

Centrifuge model study of thresholds for rainfall-induced landslides in sandy slopes

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Abstract. Rainfall-induced landslides are very common natural disasters which cause damage to properties and infrastructure and may result in the loss of human life. These phenomena often take place in unsaturated soil slopes and are triggered by the saturation of the soil profile due to rain infiltration which leads to the decrease of effective stresses and loss of shear strength. The aim of this study is to determine rainfall thresholds for the initiation of landslides under different initial conditions. Model tests of rainfall-induced landslides were conducted on the Nottingham Centre for Geomechanics geotechnical centrifuge. Initially unsaturated plane-strain slope models made with fine silica sand were prepared at varying densities at 1g and accommodated within a centrifuge container with rainfall simulator. During the centrifuge flight at 60g, rainfall events of varying intensity and duration, as well as variation of groundwater conditions, were applied to the slope models with the aim of initiating slope failure. This paper presents a discussion on the impact of soil state properties, rainfall characteristics, and groundwater conditions on slope behaviour and the initiation of slope instability.

1. Introduction

Rainfall-induced landslides are very common natural disasters which cause damage to properties and infrastructure and may result in the loss of human life. These phenomena often take place in unsaturated soil slopes and are triggered by the saturation of the soil profile due to rain infiltration which leads to the decrease of effective stresses and loss of shear strength. Often, rainfall-induced landslides develop into debris flows which can experience high velocities and result in catastrophic outcomes. The study of the initiation conditions for rainfall-induced landslides is very important in order to predict these phenomena and be able to develop reliable real-time warning systems in the future.

Physical modelling plays a fundamental role in the development of the understanding of the triggering mechanisms of landslides and is performed in order to validate theoretical and empirical hypotheses [1]. Many studies have been performed in the past regarding the centrifuge modelling of slope behaviour under rainfall conditions ([2], [3], [4], [5], [6]).

A research project being conducted at the University of Nottingham aims to use geotechnical centrifuge modelling to better understand how the initiation of rainfall-induced landslides is affected by rainfall intensity and the initial state of the soil. Small-scale slope models constructed with fine-grained sand at an angle of 50° are tested within a climatic chamber at a centrifugal acceleration of 60g. Under the increased gravitational field, controlled rainfall conditions are applied to the slopes and deformations are recorded. Rainfall parameters (intensity and



duration), void ratio, and initial boundary and groundwater conditions are all controlled or measured during the tests. Deformations are determined by taking digital images of the slopes through a transparent wall which forms one side of the centrifuge container and processing the images using image analysis techniques.

2. Apparatus and instrumentation

Model tests were conducted using the Nottingham Centre for Geomechanics 2 m radius, 50g-Tonne beam type geotechnical centrifuge facility (Figure 1). The centrifuge can operate at 100- g (at 1.7 m radius) with a payload of 500 kg and up to 150- g at a reduced payload of 330 kg [7]. A data acquisition system enables the transfer of sensor readings from the centrifuge model to the control room through a fibre optic rotary joint. De-aired water, used in rainfall simulations, is supplied to the model through a hydraulic rotary union. The model container is placed on the swinging platform and the centrifuge is rotated at an appropriate speed in order to achieve the desired g level. A key issue in centrifuge modelling is the use of appropriate scaling factors to relate model-scale parameters to their prototype-scale equivalents. Table 1 presents the scaling factors applicable to the current study [8].

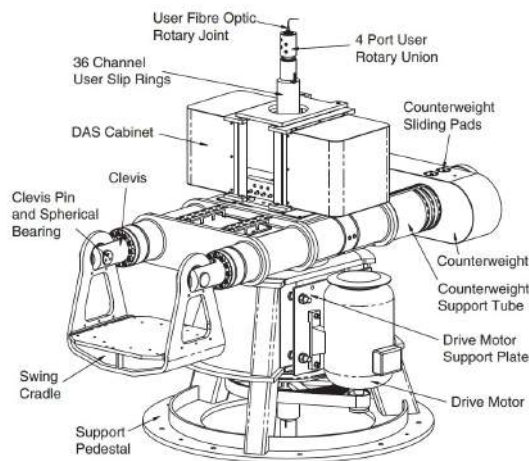


Figure 1. Main components of the University of Nottingham geotechnical centrifuge [7].

