Climate change and the role of unsaturated soil mechanics

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ABSTRACT: The Intergovernmental Panel on Climate Change (IPCC) provides convincing evidence of global warming as a result of increased greenhouse gas production. There has been a greater occurrence of extreme climate events in recent decades. We need to ensure that our buildings and infrastructure can cope with such events and possibly more extreme events in the future. A good grounding in unsaturated soil mechanics will be necessary to understand future changes involving the drying and desiccation of soils that will occur in dry seasons and the wetting and infiltration processes that prevail during wet seasons. To predict the impacts of climate change will require the use of robust numerical modelling of climate/soil interactions that can be used to model the effects of future climate regimes. To achieve this we need high quality field observations involving climate/soil interaction that can be used to validate the models. This paper reports on a study in the UK to acquire such data.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (IPCC, 2007) provides convincing evidence of global warming as a result of increased greenhouse gas production since the start of industrialisation in 1750. The implications of this, as the report states, are: "Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century".

While it is recognised that there is considerable uncertainty in future climate predictions, the IPCC provides a generally held consensus view that the world is warming and that anthropogenic greenhouse gas emissions are the primary cause. Even those who do not accept this conclusion have to recognise that we have seen greater occurrence of extreme climate events in recent decades.

In Thailand in 2011, heavy monsoon and tropical cyclone rains from July to October caused extreme flooding in Bangkok. In Singapore, December 2006 was the wettest on record (766 mm monthly rainfall) since recording of rainfall started in 1869 (NEA, 2006). In the UK, the winter of 2000/1 was the wettest on record and the period May-July 2007 was the wettest for 250 years (leading to extensive flooding in parts of the UK). Whether or not these extreme events are attributable to global warming is not important; they are the realities of our current climate and we need to ensure that our buildings and infrastructure can cope with such events and possibly more extreme events in the future.

Changes in climate are likely to lead to changes in soil conditions. For the scenario predicted for some parts of the world, where winters become wetter but summers become drier, this will result in greater extremes of wetting and drying. A good grounding in unsaturated soil mechanics will be necessary to understand the drying and desiccation of soils that will occur during dry seasons and the wetting and infiltration processes that prevail during wet seasons.

To predict the implications of future climate change will inevitably require the use of numerical modelling based on anticipated future climate regimes. To achieve this it is vital that the models used are validated against measurements from the past and present. This means such studies must involve field measurements of responses to current climate as well as the development of modelling methodologies that can deal with the complexity of climate/soil interaction.

This paper reports on a study underway in the UK to examine the effects of climate change on slopes. The project has involved constructing an instrumented embankment equipped with a system of sprinklers and covers to control climatic conditions. This paper presents the results of monitoring of pore-water pressure carried out between September 2007 and March 2009.

2. CLIMATE CHANGE

The IPCC 4th Assessment Report (IPCC, 2007) identifies the likely regional changes expected over one hundred years by comparing models calibrated against data for 1980 to 1999 with climate projections made with the same models for 2080 to 2099. The predictions are based on Atmosphere-Ocean General Circulation Models (GCMs) that aim to capture the behaviour of the global climate system. However, since these models operate at grid scales of 400 to 125 km there can be significant uncertainty about the smaller scale climate changes. Techniques are available for downscaling from the large-scale GCMs. Empirical Statistical Downscaling methods can make use of observed local data to provide access to finer scales. However, use of empirical data may not recognise long-term changes in the larger scale weather systems. An alternative is to use Dynamic Downscaling which involves running high-resolution climate models that are formulated using physical principles. However, these are computational very expensive and there is further uncertainty that they may be operating outside their range of operating parameters for predicting future events.

The IPCC 4th Assessment Report reports on expected changes to both temperature and precipitation. Figures 1 and 2 show just the predicted precipitation changes in Asia and Europe, showing the annual mean change and also the predicted changes for the December-January-February (DJF) period [Boreal (northern hemisphere) winter or Austral (southern hemisphere) summer] and the June-July-August (JJA) [Boreal summer or Austral winter].

The overall assessment for precipitation changes in Asia in the 4th Assessment Report is:

"Precipitation in boreal winter is *very likely* to increase in northern Asia and the Tibetan Plateau, and *likely* to increase in eastern Asia and the southern parts of Southeast Asia. Precipitation in summer is *likely* to increase in northern Asia, East Asia, South Asia and most of Southeast Asia, but is *likely* to decrease in central Asia."

For Europe the assessment is:

"Annual precipitation is *very likely* to increase in most of northern Europe and decrease in most of the Mediterranean area. In central Europe, precipitation is *likely* to increase in winter but decrease in summer. Extremes of daily precipitation are *very likely* to increase in northern Europe. The annual number of precipitation days is *very likely* to decrease in the Mediterranean area. Risk of summer drought is *likely* to increase in central Europe and in the Mediterranean area."

