Development of a landslide testing flume for use within a geotechnical centrifuge

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ABSTRACT
Geotechnical centrifuge testing is a technique whereby small-scale physical models can be used to simulate geotechnical construction and failure processes which are cost-prohibitive to investigate at full-scale. This technique has been successfully applied to the investigation of complex failure mechanisms, to the validation of numerical models, and to the assessment of new design concepts. In this paper, the technique of centrifuge modeling has been applied to investigate the complex interaction between landslide triggering mechanisms which may result in a flowslide. This paper documents the development of a landslide testing apparatus which enables landslides to be triggered in model soil slopes through a combination of intense rainfall and groundwater flow. In particular, the paper demonstrates the difficulty associated with modeling these events due to the large number of competing failure mechanisms.

RÉSUMÉ
La modélisation en centrifugeuse utilise à petite échelle des modèles physiques pour simuler la construction géotechnique et les processus de défaillance qui sont difficiles à étudier à grande échelle. Cette technique a été appliquée avec succès à l'étude des mécanismes complexes échec, à la validation des modèles numériques, et à l'évaluation de nouveaux concepts. Dans ce papier, la technique de modélisation au centrifuge a été appliqué pour étudier comment les glissements de terrain sont déclenchés. Le présent document décrit le développement d'un appareil d'essai de glissement de terrain qui permet des glissements de terrain à être déclenchée dans les pentes du sol modèle à travers une combinaison de fortes précipitations et écoulement des eaux souterraines. En particulier, cet article démontre la difficulté associée à la modélisation de ces événements en raison du grand nombre de mécanismes de défaillance concurrents.

1 INTRODUCTION

Rainfall induced static liquefaction of soil slopes can lead to high mobility flowslide events. Loose fills for land reclamation purposes, sandy-silty slopes, submarine slopes, mine wastes, and hydraulic fills have been identified as being particularly susceptible to this failure mechanism. The failures at Aberfan, Wachusett dam, and Nerlerk Berm, convinced researchers (e.g., Lade 1993, Olson 2000, Pillai et al. 2004, Jefferies and Been 2007) that loose materials are particularly vulnerable to liquefaction. One of the common threads through many static liquefaction slope scenarios is therefore the high void ratio of the soil prior to failure. As a result, these soils have the potential to generate significant positive excess pore water pressures during shearing.

The identification of soil types and states that are particularly susceptible to static liquefaction has been investigated though the use of triaxial tests and through the back analyses of case studies. The work of Castro and Poulos (1977) indicated that liquefaction is not confined to uniform clean sands. A fines content of 0% to 60% was reported in 33 slope failures due to static and dynamic liquefaction (Olson and Stark 2002). The role of fine particles was also investigated in undrained triaxial tests by Lade et al. (1998), Yamamuro and Lade (1997). Chu and Leong (2002) observed instability in both clean and silty sands. Yang et al. (2006) stated that a high fines content would increase instability in soil and cause flow-like failure.

Although a significant research focus has been placed on understanding liquefaction behaviour through element testing, the exact nature of the processes leading up to the triggering of liquefaction flow slides (in particular the antecedent moisture conditions required in unsaturated slope systems) are less well understood.

The technique of geotechnical centrifuge modelling enables small-scale models to be subjected to elevated soil stress states and therefore the investigation of failure mechanisms and processes at realistic stress levels. This is particularly important for slope processes as capillary forces would otherwise dominate behaviour in small-scale models, leading to unrealistically high slope angles being stable in small-scale models.

In this paper, the design considerations and challenges relating to the development of a small-scale landslide testing system designed for use with a geotechnical centrifuge are discussed and conclusions drawn regarding the suitability of this technique for investigating flow phenomena.

