Landslides and Engineered Slopes – Chen et al. (eds)

Biological and engineering impacts of climate on slopes – learning from full-scale

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ABSTRACT: Our climate is set to change significantly over the next century; future change is likely to have a serious effect on UK slopes. The scenario of hotter drier summers, followed by more intense periods of rainfall has the potential to reduce stability by increasing degradation mechanisms and/or increasing positive pore water pressure generation. There is evidence that the scenario of more intense rainfall is already having an impact on the UK slopes. However, there is also potential for stability to be improved through the generation of greater suctions during longer periods of drought. Newcastle, Southampton, Belfast, Durham and Loughborough Universities have all been carrying out research into the impacts of climate and vegetation on embankment and cut slope stability. These five Universities, along with international partners in Canada, Singapore, China, South Africa, France and Portugal, are conducting a collaboration programme the aim of which is to link research groups undertaking full-scale monitoring of slopes to improve the understanding of the complex interaction between climate, vegetation and clay soils. This paper presents results of current full scale infrastructure slope monitoring and model development at the involved universities and plans for future collaborations.

1 INTRODUCTION

The climate of the UK is set to change significantly over the next century, and is likely to have significant effects on the stability of both natural and man-made slopes.

Future UK climate change scenarios predict consistent and significant increases in temperature of up to 3°C on average in south-east UK (Hulme et al., 2002). Predicted changes in rainfall are less consistent, but key aspects are: little change or small increase in annual rainfall; a general increase in winter rainfall and decrease in summer rainfall.

This is likely to increase the rate at which certain clay soils degrade by increasing the amplitude of the seasonal shrink swell cycle. Thus failures governed by progressive failure mechanisms have the potential to increase in frequency. Increased periods of summer drought will cause clay soils to shrink, leading to surface cracking, potentially increasing surface permeability. The more intense periods of Autumnal rainfall will then allow pore pressures to increase more rapidly within slopes, triggering more failures.

There is evidence that the scenario of more intense rainfall is already having an impact on the UK 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 occurred in the Southern Region of Railtrack alone.

However, there is also evidence that the pore suctions generated by dry (summer) weather conditions control the long-term ultimate limit state stability of clay slopes (Loveridge & Anderson, 2007). It is therefore possible that drier summers will actually *increase* the stability of clay slopes. Additionally, if a similar amount of annual rainfall occurs as at present, but is experienced as shorter, more intense events, it will lead to less of the rain entering the soil as more is lost as run-off. This again could improve stability overall.

In either case, the study of the interactions of climate and pore water pressures in slopes is key to determining their long-term future stability. This paper sets out to explain how this problem is being addressed through the combined efforts of a consortium of UK-based universities.

2 COMMUNICATION AND NETWORKING

The nature of the problem of climate impacts on slopes is such that it affects many different stakeholders and end-users. The problem is also being approached from many different angles and with different objectives in mind. It thus forms a very broad multi-disciplinary field in which geographers, mathematicians, statisticians, physicists, engineers, ecologists, hydrologists, etc. try to work out their own particular problem angles and seek to forge links to provide a broader solution than would be achieved individually. This is not always easy as specialists speak different (scientific) languages and do not always share the same philosophical approach to problem solving.

With this in mind the network CLIFF*S* (climate impact forecasting for slopes) was funded by the UK Engineering and Physical Sciences Research Council (EPSRC) in 2005 to bring together academics, research and development agencies, stakeholders, consultants and climate specialists. The main aim of bringing these people together is to stimulate an integrated research response to address the intricately linked problem of forecasting, monitoring, design, management and remediation of climate change induced variations in slope instability. The size of the task and the complexity and multi-disciplinary nature of the problem requires active participation of a wide group to assess the magnitude of the resulting impact on UK society and to identify appropriate management and remediation strategies to achieve a better insight into the links between climate change and slope stability in the UK, firstly there is a need to determine the information requirements and, secondly, a need to focus research efforts on targeted assessments of long-term scenarios. Although detailed processes or individual site conditions are being addressed, general process-response issues are still not well understood or researched—a problem exacerbated by poor communication in this multi-disciplinary field (Dijkstra & Dixon 2007).