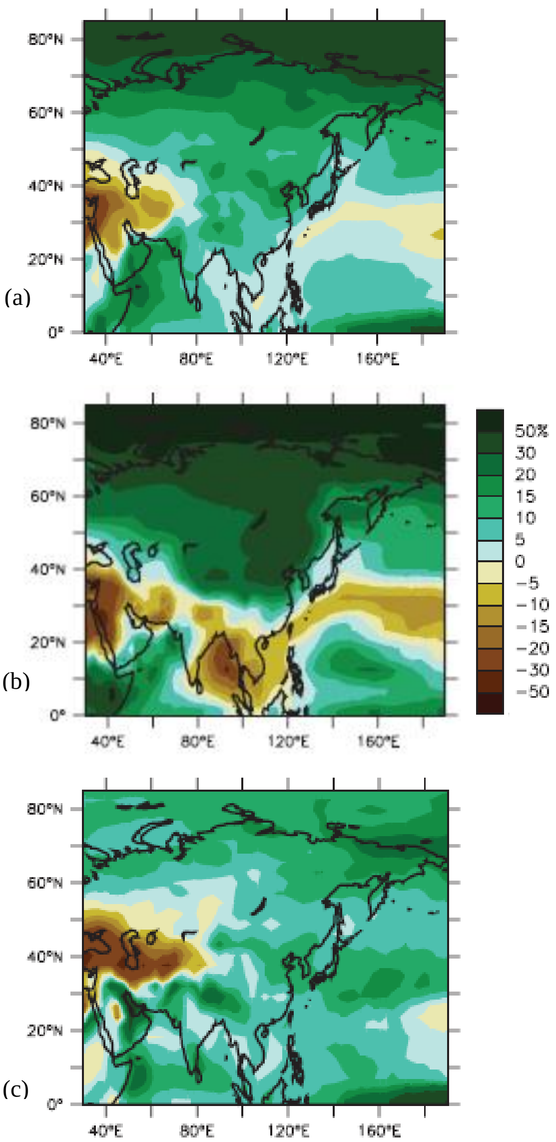

Figure 1. Predicted precipitation changes in Asia from 1980/1999 to 2080/2099 (a) Annual mean change (b) Dec-Jan-Feb (DJF) change (c) June-July-August (JJA) change (IPCC, 2007)

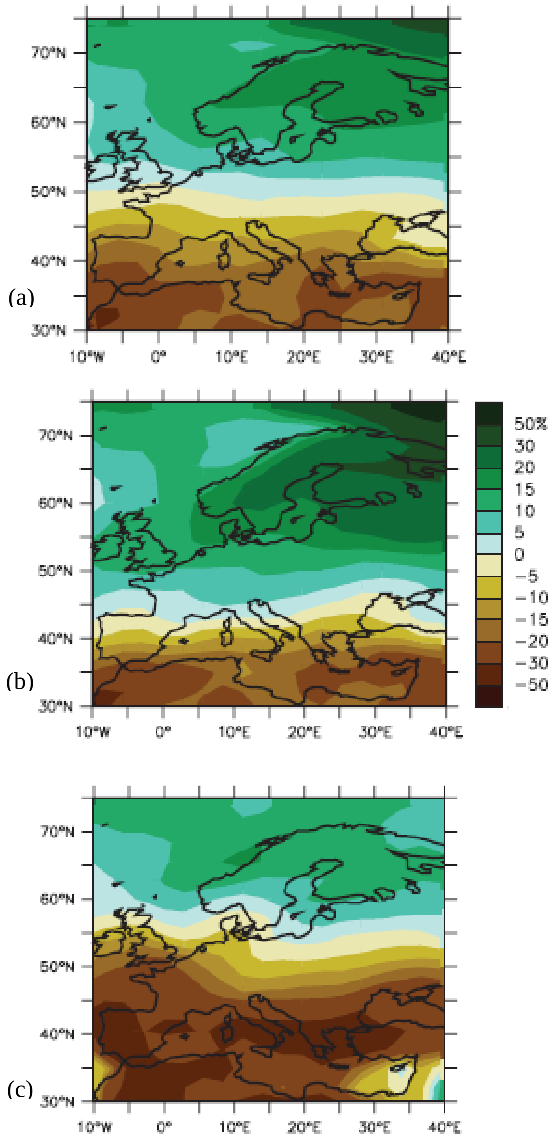

Figure 2. Predicted precipitation changes in Europe from 1980/1999 to 2080/2099 (a) Annual mean change (b) Dec-Jan-Feb (DJF) change (c) June-July-Aug (JJA) change (IPCC, 2007)

3. SOIL RESPONSES TO CLIMATE CHANGE

A major concern that engineers face with assessing earth structures is whether structures can deal with the current climate patterns and if they will maintain their serviceability when faced with different climate patterns. Models of climate change predict that parts of Europe (including the UK) could face more extreme rainfall events during winter periods (involving more intense rainfall) and also longer dry spells during summer seasons. Climate change therefore has the potential to have significant effects on the stability and serviceability of earth structures (Kilsby et al., 2009).

Smethurst and Clarke (2007) have looked at the implications of climate change in the UK on the likely changes in soil water content, using the concept of Soil Moisture Deficit (SMD). SMD is the amount of water required to reinstate the soil profile to field capacity. Field Capacity is the water content held in the soil after excess water has drained away under gravity and if the soil were to achieve equilibrium with no significant downward (or upward) flow. A SMD of greater than zero represents a non-equilibrium state where suctions will develop trying to draw water into the soil.

