Centrifuge Model Tests of Rainfall-Induced Landslides

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Abstract. Rainfall-induced landslides and debris flows constitute very serious threats to human lives and infrastructure. In many cases, rainfall characteristics which cause the initiation of landslides are not very well determined and this might lead to the misunderstanding of the failure mechanism, the kinematic characteristics and the run-out distance of the failure. In this paper, the design of three series of centrifuge model tests on soil slopes, subjected to rainfall conditions, is presented. The main goal is to investigate rainfall characteristics which cause failure initiation in soil slopes in respect to soil properties and slope geometry. Tests will be performed in a geotechnical centrifuge at the Nottingham Centre for Geomechanics (NCG) under very well defined initial and boundary conditions. For the accomplishment of these tests, a climatic chamber has been developed which accommodates plane-strain slope models and sufficient instrumentation and embodies a rainfall and an evaporation simulation systems. During the centrifuge tests, changes in pore water pressures and soil state as well as deformations of the slopes will be measured, while rainfall intensity and total rainfall will be accurately defined. Three different soil types will be used to create uniform slope models, i.e. fine sand, silty clay and clay, while rainfall intensity will be proportional to the infiltration capacity. The paper describes, also, the saturation and calibration of Druck PDCR-81 miniature pore pressure transducers and SWT5 tensiometers used for pore water pressure measurements.

Keywords: Centrifuge modelling, rainfall, slope stability.

1 Introduction

Rainfall-induced landslides are devastating phenomena which are responsible for loss of human life and serious damage to infrastructure every year. Although they have a global distribution, a significant segment is observed in areas with tropical and subtropical climates [1, 2] where residual and colluvial soils are widespread. The likelihood and time of occurrence, in respect to a triggering rainfall event, is not easy to be defined leading to a major difficulty in predicting small and large-scale disasters. Rainfall characteristics, i.e. duration, intensity and distribution, play a significant role in the pore water pressure changes and therefore influence the stability of natural and man-made slopes. Moreover, slope failures due to rainfall are often rapid phenomena and occur without warning leading to a major lack of reliable field data.

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Recent developments in geotechnical centrifuge techniques have heightened scientific interest in slope stability modelling under an increased gravity field. The idea of rainfall simulation in centrifuge slope model tests was introduced in the early '90s, involving the conservation of moisture content of the soil [3]. In another investigation, centrifuge tests of slope models, made of sandy loam, were carried out in order to investigate the effect of heavy rain on their stability [4]. The simulation of seasonal pore pressure cycles of over-consolidated clay embankments, in an increased gravity field, was performed in University of Cambridge [5]. A similar investigation was performed in Dundee University [6], describing the behaviour of a compacted clay embankment under climatic cycles. However, in this case, glacial till was used to form a small-scaled model in order to explore long-term embankment performance in light of the more severe conditions expected due to global climate change. Slope models made of silty sand were prepared in order to be tested under an oncreased gravity field in order to simulate the behaviour of a full-scale experimental natural slope in Switzerland [7]. The natural slope was subjected to rainfall for several hours until it failed due to a bottom-up saturation mechanism [8]. The initiation of static liquefaction failure mechanism was also investigated by other researchers [9, 10]. Finally, failures of sandy slope models, induced by heavy precipitation, were modelled in a geotechnical centrifuge using liquids with varied viscosity in order to simulate rainfall events [11], paying also attention to the impact pressure of the droplets to the ground surface.

The aim of this research is to evaluate the stability of soil slopes subjected to different types of rainfall conditions. For the accomplishment of the study, a number of centrifuge tests will be conducted on the Nottingham Centre for Geomechanics (NCG). Soil slope models will undergo an increased gravity field under controlled climatic conditions (rainfall, evaporation, relative humidity). The increased gravity field, due to centrifugal acceleration, will create a stress field within slope models similar to a 9m high prototype slope. The intensity of the simulated rainfall events will be proportional to the infiltration capacity of the soils. For this reason, different values of the dimensionless factor I_r/k will be used, where k is the coefficient of permeability of the soil and I_r the rainfall intensity. Changes in pore water pressures, soil state as well as slope deformation will be recorded during the tests.