A plain strain strong box with inside dimensions of $600 \times 400 \times 200$ mm (*length \times height \times width*) is used for the model slope tests. It includes a transparent Perspex front wall that allows for viewing of the soil model. Pore pressures and suctions were measured using miniature pressure transducers, however results obtained from these instruments were inconclusive and are therefore not presented in this paper. The centrifuge model includes the following systems, which are also illustrated in Figure 2:

- A rainfall system, consisting of a series of spraying/misting nozzles attached to aluminium rods (extensions) and located below a sealed lid. The length of the extensions was set so that nozzles are located approximately 70 – 100mm above the soil surface. This distance was found to be optimal for minimizing the impact of Coriolis effects and preventing soil erosion [4]. Nozzles are interconnected using a network of pipes. A supply water tank, located outside the centrifuge, is connected to the nozzles via the hydraulic rotary joint. A flow measurement device and an on/off solenoid valve are located between the water tank and the nozzles.
- A drainage system consisting of two drainage boxes located on both sides of the slope model. The boxes are perforated and allow water to move through them but prevent soil from being

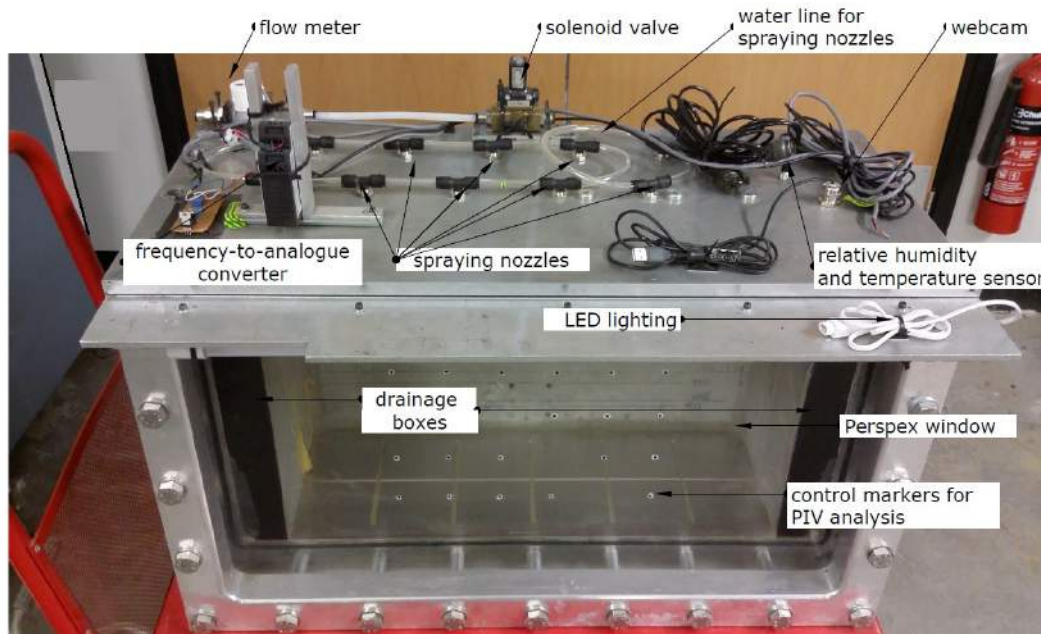


Figure 2. Main components of centrifuge container for modelling of rainfall-induced landslides.

washed away. The drainage boxes are connected to two standpipes located at the back side of the box and allow the water to be removed from the chamber.

- A groundwater table system which consists of two standpipes located outside the climatic chamber and connected through valves with the drainage boxes. Overflow at different heights of the standpipes offer the ability to control the water level within the climatic chamber and, therefore, control the water table height in the slope model.
- A recording system, including two digital cameras capturing images of the soil slope model through the transparent Perspex window. These images are processed using geoPIV [9] in order to determine the soil deformations that occur during the tests. Also, a web-cam is placed within the climatic chamber, under the lid, capturing video of the slope face during the test and allowing confirmation of the plain strain behaviour of the model.

3. Experimental program

Soil slope models are tested at $60g$ gravitational acceleration and consist of Leighton Buzzard (LB) sand (fraction E). This is a fine, uniform silica sand with $D_{10} = 0.095$ mm, $D_{50} = 0.12$ mm and uniformity coefficient ($U = D_{60}/D_{10}$) equal to 1.39 [10]. A Scanning Electron Microscopy (SEM) image and grain size distribution are shown in Figures 3 and 4, respectively. The critical state friction angle of LB sand was found to be 30° ([11]). Finally, the coefficient of saturated permeability was determined using the falling head permeability test and was approximately 5×10^{-5} m/sec.