Smethurst and Clarke (2007) used climate data from London Heathrow for the period 1960-2005 to estimate SMD values using a water balance calculation that considers the surface moisture inputs and outputs in the form of rainfall infiltration and evapo-transpiration by plants. These estimates showed good agreement with measured water contents in a London Clay site.

BETWIXT (a weather generator based on the Hadley 2002 model, Watts *et al.*, 2004) was then used to model future climate events and hence SMD. Figure 3 shows that the average SMD for each year increases from about 65mm for the period 1960–2005, to almost 100mm close to 2100. This shows the greater and longer extent of summer drying than occurs at present.

The greater extent of summer drying with the same winter wetting would indicate future larger annual cycles of moisture and displacement. Smethurst and Clarke suggest that the implications of these modelling results are:

- greater clay shrinkage for longer periods in the summer
- average shrink-swell cycles will increase in magnitude
- some existing vegetation may die off, and be replaced with drought tolerant plants
- vegetation cover may decrease, leading to greater surface erosion in winter
- average winter runoff reduces

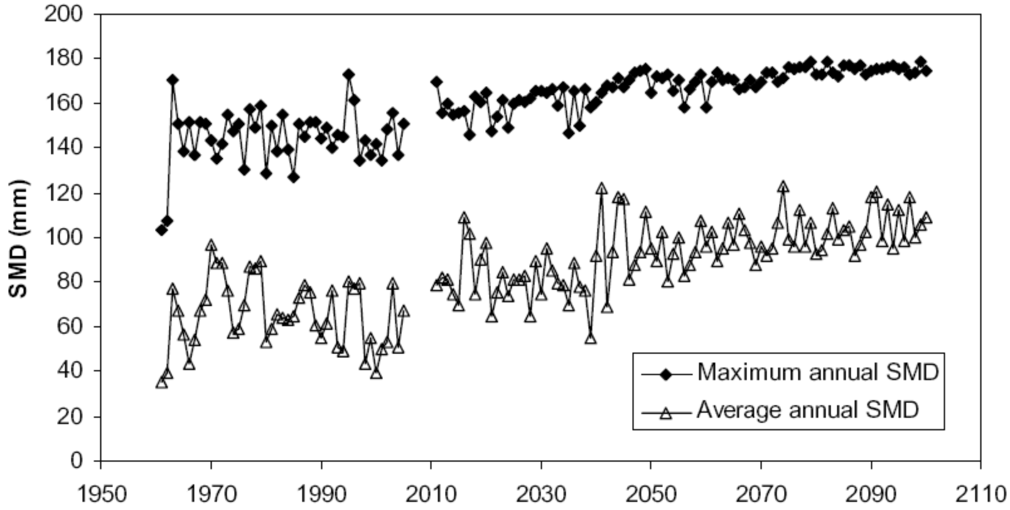

Figure 3. Maximum and average annual Soil Moisture Deficit for London using measured climate 1960–2005, and BETWIXT future climate data set for medium high emissions 2010–2100 (Smethurst and Clarke, 2007)

4. THE BIONICS PROJECT

The BIONICS project (Biological and Engineering Impacts of Climate Change on Slopes: http://www.ncl.ac.uk/bionics) is a large cooperative research project involving academic partners and industrial stakeholders focusing on the effects of the expected climate change on infrastructure embankments (Hughes et al., 2009). As was stated in the introduction, it is vital that we carry out such studies to obtain field measurements of responses to current climatic conditions that we can use to validate numerical models. This will allow us to develop robust numerical models that we can use to predict the response under anticipated future climate scenarios.

BIONICS is a £1.1M ($1.8M) project, largely funded by the Engineering and Physical Sciences Research Council (EPSRC), looking at the potential impacts of climate change on UK infrastructure slopes. It is a collaboration between the Universities of Bristol, Dundee, Durham, Loughborough, Newcastle upon Tyne and Nottingham-Trent.

The BIONICS project has involved constructing an instrumented embankment to investigate the response to changing climatic conditions. The embankment has been equipped with a system of sprinklers and covers to control climatic conditions. It has been instrumented with piezometers, tensiometers, water content and temperature sensors, inclinometers and extensometers. This paper presents the results of monitoring of pore-water pressure carried out between September 2007 and March 2009.

The BIONICS embankment was built at Nafferton farm near Newcastle upon Tyne and construction was completed in November 2005 (Hughes et al., 2009). The embankment dimensions are 90 m long by 6 m high with side slopes of 1 in 2 (V:H) and a 5 m wide crest. The end slopes of the embankment were constructed with reinforced soil with an inclination of 45o.

The embankment was divided into six different sections or panels (not including the end slopes) as shown in Figure 4. The four central panels were 18 m long and were constructed to represent two different types of construction methods ("well compacted" and "poorly compacted" as will be defined later). The outermost panels (each 4 metres in length) were for biological studies.

The "poorly compacted" panels (Panels A and D in Figure 4) were constructed using limited compactive effort to represent railway embankments from over 100 years ago when much of the UK railway network was built. These panels were placed in 1 m lifts and were simply compacted using a tracked hydraulic excavator; plant movement on the panel was kept to a minimum to limit compaction as much as possible. The "well compacted" panels (Panels B and C) were constructed to represent modern highway embankments using current highways specifications for compaction. Layers were compacted according to Method 3 as set out in the Highways Agency Specification for Highway Works (Highways Agency, 1998). The fill was placed in 300 mm layers and was subjected to 9 passes by a self propelled vibrating smooth drum roller.

