

Studies on Centrifuge Modelling of Rainfall-Induced Landslides



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1 Introduction

Rainfall-induced instability of geotechnical soil structures is a serious global issue and deserves special attention. The problem aggravates if the backfill material of soil slopes, walls, and retaining earth structures is not adequately selected. Koerner and Koerner [1] reported that 68% of the 82 cases of reinforced soil-wall failures in their database were due to improper drainage control during rainwater infiltration. In general, slope failure and associated landslides are recognized as a natural and tangible process in a landscape, involving the rainfall history as well as local geology. Anderson and Sitar [2] reported that the mechanism of rainfall-induced slope failure involves a stress change caused by the hydrologic response of the slope to rainfall. The negative pore-water pressure in unsaturated soil is highly influenced by the external climatic conditions and flux boundary changes involving infiltration, evaporation, and transpiration. As per the findings of Fredlund and Rahardjo [3], the negative pore-water pressure contributes to imparting additional shear strength to unsaturated soils. As water infiltrates into the slope, positive pore water pressure in the slope increases, causing the additional shear strength due to matric suction to decrease and eventually disappear, thereby making the slopes vulnerable to failure. Full-scale modeling of natural and engineered soil slopes subjected to rainfall is warranted in this regard for a comprehensive understanding of the actual physical phenomena involved in the process. However, full-scale physical model tests are expensive, time-consuming, and difficult to replicate in case of a complex natural hazard like rainfall. At the same

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time, small-scale physical modeling cannot predict the behavior of prototype slopes accurately owing to dissimilarities in stress levels and strains existing between the laboratory $1g$ model and the corresponding prototype. In such situations, geotechnical centrifuge modeling can be used as an effective tool for investigating the response of geotechnical structures during various rainfall events by subjecting the model to a centrifugal acceleration of magnitude N times greater (Ng) than that of earth's gravitational acceleration ($1g$).

The present study focuses on investigating the mechanism of rainfall-induced landslides in low-permeable soil slopes through a series of centrifuge model tests. The above soil type was selected as model soil in view of the acute scarcity of good-quality permeable granular material in recent times, which leads to the eventual use of low-permeability soils or marginal soils available locally at the site, as per the findings of Yoo et al. [4] and Pathak and Alfaro [5]. Three typical rainfall intensities of 10, 20, and 50 mm/h were simulated on silty sand slopes of 7.2 height with 7.5 m crest width, and 2 V:1H inclination, having an initial water table up to slope base. The results are interpreted in terms of crest settlements, face movement, deformed slope profiles, and phreatic surfaces developed during rainfall based on instrumentation data and digital image analysis.

2 Modelling Considerations

The basic principle of centrifuge modeling for geotechnical purposes is based upon the requirement of achieving identical stress fields in the model and prototype. This is achieved by developing appropriate scaling laws relating the model behavior to the corresponding prototype, as outlined in Schofield [6] and Taylor [7]. The model soil used during slope preparation is assumed to have an identical mass density as that of the prototype. However, unlike $1g$ laboratory model, the centrifuge model slope is subjected to a high gravitational field (Ng) during rotation about a vertical axis in a horizontal plane at a desired angular velocity denoted by ω . Thus, the centrifuge model is subjected to an inertial acceleration field of N times the earth's gravity, where N indicates the gravity level; the same as that of the geometric scale factor. The scale factor (model:prototype) for linear dimensions of the slope is thus 1: N . Since the model is a linear scale representation of the prototype, slope displacements will also have a scale factor of 1: N , and in accordance, strains are scaled by a factor of 1:1. Therefore, the stress-strain variation of the soil mobilized in a centrifuge model will be identical to that of the prototype. Rainfall is characterized primarily by its intensity and duration, and can be scaled at high gravities based on scaling factors derived for time and water flow under transient unsaturated conditions, as discussed in Caicedo et al. [8] and Bhattacharjee and Viswanadham [9, 10]. The relevant scaling factors involved in the modeling of rainfall-induced landslides in a geotechnical centrifuge is presented in Table 1.