2 Apparatus

2.1 Geotechnical Centrifuge in the NCG

The geotechnical centrifuge which is based in the Nottingham Centre for Geomechanics (NCG), at University of Nottingham, is a 50g-tonne machine with 2m platform radius able to achieve accelerations up to 150g [12]. It has a maximum payload of 500kg (at 100g) and an automatic "in-flight" balancing system. It includes a data acquisition system which accommodates 32 strain gauge channels and 32 channels for general instrumentation. A swinging model platform is located at the end of the centrifuge arm and is the base where the model box will be fixed. The platform initially is horizontal for facilitation of the model preparation and the necessary actions concerning instrumentation and connection of the measurement devices. As the centrifuge starts operating and the radial velocity is increased, the platform rotates outwards such that the vertical axis of the model aligns with the beam. In this position, the gravity field within the model is *N* times greater than *g* (*Ng* condition), directed along the vertical axis of the centrifuge model.

2.2 Climatic Chamber

In order to control the climatic conditions during the centrifuge acceleration of the soil slope models, a climatic chamber has been designed (Fig. 1). This comprises a plain-strain rigid container (strong box) with one transparent boundary (Perspex window) which offers the ability to observe and optically measure soil deformations throughout the entire model cross-section. A high speed camera is been placed in front of the Perspex window allowing for optical measurement of soil displacement at small time intervals. In order to ensure absolutely controlled climatic conditions, the climatic chamber is isolated preserving the internal air humidity and preventing wind gusts to affect the model. The skeleton of the container is made of steel and aluminium and it has interior dimensions of 700mm in length, 400mm in height and 200mm in the plain-strain direction.

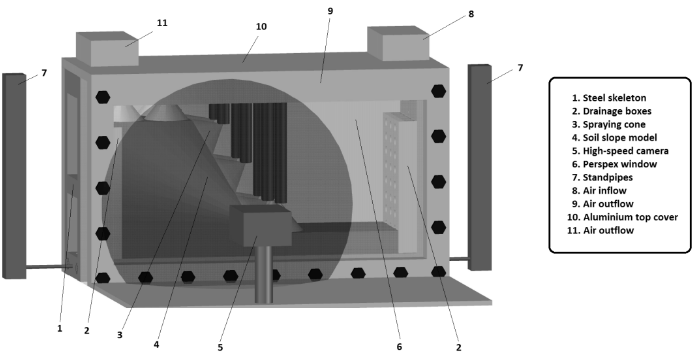

Fig. 1. Climatic chamber, which will be used in centrifuge tests

For the realistic simulation of climatic conditions (i.e. rainfall, evaporation, initial groundwater table and unsaturated conditions) different systems have been designed and constructed. Rainfall simulation takes place through a distribution system which includes a series of atomising mist nozzles located at the top cover. Water, under a pressure of 600kPa, passes through a solenoid valve into the nozzles ensuring that the formed water droplets have a small size. In this pressure, mist nozzles produce water droplets with a mean diameter of 30μm and, providing that the designed centrifuge acceleration is 60g, the mean size of the droplets corresponds to a prototype size of 1.8mm. In nature, rain droplets rarely grow larger than 5mm owing to the stability of the droplet under drag forces [5]. The position of the spraying nozzles depends on two factors, the prevention of soil erosion due to the impact pressure and the minimization of Coriolis effect. The later refers to the deformation of the movement projection of an object when this is moved in the plane of rotation and it is an effect which needs to be eliminated. To meet these requirements, the vertical distance between the surface of the model and the spraying nozzles is designed to be between 70 and 100mm.

Based on Dalton's law, the initiation of evaporation process within a climatic chamber requires one of the following conditions to be met: increased wind speed; increased temperature at the surface of the model and as a consequence the saturation vapour pressure; reduction of the vapour pressure on the atmosphere either by reduction of the temperature or the relative humidity (RH) [13]. In the current tests, dryness of the soil model will be driven by air exchange between the climatic chamber and the environment using an air circulation system installed on the top cover. The reduction of the RH of the air within the climatic chamber will cause the evaporation of the pore water, and therefore soil's dryness, as a result of the tendency of the pore air to come into equilibrium with the air above the model.

