are younger (generally less than 50 years old) and are constructed using significant fill and/or natural ground that is well compacted and homogeneous, and are founded on natural ground that has seen significant improvements through removal and/or stabilisation of topsoil and weak strata.

The asset value of road infrastructure slopes is estimated at some £20bn (Glendinning et al. 2008) with projected asset life spans ranging from 60 years (highways) to 120 years (rail).

Common problems observed in these infrastructure slopes mainly involve shallow failures in both cuttings and embankments, particularly where these cross areas of existing slope failure (see Figure 1).



Figure 1. British Geological Survey map showing the distribution of landslide potential in the UK showing landslide potential in three classes; significant, moderate and low to nil).

Because of their age and relatively poor construction methods railway embankments are more prone to instability involving both shallow and deep seated failures in cuttings and, for embankments, significant additional problems in the form of track bed deformation. Continuous maintenance is required to avoid disruption and delays to the travelling public through serviceability problems and slope failures. This is costing the network operators many tens of millions of pounds per year (Perry et al. 2003). However, repairs responding to emergencies are generally tens times more expensive (O'Brien 2001). Deep-seated failures in highway slopes are not yet a major issue.

There also appears to be a regional differentiation in the nature of the problems. In Northern UK, problems tend to be drainage related, while in Southern UK, a wide range of problems exists, including both deep seated instability and seasonal deformation, mainly in clay slopes (Loveridge 2008, Manning et al. 2008). It is therefore prudent to enhance our understanding of the temporal and spatial changes in slope deformation so that the costs involved in operation and maintenance of the UK infrastructure network can be minimised.

2.2 Infrastructure cut-slopes - addressing the links between climate, vegetation and pore pressures

A key aim of the work currently undertaken is to link climate effects on pore water pressures using climatevegetation-soil moisture deficit models. The models are being developed and tested at a variety of sites in the UK with a range of soil types and climate conditions, varying from the warmer, drier region near London in South East of England, through to the cooler and wetter areas of north England and Northern Ireland. Once developed, these links will be used to model vertical and lateral displacements/stability to determine slope serviceability.

Time variant boundary conditions that replicate expected future climate scenarios will be used to investigate the effects of climate change on slope stability.

An example of research being carried out by the University of Southampton includes an instrumented site at Newbury in Southern England, a cut slope in London Clay constructed in 1997 with a shallow slope angle (~16°) and a vegetation cover of grass and small shrubs. This site has been continually monitored since 2002 with four groups of sensors arranged down the slope. These sensors record pore pressure, soil moisture content, runoff and climatic conditions. The shallow rooted vegetation typically dries the upper 1.0m of the soil profile when typical summer temperatures of 20-25°C create a soil moisture deficit. Figure 2 shows the winter-summer variation in soil moisture deficit and Figure 3 the associated changes in pore water pressures. A noticeable winter-summer cycle is present in most years, with the soil drying to a deficit of 150mm returning to saturation in the winter and negative pore water pressures of up to -70kPa in summer.

The data and modelling work to date shows that measured changes in soil water content can be well described using a daily water balance model for grass/shrub covered slopes. The season to season changes in the balance between rainfall and actual evapotranspiration depend on the soil type (water holding capacity), vegetation (root depth, plant type/robustness) and slope aspect (cooler on north facing slope).



Figure 3. Newbury pore water pressures.

The models have been run forward to the year 2095 using synthetic climate data sets based on the UK Climate Impact Programme for a range of CO_2 emission scenarios. The predictions for changes in climate at Newbury are expected to be warmer summers and slightly wetter winters, which would cause a greater soil moisture deficit in summer and possibly higher recharge or runoff in winter (Figure 4). These climate changes are relatively small, are expected to occur over a long time base and are similar in magnitude to inter-annual variability. This means that they may be difficult to separate from year to year variations.

The year on year climate change effects will be difficult to detect but cumulative effects will become apparent as winter rainfalls fail to re-wet the soil profiles and significant impacts may occur if the relative frequency of extreme events changes.