2 CENTRIFUGE MODELING

2.1 Landslide testing system

A small-scale landslide testing system, consisting of a recirculating groundwater flow system and a distributed mist nozzle rainfall system was designed for use at the C-CORE centrifuge research facility. This centrifuge facility, located on the campus of Memorial University of Newfoundland, houses an Acutronic 680-2 geotechnical centrifuge capable of testing models to accelerations up to 200g (where g is the acceleration due to gravity). The maximum radial rotation speed is 189.2 rpm. The area of the centrifuge swing is 1.4 m×1.1 m. The data acquisition system provides 78 channels for sampling electrical signals from transducers during testing. The landslide testing system was constructed within a testing chamber of internal dimensions of 900 mm in length, 400 mm in height, and 300 mm in width. On one long side of the testing chamber the wall consists of a 76 mm thick transparent Perspex window. This window permits the observation of geotechnical processes using digital imaging whilst maintaining plane-strain boundary conditions (i.e. the transparent wall is heavily reinforced with an external steel frame to minimise deformations). A photograph of the plane-strain testing chamber is shown in Figure 1.

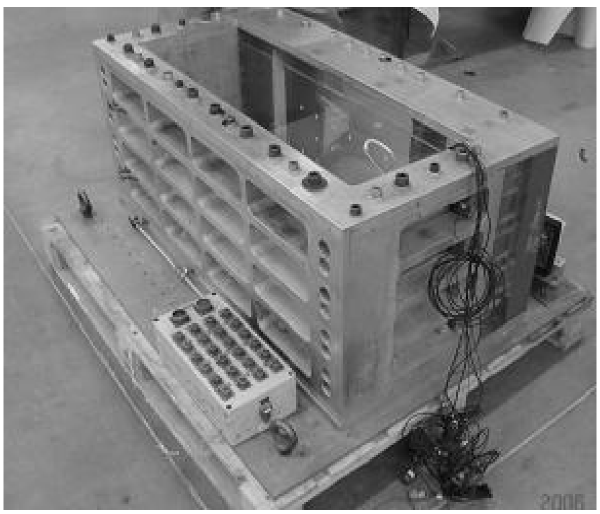

Figure 1. Plane strain testing box

Static liquefaction events cannot be expected to occur in exceedingly steep or flat slopes. Steep slopes are inherently well drained and therefore tend to not have the presence of groundwater required for liquefaction. Exceedingly flat slopes, on the other hand, are subjected to very low shear stresses and are inherently stable. Jefferies and Been (2007) reported liquefaction events, occurring in slopes of 13º to 36º with heights of 6.5 m to 67 m. For the landslide testing system a 30º slope was chosen of a 7.5 m of height, 1.5 m of soil depth, and 9 m of width to represent the target full-scale dimensions of the slopes in the present landslide testing program. At a testing acceleration of 30 g, these dimensions corresponded to a height of 250 mm, width of 300 mm and thickness of 50 mm in the reduced-scale model (Figure 2).

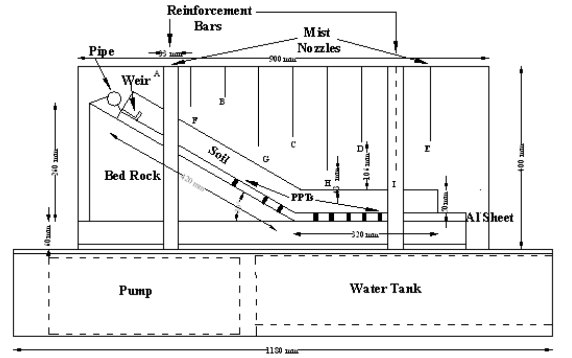

Figure 2. Test geometry

As shown in Figure 2, the geometry of the slope represents a thin layer of loose soil overlying an impermeable high-strength layer. This layer could be considered to represent bedrock. The simulated bedrock consisted of a 3/4 inch thick aluminum plate mounted on a 30º wooden wedge fabricated from plywood sheets. A layer of waterproof sand paper was attached to the aluminum sheet to increase the interface friction between the soil mass and the bedrock.

