Identification of seasonal slope behaviour mechanisms from centrifuge case studies

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Introduction
Research performed at Imperial College under Skempton has shaped our understanding of the assessment of slope stability. We perform triaxial tests to determine the effective strength envelope, we perform slip surface analyses with some assessment of worst-case future pore pressures, and we are aware of the possible influence of shear softening from peak strength to critical state and then to residual strength. However, our calculations do not explicitly recognize the process by which many slopes "creep" and degrade with time. This paper presents observation of slope behaviour pertinent to this omission.

Skempton, above all, wished geotechnical engineers to value the geological perspective. In his 1964 Rankine Lecture, Skempton remarked that seasonal moisture cycles were perhaps of great significance in geomorphological processes. Due to the shallow depth of influence of these seasonal variations, however, he dismissed them as unlikely to prove important in the deeper long-term failure of clay slopes which were his concern in that paper. The succeeding generation of geotechnical engineers have followed Skempton in adopting a design philosophy for slopes in which the highest possible pore pressures are to be estimated, allowing for long-term elimination of transient negative pore pressures whether caused at construction by cutting or compaction, or subsequently by erosion.

This paper is aimed at discussing shallow slides occurring within the zone of a clay slope that is influenced by seasonal water movements. This follows recent interest expressed by the owners of transport infrastructure in the ongoing displacements encountered in clay embankments. The development of reliable suction measurement devices (e.g., Ridley and Burland, 1995) has made it possible to measure weather-induced pore pressure cycles in the field. This, in turn, has made it possible to imagine relationships for the degradation of clays that would lead to progressive failure in finite element simulations: Kovacevic et al (2001). However, it remains very difficult to conduct scientific trials, or to validate numerical analyses, based on available field data alone. The most critical problem is that the data should be collected over a sufficient number of years for the trends of movement with the wetness of seasons to become clear.

Centrifuge testing has the potential to create model case studies in which years of equivalent full-scale slope behaviour are observed in a single day. This paper describes the development of an atmospheric chamber in which seasons are modelled by controlling the relative humidity boundary condition, varying suction is measured by a new miniature tensiometer, and the resulting displacements are observed at high resolution by digital image correlation and close-range photogrammetry. Observations have been made of soil creep due to cyclical swelling and shrinkage.

This paper presents pressure cycles can failure through the toe. It raises the question of geological or geotechnical" to "sweat pore pressure cycles."

Testing Program
The model slope was insufficient. The condition has been tests that vary in wet and d

Experimental
Model embankmen E-Grade Kaolin clay is used in bulk quantity high permeability of model preparation. The clay mixture has a 1:1 clay 1400 t: as this, it seems to be.

The model under semi-compacted soil of 500 kPa was used a stiff clay block for profile is shown in container boundary embankment geometry.

The embankment is acceleration field. T-Grade Kaolin which slope angle likely to cohesion, even if it implies that during mobilization super-cyclic tests had demonstrated scale, the 1400mm he
swelling and shrinkage, and consequent slope degradation due to tensile cracking and shear rupture.

This paper presents observations of slope behaviour which indicate that seasonal pore pressure cycles can drive the mechanism of slope creep leading eventually to a progressive failure through the development of cracks towards the crest of a slope, and a steep rupture at the toe. It raises the question of the degree to which permanent soil movements, in either geomorphological or geotechnical contexts, are progressively mobilised by "typical pore pressure cycles" leading ultimately to a slide failure of the then degraded soil slope under "severe pore pressure conditions".

Testing Programme

The model slope will be subjected to idealised seasons of varying severity but all of which are insufficient to initiate catastrophic failure. In this manner the applied seasonal boundary condition has been designed to question whether a larger number of these less "dangerous" events can slowly accrue damage to the slope which could potentially lead to failure in the long-term. A further aim of the model test is to explore more fully the behaviour of the clay slope in wet and dry seasons. In all, the model was subjected to six "annual" pore-water pressure cycles, each consisting of a wet winter and a dry summer.