CLIFF*S* is managed by Loughborough University and is supported by a large core group of academic institutions (including the Authors') and stakeholders. It currently has more than 150 members, mainly from the UK. It operates by organizing multi-disciplinary themed workshops and by providing a web-based information exchange facility. Workshop themes have included issues of risk and uncertainty, and aspects of the responses of natural and constructed slopes to changes in climate. Details of these workshops can be accessed at the network's website on cliffs.lboro.ac.uk. Whilst current membership is mainly UK based, CLIFF*S* is seeking new international members in order to learn from the experience of both researchers and practitioners who deal with slopes in a wide range of soils and vegetation, subjected to different climates.

3 CURRENT UK RESEARCH

Five universities, Newcastle University, Queens University Belfast, University of Southampton, Loughborough University and Durham University have all been carrying out research into the impacts of climate and vegetation on embankment and cut slope stability. This has already included field instrumentation work to measure seasonal moisture and pore water pressure changes in a number of embankments and cut slopes, back analysis and numerical modelling.

The research has started to give a more detailed picture of embankment response (lateral and vertical deflections) to seasonal variations of both moisture content and pore water pressure. The behaviour of these embankments is complex, and in terms of trying to model their behaviour there are still many challenges to be overcome. Recent work has shown that the numerical models are very sensitive to the values and distributions of parameters such as permeability, which in a clay embankment can vary considerably as a result of summer desiccation and cracking close to surface, and the nature and compaction of the clay fill. It is possible that a very dry summer followed by a wet winter is most critical for stability, as the summer cracking allows a path for rainfall infiltration. However, this is still not well understood.

Future changes in climate in the UK are likely to lead to more extreme rainfall events with higher intensity storms. Such rainfall events are common in the tropical regions of the world and the team is drawing on collaborative work in Singapore, Thailand, China, Canada and Hong Kong.

The five universities recently received a major travel grant from the Engineering and Physical Sciences Research Council (EPSRC). This will allow the team to visit and build better links with both UK and overseas infrastructure owners and research organizations.

The Roads Service in Northern Ireland (Department for Regional Development in Northern Ireland) and Northern Ireland Rail are funding Queens University Belfast to develop a risk based method of assessment of the geotechnical infrastructure on the Northern Ireland road network following a major slope failure on the road network in 2000 (Hughes et al, 2007). As part of this research programme a cutting on the A1, 4 miles south of Dromore has been heavily instrumented (Clarke & Hughes et al 2005).

Pore water changes were recorded during the excavation of the cutting and currently much data is being gathered on the pore water dynamics forced by rainfall and evapotranspiration effects (Figure 1). A transient predictive model incorporating climate events has been calibrated and verified against the field data using GeoStudio 2004. GeoSlope International (from Calgary, Alberta, Canada) have been supporting the project with technical assistance and the provision of the latest modelling software.

Southampton University has been carrying out intensive monitoring of soil moisture and pore water pressures at a Highways Agency owned road cutting near Newbury in Southern England since 2002. The climate is temperate with average annual rainfall of 850 mm, summer temperatures of $+20°C$ and winter temperatures of 0–3°C. An array of 40 sensors were inserted in five groups along a cut slope in the London Clay, vegetated with a mixture of short grass and small bushes up to 0.5 m tall. Data were recorded for soil moisture content using Time Domain Reflectrometry (TDR) in the upper layers of the soil (0–2.5 m) below the surface. Pore water pressures were also monitored using Vibrating Wire Piezometers. Readings have been made every 10 minutes since 2002.

