An atmospheric chamber for the investigation of the effect of seasonal moisture changes on clay slopes

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ABSTRACT: It has been theorised that seasonal pore water pressure cycles play a significant role in the progressive failure of clay embankments. This paper presents the development of an atmospheric chamber to build on the recent advances in techniques for matric suction measurement and texture-based image analysis of deformations to model these cycles in the centrifuge. The systems for regulating the relative humidity boundary condition are described, and the importance of a near-zero moisture loss environment emphasised. Through control of the relative humidity boundary condition, idealized seasonal pore water pressure cycles have been successfully created in the centrifuge. The resulting deformations observed over two years of modelling of an overconsolidated clay slope are presented. These results indicate that, although most of the deformation is normal to the soil slope, seasonal moisture cycles cause small, yet irrecoverable downslope displacement components.

1 INTRODUCTION

The interactions between hydrologic conditions, infiltration, matric suctions, creep, fatigue, and progressive failure dominate the behaviour of soil slopes, yet many of these relationships are not well understood (Leroueil, 2001). One major question pertains to the role of seasonal weather cycles in slope stability.

The complexity of the problem is illustrated by field observations of rainfall and infiltration pore water pressures for multiple rainfall events which have yielded conflicting conclusions regarding the importance of rainfall intensity and antecedent conditions. Sasaki et al (2001) have used rainfall statistics in sandy residual soils to show that landslides correlate with cumulative rainfall and intensity – a proposition which accords with most engineers' preconceptions. However, Toll et al (2001) use rainfall statistics to correlate slope failures in clayey ground with the *change* from dry to prolonged wet weather, and do *not* correlate simply with periods of severe wet weather. This discrepancy suggests that rainfall statistics, although useful as a local warning criterion are not sufficient by themselves to explain slope behaviour.

The numerical analyses of Potts et al. (1990, 1997) have predicted that stiff clay embankments are susceptible to progressive failure. Further analysis by Kovacevic et al. (2001) have led them to propose that this progressive failure could be driven by seasonal pore pressure cycles even though the individual cyclic deformations are small. Field measurements of the incremental lateral displacements due to shrinking and swelling of embankments constructed of London Clay have been observed to be on the order of 5-10 mm per annum (Standing, 2001).

The difficulty associated with long-term field measurement of relatively small slope deformations make the physical modelling of seasonal moisture cycles an attractive proposition. A 1/60 scale model, subjected to an elevated acceleration level of sixty times earth's gravity (60g) will scale the time required for seepage flow by a factor of 60^2. At this scale, the cumulative effect of six years of wetting and drying cycles can be observed in an extended working day.

An instrumented embankment in the field has many complications which increase the complexity of back-analysis – a variable cross-section in three dimensions, layered and highly heterogeneous soils, perched water tables, and variations in vegetation cover. Although these features may alter the severity or period of wetting and drying cycles, they only obscure the necessary back-analysis. An instrumented model embankment, therefore, has the benefit of an idealised cross-section created entirely of a soil of known density and stress history.

2 PHYSICAL MODELLING OF SLOPES

One of the first applications of the centrifuge as a tool for the physical modeling of geotechnical problems was that of slope stability (Lyndon & Schofield, 1970). Model slopes were subjected to increasing acceleration levels before reaching a "critical height" at which an undrained failure was observed. The popularity of slope modelling in the early days of centrifuge technology relied heavily on the fact that these tests did not employ a great deal of instrumentation, yet produced dramatic results which could be back analysed by limit equilibrium methods. Undrained failures initiated in this manner, are analogous to failure during construction due to excess pore water pressures, and do not address the problem of infiltration instability.

The problem of rainfall-induced failure of soil slopes has been tackled in the centrifuge by applying moisture directly to the soil surface. The results of these tests indicate that soil slopes are very resilient to short-term, monotonic, pore water pressure increases despite having slope angles in excess of the critical state friction angle (eg. Jackson and Craig, 1998). Model testing of homogeneous soil slopes, therefore, inherently models behaviour consistent with mobilised peak soil strengths, potentially leading to dangerous conclusions.