Slope models are prepared within the centrifuge container to a height of 150 mm. The model is prepared by dry sand pouring, followed by saturation of the soil, and subsequent desaturation. Subsequently, soil mass remains in a partially saturated state, with the water content ranging between 8% and 11%, allowing for the slope to be cut to an inclination of 50° using a sharp cutting tool.

Table 1. Scaling factors for the parameters involved in the current study. L stands for units of length and T for units of time [8].

Parameter	Dimension	Model	Prototype
Length (macroscopic)	L	1	N
Seepage velocity (soil permeability)	L/T	1	N^{-1}
Seepage time (macroscopic)	T	1	N^2
Total rain	L	1	N
Rainfall duration	T	1	N^2
Rainfall intensity	L/T	1	N^{-1}
Seepage time (microscopic)	T	1	N
Hydraulic gradient (macroscopic)	L/L	1	N^{-1}
Hydraulic gradient (microscopic)	L/L	1	N^{-1}

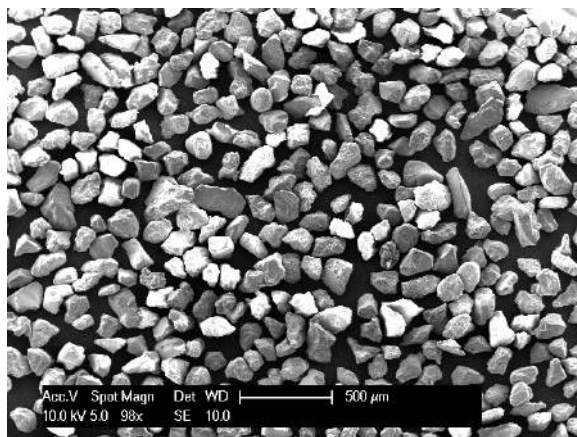


Figure 3. SEM photo of the Leighton Buzzard Sand, fraction E.

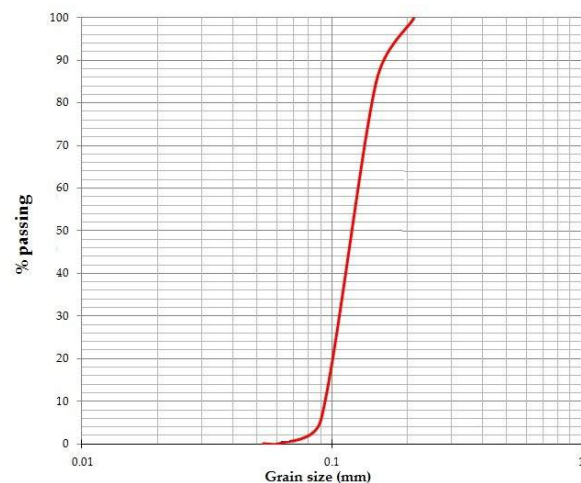


Figure 4. Grain size distribution

Three different sets of centrifuge tests are currently being performed, involving different rainfall and groundwater scenarios, as described in Table 2. Relative intensity, I_r , is the ratio between the prototype rainfall intensity and the saturated soil permeability. I_r gives a measure of the rate of rainfall provided to the slope in relation to the maximum rate at which water can infiltrate the soil. The test scenarios indicated in Table 2 correspond to the descriptions provided in Figure 5.

Digital images were captured throughout the centrifuge tests and geoPIV analyses were performed in order to determine soil displacements.

4. Results and discussion

For discussion purposes, the times and displacements mentioned in this section all refer to scaled prototype values unless otherwise indicated.

4.1. Scenario 1

In Scenario 1 tests (Figure 5a), rainfall is applied to the slopes while both drainage valves are kept open, allowing drainage to take place at both sides of the model. Therefore, a horizontal water table is formed and maintained just below the slope toe.

Table 2. Centrifuge test program.