A groundwater control system will be fixed to ensure a controlled groundwater table within the soil slope and to prevent sufficient drying of the model during the centrifuge flight. This includes the installation of two vertical standpipes at both sides of the model. These will be connected with the climatic chamber, allowing water to drain through the soil. The level of the water inside the tubes will be measured all the time by using LVDTs and it will be controlled by providing or removing water, according to the needs of the test.

A recording system with a high-speed digital camera with a frame rate of 15 fps is going to be used for capturing high-quality images of the slope model through the transparent Perspex window. For the measurement of deformations during the centrifuge tests, Particle Image Velocimetry (PIV) method [14] will be used.

3 Soil Slope Models

Three sets of centrifuge tests will be carried out, each one of them in a different soil type. The soil types used for the formation of the slope models are sand, silty clay and clay.

For the sandy models, Leighton Buzzard Sand (Fraction E) will be used. That is fine-grained sand with D_{10} at 0.095mm and D_{50} at 0.12mm [15]. The maximum dry density and optimum moisture content for compaction were determined using the Heavy Compaction method (BS1377:Part 4:1990). These are 1.61 Mg/m^3 and 11%, respectively. Also, the minimum dry density was determined at 1.33 Mg/m^3 and the maximum and minimum void ratio at 0.99 and 0.65, respectively. The coefficient of permeability is 1.44x10^{-4} m/s and is estimated using Hazen's approximation ($k = 100D_{10}^2$).

The silty clay soil used in this study comes from the Scrooby Top Quarry in South Yorkshire. It consists of clay (49%), silt (39%) and sand (12%). The petrographic examination showed that the great proportion of the material consists of quartz (68%) and quartzite (19%), with minor proportions of sandstone and chert, and traces of alkali feldspar, ironstone, limestone, opaque minerals, calcitic sandstone, shell, coal and shale. Its liquid limit was determined to be 51% and the plastic limit 33%, with the plasticity index at 18%.

A third series of tests will be carried out in clayey slopes. The material which will be used in this series is Speswhite kaolin clay, known also as *China Clay*. The specific gravity (G_s) of Speswhite kaolin is 2.60 and its Liquid and Plastic limits are 61% and 27%, respectively [15]. From one-dimensional consolidation tests in Speswhite kaolin, performed in a standard oedometer, the coefficient of compression (C_c) determined at 0.47, Young's Modulus (E_o) ranges between 1.2 and 7.5, coefficient of consolidation (C_v) lies between 1 and 4 (with σ_v between 0 and 200 kPa) and the coefficient of permeability (k) ranges between 1.1×10^{-10} and 5.1×10^{-9} m/s, assuming E_o constant and equal to 7.5 MPa [16].

Two different slope angles will be examined for each soil type. The intensity of rainfall which will be applied to each model will be a function of the soil's permeability. The dimensionless factor k/I_r applied to each model will be set to 0.5 and 1, indicating two different rainfall and, therefore, infiltration conditions within the soil mass.

4 Scaling Laws

Scaling laws are derived from the need to ensure stress similarity between the model and the corresponding prototype. It is well known that soil behaviour depends on the stress level and stress history and, also, that in-situ stresses change with depth, so it is necessary to replicate these features during centrifuge modelling. For this reason, a small-scaled model is placed at one end of the centrifuge arm and is subjected to an inertial radial acceleration field which, for the model, turns to be an increased gravity field.