If seasonal pore water pressures drive progressive failure of soil slopes, both wetting and drying cycles must be modelled in the centrifuge. Of these two seasons, the dry summer poses a particular technological difficulty. Historically, the inability to reliably measure matric suctions has typically restricted centrifuge modelling to a saturated surface boundary condition. Recent advances in suction probe design and saturation techniques have allowed the measurement of matric suctions above the 'false ceiling' of 100 kPa which was traditionally thought to be the maximum directly measurable suction value. Based on the work of Ridley (1993), a new device has been developed for the measurement of matric suctions in the centrifuge environment (Take and Bolton, 2002). As a result, the drying phase of seasonal moisture boundary conditions can now be quantified in terms of matric suction.

3 ATMOSPHERIC CHAMBER

An atmospheric chamber designed for the physical modelling of seasonal pore water pressure cycles is required to perform two functions: control of the relative humidity of the air contained within the chamber, and isolation of the internal environment from that of the centrifuge chamber.

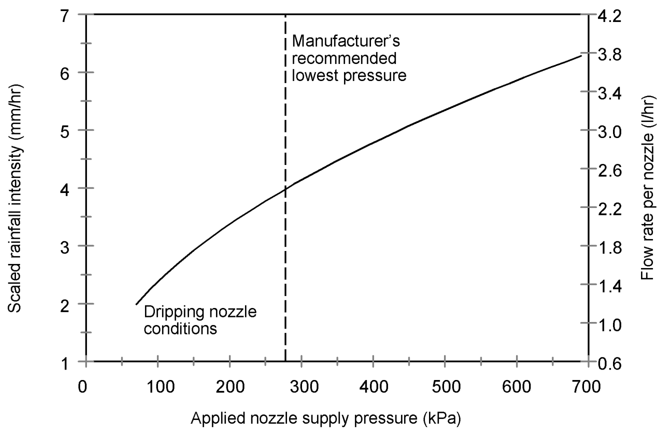

Figure 1. Manufacturer's calibration for model rainfall intensity in model and field scales.

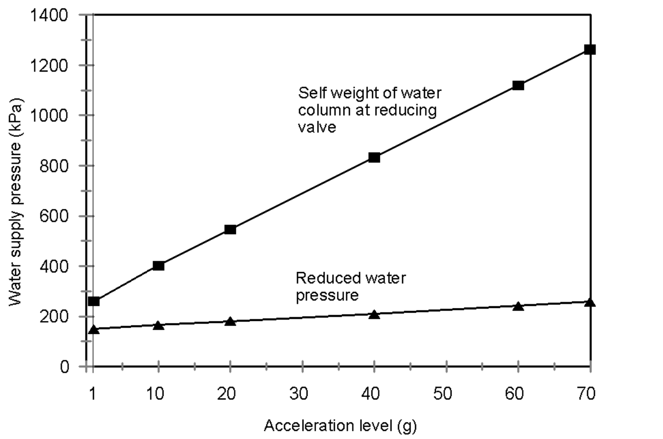

Figure 2. Self-weight of nozzle pressure supply column and acceleration sensitivity of water pressure reducing valve.

3.1 *Relative humidity boundary condition*

The relative humidity within the atmospheric chamber is increased by forcing high pressure water through small diameter nozzles to create atomised mist droplets of the order of 30 microns in diameter. Applying scaling laws for linear dimensions, these droplets would have a prototype dimensions of 1.8mm at 60g. In nature, rain droplets rarely grow larger than 5mm owing to the stability of the droplet under drag forces. Although no conscious effort has been placed on rainfall droplet similitude, model precipitation of a small droplet size will reduce the energy of impact, and therefore the propensity for the model rainfall to cause erosion.