Vertical impermeable membranes were placed between panels and end slopes to ensure engineering and hydraulic isolation. At the top of the embankment a 0.5 m thick capping layer of coarse fill (crushed basalt) was built. The coarse, free draining material was placed in order to simplify boundary conditions by preventing surface cracking on the crest of the embankment but still to allow water access into the embankment.

5. THE FILL MATERIAL

The fill material used to build the BIONICS embankment was a glacial till (Durham Lower Boulder Clay), a common fill material in the North East of England and hence representative of earthwork

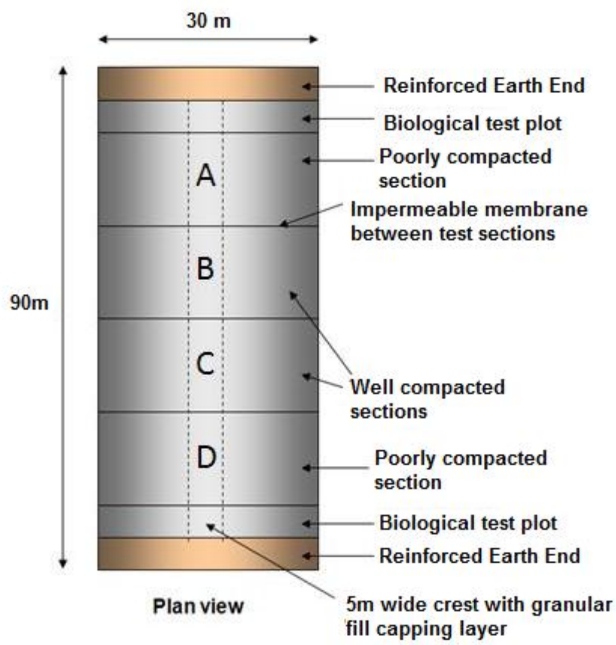

Figure 4. Plan view of the BIONICS embankment

construction. The fill material can be classified as a sandy clay of intermediate plasticity.

During construction, density measurements were taken to assess the field compaction level (Hughes *et al*., 2007). The construction was performed wet of optimum, with water contents ranging from 16% to 24%. Most of the measurements in the well compacted panels showed densities of 94-101% of Maximum Dry Density (MDD) from laboratory light compaction (average 99%). However, a small number of measurements on layers compacted nearer to optimum (with water content below 17%) showed densities near to MDD for heavy compaction (equivalent to 106% of MDD from light compaction). The densities achieved for the poorly compacted panels were 90-99% of MDD from light compaction (average 94%).

A laboratory permeability test on fill material from a well compacted panel showed a saturated permeability value, k_s= 8.77x10^{-11} m/s while a laboratory measurement on the material from a poorly compacted panel gave a result of k_s = 1.6x10^{-10} m/s.

6. INSTRUMENTATION

The instrumentation at the BIONICS embankment comprised inclinometers, extensometers and piezometers commonly found in instrumented embankments and also devices for monitoring the suction and water content changes. The instrumentation arrangement for the well compacted panel B is shown in Figure 5.

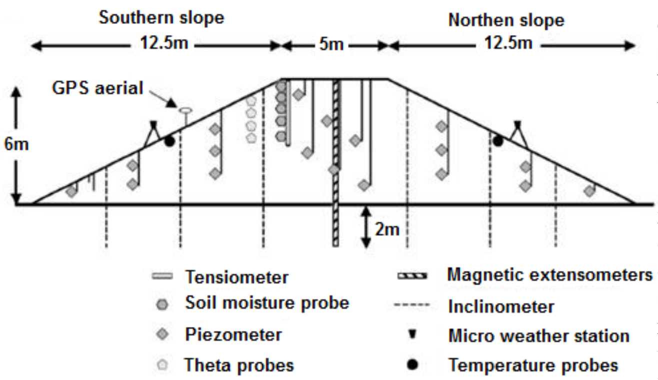

Figure 5. Instrumentation arrangement for a well compacted panel

Extensometers were installed at the centre of the crest in each panel, inclinometers were installed in both the North and South slopes (a total of six per panel) and standpipe piezometers were spread out through the embankment to measure pore-water pressure.

The specialised equipment included tensiometers and flushable piezometers for measurement of suction. This paper describes in detail the installation of high capacity tensiometers (suction probes) developed by Durham University. In addition, flushable piezometers from Geotechnical Observations (GeO) capable of measuring negative pore-water pressures down to -100 kPa were installed. High capacity suction probes (Ridley and Burland, 1993) from GeO were also available for measurements in dry vertical boreholes. Further instrumentation included Theta probes and moisture profile gauges to measure volumetric water content. Collection points were used to determine the surface runoff (located near the base of the slope).

Three different weather stations were used to monitor the climate at the embankment. One of the weather stations was located 300 metres from the embankment and monitored the annual weather pattern (i.e. rainfall, air speed etc); this station complies with Meteorological Society Guidelines (Overton, 2007). The other two weather stations (micro weather stations) were installed on top of the North and South slopes of the embankment; these did not fully comply with Meteorological Office guidelines but were deliberately positioned closer to ground level in order to capture the differences in climate between different faces of the embankment. The latter two weather stations were used to monitor the local climate effects, most particularly when the climate control system was in operation.