Hydrological inputs and losses at the site have been measured, including rainfall, surface runoff, depth to saturation together with climatic parameters to estimate potential evapotranspiration (temperature, humidity, wind speed, solar radiation). Soil characteristics have been determined using both field and laboratory approaches and the soil moisture sensors were calibrated using gravimetric methods and backed up with regular neutron probe measurements

Figure 2 shows the variation in volumetric soil moisture content (m^3/m^3) between 0.3 and 1.5 m depth This long term monitoring clearly shows the cyclical changes between summers (warm and relatively dry) and winters (cool and relatively wet). Most drying occurs in the upper 1.0 m of the soil profile, where the roots from the vegetation are most active. The maximum drying usually occurs at the end of summer in September (month 9), followed by a rapid re-wetting of the profiles in November-January. Also apparent is the effect of the climatic patterns of different years; 2003, 2005 and 2006 were relatively dry in the summer whereas 2004 and 2007 had higher than average rainfall.

Figure 3 shows the associated variations in pore water pressures for the same period. Near hydrostatic conditions occur in the winter months (November-March) but the seasonal growth of vegetation between April and September dries the soil and negative pore water pressures develop up to 2.5 below the surface. Suctions of up to -70 kPa are recorded at 1.0 m depth and we have recorded suctions as high as -400 kPa 30 cm using some temporary instruments. The magnitude and duration of the negative pore water pressures varies from year to year, again depending on the climatic conditions experienced.

A series of hydrological and numerical models have been developed to describe and explain the behaviour of the processes at the site. Figure 4 shows the result of a Soil Moisture Deficit model based on the FAO CROPWAT methodology. The losses of moisture from the soil profile are calculated based on evapotranspiration and a root zone model and converted to an equivalent pore water pressure. These have been used to validate a FLAC model of the slope.

This work has demonstrated the use of hydrological models in describing the surface boundary conditions and their impacts on pore water pressures.

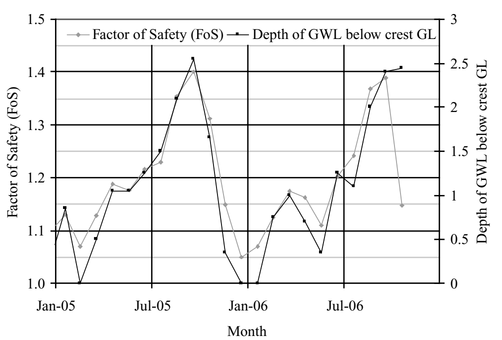

Figure 1. Monthly fluctuation of GWL.

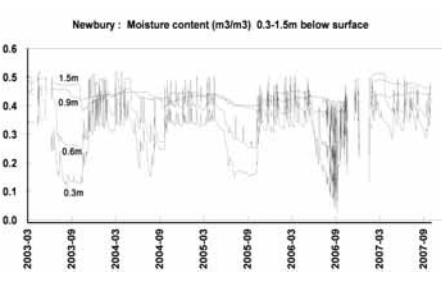

Figure 2. Moisture content (m^3/m^3) 0.3–1.5 m below surface.

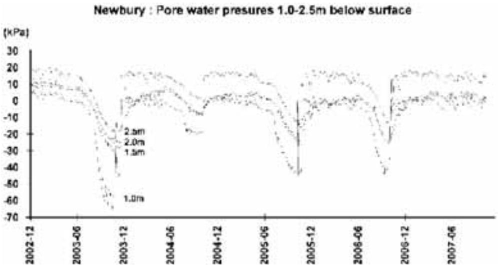

Figure 3. Pore water pressures 1.0–2.5 m below surface.

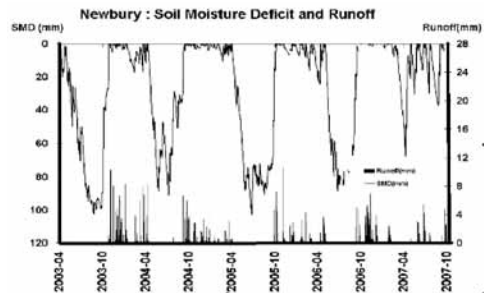

Figure 4. Soil moisture deficit and run-off.