The rainfall intensity provided by the atmospheric chamber has been designed for low permeability clay slopes. To ensure a flooded slope boundary, two rows of nozzles have been provided at the appropriate distance from the soil surface to apply a uniform rainfall on the model slope. The manufacturer's calibration for the atomising mist nozzles in terms of flow rate and scaled rainfall intensity as a function of inlet pressure is shown in Figure 1.

The high pressure water supply to drive the mist nozzles is provided by the self weight of a column of water originating at the centre of the beam centrifuge and running the length of the centrifuge arm through an increasing radial acceleration field. The water pressure delivered to the atmospheric chamber is therefore dependent on the acceleration level, geometry of the centrifuge, and the mains water pressure (Figure 2). Once delivered to the atmospheric chamber, the water pressure is regulated using a water pressure reducing valve. The pressures are monitored with pressure transducers both up and downstream from the reducing valve. The sensitivity of the pressure reducing valve to centrifugal acceleration is shown in Figure 2. The nozzle pressure, originally set at a nominal pressure of 150 kPa for proof testing, increases at a rate of 1.7 kPa/g. Based on this result, the valve was set at 1g at a value of 400 kPa which, accounting for the drift under acceleration, results in a scaled rainfall rate of approximately 5 mm/h.

The rainfall delivery system is shown in Figure 3a. The onset of model rainfall through the mist nozzles is controlled through a two-way solenoid valve. When energised, the valve delivers water to the mist nozzles. As shown in Figure 1, the nozzles do not perform well at low driving pressures – they tend to drip rather than form a fine mist. This can cause a potential problem at the end of the modelling of a wet winter. Upon cessation of model rainfall, the low pressure water remaining in the distribution system will empty through the nozzles, dripping onto the slope creating impact craters. This problem has been overcome through the use of a two-way solenoid valve. When deactivated, the solenoid relieves the pressure in the nozzle delivery system by routing it to atmospheric pressure.

Dry air can be circulated through the atmospheric chamber to lower the relative humidity boundary condition within the atmospheric chamber. The initial design for the drying system consisted of two pairs of 50mm diameter fans mounted on the top plate of the atmospheric chamber to blow air from the centrifuge pit into the chamber and to extract the moisture laden chamber air. This system was abandoned because the fans behaved poorly under elevated acceleration levels, the presence of fans meant that the chamber could not be sealed, and the relative humidity could only be dropped to the ambient conditions on the test day. The latter two drawbacks also hampered a subsequent design which consisted of pneumatically controlled louvers and an air scoop.

The problem of a consistent dry air supply was finally overcome using dried compressed air transferred via sliprings to the atmospheric chamber. As shown in Figure 3b, air enters the atmospheric chamber near the toe of the embankment through a solenoid valve, picks up moisture, and exits through