7. CLIMATE CONTROL SYSTEM

A climate control system was developed for the embankment to be able to impose different scenarios predicted for climate change. The system employed at the BIONICS embankment can recreate extreme scenarios; designed to reproduce intense rainfall and dry events. To reproduce extreme rainfall events, rainfall sprinklers mounted on poles were installed on panels A and B. The location of the sprinklers across the embankment ensured a spatially uniform rainfall at the ground surface with appropriate droplet sizes.

To reproduce dry events, segments of the embankment were covered with a retractable transparent flexible cover system. With this design, precipitation from natural climate events could be prevented from reaching the embankment. Due to its proximity to the surface (1 m above the ground) temperature loss was also greatly reduced. By reducing infiltration and by inducing a small increase in temperature, higher rates of evaporation could be generated to represent drying conditions.

8. HIGH CAPACITY TENSIOMETERS

A novel experimental set-up for field monitoring of soil suctions was developed for the BIONICS project (Mendes *et al*., 2008; Toll *et al*., 2011). The experimental set-up used Durham University-Wykeham Farrance (DU-WF) high capacity tensiometers (Lourenço *et al*., 2006) to provide real-time continuous measurements of suction inside the embankment. The wide measuring range of the tensiometers (suctions of 2 MPa) allows the monitoring system to be used in most natural and constructed earth structures.

The tensiometers were installed with the help of a *probe locator* (Figure 6), which consisted of a 3 m long PVC cylinder buried in the ground. The probe locator had an outer diameter of 90 mm and an inner diameter of 70 mm. Four small openings existed on the sides of the probe at depths of 0.5 m, 1 m, 1.5 m and 2 m (Figure 6b) with one further opening on the bottom cross-section at a depth of 3 m (Figure 6c). Each of these openings was connected to the surface by means of a flexible hose with an inner diameter of 19 mm. The flexible hoses ran inside the probe locator and served as guides for inserting or removing tensiometers (Figure 6a). These guide hoses were fitted at the bottom extremity with a cylindrical clasp made of aluminium, which tapered the inner diameter from 19 mm down to 14 mm and fitted tightly around the tensiometer preventing movement of soil inside the guide. The inner space at the top of the probe locator was injected with silicone and foam to seal the gap around the guide hoses, to avoid any infiltration of water or other kind of material from the surface.

The tensiometers were fitted with a nylon tube (over the electrical cable) which was glued to the back of the tensiometer. This nylon tube had a twofold function, to facilitate insertion and removal of each tensiometer individually and to protect the electrical connection. In case of cavitation or fault, tensiometers could be easily removed from the ground by pulling the nylon tube to which they were strongly attached. After re-saturation or repair, it was also possible to install the tensiometer back in the ground by pushing the nylon tube until the tensiometer was firmly inserted in the cylindrical clasp at the end of the guide hose. The nylon tube, which has outer and inner diameters of 8 mm and 6 mm respectively, was sufficiently stiff to allow a considerable force to be applied during installation without buckling. The tensiometer casing was smoothed to remove sharp edges to allow easy removal and insertion.

Electrical cables from each tensiometer ran through the guide tubes inside the probe locator and were connected to a logging unit sited on the embankment crest. The logging unit was in turn connected to a personal computer, hosted in a nearby hut, which read the suction data and transmitted it by means of an internet broadband connection. This allowed remote real time records of the suction profile to be obtained with time as well as with depth.

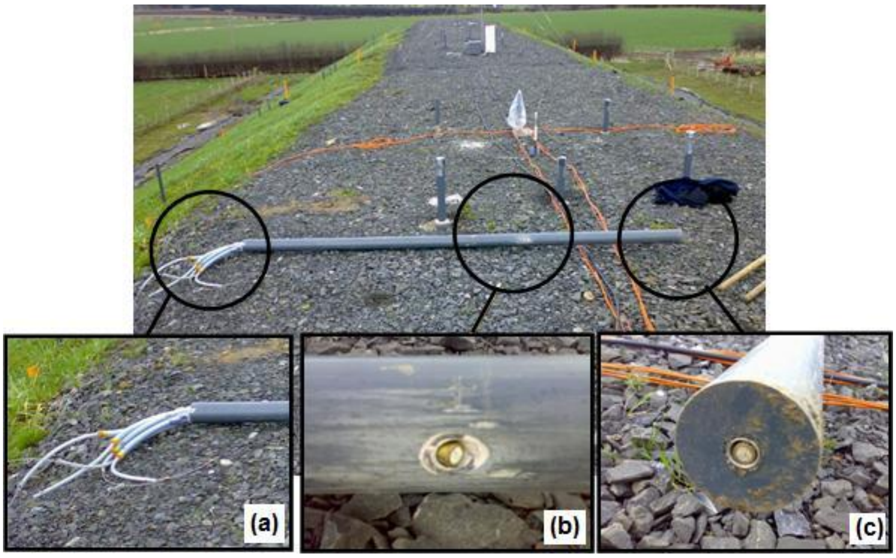

Figure 6. Probe locator for installing high capacity tensiometers in the embankment

Two probe locators were installed in February 2007 in two sections of the BIONICS embankment, one in a well compacted section and one in a poorly compacted section. It was initially intended to grout the probe locators in place. However, measurements of suction across specimens of grout (Mendes, 2011; Toll et al., 2011) showed that the grout was unable to transmit suctions in excess of 600 kPa when placed in contact with soil. This means that suction values measured through such a grout could give a false reading at these higher suction levels and could underestimate the true suction in the soil.