Measured climate and stochastically generated climate data sets were used to calculate the likely changes in soil moisture deficits and runoff from a London Clay slope between 1961-1990 and 2000-2095. Although the patterns of rainfall did not differ significantly between the two time periods, the simulations showed that temporal changes in rainfall and warmer summers will cause the maximum soil moisture deficit at the end of the summer to increase by 40mm, which will cause a larger seasonal cycle of pore water pressures.



Figure 4. Expected change in rainfall and potential evapotranspiration near Newbury.



Figure 5. Expected changes in frequency of maximum summer soil moisture deficit at Newbury, 1961-90 and 2100-2090.

The relative impact of these changes is illustrated in Figure 5 which shows a frequency analysis of historical (1961-1990) and predicted (21st century) soil moisture deficits. Two recorded exceptionally dry years (1995 and 2003) were chosen. In these summers, drying caused significant impacts such as slope desiccation, displacement of railway tracks and building subsidence. In 1995 the maximum soil moisture deficit was 172mm and equated to a 1 in 33 year event (3% probability) and the 2003 deficit of 152mm was calculated as a 1 in 10 year event (10% probability). When these are mapped on

to the expected pattern of maximum deficits in the 21st century the probabilities change from 3% to 50% and 10% to 90% respectively. This means that if the expected changes in climate do occur then what is at present a 1 in 33 year dry summer at Newbury is likely to become the average summer and a moderately dry summer (currently a 1 in 10 year event) is likely to occur 9 years out of 10.

2.3 Infrastructure embankments - learning from fullscale

In addition to the monitoring of 'real' infrastructure slopes, subjected to 'real' UK climate, a consortium of asset owners has been put together by Newcastle University to oversee the BIONICS (Biological and Engineering Impacts of Climate change Slopes; on www.ncl.ac.uk/bionics) research project. This is a four year programme that aims to establish a unique facility for engineering and biological research. This facility is in the form of a full-scale, fully instrumented embankment, with climate control over part of its length. A diagram of the embankment is shown in Figure 6. Thus, the facility allows the control of the climate necessary to study the effects of future climates, coupled with a fully characterized engineering soil and vegetative cover.



Figure 6. BIONICS embankment plan.

After consultation with academic and industry stakeholders a final design for the embankment was selected to be representative of UK transport infrastructure. The embankment is 90 meters long and has been constructed in two distinct parts. Half of the embankment is constructed to modern highway specifications using modern compaction plant (0.3m lifts, 18 passes with a vibrating roller), and half has been constructed to poorer specification using as little compaction as possible in order to simulate older rail embankments (1m lifts, minimum tracking with construction plant). Core cutters were used during construction to assess the levels of compaction being achieved in each of the test sections of the embankment. As can be seen in Table 1 higher densities were achieved in the "well" compacted sections of the embankment although the difference was smaller than had been anticipated from laboratory testing.

Table 1. Summary of core cutter density results.

Characteristics	"Poor" compaction	Good compaction
Bulk Density (Mg/m ³)	1.93	2.01
Water Content (%)	20.7	20.1
Dry Density (Mg/m ³)	1.6	1.7
Air voids (%)	6.0	3.2
Degree of saturation (%)	85.3	91.4



Figure 7. Pore pressures embankment core: 09/06-12/06



Figure 8. Pore pressures embankment core 08/07-11/07

Since the construction was completed the embankment has been extensively instrumented with extensometers, inclinometers, flushable piezometers, and soil suction tensiometers. The data from these instruments shows that both settlement and slope movement so far has been low. The pore pressure within the embankment has been more active however. During construction negative pore pressures were measured in both the "well" and "poorly" compacted parts of the embankment.

Figures 7 and 8 show pore pressures recorded in the two sections of the embankment 12 months after the compaction was completed. As can be seen in Figure 7 the pore pressure recorded in the core of the embankment was positive 12 months after construction. Readings taken between August and October 2007 from the same positions show that the core of the embankment is now in suction. It is believed that the construction process and foundation conditions contributed to the dissipation of the initial high negative pore pressures. The establishment of vegetation has now begun to generate negative pressures once more, albeit much lower values.