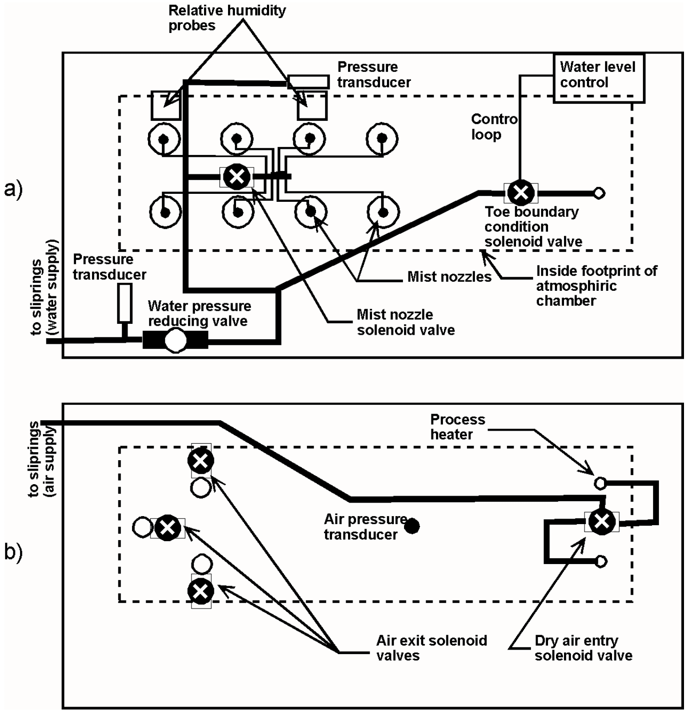

Figure 3. Plan view of atmospheric chamber isolating a) rainfall modelling system, and b) drying system.

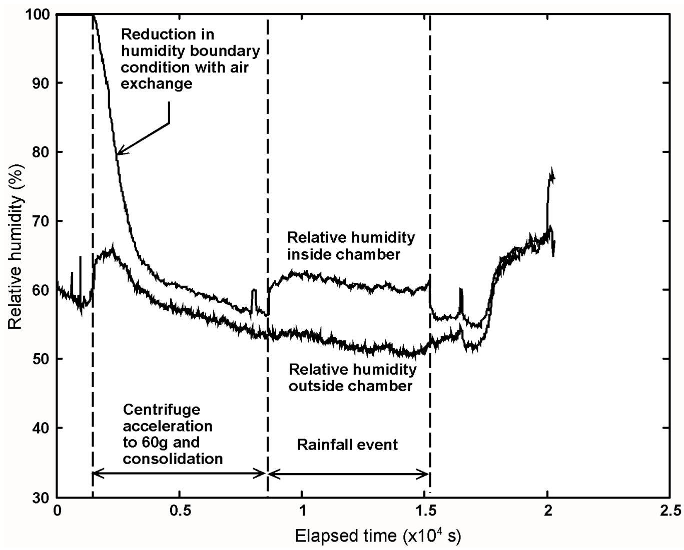

Figure 4. Relative humidity during centrifuge acceleration and model rainfall in a non-sealed chamber.

three large-bore solenoid valves at the crest of the embankment. Since a pressure gradient is necessary to drive air exchange, an air pressure transducer records the increase in air pressure within the atmospheric chamber. Running at a supply pressure of 150 kPa, the air pressure in the chamber rises by only 3 kPa when all three exit valves are opened. Therefore, the increase in air pressure associated with simulating seasonal dry conditions will result in only a small change in pore air and water pressures. Furthermore, as a safety precaution, a blow-off valve has been incorporated into the atmospheric chamber to ensure that, in the eventuality of malfunction, the air pressure cannot exceed 100 kPa within the atmospheric chamber. Finally, the drying system also has a provision for temperature control of the incoming air, if desired. This is achieved through the use of two process heaters situated to preheat the air as it is entering the chamber.

3.2 *Near-zero moisture loss environment*

Soil, whether left on the laboratory bench, or in a exposed centrifuge model will experience moisture loss as water is transferred from the soil surface to the surrounding air. If situated in a sealed chamber, this process will be arrested once the surrounding air becomes saturated with moisture. However, if the air above the soil surface is constantly replaced, this equilibrium cannot be reached and moisture will be continuously stripped from the soil surface. This problem is especially pertinent to centifuge testing, as centrifuge chambers are inherently windy environments. Therefore, if the soil model is not protected in a sealed chamber, the constant circulation of air will desiccate clay soils generating hitherto unquantified matric suctions.

This problem of moisture loss to the air has historically been acknowledged but remained unquantified in terms of pore water pressure (eg Malushitsky, 1981), or avoided by applying saturated boundary conditions (eg. Bolton and Powrie, 1988). Avoidance of the problem in this manner, however, restricts the type of problems which can be investigated and excludes the possibility of physically modelling progressive failure of embankments.