2.2 Boundary Conditions

Groundwater flow was simulated using a closed system, including a reservoir and settling tank, a pump, a weir, pipes, and tubes. A GC-M25-KVSE micropump, which provided a selectable flow rate from 200 to 3500 ml/min (i.e., 6 to 105 l/min in prototype), was employed to introduce the water to the top of the model slope. During cycles of filling and emptying of the standpipe, the volume of water was measured using an installed PPT which was connected to Signal Conditioning Box (SCB). The final calibrated flow rate graph is illustrated in Figure 3. A uniform distribution of the flow was accommodated by installing a perforated pipe and a weir at the top of the model slope. The seepage water was collected at the bottom of the slope and returned to the reservoir and settling tank.

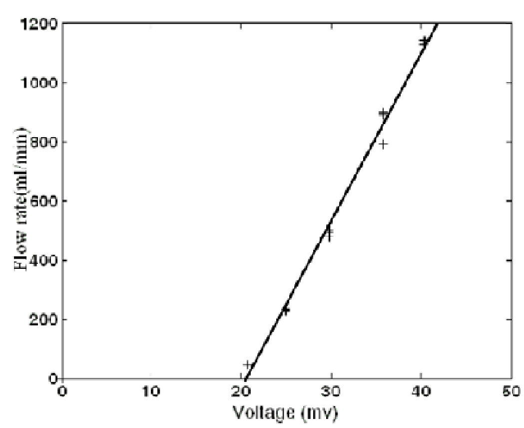

Figure 3. Calibration of flow pump at 30g

The rainfall simulator was composed of a series of M5 Hago misting nozzles. The M5 nozzles created the droplets with the mean diameter of 38.8 to 45.2 μm at 60 and 40 psi operation pressure. The introduced droplet size, assuming acceleration a scale factor of 30, would be 0.9 mm to 1.01 mm in prototype. The introduced rainfall to the slope corresponded to 8.8 mm/hr of intensity in prototype.

2.3 Instrumentation

Pore pressure transducers (PPTs) were embedded in the bedrock layer to monitor the pore pressure changes at the soil-bedrock interface as the process of failure unfolds. The miniature pressure transducers used are approximately 6 mm in diameter PDCR-81 sensors manufactured by GE-Druck. The PPTs with bronze filters were easily saturated prior to tests; however, those with ceramic filters did not remain saturated during the tests. These PPTs could not be disassembled in the course of tests. As a result, only the readings from PPTs with bronze filters were considered reliable.

The deformation of the slope was measured using image processing technique of Particle Image Velocimetry (PIV), and the software geoPIV developed by White et al. (2003). The use of PIV and close-range photogrametry provides a non-invasive deformation measurement tool in which the failure process of the landslide can be observed and the resulting velocity of failure quantified. Two digital cameras – a digital still camera (Canon G6) and a high-speed camera (Phantom V9) - were mounted to the centrifuge platform to observe the soil slope through the transparent transparent side wall of the plane-strain box (Figure 4). The G6 and V9 cameras captured the entire simulating process at every 15 and 0.005 seconds, respectively, in the area of interest which was the toe of the model slope.

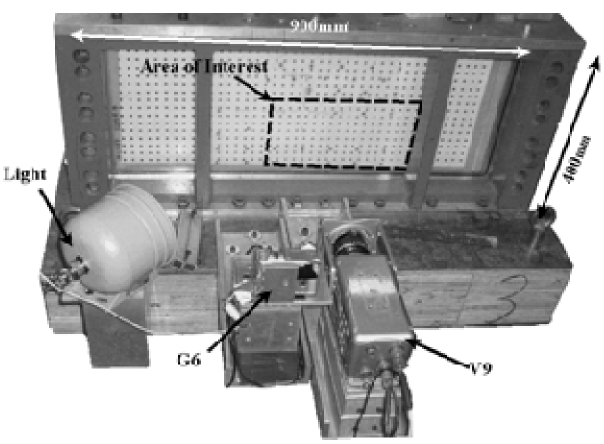

Figure 4. Location of the high-speed camera (Phantom V9) and the high-resolution still camera (Canon G6) with respect to the transparent side wall of the centrifuge test chamber. The black dots visible through the transparent window are a pre-test calibration of camera distortion through the 76 mm thick Perspex window.