In addition to the geotechnical instrumentation installed within the embankment BIONICS is also host to several spin off projects, including the Remote Asset Inspection for Transport Corridors project headed by John Mills at Newcastle University. As part of this project the embankment is routinely surveyed using GPS and Terrestrial Laser Scanning technology. These tools are being developed to be used in network scale assessments of transport infrastructure. A typical output from the terrestrial laser scanner is shown in Figure 9.



Figure 9. 3-D model from terrestrial laser scan of BIONICS embankment.

Additional instrumentation has recently been installed (principally standpipe piezometers and theta probes) to obtain further data on infiltration rates and soil permeability. These additions coincide with the recent installation of a climate control system which is being used to simulate extreme rainfall events over half the length of the embankment. Ground temperature and water content probes have also recently been installed along with 2 mini weather stations which are used to calculate evapotranspiration and determine the effects of slope aspect on water content and pore pressure. Figure 10 shows data from the first month of recording, the plot shows a clear positive difference in temperature between the North and South aspect, which will result in different rates of evapotranspiration. Figure 11 shows water content results from theta probes installed near the surface of the embankment against antecedent rainfall.



Figure 10. Ground temperature of north and south facing slopes.



Figure 11. Soil water content variation in well compacted zone.

Numerical analysis has shown that the permeabilities measured in the laboratory do not reflect the mass characteristics of the embankment therefore further analysis of field permeability will form part of the inundation tests. It is intended to repeat in-situ permeability tests throughout 2008 in order to investigate temporal variability. Also in 2008 a cover system will be in operation over part of the embankment length enabling drought conditions to be simulated. In the longer term it is hoped that the BIONICS embankment will be used for further spin-off projects.

2.4 Detailed pore-water pressures analyses

One of the gaps in knowledge of slope stability issues is the likely range of pore-water pressures (or suctions) that exist in slopes in the UK, and how these change with seasons and over longer timescales. To be able to develop adequate numerical models to help in forecasting the response to future events, we need good quality data that can be used to calibrate our models against current events. The BIONICS project is one of the case studies where such data is now being collected.

One of the limitations in measuring negative porewater pressures (suctions) has been the fact that conventional tensiometers cannot measure suctions below -100kPa (as cavitation occurs within the measuring system at lower pressures). However, there is now a generation of high capacity tensiometers that can be used to measure suctions directly, even down to -2MPa (Toll et al., 2008). The high capacity tensiometers used in the BIONICS embankment were jointly developed by Durham University and Wykeham Farrance Limited (Lourenço et al., 2006). The design of the tensiometer is based on the same principles as the suction probes first produced by Ridley and Burland (1993) but the manufacturing process is entirely novel. The tensiometer developed by Durham University and Wykeham Farrance Limited can measure water pressures down to -2 MPa.

For use in the field, tensiometers were installed in a borehole probe locator as described by Mendes et al. (2008). Such a design allowed each tensiometer to be

inserted and removed individually whenever necessary (for example if re-saturation was necessary). The borehole locator consisted of a 3m long PVC tube with 70mm internal diameter containing five guide tubes (made of reinforced flexible plastic) with 19 mm internal diameter. The ends of each guide tubes exited through holes drilled in the probe locator at depths of 0.5m, 1m, 1.5m, 2m and 3m respectively. An aluminium fitting at the exit of the guide tubes helped to hold the tensiometer in place. The tensiometer cables were enclosed in a stiff nylon tube that allowed the tensiometer to be pushed through the guide tube and into contact with the soil.