The problem with imperfectly sealed chamber is shown in Figure 4. Initially the relative humidity within the nearly sealed chamber indicates moisture equilibrium between air and soil. As the centrifuge is accelerated, air-exchange between the inside of the chamber and the external environment drops the relative humidity to a value similar to that of the centrifuge pit. Perhaps even more telling is the lack of success of rainfall infiltration modelling within the unsealed chamber. Despite mist generation from the nozzles, the relative humidity within the chamber cannot reach 100%.

In an attempt to create a zero moisture loss environment, great care was exercised in sealing the atmospheric chamber. The top plate housing the mist nozzles was fitted with a compression seal and bolted to the centrifuge package. The mist nozzles, relative humidity probes, and a CCTV camera situated in this plate were all fitted with an o-ring seal and bolted in place. Finally, the electrical leads from the matric suction probes exit the atmospheric chamber via a groove which is subsequently infilled with Aquaria, thereby providing a seal between the sleeved cables.

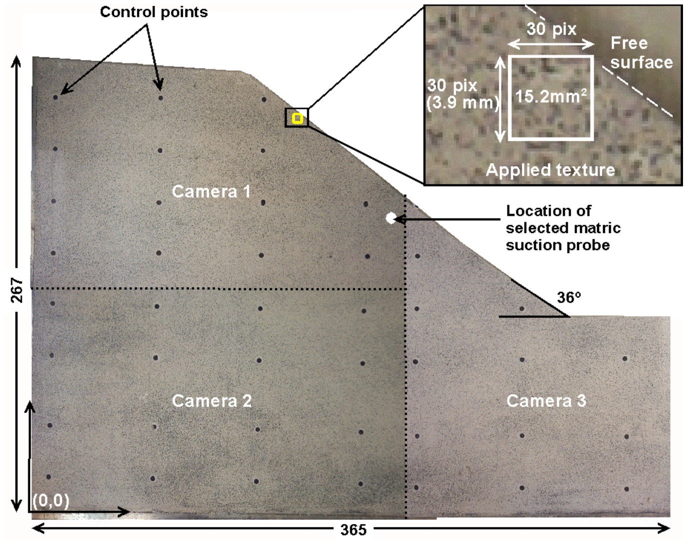

Figure 5. Model overconsolidated clay embankment, and locations of selected deformation and pore pressure measurements.

4 SLOPE EXPERIMENTS

4.1 *Embankment description*

A model embankment was formed with a slope angle of 36 degrees from a block of Speswhite Kaolin that had been normally consolidated under K_o conditions to 500 kPa and allowed to swell back in stages to a pressure of 60 kPa. At this final unloading stage, all free water was removed from the consolidometer before the last loading increment was released, resulting in an initial suction condition of approximately 60 kPa. Once the soil slope was formed, suction probes were inserted into pre-drilled holes and backfilled with a Kaolin slurry. The slope profile was shaped to account for the radial acceleration field to correctly model the infiltration boundary condition by ensuring no ponding of water will occur on the crest of the embankment (Figure 5). To enable later image analysis of deformations using Particle Image Velocimetry (PIV), texture was applied to the front face of the white clay embankment. Finally, the embankment was sealed into the atmospheric chamber and loaded onto the centrifuge (Figure 6).

4.2 *Applied seasonal conditions*

Seasonal variations of relative humidity between 100% and approximately 40% were applied to the soil surface to model extreme weather conditions – five very wet months followed by seven months of drought. At an acceleration level of 60g, this corresponds to one hour of model rainfall followed by one and a half hours of drying. The measured relative humidity boundary condition applied to the embankment for two years of modelling is presented in Figure 7. The seasonal cycles shown in Figure 7 are midway through a test sequence and begin at the end of a wet winter. Points of interest are flagged at the end of each of the seasons, and will be referred to in later figures.