These models are being used to explore the impact of many years repeated cycling of wetting and drying on the slope stability and UKCIP climate change scenarios are being using to investigate the long term performance of the slopes.

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 on Slopes; 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. 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. A database of embankment performance data is being compiled of the results of testing and monitoring during both the construction and the climate experiments. This unique set of data, describing the full history of the embankment will be available for all future research based at the facility. 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, and half has been constructed to poorer specification using as little compaction as possible in order to simulate older rail embankments.

Data from the in-situ testing conducted on the embankment during its construction utilizing high suction tensiometers developed at Durham University (Lourenço et al, 2006) has demonstrated that high negative pore pressure were generated during the construction process. Figures 5 and 6 show suctions measured in the "poor" and "well" compacted zones respectively. These tests clearly indicate that modern construction techniques generate higher soil suctions than older methods.

Piezometers installed after construction have shown that the initial soil suctions had in part dissipated six months after construction was complete. Now that vegetation has become more established on the embankment soil suctions of up to −30 kPa have been measured in both poor and well compacted sections at 4.5 m depth using fully flushable piezometers. An additional system for measuring soil suctions, developed by Durham University has been installed in the BIONICS embankment using

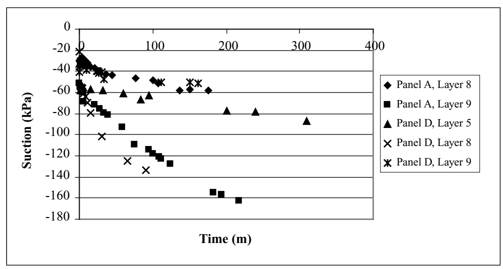

Figure 5. Suctions measured during construction of the poorly compacted sections.
Note: Section constructed in 1 m layers, beginning with layer 1.

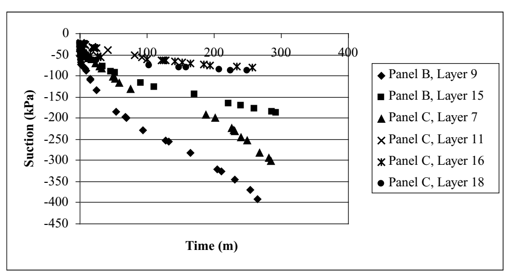

Figure 6. Suctions in the well compacted sections.
Note: Sections constructed in 0.3 m layers.

Wykeham Farrance—Durham University tensiometers (Mendes et al, 2008). The borehole locator system allows readings at different levels in a single borehole, permitting observations of the variation of suction with depth. It also allows tensiometers to be removed for resaturation whenever necessary. The wide measuring range of the tensiometers (down to -2 MPa) allows usage of such a system in most natural and manmade earth structures.

Preliminary results (from three months of monitoring) show that there are different patterns of suction measurements from the tensiometers installed in the well compacted section of the embankment compared to those installed in the poorly compacted section (Mendes et al, 2008). It has been observed that tensiometers installed in the poorly compacted section of the embankment react rapidly to rainfall. The well compacted section instead shows a slower change of suction and does not respond rapidly to rainfall.

Currently a climate control system is being constructed, consisting of flexible, roofing sections that can be pulled over the embankment when required (similar to those used to cover sports facilities), and arrays of computer controlled rainfall sprinklers mounted on poles. Automatic weather stations will monitor wind speed, net radiation, temperature, relative humidity and atmospheric pressure, with tipping bucket and storage rain gauges to measure rainfall rates and totals. The performance of the proposed arrangements will be measured to ensure that it provides the climatic conditions required. In particular, the heating effect provided by covering (and leaving covers in place over night to prevent heat loss) will be compared to the temperatures predicted by climate change. This system will then be used to study the response of the embankment and the vegetation to controlled patterns of rainfall and heating.