Table 1 Scaling laws adopted in centrifuge modeling of rainfall-induced landslides

Parameter	Unit	Scale factor
Unit weight of soil (γ)	kN/m ³	N
Cohesion (c)	kPa	1
Co-efficient of soil friction (ϕ)	°	1
Co-efficient of soil permeability (k)	m/s	N
Pore water pressure in soil (u); Suction (ψ)	kPa	1
Slope inclination (β)	°	1
Slope height (H)	m	$1/N$
Duration of rainfall (t)	h	$1/N^2$
Rainfall intensity (r)	mm/h	N
Amount of rainfall (R)	mm	$1/N$
Impact pressure on ground (P)	Pa	1

3 Selection of Model Soil

In view of the significance of backfill material in controlling the performance of reinforced soil structures, special emphasis has been given to studies performed in low-permeable soils, and the detrimental effect of water on the performance of these structures. Zornberg and Leshchinsky [11] summarised the design criteria for geosynthetic reinforced walls, slopes, and embankments put forth by various world-wide agencies which limit the percentage of fines in backfill material preferably to within 15%. The Ministry of Road Transport and Highways (MORTH), Government of India specifies up to 10% fines, whereas The Federal Highway Administration (FHWA) allows up to 35% fines (passing 0.075 mm) in the reinforced soil zone. Accordingly, the model soil used in slope preparation was formulated in the laboratory to arrive at 20% fines by blending locally available fine sand and commercially available kaolin. The Goa sand is classified as SP according to USCS, whereas, the kaolin sample is classified as CL as per USCS, and consists predominantly of silt and clay in the ratio of 47% and 53%, respectively.

The blended silty sand is SM as per USCS, and consists of sand and kaolin in the ratio of 4:1 by dry weight with a saturated permeability (k_{sat}) of 1.54×10^{-6} m/s. The model soil is thus representative of the properties of locally available marginal soils which contain fines in excess of 15% and exhibit a saturated coefficient of permeability of $<1 \times 10^{-6}$ m/s, prescribed, respectively, by Christopher and Stuglis [12] and Holtz and Kovacs [13].

4 Model Preparation and Test Program

Centrifuge-based physical modeling was performed at 30 gravities on a representative silty sand slope of 240 mm height, 60 mm base layer, and 2 V:1H inclination, having a crest width of 250 mm. Tests were conducted using the 4.5 m radius beam centrifuge facility of 2500 g-kN capacity available at IIT Bombay, INDIA. The detailed specification of the centrifuge equipment is available in Chandrasekaran [14]. Rainfall was simulated using a custom-designed rainfall simulating assembly consisting of specially designed air-atomizing nozzles, nozzle hanging rods, nozzle assembly attaching plate, water container assembly, and a seepage tank. The water container was designed to act like a modified Mariotte's tube when filled with pressurized water at high gravities. Additionally, a solenoid valve was used to control the duration of rainfall during the centrifuge tests, and the excess water flowing as run-off was collected in a run-off collector. The calibration results discussed in Bhattacharjee and Viswanadham [9] indicate that the simulator is capable of producing fine mist at a uniform rate in-flight condition with intensities of 2–80 mm/h. In the present study, three typical rainfall patterns were simulated on slope models referred to as Model T1, Model T3, and Model T4. Model T1 was subjected to a low intensity but a lingering storm of 10 mm/h persisting for a longer duration, whereas Model T3 was subjected to a medium rainfall event of 20 mm/h similar to seasonal monsoon showers. Model T4 depicted an extreme case of short and intense cloudburst of 50 mm/h intensity, which can be associated with global warming and allied climatic changes. As per the classification system suggested by Llasat [15], the three rainfall events can be regarded as a light drizzle, moderate shower, and torrential rainfall respectively, thereby replicating all possible ranges of natural hazards.

An initial groundwater table was simulated in-flight up to the slope base at the onset of rainfall using the perforated seepage tank mentioned previously. The slopes were instrumented with four commercially available miniature Druck-PDCR-type pore pressure transducers (PPTs) placed above the base layer at distances of 20 mm (PPT4), 125 mm (PPT3), 250 mm (PPT2), and 350 mm (PPT1) from the perforated face of seepage tank in model dimensions. Further, L-shaped plastic markers made from thin transparency sheets of 20 mm × 10 mm dimensions were embedded within the slope front elevation and slope face to track displacements with the progress of rainfall. The various stages involved in the construction of slope models in the centrifuge are discussed elaborately in Bhattacharjee and Viswanadham [16].