Given that it was initially uncertain whether suction levels in the embankment would exceed this limit, it was cautiously decided not to seal the gap by using the cement-bentonite grout but rather to rely on the natural closure of the borehole around the probe locator. Adequate sealing around the probe locator was later confirmed by pumping out water from the location of one tensiometer. There was no response shown by adjacent tensiometer positions, confirming there was no preferential connection path along the sides of the borehole locator.

9. RESULTS OF FIELD MONITORING

Field monitoring was performed using the Durham University-Wykeham Farrance tensiometers at the BIONICS embankment. The system to measure pore-water pressure was installed in April 2007. Figure 7 shows continuous measurements for the period of October 2007 to March 2009 for a well compacted panel. Although high suctions (>150 kPa) were measured on the embankment during construction in 2005 (Hughes et al., 2007) the values since November 2007 were small (less than 20 kPa). Such low values of suction might be expected as the period May-July 2007 was the wettest on record for 250 years and caused extensive flooding in the UK. September 2008 was also a very wet month, with 158 mm of rainfall and this followed a period May-July 2008 when artificial inundation was applied with the climate control system, totalling 456mm. The responses do demonstrate that the tensiometers were able to record positive pore-water pressures as well as suctions.

The profile of pore-water pressures with depth for a well compacted panel is shown in Figure 8. For reference, a hydrostatic pore-water pressure line is shown in the figure, referenced to zero pore-water pressure at the top of the clay embankment i.e. assuming no pore-water pressure would build up in the 0.5m thick coarse ballast layer. It can be seen that the initial pore-water pressures show generally positive values in the upper 3 m of the embankment although suctions exist at 4.5 m depth (measured by flushable piezometers). These lower values could represent construction induced suctions, but are also likely to be affected by under-drainage of the embankment by field drains. The initial values are lower than hydrostatic conditions, even in the upper 3 m.

By December 2007, the pore-water pressure profile had increased somewhat, but still falls below the hydrostatic line. However, by January 2008, after a period of heavy precipitation, pore-water pressures near the surface (0.5 and 1 m depth) rose above the expected hydrostatic condition. They approach a hydrostatic profile defined by a water table above the top of the clay, suggesting that the coarse (ballast) layer had become flooded and water pressures had built up within this layer.

By March 2008, pore-water pressures had dropped back to similar values to December 2007. Then in June 2008, after artificial inundation using the climate control system, pore-water pressures rose again to approach the upper hydrostatic profile with the coarse ballast layer flooded. By December 2008, after 6 months of only natural precipitation, pore-water pressures had dropped back again to similar values to December 2007. By March 2009, values had dropped back further to some of the lowest values since the initial installation. This was the result of a dry winter period with little rain from mid December 2008 until end of January 2009.

These results show the cycles of pore-water pressure that might be expected in an embankment, with higher pore-water pressures (near to hydrostatic) during winter months (typically January) falling back to lower values in March. Lower values might normally be expected during summer months, but the climate during the summers of 2007 and 2008 were “untypical” with high levels of summer rainfall (as noted earlier, the period May-July 2007 was the wettest summer period on record in the UK for 250 years). Also, artificial inundation was applied to the embankment during the period May-July 2008.

Further monitoring over coming years will now be required to understand the pore-water pressure responses to rainfall over the longer term. A dry summer would be particularly welcome to give an indication of the generation of suctions during a dry period.

10. NUMERICAL MODELLING

The monitoring described in this paper will be used to calibrate a numerical model that couples the unsaturated flow with the geo-mechanical behaviour of the fill material. The model has been described by Rouainia et al. (2009) and makes use of a combined hydrological model (Shetran) and a geotechnical model (FLAC). Laboratory data on the soil water retention behaviour and constant water content triaxial tests carried out on unsaturated specimens will be used to identify the geo-mechanical properties (Mendes, 2011). The triaxial tests were carried out on specimens that have been subjected to wetting and drying after compaction.

