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# Centrifuge modelling of post failure behaviour of a compacted sandy clay slope induced by rainfall and flood

M.A. Alfergani, E.T. Bowman, T.A. Gaspar, T.A. Elmrom
*University of Sheffield, Sheffield, UK, malfergani1@sheffield.ac.uk, e.bowman@sheffield.ac.uk, t.a.gaspar@sheffield.ac.uk, telmrom@sheffield.ac.uk*

**ABSTRACT:** Slope instability of engineered earthworks induced by rainfall can cause considerable damage to infrastructure, economic cost and loss of life. A small-scale physical model test was conducted using the 50gT beam centrifuge at the University of Sheffield in order to investigate the triggering and post-failure mechanisms of slope failure due to rainfall and flood events. The slope model was prepared from a sand-kaolin soil fill, compacted at optimum water content. Close range photogrammetric techniques were used to monitor slope movements and the volumetric changes of the ground during the cycles of wetting and drying as well as the changes in pore water pressure. This paper outlines the post-failure deformation of the slope and shows that movement thereafter can occur spontaneously during heavy rain, suggesting that the slope is in a metastable condition.

**Keywords:** Slope, Centrifuge, Post failure.

## 1 INTRODUCTION

Flood embankments, also known as levees or dykes, are a vital part of flood defences in low lying areas and it is therefore important to assess the stability of these structures against rainfall and flooding. The climatic condition, environment, vegetation, geology, and human activities are all considered as potential contributing factors to failure. Long and/or intense rainfall events cause serviceability problems, such as erosion, in earth structures. In addition, it is well known that the performance of earth structures such as clay embankments is influenced by climate, with wetter periods resulting in greater numbers of slope failures. Changing climate conditions affecting the UK are likely to consist of higher average temperatures, wetter winters and drier summers, with uncertain rainfall patterns and more extreme temperatures. It is increasingly evident that the performance of the UK's infrastructure slopes, such as flood embankments and railway embankments is deteriorating. For this reason, increased efforts are required to understand the likely impacts of changing climate conditions in order to establish effective asset management approaches to boost resilience.

While there are considerable efforts to unearth the answers to rainfall/climate induced slope failure in earth embankments via full scale monitoring and instrumentation, this process is protracted and may not yield effective understanding due to the isolation and variability of the test case. Conversely, centrifuge testing is an effective method to simulate movements in geotechnical phenomena and allows for careful control of boundary conditions and for multiple scenarios to be examined. The instability of slopes during rainfall has been linked to a number of parameters, including soil characteristics, rainfall intensity, the location of the initial water table, and slope geometry, according to previous studies on climate-induced slope instability (Kim et al., 2004; Yoshida et al., 1991).

Earthen dam failure is mostly caused by the cycle of rainfall and drought on unsaturated soil. Soil layers near the slope surface, which may be initially unsaturated during dry seasons, have negative pore-water pressure (i.e. matric suction), which contributes to the shear strength of soils and to the stability of soil slopes. During rainy seasons, rainfall infiltration into the soil raises the water content (particularly in cases where there is inadequate or no drainage), which lowers soil suction and thus the shear strength of soil which increases the possibility of slope movement (Fredlund and Rahardjo, 1993)..

Increased rainfall infiltration and more intense precipitation incidents have been found to be significant factors contributing to slope instabilities and gradual deterioration (Ling et al., 2009; Take, 2003). The loss of matric suction in unsaturated soils and the increase in pore water pressure, which in turn causes a decrease in shear strength owing to a decrease in the effective stress, are the main factors causing the collapse of earthen dams. The situation that occurred recently in Libya is a catastrophic example, as Hurricane Daniel caused the collapse of the Derna dams, which resulted in the deaths of over 10,000 people and caused extremely large damage to infrastructure.

For flood embankments, during the lifetime of the structure, multiple flooding and drying events may occur during which the embankment is expected to remain stable. Given that there are over 35,000 miles of flood embankment in the UK (Dyer, 2004), inspection of each section may not be done regularly. As a result, hidden failures may occur which are not evident at the surface. This paper evaluates the failure patterns of a compacted slope under various rainfall patterns, flooding, and drawdown conditions in the 50g-tonne 2 m radius beam centrifuge at the University of Sheffield. The model flood embankme nt was subjected to failure (during spin up) and this paper is concerned with the post-failure response of the slope to ongoing rainfall and flooding events.