Experimental methodology

Model embankment

E-Grade Kaolin clay was chosen as the model material. This clay is available in powdered form e.g. bulk quantities and has been used extensively as a research material. The relatively high plasticity of Kaolin when compared to other clays such as London Clay also makes model preparation, as the clay may be consolidated in a reasonable time frame. However, this clay neither has a large plasticity index nor a large drop in strength from peak to residual. Thus, if seasonal moisture cycles can be shown to drive progressive failure in a material such as this, it seems certain to do so in other clays.

The model under consideration, WAT6, is intended to be representative of steep slopes in well-compacted embankments of stiff clay. As such, a relatively high consolidation pressure of 300kPa was used to consolidate the clay from a slurry prepared at twice its liquid limit, to a stiff clay block from which an embankment profile may be chosen. The chosen embankment profile is shown in Figure 1a. Rather than modelling the entire embankment, the vertical container boundary is used as a plane of symmetry. This leads to only half of the model embankment geometry being required for testing.

The embankment is inclined at thirty-six degrees, with allowance made for the curved radial acceleration field. This is considerably higher than the critical state angle of friction for E-Grade Kaolin which is approximately twenty-four degrees. It is therefore also steeper than the slope angle likely to be specified by an engineer who has been taught to be sceptical of re-cohesion, even if that engineer is unaware of the importance of water infiltration. This implies that during a typical wet winter season the embankment will find itself trying to mobilise super-critical strength to maintain stability. These are the conditions which earlier work had demonstrated to be necessary to engender progressive failure. At 1/50th model scale, the 14mm height of the embankment corresponds to an embankment height of 4.2m.
Atmospheric Chamber

The translation of the concept of season into a boundary condition which can be provided on a geotechnical centrifuge requires the control of the quantity of water vapour in the space above the model embankment. During the wet season, the air above the soil surface must be saturated with water vapour as model rainfall infiltration is applied. The dry summer season demands a very low concentration of water vapour above the soil surface to drive the process of evaporation. This variable moisture boundary above the first surface of a centrifuge model required the development of a sealed model chamber offering controlled atmospheric conditions to the soil within. Take and Bolton (2002) described the development of such a chamber in which the relative humidity boundary condition can be controlled alternatively using two rows of stomating mist nozzles; and the injection of dry compressed air. Wet winters are provided in which low intensity precipitation is applied to the soil surface, ensuring a flooded slope boundary condition characterised by both infiltration and runoff. Dry summers desiccate the soil surface, extracting moisture by evaporation from the soil into the adiabatic stream of dry air above.

Instrumentation

The response of the model embankment to seasonal weather cycles must be measured in terms of pore water pressures, positive in the wet season and negative in the dry season. The latter is more demanding, as there is considerable difficulty with the reliable long-term measurement of soil suction. These difficulties have been overcome in the present study through the development of a new miniature tensiometer for small scale modelling, and a quality-assured method of tensiometer saturation (Take and Bolton, 2003). By placing seven of these miniature tensiometers within the embankment profile, the pore pressures in the critical zone of soil movement could be ascertained as contours between the devices.

The resulting soil displacements driven by these seasonal pore pressure cycles must be measured. Assuming a linear slope-movement of the order of 10 mm at prototype scale, the magnitude of this displacement reduces to 0.17 mm at 1/600th model-scale. Therefore, in order to adequately describe such a movement, the resolution of the required measurement system must be capable of a measurement precision better than 10 microns, whilst providing a reasonable field of view to capture the behaviour of the entire slope. White et al. (2003) describe an image-based system which is capable of this task using digital imaging, photogrammetry, and the image processing techniques of Particle Image Velocimetry (PIV) and advanced control systems. As a cross-correlation matching algorithm between patches is at the core of the image processing technique of PIV, displacements can be assessed at any point in the image — that is, the algorithm relies on identifiable features in the image rather than expensive target markers. These features can be soil grains, or in the case of photo-grazed materials, applied texturals. Thus, the practical limitations on the number and location of measurement points within a physical model no longer exist.