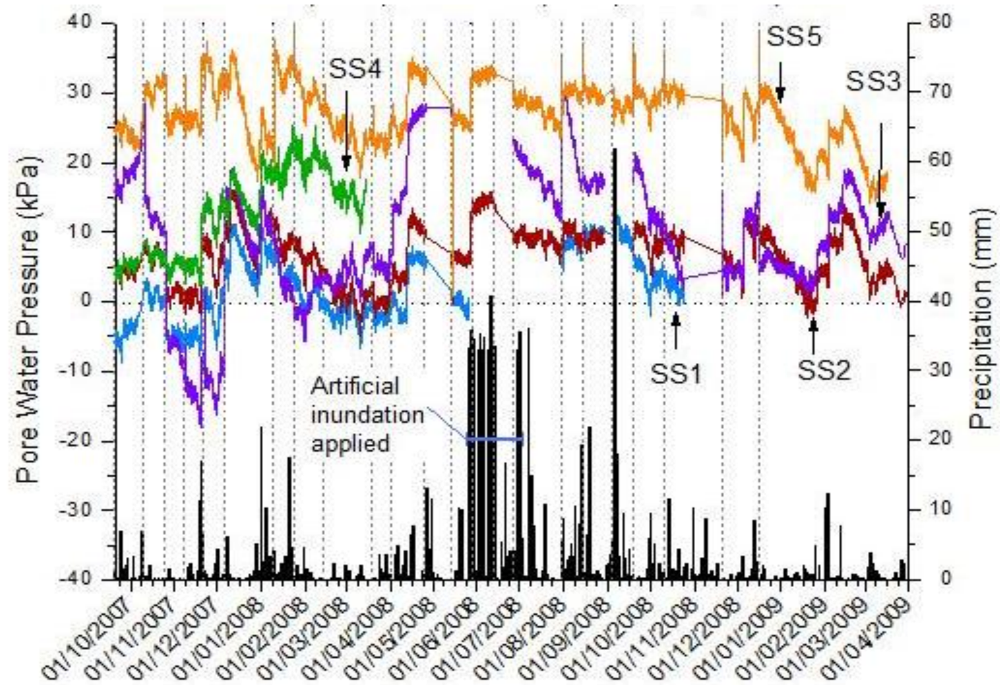

Figure 7. Results of field monitoring using DU-WF tensiometers (SS- suction station)
SS1 (0.5m), SS2 (1.0m), SS3 (1.5m), SS4 (2.0m), SS5 (3.0m). Bar graph shows precipitation.

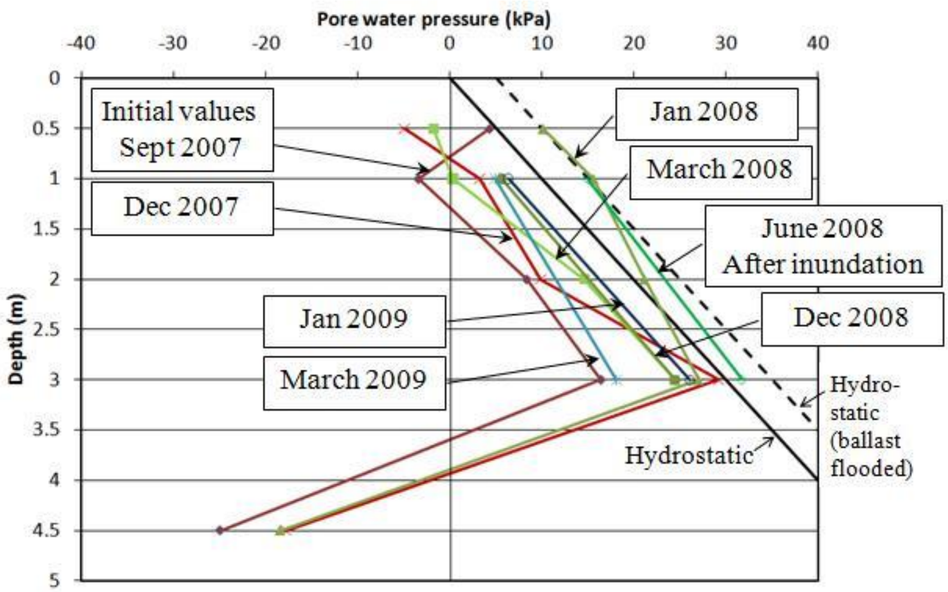

Figure 8. Pore-water pressure profiles with depth for the period 2007 to 2009

One of the major uncertainties in modelling infiltration and runoff on clay slopes is the permeability and how this changes with water content and with time. The unsaturated permeability to water can drop by 4-5 orders of magnitude relative to the saturated permeability as the soil desaturates. The near surface permeability also changes temporally as desiccation cracks form and as vegetation develops and creates root passages. Tsaparas and Toll (2002) found that near surface permeability values needed to correctly predict infiltration rates in numerical models were 2 orders of magnitude higher than values measured in the field below the surface desiccated zone.

These uncertainties make it difficult to undertake numerical prediction of the soil responses based only on laboratory data. Therefore, the numerical model has to be calibrated against field monitoring to ensure that the soil water retention properties and permeability functions adopted are able to correctly model the observed responses.

Once the model has been calibrated against current climate conditions, it can then be used to predict changes that might occur in the future. The climatic conditions for modelling future scenarios will be generated using the weather generator described by Kilsby et al. (2007). The use of this generator for modelling the impacts of climate change on slopes is described by Davies et al. (2008).

11. SUMMARY AND CONCLUSIONS

To predict the impacts of future climate change will require the use of robust numerical modelling of climate/soil interactions. Such models will have to be based on a good understanding of unsaturated soil mechanics that can describe the drying and desiccation of soils that will occur in dry seasons and the wetting and infiltration processes that prevail during wet seasons. To achieve this we need high quality field observations involving climate/soil interaction that can be used to validate the models.