Test	Test scenario	Relative density [%]	Void ratio [-]	Prototype I [mm h ⁻¹]	I_r [-]
1.1	1	52 (<i>loose</i>)	0.81	7.4	0.04
1.2	1	52 (<i>loose</i>)	0.81	27.7	0.15
1.3	1	52 (<i>loose</i>)	0.81	87.7	0.50
2.1	1	100 (<i>dense</i>)	0.65	7.4	0.04
2.2	1	100 (<i>dense</i>)	0.65	27.7	0.15
2.3	1	100 (<i>dense</i>)	0.65	87.7	0.50
1.4	2	52 (<i>loose</i>)	0.81	87.7	0.50
2.4	3	100 (<i>dense</i>)	0.65	0	0

I is prototype rainfall intensity.

Relative intensity, $I_r = Ik^{-1}$, where k is saturated permeability.

$e_{min} = 0.65$, $e_{max} = 0.99$.

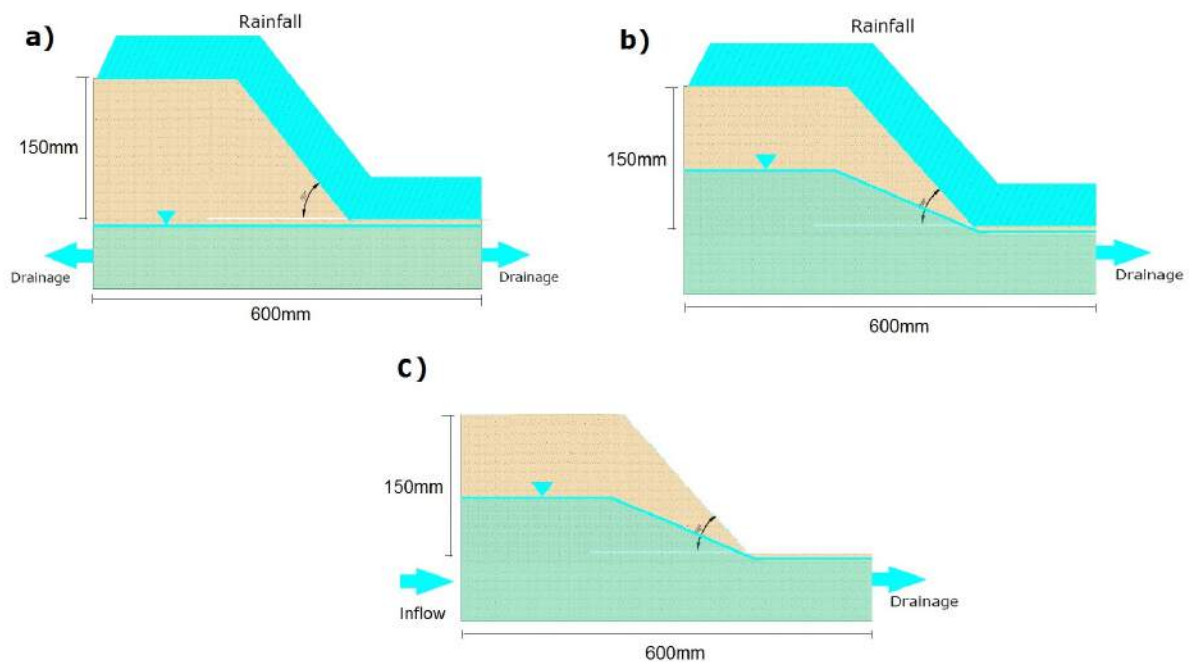


Figure 5. Test scenarios. a) Scenario 1: rainfall applied with drainage on both sides; b) Scenario 2: rainfall applied with drainage on down-slope side only; c) Scenario 3: no rainfall, water inflow from up-slope, outflow from down-slope.

Slope models, under loose and dense states, were subjected to light, moderate and heavy rainfall conditions, i.e. 7.4mm/hr, 27.7mm/hr and 87.7mm/hr, respectively. Before rainfall was applied to the models, the soil mass experienced excessive desaturation due to the enhanced acceleration field. The water content was determined through separate test to be close to 3%, corresponding to a degree of saturation (S_r) of 10%.

For the cases of the light and moderate rainfall events, slopes showed only minor deformation

after 70 days of rainfall and no global failures occurred. This indicates that the low intensity rainfall events on sandy slopes have minor effects even after prolonged periods of rainfall. On the other hand, during heavy rainfall events ($I = 87.7\text{mm/hr}$) larger displacements occurred to the slopes which progressively increased with time, as shown in Figure 6. In the case of the dense slope, a local failure occurred near the slope toe after 1800 hours of constant rainfall (Figure 7). However, no global failure occurred in either case.