Table 1. Scaling factors for the testing parameters involved in this study

Parameter	Model	Prototype
Length (macroscopic)	1	N
Seepage velocity	1	$1/N$
Seepage time (macroscopic)	1	N^2
Total rain	1	N
Rain duration	1	N^2
Rain intensity	1	$1/N$
Seepage time (microscopic)	1	N
Hydraulic gradient (macroscopic)	1	$1/N$
Hydraulic gradient (microscopic)	1	$1/N$

Soil model, held in a container, has an unstressed upper surface while in-situ stresses are increasing with depth at a rate which depends on the soil density and the strength of the acceleration field. If the model is subjected to an inertial acceleration field of N times the Earth's gravity, the vertical stresses at a depth h_m will be identical to those in the corresponding depth h_p of the prototype, with $h_p=Nh_m$, providing that the same soil type is used and the stress history has been replicated accurately. This is the basic scaling law of centrifuge modelling, stating that stress similarity in model and prototype is achieved if the model has been scaled-down by *N* times, in respect to the prototype, and is subjected into an acceleration of *N* times Earth's gravity. Seepage velocity is *N* times higher in the model under *Ng* centrifugal acceleration, so the velocity of the infiltrated water in the prototype must be scaled down by *1/N* [18]. Also, the seepage time will be N^2 times less than the prototype as the seepage length is *N* times shorter in the model.

The duration of the rainfall in the model will be N^2 times less than that of the prototype and the total rainfall (expressed as height of water) will be *N* times less than that of the prototype. Finally, the rainfall intensity will be N times higher in the model than in the prototype. For example, if a 24h rainfall event with constant intensity of 15mm/hr is to be simulated at an acceleration of 60g, the modelled rainfall event should have intensity of 900mm/hr for a period of 24sec. Scaling factors of the most important parameters involved in this study can be seen in Table 1.

5 Instrumentation

5.1 Relative Humidity and Temperature

The Relative Humidity (RH) and Temperature (T) measurements within the climatic chamber will be performed using a couple of HMP60 Vaisala Humidity and Temperature probes. They consist on an IP65 stainless steel body and a membrane filter which is mounted at one side, while they provide accurate measurements of RH (0-100% measuring range with a typical mean accuracy of ±4%) and T (measuring range from -40 up to +60 °C, with a typical accuracy of ±0.6°C). These sensors are going to be installed at the two ends of the climatic chamber, in positions where no water will be sprayed. This will ensure reliable measurements during the application of rainfall events. Also, their positions will be away from the air inlet and outlet units of the evaporation system in order to prevent the influence of the wind to the measurements.

5.2 Pore Water Pressures

Reliable measurement of pore water pressure before, during and after the application of rainfall events at the soil slope models is crucial for the understanding of their elemental behaviour. Therefore, it is important to use reliable sensors with very small size so as to prevent the disturbance and reinforcement of the soil models.

Two types of sensors are going to be used during this series of tests, the Druck PDCR-81 Pore Pressure Transducers (PPTs) and the SWT5 tensiometers. These sensors are being used primarily for measuring positive pore water pressures; however, they can also be used as negative pore water pressure measurement devices and in order to do so the filter element they bring needs to be very well saturated. To achieve very high degree of saturation, a new apparatus (Fig. 2) has been designed and implemented, based on a previous research work [19]. This device is made of brass and brings 8 slots for the instantaneous saturation and testing of 8 sensors, preventing their drying out during the waiting time between saturation and centrifuge testing.

A de-airing water system has been implemented to this configuration ensuring that the water used for the saturation process contains significantly reduced amount of dissolved oxygen, preventing the formation of large air bubbles at high negative pressures. The de-airing process was applied to distilled water and these results can be seen in Table 2. Compressed air is used for applying positive water pressure in the system, through an air-water interface, while negative pressures are applied through a vacuum pump.