5 Results and Discussion

The seepage and stability aspects of marginal slopes during the simulated rainfall event were analyzed using data recorded by pore-pressure transducers and through image analysis [17] of photographs captured in-flight. The results are discussed in subsequent sections and briefly summarized in Table 2. The results are presented in

Table 2 Summary of centrifuge test results

Parameter	Model T1	Model T3	Model T4
Intensity of rainfall (I) (mm/h)	10	20	50
^a Time elapsed during rainfall (days)	33.75	9.375	3.75
^b $u_{max}/\gamma H$	0.636	0.554	0.411
$S_{c,max}/H$	0.354	0.492	0.525
$S_{f,max}/H$	0.141	0.166	0.250

Note: All values are reported in prototype dimensions

^aTime corresponding to the ultimate stage of the test

^b $u_{max}/\gamma H$: Normalized pore pressure for PPT 4 placed at 350 mm from the slope toe; h : Height of slope; $S_{c,max}$: Max. crest settlement; $S_{f,max}$: Max. deformation along slope face; For all the tests, the water table is at slope base; $\beta = 63^\circ$

this study up to the “ultimate stage” of test, which marks the time frame beyond which the observed slope deformations and recorded pore-water pressure values depicted negligible variations with the progress of rainfall. It thus represents the ultimate state of distress underwent by each individual model slope during rainfall.

5.1 Deformed Slope Profiles with Progress of Rainfall

The front elevation of slopes subjected to rainfall intensities of 10, 20, and 50 mm/h captured at various time intervals until the ultimate stage of centrifuge tests are presented in Fig. 1a–c, Fig. 2a–c, and Fig. 3a–c, respectively. Model T1 of 2 V:1H inclination subjected to a light rainfall intensity of 10 mm/h failed progressively, as shown in Fig. 1a–c, and instability occurred at the end of 54 min (33.75 days). A deep-seated face failure was encountered on account of deeper rainwater infiltration into the slope.

On the contrary, Model T3 subjected to a moderate rainfall intensity of 20 mm/h underwent a clear and distinct sliding failure about the toe at an interval of 15 min (9.375 days) of rainfall infiltration into the slope (Fig. 2a–c). Model T4 subjected to

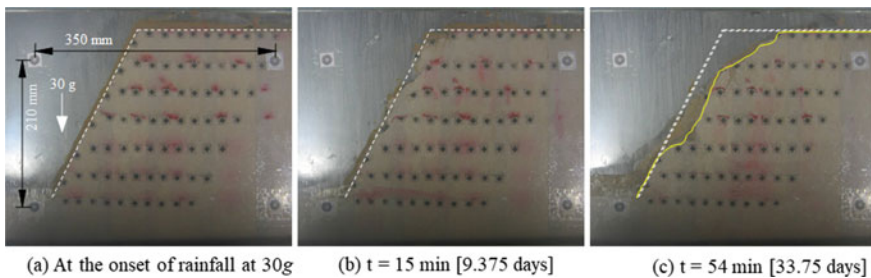


Fig. 1 Front elevation of model T1 [$I = 10$ mm/h] with the progress of rainfall

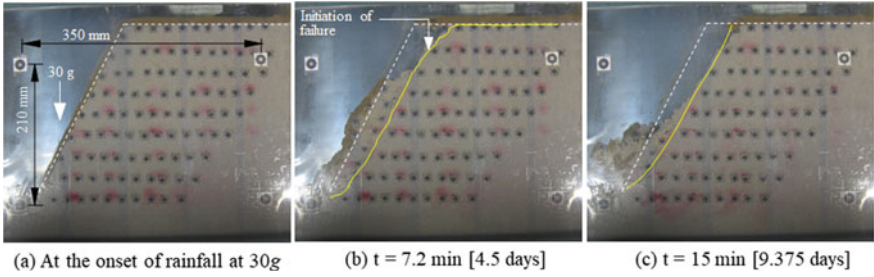


Fig. 2 Front elevation of model T3 [$I = 20$ mm/h] with the progress of rainfall

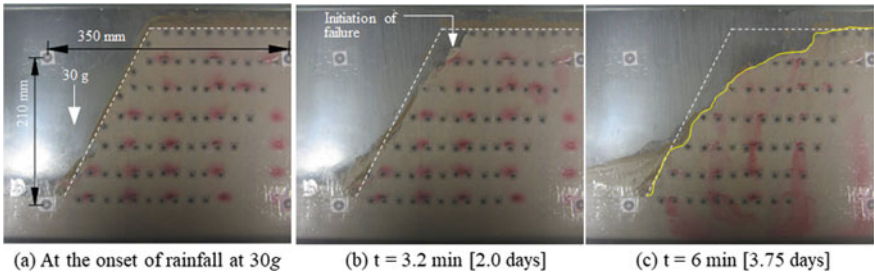


Fig. 3 Front elevation of model T4 [$I = 50$ mm/h] with the progress of rainfall

a heavy torrent of 50 mm/h failed catastrophically and instantaneously within 6 min (3.75 days) of rainfall due to extensive erosion, as depicted in Fig. 3a-c. The failure, in this case, resembled that of mass block sliding. This suggests the existence of a threshold rainfall intensity, beyond which rainwater can no longer infiltrate into the slope and disappears mostly as run-off. The type of slope failure is thus inferred to depend on the ratio of the saturated soil permeability to the input rainfall flux.