### 1.1 Physical Modelling of rainfall induced slope instability.

The relationships between rainfall patterns and slope instability are reported in the literature for a range of slope failure mechanisms e.g. shallow and deep-seated first-time slides and reactivated movements (Aleotti, 2004; Tan et al., 1987; Ng et al., 2001). Centrifuge modelling has proven to be a powerful tool for analysing long-term soil responses to climate change (Take et al., 2004), since various physical processes such as heat transfer, seepage, rainfall intensity and duration are accelerated. Various centrifuge tests have been carried out with rainfall simulators to investigate the stability of fills subjected to heavy rains for a general slope case (Kimura, 1991; Tamate et al., 2010).

This paper presents an experimental investigation, benefitting from the accelerated time scaling proved by centrifuge modelling, to observe the behaviour of sandy clay flood embankment structures over a period of several "years" at prototype scale. During the modelled period, various climatic conditions were considered including seasonal fluctuations in rainfall, flooding and drawdown events.

### 1.2 Centrifuge scaling laws

The modelling of geotechnical problems in a centrifuge allows recreation of prototype stress conditions in small scale models. To relate measurements in the centrifuge model to equivalent values at prototype scale, various scaling laws need to be utilised. Table 1 contains important scaling laws that are particularly relevant to the modelling of rainfall in slopes (Askarinejad et al., 2015; Take, 2003) and include seepage, rainfall intensity, and rainfall duration.

*Table 1.Scaling laws used.*

| Term | Dimension | Model/Prototype |
|---|---|---|
| Length | L | 1/N |
| Seepage velocity | L/T | N |
| Consolidation time | T | $1/N^2$ |
| Rain duration | T | $1/N^2$ |
| Rain intensity | L/T | N |

## 2 EXPERMENTAL SETUP

### 2.1 Soil properties and slope preparation.

The model soil slope described here was formed by compaction, to provide realistic conditions with a slope angle of 1.5:1 (H: V), representative of typical prototype geometries and construction processes. The compaction was conducted into the centrifuge strong box payload in 30 mm thick layers and compacted equally using a steel plate attached to a vibrating machine , as shown in Figure 2-1.

*Figure 2-1 Soil preparation and compaction.*

The soil mixture (sand 65% / kaolin 35%) was selected on the basis that compacted gravel and chalk were typical embankment fill materials of early generation embankments (Skempton, 1964). A series of compaction tests were previously conducted on the mixture, where a maximum dry density of 1.8 g/cm$^3$ was obtained at an optimum water content of 12.3%. The specific gravity (Gs) of the soil mixture was measured to be 2.65. The liquid limit (27%) of the kaolin-sand mixtures was determined through Atterberg limit tests, following the specifications of BS 1377:1999. The plastic limit was not possible to precisely determine due to the crumbly nature of the soil. However, from this the soil should be characterised as having a very low plasticity. Via a falling head test as outlined in Head (2006) the saturated permeability coefficient, $k$, of the soil was found to be $9 \times 10^{-10}$ m/s. Via oedometer testing, the coefficient of consolidation, $c_v$, was found to be around 40 mm$^2$/min.

## 2.2 Geometry and model configuration

The model slope was created to replicate a common earthwork slope as might be found in UK flood embankments or railway embankments. Flood embankments range in height from around 2 m to 7 m. However, while railway embankments (which can be up to 18 m high) are not necessarily designed as flood embankments, it is estimated that around 35% of railway embankments are also prone to flooding across river, coastal and groundwater scenarios (Johnston et al., 2021). Therefore, a slope height was selected that was at the upper end of typical flood embankments and typical of railway embankments.

For the test described here, five individual bags of soil were prepared at the optimum moisture content and left overnight to enable even water distribution before use. From these, the soil block was compacted to 98% relative density – i.e. very dense. Using side cutting templates and a wire saw, the compacted soil block was then cut to the required shape, as shown in Figure 2-2. After two days to allow the water pressures in the block to equilibrate, the test was mounted for testing on the centrifuge.

*Figure 2-2 Model construction – left: template positioned before cutting compacted slope; right: slope after cutting.*

The test was conducted at 70g using a model slope height of 110 mm, representing a 7.8 m prototype and a slope angle of 33.7° or 1: 1.5. A 50 mm thick layer of saturated gravel was used as a free draining boundary at the toe of the slope.