The BIONICS project (Biological and Engineering Impacts of Climate Change on Slopes) is a research project in the UK with the aim to develop such a high quality data set. The project has involved constructing an instrumented embankment equipped with a system of sprinklers and covers to control climatic conditions. It has been instrumented with piezometers, tensiometers, water content and temperature sensors, inclinometers and extensometers.

A novel experimental set-up for field monitoring of soil suctions has been developed for the BIONICS project. The system allows multiple tensiometers to be used within a single borehole and can provide continuous measurements with time and at different depths.

12. REFERENCES

Davies, O., Rouainia, M. and Glendinning, S. (2008) Numerical predictions of seasonal pore pressure fluctuations using FLAC tp flow. Unsaturated Soils: Advances in Geo-Engineering, Proc. 1st European Conference on Unsaturated Soils, (eds. Toll, D.G., Augarde, C.E., Gallipoli, D., Wheeler, S.J.), Leiden: CRC Press/Balkema, Vol. 1, pp. 817–822.

Highways Agency (1998). Specification for Highway Works, Manual of Contract Documents for Highway Works, Volume 1. London: The Stationary Office.

Hughes, P., Glendinning, S., and Mendes, J. (2007) Construction Testing and Instrumentation of an Infrastructure Testing Embankment. Proceedings Expert Symposium on Climate Change: Modelling, Impacts & Adaptations (eds. Liong, S.Y., Phoon, K.K. and Toll, D.G.), Singapore: Research Publishing Services, pp. 159-166.

Hughes, P.N., Glendinning, S., Mendes, J., Parkin, G., Toll, D.G., Gallipoli, D. and Miller, P. (2009). Full-scale testing to assess climate effects on embankments. Special Issue of Engineering Sustainability, Proc. Institution of Civil Engineers, 162, No. ES2, pp. 67-79.

IPCC. 2007. Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (http://www.ipcc.ch/pdf/ assessmentreport/ar4/wg1/ ar4wg1spm.pdf)

Kilsby, C., Glendinning, S., Hughes, P. N., Parkin,G. and Bransby, M. F. (2009) Climate-change Impacts on Long-term Performance of Slopes, Special Issue of Engineering Sustainability, Proc. Institution of Civil Engineers, 162, No. ES2, pp. 59-66.

Kilsby, C. G., Jones, P. D., Burton,A., Ford, A. C., Fowler,H. J., Harpham, C., James, P., Smith, A. and Wilby, R. L. (2007) A daily weather generator for use in climate change studies. Environmental Modelling and Software, 22 (12), pp. 1705–1719.

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, Geotechnical Special Publication No. 147, Reston: American Society of Civil Engineers, Vol. 2, 1875-1886.

Mendes, J. (2011) Assessing the Impact of Climate Change on an Instrumented Embankment: An unsaturated soil mechanics approach, PhD thesis, Durham University (http://etheses.dur.ac.uk/612/).

Mendes, J., Toll, D.G., Augarde, C.E. and Gallipoli, D. (2008) A System for Field Measurement of Suction using High Capacity Tensiometers, Unsaturated Soils: Advances in Geo-Engineering, Proc. 1st European Conference on Unsaturated Soils, (eds. Toll, D.G., Augarde, C.E., Gallipoli, D., Wheeler, S.J.), Leiden: CRC Press/Balkema, pp. 219-225.

NEA. 2006. Singapore experienced its wettest December since 1869, National Environment Agency, Singapore http://app.nea.gov.sg/cms/htdocs/article.asp?pid=2815

Overton, A.K. (2007) A Guide to the Siting, Exposure and Calibration of Automatic Weather Stations for Synoptic and Climatological Observations, Royal Meteorological Society, Reading, 2007.

Ridley, A.M. and Burland, W.K. (1993). A New Instrument for the Measurement of Soil Moisture Suction, Géotechnique 43(2), pp. 321-324.

Rouainia M., Davies O., O'Brien, T. and Glendinning, S. (2009) Numerical modelling of climate effects on slope stability. Special Issue of Engineering Sustainability, Proc. Institution of Civil Engineers, 162, No. ES2, pp. 81–89.

Smethurst, J. and Clarke, D. (2007) Climate Change Impacts on Soil Drying in Clay Slopes, Proceedings Expert Symposium on Climate Change: Modelling, Impacts & Adaptations (eds. Liong, S.Y., Phoon, K.K. and Toll, D.G.) Singapore: Research Publishing Services, pp. 167-174.

Tsaparas, I. and Toll, D.G. (2002) Numerical Analysis of Infiltration into Unsaturated Residual Soil Slopes, Proc. 3rd International Conference on Unsaturated Soils, Recife, Brazil, Lisse: Swets & Zeitlinger, Vol. 2, pp. 755762.

Toll, D.G., Lourenço, S.D.N., Mendes, J., Gallipoli, D., Evans, F.D., Augarde, C.E., Cui, Y.J., Tang, A.M., Rojas, J.C., Pagano, L., Mancuso, C., Zingariello, C. and Tarantino, A. (2011) Soil Suction Monitoring for Landslides and Slopes. Quarterly Journal of Engineering Geology and Hydrgeology, 44(1), pp. 23-33.

Watts, M., Goodess, C. M. and Jones, P. D. (2004). The CRU Daily Weather Generator. BETWIXT Technical Briefing Note 1. Version 2, February 2004. pp. 7.