5.2 Crest Settlements and Slope Face Movements

Figure 4 presents the variation of crest movement with time for the entire duration of rainfall until the ultimate stage of the test. Model T1 subjected to a light rainfall of 10 mm/h exhibited a slow but steady increase in crest movements with time. In the case of Model T3 and Model T4 subjected to moderate and heavy showers of 20 mm/h and 50 mm/h, respectively (Results of Model T2 are not presented in this paper), the rate of increase in crest settlement was more rapid. The final settlements incurred at the crest for all three slopes are observed to be extremely high, and in the order of about 2.55 m, 3.54 m, and 3.78 m, respectively, in prototype scale for Models: T1, T3, and T4. The above is indicative of the catastrophic failure underwent

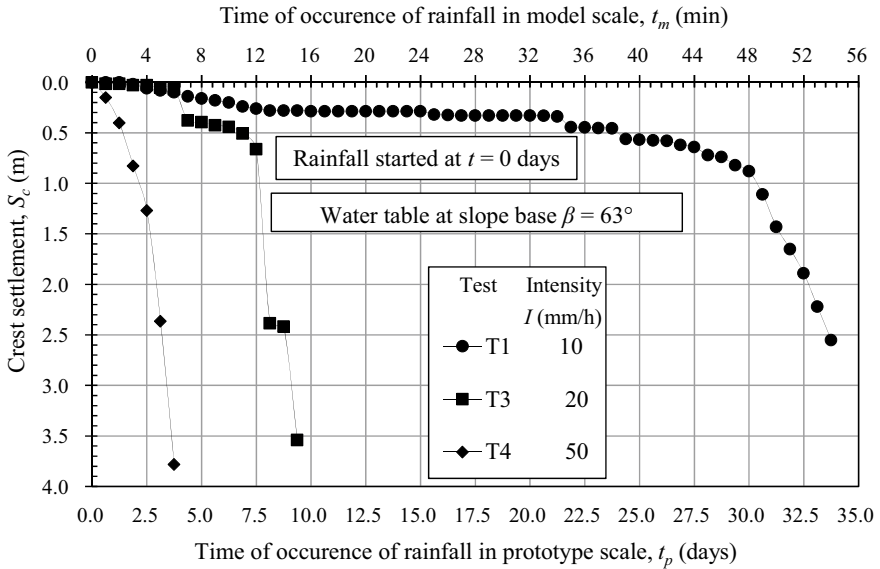


Fig. 4 Variation of crest settlement with time

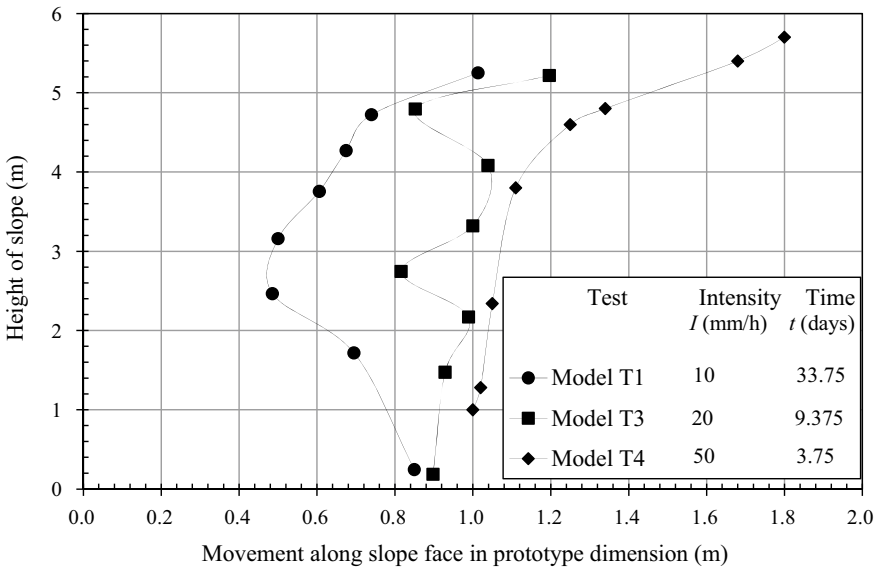


Fig. 5 Slope face movements during rainfall

by each slope model on being subjected to rainfall. A similar observation holds good for the slope face movements depicted in Fig. 5, wherein prototype values of the