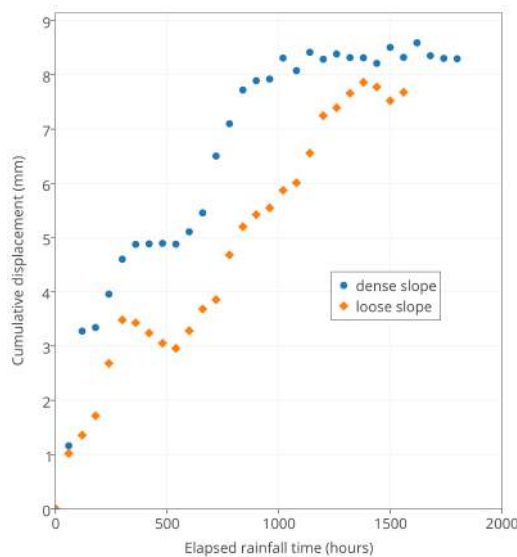


Figure 6. Cumulative displacement at slope crest during heavy rainfall event for loose and dense slopes (tests 2.3 and 1.3, respectively). Rainfall duration and settlement appear in prototype scale.



Figure 7. Local failure at the slope toe after 1800 hours of rainfall ($I = 87.7\text{mm/hr}$).

The displacements shown in Figure 6 are very small compared to the size of the slope. The exact cause of these displacements is not yet known, therefore further work is being conducted in order to determine if these deformations are caused due to the rainfall events or due to other phenomena, such as creep. The results reported here support the statement that initiation of rainfall-induced landslides, especially under unsaturated conditions, is very difficult to replicate through centrifuge modelling ([12]). However, alternative mechanisms for landslide initiation have been proposed, such as groundwater level rise ([13]) and adverse layering ([2], [14]).

4.2. Scenario 2

In the Scenario 2 test, rainfall with the higher intensity was applied to the loose slope, however the drainage from the upslope side was closed and an inclined water table formed (Figure 5b). The soil mass above the groundwater table was again in a residual water content state before rainfall. In this case, a progressive failure occurred, starting from the slope toe, as shown in Figure 8.

In Figure 8a, a horizontal water table formed just before rainfall was applied. After 68 hours of rainfall the water table was inclined, crossing and passing close to the slope toe (Figure 8b). After an additional 24 hours, the first failure occurred near the slope toe (Figure 8c), while a number of subsequent instabilities took place soon afterwards (Figures 8d and 8e). The final

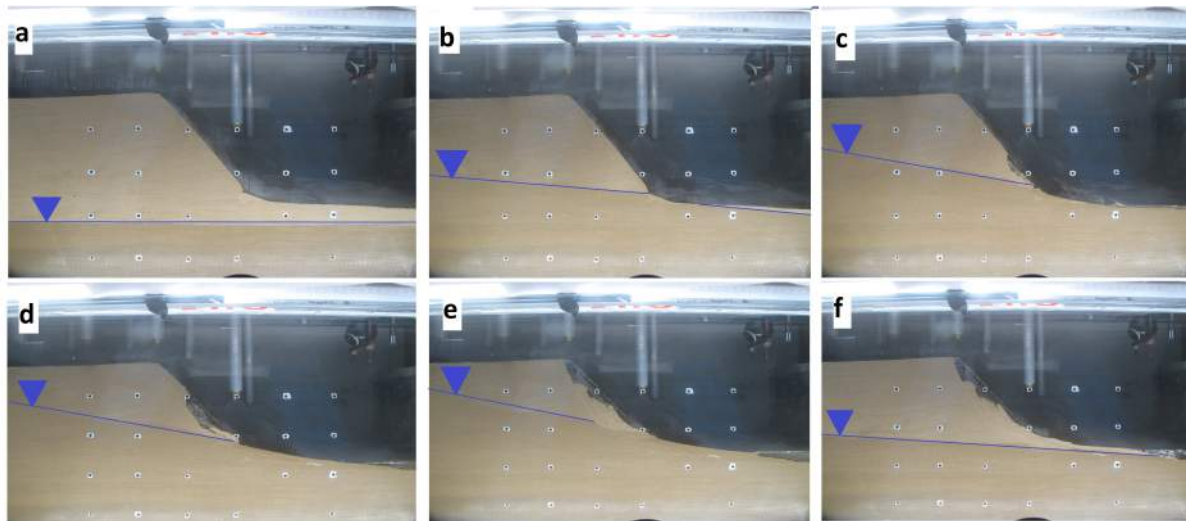


Figure 8. Progressive slope failure for test 1.4 (Scenario 2).