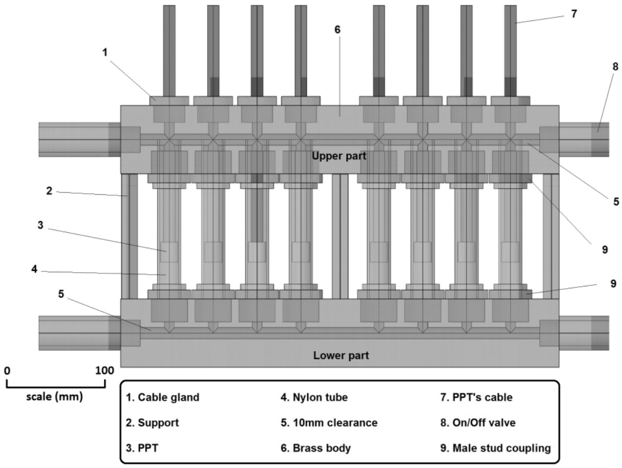

Fig. 2. Saturation and calibration apparatus for PPTs and SWT5 tensiometers (x-ray view)

Table 2. Results from the de-airing of distilled water. The first column contains the percentage of Dissolved Oxygen (DO) in the water in comparison to the amount of oxygen in the air (100%) and the second column milligrams of oxygen per litre of water. The abbreviations T and P stand for temperature of water and pressure within the laboratory, respectively.

	DO (%)	**DO (mg/lt)**	**T (°C)**	**P (mbar)**
Distilled water	88.1%	7.61	21	991
De-aired distilled water	56.1%	4.89	21	991

Druck PDCR-81 PPT. The main advantage of the Druck PPTs is their miniature size (Fig. 3) which allow for the minimum disturbance of the small-scaled slope models. Their measuring range is between 3 and 7 bar and they bring a porous stone with an air entry value of 1bar. They are primarily used for measuring positive pore water pressures, but they can also measure negative pore water pressures (suctions) when the filter element (porous stone) is very well saturated. For that reason, a rigorous program of filter saturation has been used to ensure high degree of saturation for the porous stone.

The saturation of these sensors includes the application of repeated cycles of positive and negative pressure [19]. The process involves the application of an initially low pressure (near 0kPa of absolute pressure or -100kPa in respect to the atmospheric) for about 15 minutes and then the application of positive pressure of 100kPa for 30 minutes. The same saturation procedure was applied, also, to this case improving significantly the performance of these sensors at negative pore pressures measurements.

Prior to the centrifuge testing, PPTs were calibrated using the saturation and calibration apparatus. The results can be seen in Fig. 4. In this case, PPTs have been saturated using the procedure described above.

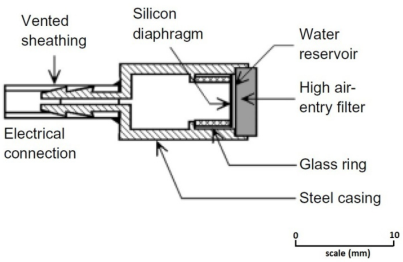

Fig. 3. Druck PDCR-81 Pore Pressure Transducer [20]

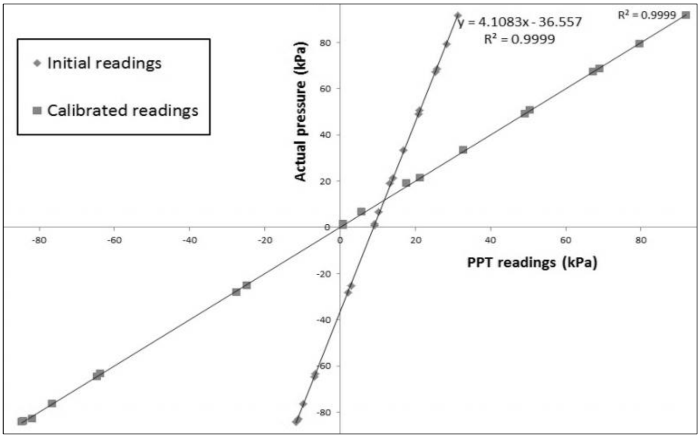

Fig. 4. Calibration of Druck PDCR-81 PPTs

SWT5 Tensiometers. These sensors (Fig. 5) can also be used for measuring negative pore water pressures, while the small size of the saturated shaft and porous stone makes them ideal for centrifuge applications. They consist of a sensor body and a 70mm long shaft fully saturated with water. A porous stone is attached at the edge of the shaft. The thickness of the shaft is 5mm, almost equal to the thickness of the PPT. During the centrifuge tests, the shaft with the porous stone will be inserted within the soil mass through drilled holes at the back wall of the climatic chamber. An aluminum casing will provide adequate strength to the shaft so as to withstand the high stresses acting due to the centrifuge spinning. The part of the tensiometer which will be inserted inside the model has a length of 3mm, ensuring that reinforcement of the soil is negligible.