Two probe locators each containing five tensiometers were installed in April 2007. One probe locator was installed in a "well compacted" panel of the embankment and the other in a "poorly compacted" panel. The suction measurements recorded in the well compacted panel (panel B) are shown in Figure 12. Measurements appear to be quite consistent with time and respond as expected to wet and dry periods. Inspection of the pore water pressure profiles at different times (see Figure 12) indicates that pore-water pressure tends to decrease with depth attaining a value of about -30 kPa at 3m.

Quite a different picture is shown for the poorly compacted panel (panel B) in Figure 13 compared to the data obtained in the well compacted panel. One significant difference is that the tensiometers show a notably faster response and register larger changes of suctions during rainfall events with respect to the well compacted panel. In addition, unlike the well compacted panel, the response to rainfall events appears to be different in magnitude and direction at different depths.

It should be noted that the measurements reported here were made following the wettest summer in the UK for 250 years. Therefore, it is likely that the relatively small values of suction observed (<40 kPa) are a result of this very wet period and it might be expected that larger suctions will be observed during a dryer summer season.



Figure 12. Chronological variation of pore water pressure at different depths in the well compacted panel (shown together with daily rainfall).



Figure 13. Chronological variation of pore water pressure at different depths in the poorly compacted panel (shown together with daily rainfalls).

2.5 Long-term pore pressure monitoring

Elevated as well as pore-pressure cycling are both responsible for decreases in soil strength and the stability of slopes (Potts et al. 1997). Recent studies in Northern Ireland have been directed towards investigating the effects of rainfall events on the long term stability of cuttings on both railway and road infrastructure. Cuttings in glacial till have been investigated by Queen's University Belfast in detail and long-term monitoring of near surface pore pressure changes have been recorded and correlated with rainfall events (Hughes et al 2001, Clarke et al 2005).

Climate change in Northern Ireland is characterised by greater inter-annual variation in precipitation and evapotranspiration, with minimal overall annual variation. This inter-annual variation has caused more extremes in weather, and more prolonged dry and wet periods.

The current and future increase in frequency of extreme events will have detrimental effects on the long term stability of slopes. If the magnitude and frequency of both climate events and pore pressure responses increase, there will be a subsequent increase in the number of progressive slope failures. Pore pressure response to rainfall is a function of initial soil moisture conditions, rainfall intensity, time, slope permeability and slope depth. The relative importance of these parameters is being evaluated at a site of a major road cut through a glacial till deposit (drumlin) at Loughbrickland, Northern Ireland (Figure 14).



Figure 14. Loughbrickland, NI, site photograph (10-2004).

Installing piezometers that will survive for very long periods (e.g. 10 to 20 years) and monitoring pore pressures over the full range of conditions (i.e. prolonged wet winter to dry hot summer) is crucial in assessing the long-term stability of slopes. The monitoring data from these pore pressure observations can be used to assess the stability and serviceability of earthworks and prioritise these for remediation. The experimental programme at Loughbrickland Drumlin is providing preliminary insights into the factors influencing the groundwater flow system and the interaction between climate and pore pressure dynamics.

Antecedent rainfall is one of the crucial factors in determining the initial soil moisture conditions and subsequently the pore water response to rainfall. Figure 15 shows the pore pressure responses to rainfall events, clearly indicating the significant time lag that increases with depth.

The occurrence of pronounced groundwater peaks rapidly following precipitation events is greatly dependent upon the initial groundwater conditions. The 1m unsaturated zone between the phreatic surface and ground surface remains at a high level of partial saturation, and therefore only requires low levels of rainfall to cause significant pore pressure responses. For example, the near surface layer with a water content of approximately 25% and a porosity of 35% only has 10% volume available to reach saturation. An infiltration of 100mm will therefore lead to a tenfold increase in pressure head.



Figure 15. Pore pressure responses to rainfall in the Loughbrickland Drumlin.

Despite the increasing frequency of slope failures and the subsequent public safety and financial implication of slope failures, there are still many failures caused by changes in hydrogeology that still remain unanswered. Monitoring the conditions of old cuttings and embankments is a vital exercise in understanding these processes and will contribute significantly to maintaining the integrity of the UK transport infrastructure.