4.3 *Pore pressure response*

Only one pore pressure trace will be discussed to illustrate the effectiveness of the atmospheric chamber to generate seasonal pore water variations. The selected suction probe is located at mid-slope at a depth of 20 mm below the soil surface (Figure 5). The seasonal response of the embankment at this location was a 40 kPa swing in pore water pressure, as shown in Figure 8. Upon the application of rainfall infiltration, a large proportion of the suctions generated during the dry summer are quickly dissipated, with further rainfall causing a slow progression to steady-state conditions. It is important to note that the 36 degree embankment, which has a critical state friction angle of 23 degrees, does not experience catastrophic failure despite the pore water pressures approaching positive values throughout the slope.

4.4 *Deformations*

The small magnitudes of slope deformations due to seasonal moisture cycles at field-scale provide an additional challenge for their observation at a reduced scale in a centrifuge model. Conventional displacement measurement techniques rely on targets of the order of 1-3mm in diameter embedded into the clay model. These displacement targets are then analysed, usually by calculating the centroid of pixels passing a certain threshold intensity, to determine the pixel location of the centre. This technique is susceptible to errors originating from variations in lighting (circular targets becoming ellipses), soil obscuring the edges of targets as deformation occurs, and from small targets (the loss of one pixel becoming very significant). Further, this technique is limited to giving information only at the target locations.

A novel system of deformation measurement for soil models has been developed (White et al. 2001a,b). At the heart of this system is the image processing technique of PIV. Rather than relying on discrete marker targets, PIV compares a patch of intensity values to the values in a target area of a subsequent image to determine the position of best-match to a precision of 1/15th of a pixel (White et al 2001b). The change in patch location between images gives a movement vector in image space. To obtain a deformation measurement, the patch positions must be translated from image space (units of pixels) to real space (units of mm) through a process called camera calibration. Based on the principles of close-range photogrammetry, this accounts for camera movement between frames, changes in camera

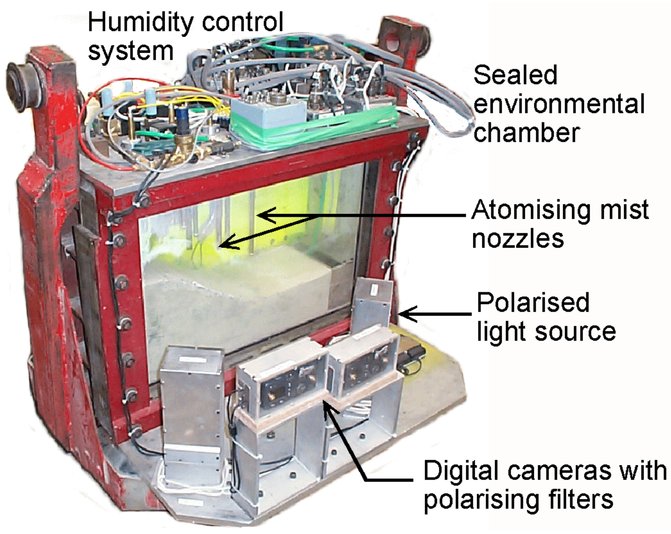

Figure 6. Atmospheric chamber and digital image acquisition system.

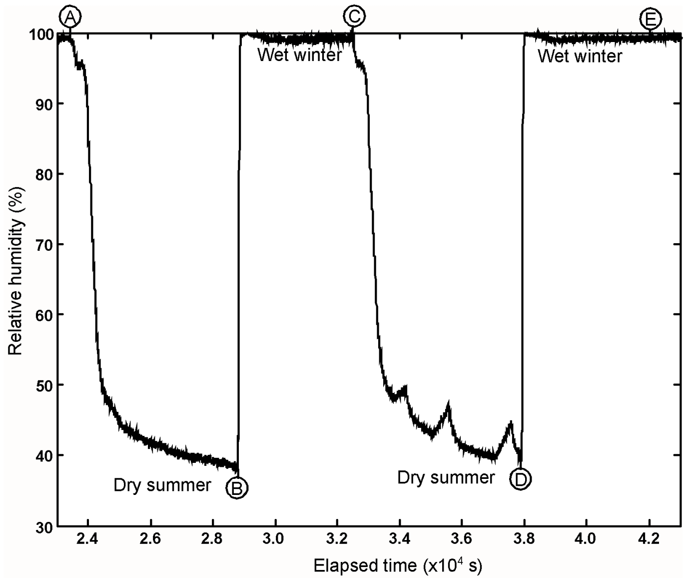

Figure 7. Idealised model seasonal relative humidity boundary conditions.