Experimental Results

Initial conditions

The technique of centrifuge modelling has the potential to create model case studies which have well defined initial conditions. However, gravity must first be switched on before testing can commence. This process is of particular importance in the present study as the undamaged delivery of the model embankment to the test acceleration is essential for the assessment of whether seasonal moisture cycles can initiate a first crest failure. Further, over-steepened slopes such as the model clay embankment are particularly sensitive to the manner in which gravity is turned on to avoid several instances were a during “construction.” Using water pressures within the soil elevating the initial effective stress subsequently lowering the initial effective stress. It is important, allowing for the process of staged construction further encouraging the relief of the surface. The response of the captured in the pore pressure at the initial conditions prior to failure after the final load construction period has measurement of the process. This r with a relatively small magnitude at the crest of the approximately 2.5mm (model excess pore water pressures r with the zero pore pressure material) (Figure 1a). Seasonal pore pressures

The model embankment was kept wet winter and dry summer, the situation of the wet winters (Figure 2a). This modelled embankment is translated in embankment. Observations are measurement away in the season pore pressures quickly rise, the embankment. However, the soil system reveals that the the air infiltration is much higher and evaporation. A closer look in t that the rate of pore water rises. This is to be expected as the rate of infiltration progresses, the pore water pressure accumulates of evaporative, on the other hand, pressures assist more current.

Seasonal displacements

The first wet winter applied to the pore water pressure response developed in the model began the season completely in cycle, the magnitude of which is 3a. Quite surprisingly, then, the most the embankment. However, it
tions which can be provided on y of water vapour in the space r above the soil surface must be applied. The dry summer season soil surface to drive the process as surface of a certain range model offering controlled atmospheric field the development of such a can be controlled alternatively on of dry compressed air. Wet is applied to the soil surface, by both infiltration and runoff. ry evaporation from the soil into

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in which gravity is turned on, as they are susceptible to undrained failure. Bearing this in mind, several strategies were adopted to minimize the deformation of the model embankment during "construction." Using the atmospheric chamber to encourage evaporation, the pore water pressures within the slope were dropped to -558 kPa prior to acceleration, thereby elevating the initial effective stress point of the model but without de-airing it. Rather than proceeding directly to the test acceleration, the self-weight loading was then applied incrementally, allowing for pore pressure dissipation between the load stages. Further, during this process of staged construction, the atmospheric chamber modelled dry season conditions, further encouraging the relief of the construction stage pore water pressures to the free surface. The response of the model embankment to these damage limitation strategies is captured in the pore pressure observations of Figure 2b. In this figure, time window 0 marks the initial conditions prior to gravity turn-on, and window A the end of pore pressure dissipation after the final load increment to 60 kN-m. This data indicates that the lengthy construction period has ensured that the embankment has remained in suction throughout the duration of the process. This results in slope displacements which are predominantly elastic with a relatively small magnitude. As shown in Figure 1b, the construction displacements are a maximum at the crest of the embankment, where they are purely vertical settlements of approximately 2.5 mm (model scale). At the end of the period allotted for the dissipation of excess pore water pressures (time window A), the model embankment is fully in suction, with the zero pore pressure contour lying below the measurement array in the foundation material (Figure 1a).

Seasonal pore pressures
The model embankment was subjected to six seasonal weather cycles, each consisting of a wet winter and a dry summer. To investigate the influence of the length of the wet season, the duration of the wet winters is initially rather short, but increase with the passing "years" (Figure 2a). This idealised seasonal boundary condition on the free surface of the embankment is translated into idealised pore water pressure cycles within the soil embankment. Observations are presented in Figure 2b of the response of the pore pressure measurement array to the seasonal boundary condition. With the onset of the winter rains, the pore pressures quickly rise. The harsh summer winds drive suctions into the model embankment. However, the soil's response to the applied seasonal boundary condition is not symmetrical. That is, the average rate of pore water pressure increase during rainfall infiltration is much higher than the corresponding rate of decrease associated with summer evaporation. A closer look at the pore water pressure response during infiltrations indicates that the rate of pore water increase is initially quite steep before dropping off significantly. This is to be expected as the initial hydraulic gradient for infiltration is very large. As the process of infiltration progresses, the hydraulic gradient drops considerably and the rate of pore water pressure accumulation becomes asymptotic to the steady-state condition. The rate of evaporation, on the other hand makes the rate of generation of negative pore water pressures much more constant over the pressure range presented in Figure 2b.