3 CONCLUSIONS

It is now increasingly accepted that creating slope stability models based on static information such as fixed recharge boundary conditions calculated from past behaviour is no longer acceptable for the long-term forecasting of responses of slope systems to climate change. Model building needs to incorporate the observed seasonal and short term behaviour of pore water pressures in slopes to create non-steady state systems which can then be simulated with sequences of possible future climate scenarios relevant to the longterm responses of slope systems. Once a better, formalised, set of scenarios of climate-vegetation-slope interactions has been developed, it is proposed to develop flexible models based on UKCIP08 probabilistic outputs of climate change. In turn, this could then lead to the development of solutions for the optimum design and management of slopes.

REFERENCES

- CLIFFS 2008. A collection of workshop presentations and other documents related to climate forecasting for slopes in the UK can be downloaded from cliffs.lboro.ac.uk
- Dijkstra, T. and Dixon, N. 2007. Networking for the future – addressing climate change effects on slope stability. *Proceedings Int. Conf. on Landslides and Climate Change: Challenges and Solutions*, Isle of Wight, UK, May 2007 (CD).

- Dijkstra, T.A., Dixon, N., Forster, A. and Connel R. 2007. Climate change impact forecasting for slopes (CLIFFS) in the built environment. IAEG proceedings paper 528 (CD).
- Glendinning S., Hughes, P. N., Hughes, D.A.B., Clarke, D., Smethurst, J., Powrie, W., Dixon, N., Dijkstra, T.A., Toll, D.G., and Mendes, J. 2008. Biological and engineering impacts of climate on slopes – learning from full-scale. *Procs.* 10th International Symposium on Landslides and Engineered Slopes, Xi'an, China, July 2008.
- 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. 120pp
- Jenkins, G. 2008. New scenarios of UK climate change. CLIFFS symposium presentation, February 2008, Loughborough, UK.
- Lourenço, S.D.N., Gallipoli, D., Toll, D.G. and Evans, F. D. 2006. Development of a commercial tensiometer for triaxial testing of unsaturated soils. *Proc. Fourth International Conference on Unsaturated Soils*, Carefree, Arizona, USA, Geotechnical Special Publication No. 14., Reston: ASCE, Vol.2, pp. 1875-1886.
- Loveridge, F. 2008. *Climate change and infrastructure slopes what does it all mean*? CLIFFS symposium presentation, February 2008, Loughborough, UK.
- Manning, L.J., Hall, J.W., Kilsby, C.G., Glendinning, S. and Anderson, M.G. 2008. Spatial analysis of the reliability of transport networks subject to rainfallinduced landslides. *Hydrol. Processes.* Published online in Wiley InterScience. DOI: 10.1002/hyp.6927
- Mendes, J., Toll, D.G., Augarde, C.E. and Gallipoli, D. 2008. A System for Field Measurement of Suction using High Capacity Tensiometers. *Proc. First European Conference on Unsaturated Soils*, Durham, UK, July 2008.

O'Brien 2001 Personal communication.

- Perry J., Pedley M. and Reid M. 2003 Infrastructure embankments: condition appraisal and remedial treatment. CIRIA Report C592. Construction Industry Research and Information Association, London.
- Ridley, A.M. and Burland, J.B. (1993). A new instrument for the measurement of soil moisture suction, *Geotechnique* 43, No. 2, 321-324.
- Street, R. 2008. Using UKCIP08: challenges and opportunities. CLIFFS symposium presentation, February 2008, Loughborough, UK
- Toll, D.G., Lourenco, S.D.N., Mendes, J., Augarde, C.E., Cui, Y.J., Tang, A.M., Gallipolli, D., Rojas Vidovic, J.C., Pagano, L., Mancuso, C., Zingariello, C., Tarantino, A., Hoffmann, C. and Pozzato, A. 2008. Soil suction monitoring for landslides. *Geophysical Research Abstracts*, 10: European Geosciences Union General Assembly EGU2008-A-05915 (abstract only).