3 EXPERIMENTAL RESULTS

The behaviour of four different soil materials were investigated using the landslide testing system. These materials included a medium sand (Alwhite sand), a medium sand spiked with some fines (85% Alwhite sand mixed with 15% Kaolin fines by mass), a fine sand (F110 Ottawa sand) and a silt. These materials were chosen to represent a range of varying permeability and varying magnitude of capillary effects on the slope behaviour (Table 1). The particle size distributions for all slope materials are shown in Figure 5.

Table 1. Description of soils tested

Slope Material	Grainsize		Relative Permeability	Capillary Effects
	D_{50} (mm)	D_{10} (mm)		
Medium Sand	0.3	0.1	High	Low
Medium Sand with added fines	0.25	0.06	↑	↓
Fine Sand	0.13	0.08		
Silt	0.06	0.02	Low	High

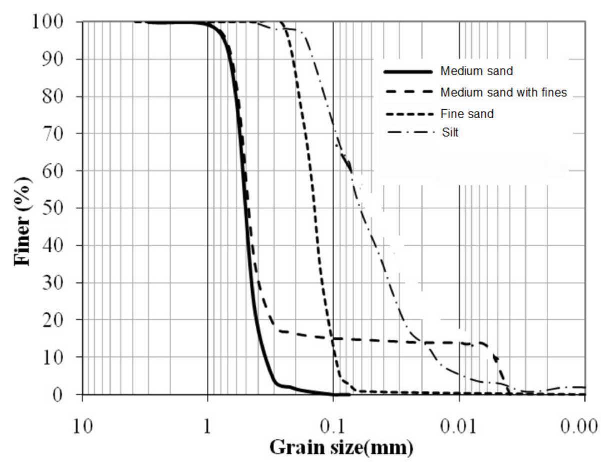

Figure 5. Grain size distribution curves for all four slope materials

In the first slope material, the medium sand, a landslide could not be triggered. A photograph of the toe of the medium sand slope taken immediately prior to groundwater flow is shown in Figure 6a. The permeability of this sand was sufficiently high to ensure that very little groundwater build-up occurred at the toe of the slope despite the groundwater flow pump operating at maximum capacity. As a result, the critical area of the slope (the toe) remained dry and stable during groundwater flow (Figure 6b). Upon rainfall infiltration, the slope remained stable. Once again, the high permeability of the sand eliminated the possibility of obtaining pore water pressures high enough to fail the slope at the boundary conditions applied.

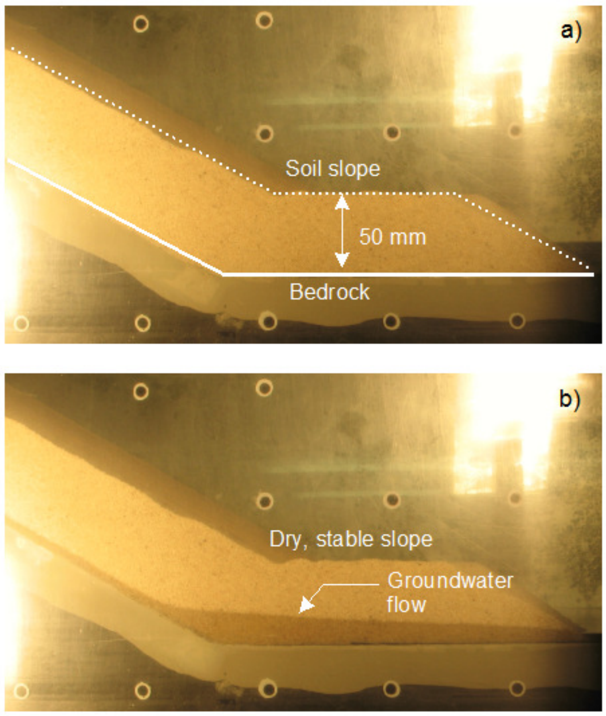

Figure 6. Photographs of toe of medium sand slope a) prior to, and b) after groundwater flow being initiated.