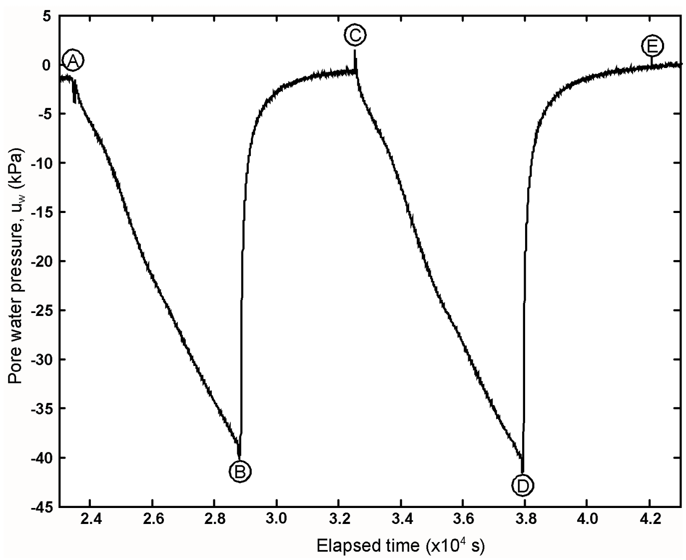

Figure 8. Seasonal pore water pressures.

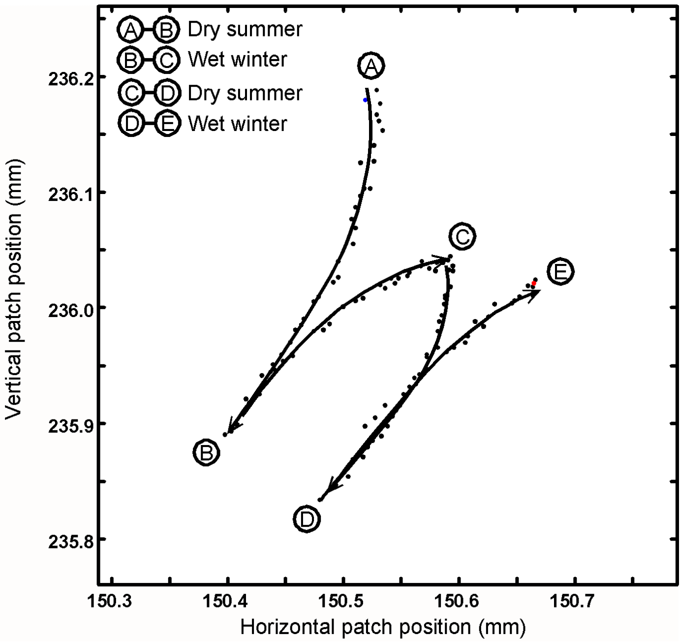

Figure 9. Irrecoverable seasonal deformations (model scale)

orientation, radial and tangential lens distortions, and refraction through the observation window.

Although the deformation measurement can be tracked at thousands of locations, the influence of seasonal pore pressure changes on slope movement will here be assessed only for a single patch of soil near the slope surface. The selected patch is located near the crest of the embankment, and has real dimensions of approximately 3.9mm (Figure 5). Incremental displacements have been calculated for the 114 images covering the period of two years of modelled seasons (points A to E). The position of the patch relative to the coordinate system in Figure 5 during this time history is presented at model scale in Figure 9. Although most of the movement is in the direction normal to the soil surface, there exists a component of irrecoverable downslope deformation during the wettest portion of both seasons. Seasonal wetting and drying cycles can, therefore, generate "solifluction". At field scale, the observed down slope displacements corresponds to approximately 7 mm per annum (eg. Points B-D). These deformations cause tensile strains which can cause tension cracking at the crest and potentially lead to progressive failure.