Seasonal displacements
The first wet winter applied to the model embankment is of a particularly short duration. Yet, the pore water pressure response indicates a rapid destruction of the suctions which were developed in the model scope in its initial condition (Figure 2a). The model embankment that began the season completely in suction (Figure 1a) has been subjected to an effective stress cycle, the magnitude of which is evident from the observations of pore pressure rise in Figure 2a. Quite unsurprisingly, the maximum pore water pressure change is located at the crest of the embankment. However, despite raising the pore water pressures at the crest of the
embankment by over 60kPa, the short duration of the season has the result that much of
slope's surface remains in suction, with pore pressures lower than 3kPa (Figure 3b).

In response to these seasonal stress cycles, the model embankment is observed to have
undergone swelling in a direction approximately normal to the slope surface (Figure 3c).
These swelling vectors are expressed as contours of seasonal movement in Figure 3d, more
clearly illustrating the magnitude and distribution of the displacements. This data indicates
that the swelling is confined to the near surface, the depth of influence being relatively
uniform along the entire length of the infiltration surface. The embankment swells most at
the toe. However, even scaled by a factor of sixty, the maximum magnitude of the observed
swelling vectors (0.2mm) would correspond to only 12mm seasonal movement. Without
the recent advances in image-based deformation measurement techniques, these displacement
vectors would have been too small to observe in physical models.

During the first dry season, the harsh drying action of the cyclic drying (35% relative
humidity) drives the slow and steady reduction in pore water pressure within the
embankment. Once the suction had regained their pre-wet season magnitudes, the dry season
was stopped. As shown in Figure 4a, the summer season saw a reduction in pore water
pressure of over 60kPa at the crest, leaving the entire embankment once again in suction
(Figure 4b). The shrinkage associated with this first summer season is predominately normal
to the slope crest, with magnitudes decreasing with depth into the embankment (Figure 4c-d). No significant movement has been observed at the toe during this season, indicative of a
small pool of water remaining trapped in this location for part of the dry season’s duration.

Similar behaviour was subsequently observed in the third subsequent “years” of seasonal
moisture cycles (Take, 2003). In the fifth cycle, the duration of the wet season was extended
to nearly three times that of the first wet season. How has this affected the observed seasonal
behaviour? Let us begin by looking at the pore water pressure response. Beginning is a
slightly drier condition, the seasonal swing in pore pressure is somewhat larger than that
observed in the first wet season (Figure 5a). The subtle differences between these winter
seasons is perhaps better illustrated by the comparison between the end-of-winter pore water
pressure distributions (Figure 3b, vs. Figure 4b). Despite the rainfall duration being nearly
more times longer, the end-of-season pore water pressures have only risen by approximately
5 kPa over their shorter duration distributions. This should be expected as the rate of pore
pressure increase becomes asymptotic to the final steady-state value with time (Figure 2a).

In stark contrast, the extended duration of the wet season has significantly increased the
amount of observed swelling. As shown in Figure 5d, the depth of swelling (in this case
developed using the 0.05mm movement contour) has increased to include the majority of the
embankment. The vector field of observed displacements (Figure 5c) indicates that entirely
vertical swelling has taken place at the crest of the embankment. However, as the crest is
approached, the direction of the swelling vectors indicates a decreasing inclination,
becoming nearly horizontal near the toe. Since the soil at the crest of the embankment is
growing vertically up in the wet season (Figure 5c) and vertically down in the dry season
(Figure 4c), the presence of a lateral component in the seasonal swelling vectors will place
the crest of the embankment into tension. The nearly horizontal swelling vectors concentrated
at the toe of the embankment indicate a considerable shear zone. This is further confirmed by
the images from the toe camera which indicate the initiation of a small localized shear failure
during this season. The image-patches once tracked at the toe are thereafter no longer
recognizable, leading to their absence in Figure 5c.