In order to reduce friction and ensure plane strain conditions were met, a low friction Perspex sheet was provided on the back (non-window) side of the model while the Perspex window on the one face of the strong box enabled efficient observation and evaluation of soil deformations during testing. LED panel lights was applied to the top and right side of the window to ensure even lighting during the tests. Black seed texture was applied to the front face of the model slope during preparation in order to facilitate digital image correlation (DIC) analysis via GeoPIV-RG software (Stanier et al., 2016). Using a GoPro camera positioned in front of the Perspex window, soil displacements were tracked optically at 10-second intervals and at a resolution of around 10 pixels / mm. The model was observed in real time via a webcam that could be accessed from the control room. Overlapping strips of filter paper were positioned from the crest of the slope to the toe to reduce the possibility of erosion over the long seasonal moisture cycles.

### 2.2.1 Pore Pressure Instrumentation (PPT)

Constructing the model slope involved installation of eleven pore water pressure transducers (PPT) in the area of interest on the slope. The PPTs were inserted into the slope through the rear face of the model as indicated in Figure 2-3. All PPTs were capable of measuring both suction and positive pore water pressure, and were appropriately saturated and calibrated prior to testing.

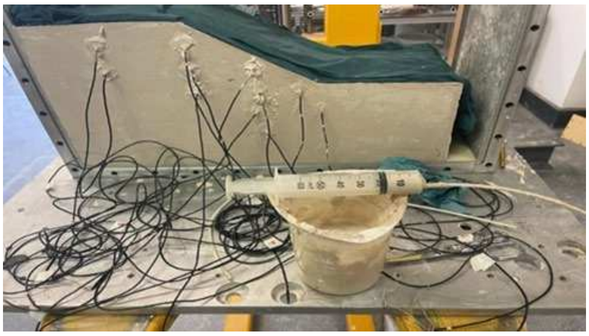

*Figure 2-3 Positions of PPTs used during construction.*

### 2.2.2 Environmental and rainfall simulator

The strongbox used for this study has been modified to facilitate the controlled application of various rainfall conditions to the model while in-flight. The rain simulation in the centrifuge environment was achieved by using four nozzles that generate dispersed water droplets, similar to the method reported by Take (2003). Based on direct measurement, this led to a scaled rainfall rate of 1.14 mm/h. Two temperature and two humidity sensors were also connected to the lid of the strongbox. Note that the fluctuation of humidity and temperature were not independently controlled as the air passed through the test chamber. Instead, rainfall or flood conditions were applied and the temperature and relative humidity varied in response. As a result, the maximum variation in temperature was from 21°C to 25°C and relative humidity from 56% to 92% which, for humidity, are typical extremes encountered in the UK. The experimental configuration, which includes the precipitation simulator and centrifuge model, is illustrated in Figure 2-4.

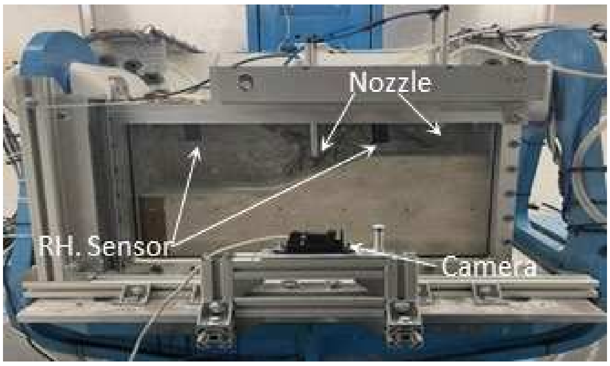

*Figure 2-4 Experimental design of the centrifuge model and rainfall simulator.*

## 2.3 Test procedure

The experiment was carried out with a step-wise increase in acceleration until it reached 50g for the auto-balance phase, which lasted approximately 25 minutes. Then, after reaching the targeted centrifugal acceleration of 70g, the model was left for 40 minutes (136 days at prototype scale) to equilibrate. Pore pressures developed steady readings in around one minute, which is in agreement with theory.

After this initial equilibration / summer phase, three “seasons” (winter, summer, winter) were applied to the slope model to observe the impact of rainfall duration on slope deformation and stability. The first “winter” lasted for 7 months at prototype scale, and consisted of alternating weeklong periods of rain and no rain respectively. During the “summer” period which lasted 5 months, no rainfall was applied. Finally, during the second (7 months long) winter, the rainfall period was increased to two weeks, separated by weeklong breaks of no rain. Following the above seasonal fluctuations, the model slope was subjected to a half-winter that lasted as three weeks of rain, followed by a dry week, where the other half-winter was continuous rain, with drainage allowed at the toe of the embankment. After this period, the drainage outlet at the toe of the embankment was closed to allow the applied rainfall to create a flooding scenario with the water level rising just above the embankment crest. Thereafter, the outlet valve was opened to facilitate a drawdown scenario. The flooding and drawdown conditions were applied twice before the model experienced a 310-day-long summer period with no rain. For all rainfall applications, a rainfall intensity of 1.14 mm/h (prototype) was used. In order to generate the precipitation patterns, the rainfall was manually activated and deactivated at predetermined time intervals.