Associated with the BIONICS project is an EPSRC funded research project at Loughborough University to develop novel instrumentation to detect slope instability (Dixon & Spriggs 2007). A real-time continuous slope monitoring system based on detection and quantification of acoustic emission generated by slope deformations is currently being trialed on the BIONICS embankment. Performance of the acoustic system is being compared to traditional deformation measurement techniques including in place inclinometers. Acoustic emissions are related to slope deformation rates. The system is sensitive to both small magnitudes and rates of displacements and the technique has potential to provide an early warning of instability. This too will be monitored closely during the controlled climate experiments.

Durham University has been studying rainfall-induced slope failures in collaboration with Universities in Singapore and Thailand who currently experience more extreme patterns of rainfall and temperature. Experience in both countries is that there has been an increase in landslide activity associated with increased rainfall events (Toll et al, 2008; Jotisankasa et al, 2008).

Rainfall has been the dominant triggering event for landslides in Singapore and Thailand. Studies show spates of landslides occurring after unusually wet periods. Observations of past landslides in Singapore suggest that a total rainfall of 100 mm within a six day period is sufficient for minor landslides to take place (Toll, 2001). In Thailand, a total rainfall of 150–400 mm would tend to trigger major landslides (Jotisankasa et al, 2008).

Measurements of pore-water pressures in slopes in Singapore and Thailand show that rainfall infiltration produces changes in pore-water pressure near to the surface. However, at greater depths (around 3 m) the pore-water pressures do not change significantly (Tsaparas et al, 2003). Numerical modeling shows that this is because water tends to flow down the slope within the zone of higher saturation (which has higher permeability) that develops near the surface (Tsaparas and Toll, 2002). As a result, rainfall-induced failures tend to occur within the near surface zone and are not usually deep-seated.

Pore-water pressures measured within slopes in Singapore (Tsaparas et al, 2003) were, for a large part of the monitoring period, only slightly negative and at 3 m depth were generally positive. However, there were periods during the year when pore-water pressures reduced significantly following a drier period. Pore-water pressures dropped to as low as -70 kPa near the surface (0.5 m depth). Interestingly, this is similar to the values of suction measured at similar depths by Southampton University in very different climatic conditions in the UK. However, piezometer data in Singapore shows that there was little change in ground water table level (which remained below 15 m depth). Therefore, these suction changes were the result of infiltration and evapotranspiration occurring at the surface and were not due to changes in water table.

Therefore, it is important that when studying climate effects on slopes that we do not always assume that rainfall will produce a rise in water table level. Infiltration of rainfall at the surface can produce significant changes in pore-water pressure without a change in water table (although a perched water table may be induced at the surface).

Field measurements in Singapore suggest that pore-water pressures do approach the hydrostatic condition near the surface due to infiltration (Toll et al, 2001). However, pore-water pressures remain significantly below the hydrostatic line, even at the wettest time of the year. Therefore, assuming that pore-water pressures were hydrostatic throughout the slope (as would often be assumed in a saturated soil analysis) would be over-conservative.

Work is now underway with the National University of Singapore to investigate the impact that future climate change will have on Singapore, including slope stability problems (Toll et al, 2008).

4 CONCLUSIONS

There is compelling evidence that our climate is changing and that this change will have a significant impact on the behaviour of slopes globally. In the UK, there is sufficient concern for the owners and operators of its transport networks to be actively funding research to investigate the problem. However, it has been recognized that the problem of climate influences on slopes is a sufficiently complex problem that a much greater understanding of the problem can be gained by sharing the existing knowledge from a wide range of disciplines. The CLIFF*S* network has been funded to facilitate such an exchange of ideas. Additionally, there is much to be learned by exchanging ideas on an international scale where researchers necessarily have been determining the effects of a range of climates, vegetation and soil types. This exercise is currently being kick-started using a travel grant awarded to five UK-based Universities. The rewards, in terms of shared experience and improved understanding are only just beginning to be realized and it is anticipated that the shared experience will provide a more complete picture of the impacts of climate (and climate change) on slopes.

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