5 CONCLUSIONS

The technique of centrifuge modelling in clay has historically been limited to problems which have a saturated surface boundary condition due to the difficulty of measurement of soil suctions. Through control of the relative humidity boundary condition, idealized seasonal pore water pressure cycles have now been successfully created. The resulting deformations indicate that, although most of the deformation is normal to the soil slope, seasonal moisture cycles cause small, yet irrecoverable down slope displacement components.

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REFERENCES

Bolton M.D. & Powrie W. 1988. Behaviour of diaphragm walls in clay prior to collapse, Geotechnique, 38(2): 167-189.

Jackson, A.M.R. & Craig, W.H. 1998. Modelling vertical geosynthetic reinforcement of soil slopes. Centrifuge '98. 753-759. Rotterdam: Balkema.

Kovacevic, N., Potts, D.M. & Vaughan, P.R. 2001. Progressive failure in clay embankments due to seasonal climate changes. Proc. 15th Int. Conf. Soil Mechanics and Geotechnical Engineering, Istanbul, Turkey: 2127-2130.

Leroueil, S. 2001. Natural slopes and cuts: movement and failure mechanisms. Geotechnique, 51(3): 197-243.

Lyndon, A. & Schofild, A.N. 1970. Centrifugal model test of a short-term failure in London Clay. Geotechnique 20(4): 440-442.

Malushitsky, Y.N. 1981. The centrifugal model testing of waste-heap embankments. Cambridge University Press.

Potts, D.M., Dounias, G.T. & Vaughan, P.R. 1990. Finite element analysis of progressive failure of Carsington embankment. Geotechnique, 40(1):79-101.

Potts, D.M., Kovacevic, N. & Vaughan, P.R. 1997. Delayed collapse of cut slopes in stiff clay. Geotechnique. 47(5): 953-982.

Ridley, A.M. 1993. The measurement of soil moisture suction. Ph.D. dissertation, Imperial College, London.

Sasaki, Y., Moriwaki, T. & Kano, S. 2001. Rainfall index for warning against slope failure disaster. Proc. 15th Int. Conf. Soil Mechanics and Geotechnical Engineering, Istanbul, Turkey: 1249-1252.

Standing, J.R. 2001. Personal communication.

Take, W.A. & Bolton M.D. 2001. The use of centrifuge modelling to investigate progressive failure of overconsolidated clay embankments. Centrifuge and Constitutive Modelling: Two extremes, Ascona, Switzerland, Springman S.M. (ed.) Balkema, Rotterdam

Take, W.A. & Bolton, M.D. 2002. A new device for the measurement of negative pore water pressures in centrifuge models. Proc. Int. Conf. Physical Modelling Geotechnics, St. John's. Rotterdam: Balkema.

Toll, D.G., Tsaparas, I. & Rahardjo, H. 2001. The influence of rainfall sequences on negative pore water pressures within slopes. Proc. 15th Int. Conf. Soil Mechanics and Geotechnical Engineering, Istanbul, Turkey: 1269-1272.

White D.J., Take W.A, & Bolton M.D. 2001. Measuring soil deformation in geotechnical models using digital images and PIV analysis. Proc. 10th Int. Conf. Computer Methods and Advances in Geomechanics. Tucson, Arizona. pp 997-1002

White D. J., Take W.A, Bolton M.D. & Munachen S.E. 2001. A deformation measuring system for geotechnical testing based on digital imaging, close-range photogrammetry, and PIV image analysis. Proc. 15th Int. Conf. Soil Mechanics and Geotechnical Engineering. Istanbul, Turkey.