## 3 EXPERIMENTAL RESULTS AND DISCUSSION

During the acceleration to 70g, the centrifuge at the University of Sheffield undergoes an auto-balance phase at around 50g. This phase caused small but discernible deep seated strains in the model (≤ 5%), as shown in Figure 3-1, which, using a GeoPIV-RG mesh size of 100×100 pixels with a 50 pixel overlap, illustrates the development of shear strain over a period of 10 seconds in model time. Additionally, a small crack in the crest was evident by the end of this auto-balance phase and has been labelled in Figure 1-5. This crack disappeared during the next few minute of auto-balance, possibly due to being infilled with fines (kaolin), and did not reappear subsequently. Similar slope movements were observed by Take (2003) during centrifuge spin up of pure kaolin models; he also noted that this did not appear to influence subsequent strain development. Once the model achieved a centrifugal acceleration of 70g, it was allowed to consolidate for 40 minutes in the absence of any precipitation events. During this period, visible movement was observed through DIC, where strain was occurred in the model, as depicted in Figure 3-2. The strains experienced during this period were approximately 4%.

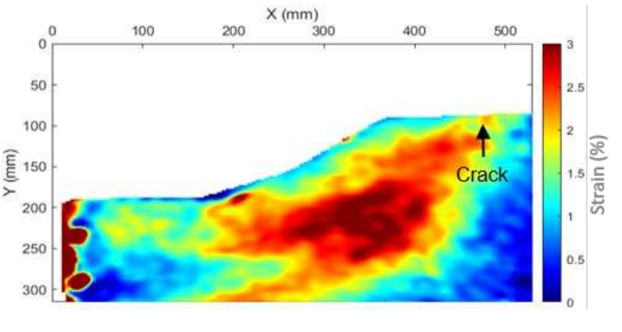

*Figure 3-1 Shear strain developed during auto balance stage.*

During the application of initial seasonal variations, no observable strains were detected. However, after the continuous application of rainfall for a period of the third winter, the greatest amount of strain (approximately 10%) during testing was observed, as illustrated in Figure 3-3. This occurred on a plane above the original slip surface.

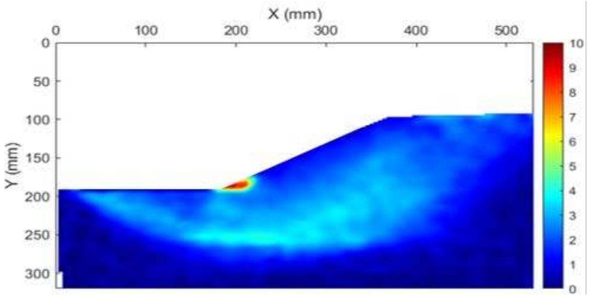

*Figure 3-2 Shear strain developed during consolidation phase.*

No movement was observed during the flood phase as shown in Figure 3-4. On the other hand, some movement occurred with the reduction of water level (drawdown phase) following the flood, as shown in Figure 3-5. While all the movements discussed above were clearly discernible from the DIC analyses, they were not accompanied by any abrupt changes in pore-water pressure. This is potentially indicative of drained instability; however, it cannot be ruled out that the sensors were simply not close enough to the shear zones to record changes in pore pressure associated with the movement.

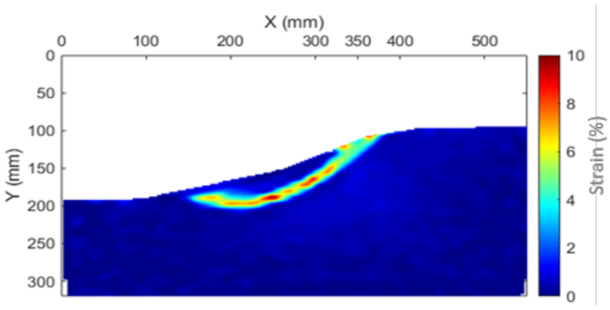

*Figure 3-3 Shear strain accumulation: failure during continuous rainfall season.*