slope failure is shown in Figure 8f and took place 144 hours after the initiation of rainfall. These images illustrate that the base of the rupture surfaces passed near to the location of where the water table met the soil surface. Since the soil mass above the groundwater table is in a partially saturated state, it can be concluded that rupture surfaces formed just above the boundary of zero pore water pressure or where soil suctions have been reduced. The groundwater flow will also have contributed to the initiation of slope instability.

4.3. Scenario 3

In the Scenario 3 test, no rainfall was applied to the slope, which was initially in a dense state. A water inflow line was connected to the up-slope side of the container providing the model with the necessary amount of water to form an inclined water table (Figure 5c). Test results can be seen in Figure 9.

As was the case for the Scenario 2, progressive failure took place during the rise of the groundwater table. However, in this case the soil mass above the groundwater table during the whole test procedure is in a residual water content state due to the absence of rainfall. In both Scenarios 2 and 3, failure surface had a similar geometry.

5. Summary

A series of centrifuge tests on soil slope models have been performed on the Nottingham Centre for Geomechanics centrifuge in order to evaluate the impact of rainfall intensity and initial soil and groundwater conditions on slope stability. Soil slopes, consisting of fine silica sand, were subjected to varied rainfall and initial conditions at 60g centrifugal acceleration. Three Scenarios have been simulated in order to evaluate the impact of rainfall on landslide initiation. Initially, three different rainfall intensities were applied to loose and dense slopes while the water table remained at a constant level. Results showed that more intense rainfall events cause greater soil displacement, but did not always result in full slope collapse. Failure occurred only in models in which the groundwater table rose above the slope toe. Further testing is ongoing in order to examine additional configurations and to obtain a better understanding of the initial conditions of the partially saturated soil at elevated gravity (i.e. saturation and pore suctions).

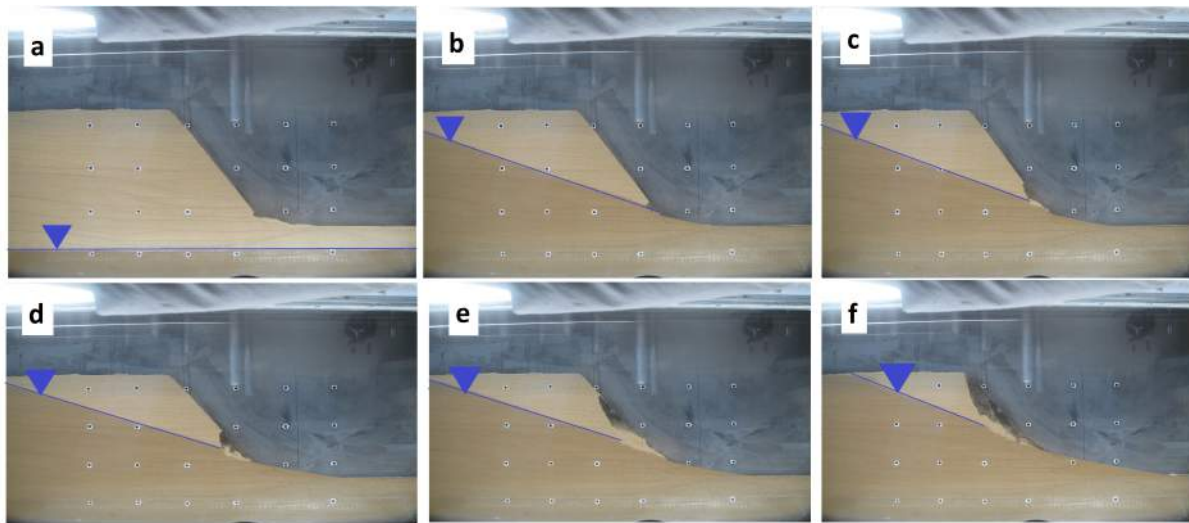


Figure 9. Progressive slope failure test 2.4 (Scenario 3).

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