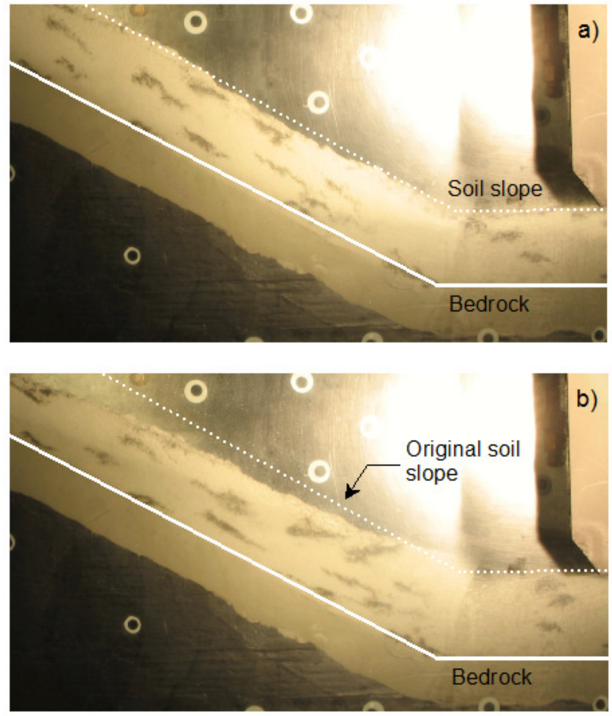

Figure 7. Photographs of toe of fine sand slope a) prior to, and b) after landsliding.

The second slope material consisted of the same medium sand used in the first experiment, but with the addition of 15% of Kaolin fines by mass to decrease the permeability of the slope and to increase the stable void ratio prior to testing (i.e. higher suctions leading to a looser and more fragile pore structure). As shown in the grain size analysis in Figure 5, this material is gap graded. During testing, the elevated fines content initially reduced the permeability of the mixed soil at the beginning of the initial transient groundwater seepage flow. However, once the groundwater seepage regime was established, the groundwater leaving the slope was observed to have a high fines content. Once again, despite the process of internal erosion, pore pressures at the toe of the bedrock remained small, and the slope remained stable.

The third slope material was a uniform fine sand. The mean grain size of this material was sufficiently small (0.13 mm) that the individual grains could not be easily seen in the digital images taken through the transparent side window. In order to enable PIV tracking, some sand was dyed black, and placed randomly in the material to increase the pixel contrast of the various soil regions comprising the slope. A photograph of the toe of the fine sand slope taken immediately prior to groundwater flow is shown in Figure 7a. Unlike the coarser sand slope, the lower hydraulic conductivity of the fine sand slope resulted in groundwater ponding at the base of the slope and the ability to trigger landslides within the operational window of the groundwater and rainfall systems.

An example of the post-landslide profile from one of these events is presented in the photograph Figure 7b. This image shows a significantly reduced angle of the remaining material on the slope and the general downslope movement of the darker tracking patches in the soil.

Finally, the fourth slope tested consisted of an identical slope geometry as the first three, but made with a silt. The low permeability of this silt resulted in an erosional failure from the crest due to the overtopping of the groundwater flow system. A subsequent model was tested under rainfall infiltration, but remained stable.

4 SUMMARY AND CONCLUSIONS

The paper presents some preliminary results from a series of centrifuge tests examining the design considerations and challenges relating to the development of a small-scale landslide testing system designed for use with a geotechnical centrifuge. The four tests performed indicate, rather ironically, how difficult it is to trigger flow slide events in physical models. The results of this study illustrate that if this operational window of possible boundary conditions is not carefully matched to the hydraulic properties and geometry of the slope, the slope will either remain stable (too little water) or fail due to the competing failure mechanism of erosion (too much water). Work is currently underway to investigate the effect of antecedent groundwater conditions on flowslide mobility through the analysis of the high-speed camera's images and to compare these experimental results to current prediction methods.

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