Seasonal shear strain accumulation target-based displacement

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The observed distribution of maximum shear strain, $\gamma_{max}$ indicates that the seasonal shrink-swell cycles have resulted in a wetted embankment. The embankment (Figure 4c-d) is characterized by the repeated seasonal $\gamma_{max}$ cycles. The increased shear strain $\gamma_{max}$ during the dry season is due to the increased pore water pressure within the soil. The embankment is a well-structured system, allowing the tracking of displacements at any point within the embankment cross-section. Thus, strain elements of any size or shape may be defined with complete freedom, each element being defined by the image-tracking patches located at its vertices. For the present study, a strain mesh consisting of a rectangular grid of 12.5mm x 12.5mm triangles was overlaid upon the acquired images of the embankment profile.

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balance between these portions of the year which consist of predominantly wet and dry weather that determines the annual rate of "camb". The progressive slope movement arising from seasonal changes gives rise to soil degradation, with the clay vulnerable to tension cracks, and the too vulnerable to shear ruptures. The downward flow of water through the soil therefore progressively reduces the critical pore water pressure distribution required to cause catastrophic failure, until this eventually occurs in some future wet season.

The model tests reported here were carried out on a relatively permeable, but low-shrinkage, low-brilliance over-consolidated Kasilis clay. London Clay, for example, would consist lower permeability; clay pads separated by fissures that could open due to shrinkage, so that the mass permeability could vary widely. If the mass permeability were smaller, the depth of the progressive shear zone would be correspondingly smaller. On the other hand, the swelling potential of London Clay is larger than that of Kasilis, and so brittleness is greater, so the tendency for progressive shear ruptures would be enhanced.

It has sometimes been reported that a few centimetres of relative sliding are required in a ring shear apparatus if clay are to retain their residual strength. On the other hand, we have now shown that shear ruptures develop easily in centrifuge tests subject only to a few millimetres of relative sliding. Perhaps paradoxically, considering the previous anxieties concerned with scaling progressive failure, centrifuge tests might now be seen as the best way to validate design rules to limit progressive movements due to cyclic pore pressure changes in slopes. Certainly, a validation based only on triaxial tests would have to overcome the very small effective stress levels and the absence of a free surface from which tension cracks and shear ruptures could propagate. More detailed analyses of the test reported here, and others, are now under way. These analyses are aimed at exploring the mechanisms underlying Skempton's widely supported recommendation (Skempton, 1970) that over-slopes in heavily over-consolidated clay, with much "true cohesion" evident in undisturbed cores tested in the triaxial apparatus, should be designed on the basis of their critical state friction angle alone, to avoid "first failure sliding".

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Figure 1. Initial conditions of embankment model.
Figure 2. a) Applied seasonal boundary condition and b) observed pore pressures

Figure 3. Short wet season stop
Figure 3. Short wet season slope behaviour

1) observed pore pressures
Figure 4. Dry season slope behaviour

Figure 5. Extended irrigation we
Figure 5. Extended duration wet season slope behaviour
The shear strength highly overconsolidated

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Abstract
As stressed by Skempton, the overconsolidated clays can be laboratory tests. This paper is field which produce the slope failure imply a rotation of the zone above it. The thickness depends on the shear strength at the critical strength. This paper does not include the factors affecting the shear strength.

Foreword

Since the beginning of modern engineering, the shear strength mobilized in the field is always less than the peak shear strength concept. It remains one of the most challenging problems.

Several phenomena of local and general slope failure by creep are generally mentioned as soil movements. The soil failure is a consequence of cyclic shear. Therefore, it must be associated with changes of stress (Laveda, 1976). A decrease of shear strength of soft clays and other soils is a consequence of the shear strength in the long term.

Figure 6: Evolution of shear strain concentration

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