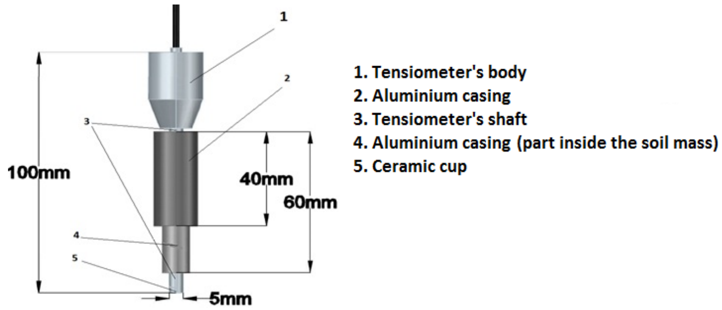

Fig. 5. SWT5 tensiometer and designed aluminum casing

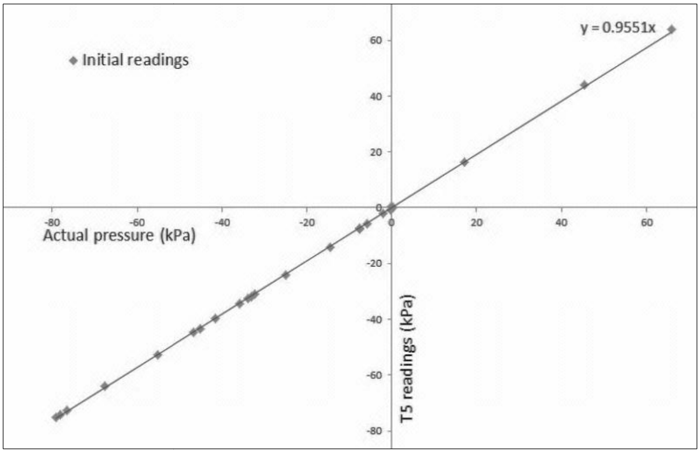

Fig. 6. Calibration of the SWT5 tensiometer and determination of the correction factor

The results from the SWT5 tensiometer testing and calibration can be seen in Fig. 6, where the tensiometer readings have been plotted against the actual readings. In this way, a correction factor of 1.047 has been determined and is used for the correction of the instrument readings.

Tests conducted on these sensors revealed the need for a very good saturation of the sensor body and the shaft. Also, after each test small bubbles appeared inside the shaft leading to incorrect measurements. For all these reasons, it is important to proceed with the saturation of the sensor body and shaft right before each centrifuge test in order to ensure the preservation of porous stone saturation. Finally, due to the fact that the contact of the porous stone with the unsaturated soil causes inevitable desaturation, calibration of the PPTs and T5 tensiometers takes place right before and exactly after each centrifuge test.

6 Conclusions

A series of centrifuge tests for the study of initiation conditions of slope failures, under rainfall, have been designed. These will be performed in the Nottingham Centre for Geomechanics geotechnical centrifuge facility. For the accomplishment of this study, a climatic chamber has been designed in order to accommodate the soil slope models and provide fully control of the climatic conditions. Pore water pressures will be measured by two different types of sensors, Druck PPTs and SWT5 tensiometers. The saturation process of these sensors is very important in order to ensure reliable measurements of both positive and negative pore water pressures throughout the test procedure. Deformations will be observed and optically measured, using PIV, through a transparent boundary and with the use of a high-speed camera. Three different soil types will be used to form the slope models and two different rainfall intensities will be used for the rainfall simulation. Results will form a very well documented database, with well-defined initial and boundary conditions, which can be used as feedback to the validation of numerical models dealing with the prediction of slope stability under rainfall conditions.

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