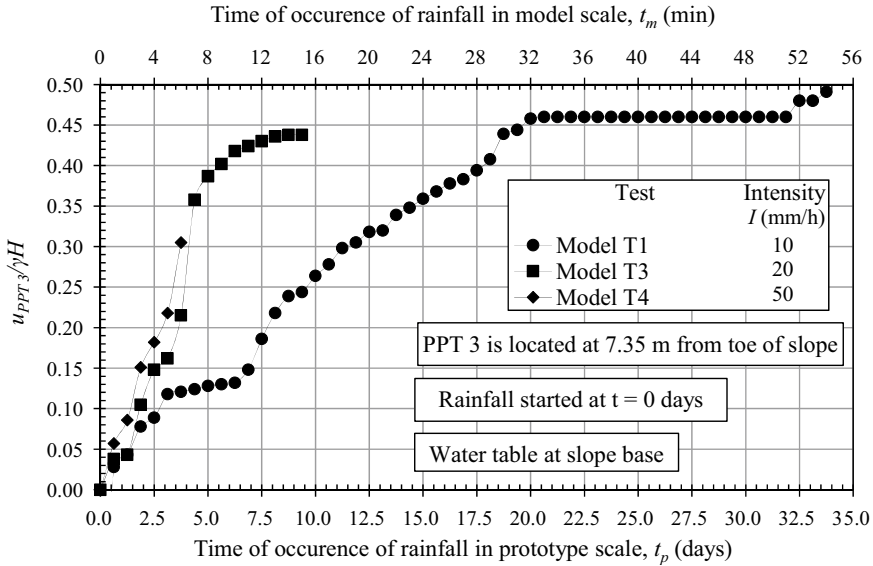


Fig. 6 Variation of normalized excess pore water pressure ($u_{PPT3}/\gamma H$) with rainfall

order of 1.02, 1.19, and 1.8 m were reported at the ultimate stage for Models: T1, T3, and T4, respectively. As expected, the face movements and surface settlements increased with increasing rainfall intensity.

5.3 Pore Water Pressure Developments with Rainfall

The pore water pressure generation during rainfall for the slope models is shown in Fig. 6. The values measured by PPT3 ($u_{PPT3}/\gamma H$) placed vertically below the mid-point of the crest on the base layer are herein presented. The pore pressures (u) are normalized with respect to the unit weight of model soil (γ) multiplied by the slope height (H), and are expressed in prototype dimensions, starting from the time of occurrence of rainfall. As can be observed from Fig. 6, Model T1 subjected to 10 mm/h rainfall exhibited a slow but steady rise in pore water pressure with rainfall resulting in progressive deformations and multiple sliding stages, where each stage of sliding corresponded to a level of increase in excess pore water pressure. However, the pore water pressures increased rapidly for Model T3 and Model T4 subjected to higher intensities of 20 mm/h and 50 mm/h, respectively, resulting in instantaneous slope instability.

6 Conclusions

The present study aims at investigating the mechanism of rainfall-induced landslides in low-permeable soil slopes. Centrifuge-based physical modeling was performed in this regard on prototype silty sand slopes of 7.2 height with 7.5 m crest width and 2 V:1H inclination, having an initial water table up to slope base. Three typical rainfall intensities were simulated, wherein, the first slope model was subjected to a prolonged and light rainfall intensity of 10 mm/h, whereas, the second and third models were subjected to short-span moderate and heavy simulations of 20 mm/h and 50 mm/h, respectively. The intensity of rainfall was observed to play a crucial role in governing the failure mechanism of landslides. A light rainfall intensity of 10 mm/h of longer duration caused a progressive deep-seated face failure on account of deeper rainwater infiltration inside the slope body, where each stage of sliding corresponded to a level of increase in excess pore water pressure. A moderate rainfall intensity of 20 mm/h of medium duration similar to that of seasonal showers corresponded to an abrupt rotational slip originating at the toe and gradually propagating upwards with increasing levels of saturation. In contrast, a short and intense cloudburst of 50 mm/h triggered a major block sliding type of failure due to extensive erosion on account of the rainfall flux exceeding that of the saturated soil permeability.

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