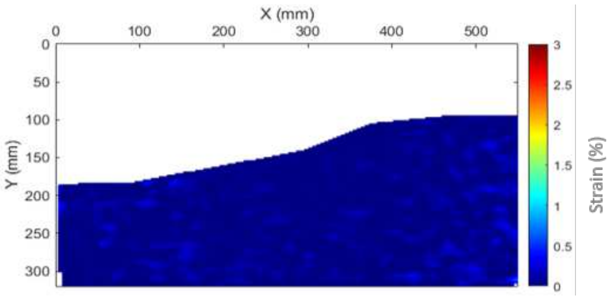

*Figure 3-4 Shear strain developed during flood stage.*

As illustrated by the DIC results presented, the application of various climatic scenarios resulted in significant slope deformations. Additionally, after testing it was observed that these slope movements were accompanied by surface erosion on the face of the slope near the crest.

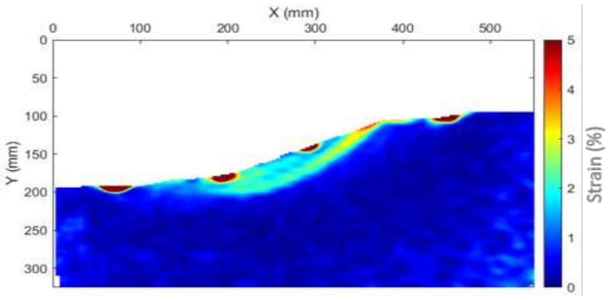

*Figure 3-5 Shear strain accumulation: post-failure movement during flood drawdown.*

Evidence of erosion was observed to a depth of approximately 10 mm as shown in Figure 3-6, indicating that the filter papers used to cover the soil surface did not adequately protect the slope during the extreme climatic conditions applied. Based on a post-test dissection however, it was deemed unlikely that this erosion led to the global failure of the slope.

The cumulative crest settlement following the auto-balance stage was 15mm, indicating possible slope instability under current climate conditions as presented in Figure 3-7.

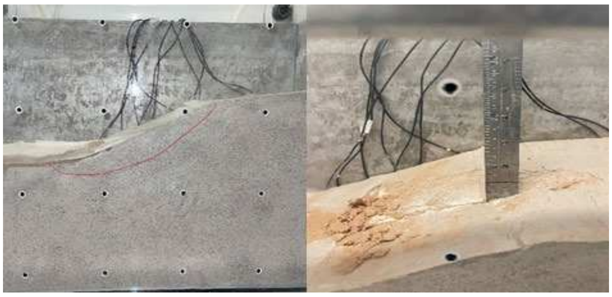

*Figure 3-6 The failure and erosion at the end of the test.*

*Figure 3-7 Crest settlement during auto balance phase.*

## 4 CONCLUSIONS

This paper presents the results of a centrifuge test conducted to evaluate the response of a model slope to extreme climatic conditions. With this procedure, a single, instrumented, and carefully controlled centrifuge test can be used to evaluate the performance of the slope over a number of years – under expected in-service loading to more extreme events. Although slope movement occurred during spin-up (auto-balance phase), there was no visible evidence of it on the model surface during subsequent testing. This suggests that the initial failure (even developing a crack that then "self-healed") did not cause any significant external damage or noticeable changes that could be later observed. This shows there is a possibility of slope deformations occurring as a result of the failure, which may only become evident when additional loading or stress is applied to the slope.

While there were the aforementioned initial deep seated strains during spin up and consolidation phases, no detectable strains were observed when the initial seasonal variations were applied. However, a relatively shallow shear plane (10% shear strain) developed during the third winter of continuous rainfall. This suggests that the lighter rainfall of the first two winters was insufficient to raise the pore pressure sufficiently to detablise the slope.

The subsequent flood phase did not cause any noticeable displacement or movement. However, there was some movement (approximately 2-3% additional shear strain) within the same shallow shear zone observed as the water levels decreased during the drawdown phase. There are various factors that could contribute to this phenomenon, including the settling or shifting of sediment, movement of groundwater, and other dynamic processes influenced by the decreasing water levels.

In summary, while this study only examined one soil type – namely a very low plasticity sandy clay – it has shown that a well-compacted embankment in such a material can experience significant long-term soil movements under current climatic conditions. These movements may not be easy to detect at the surface of the slope, resulting in difficulty in choosing to remediate such failures.

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