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Centrifuge modelling of unsaturated slopes subjected to the integrated effect of groundwater and rainfall infiltration

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Abstract. The stability of unsaturated soil slopes is comprehensively discussed with the rainfall characteristics. However, pre-existing groundwater table is also common in many tropical mountainous regions. Additionally, perched water table could be generated due to antecedent rainfall conditions on the soil-bedrock interface. The complex hydrological response process of slopes subjected to the integrated effect of groundwater and rainfall infiltration has not yet been entirely realized. Therefore, the current study aimed at investigating the influence of initial groundwater table on initiation of landslides in slopes exposed to rainfall infiltration. The centrifuge modelling technique is utilized in this study. A centrifuge container was newly designed to reproduce the rainfall and groundwater table effects. Identical soil slopes made from silty sand were tested under 50g conditions. The unsaturated slopes behaviour was evaluated under two cases during the analysis: 01) rainfall only and 02) rainfall on a pre-existing groundwater table. The results demonstrated that the failure happened in case (02) was quicker, larger in volume and faster to respond to rainfall infiltration. The factor of safety calculated using the infinite slope equations portrayed a slight mismatch of failure timing compared to the experimental results. These results suggested i) a higher risk of slope failure under pre-existing groundwater flow and ii) acceleration of the progression of landside due to a potential surcharge flow.

1 Introduction

Rain-induced landslides are frequently happening around the world varying from small slope failures to long runout debris flow. Irrespective of the magnitude, it is a well-understood phenomenon that loss of matric suction and saturation-dependent reduction of shear strength is the cause of rain-induced landslides in unsaturated slopes. The recent landslide reports showed how destructive and deadlier these events could be [1] and concluded that continuous rainfall could be the main cause of these tragic incidents. Thus, rainfall intensity is always considered a key triggering factor of landslides, as well as a measurable quantity to be used in landslide prediction frameworks. In real field conditions, notably in tropical regions, presence of a phreatic surface is common. Additionally, the formation of a phreatic surface on the soil-bed rock interface would be possible because of the antecedent rainfall conditions. Take et al (2015) showed that existence of an antecedent groundwater level makes the slopes more vulnerable to failure than drier conditions under rainfall infiltration [2]. However, the combined effect of rainfall infiltration, and presence of a groundwater flow and its surcharge flow has not been investigated enough. These conditions might make the progression of landslides more complex when the steady component of the porewater pressure response interacts with the transient infiltration.

The complexity of the unsaturated slope stability has been studied employing many tools such as analytical solutions, numerical simulations, and physical modelling. Especially in analytical solutions for slope stability, assumptions such as the groundwater table remains stable and parallel to the slope during rainfall infiltration was adopted [3,4]. However, it is hypothesised that the presence of groundwater table will ease the unsaturated infiltration and then a surcharge flow could be created above the pre-existing groundwater table. Under these conditions, a slope is subjected to three hydraulic boundary conditions: existence of i) a groundwater flow, ii) rainfall infiltration, and iii) a surcharge flow. Hence, it is vital to understand the physical process when an unsaturated soil slope is overlayed by a saturated soil layer. Therefore, the objectives of this study are to assess 1) the significance of the presence of the groundwater conditions to the unsaturated soil slope by conducting centrifuge experiments and 2) whether the assumption of a stable groundwater level is applicable.

2 Experimental set up

2.1 Centrifuge model testing

The model testing was conducted at the geotechnical centrifuge facility in the Disaster Prevention Research

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Institute (DPRI), Kyoto University. To perform the unsaturated slope stability in centrifuge modeling under both rainfall and phreatic surface simulation, a new soil container was developed. This box has the capacity of performing rainfall and groundwater simulation as two independent events that can be controlled parallel to each other. Fig. 1 shows the schematic diagram of the centrifuge container which has dimensions of 800*150* 600 (mm). The scaling factors relevant to this study are provided in Table 1. All the experimental results reported in this study are model scale unless otherwise stated.

2.2 Slope construction

The slope configuration was set to discuss the transient porewater pressure development and deformation before the failure. The dry density of the soil slope was maintained at 1.5 g/cm3. Air-dried soil was mixed with 10% gravimetric water content and kept for 24 hours for homogenizing before being used in slope construction. The slope was constructed layer-by-layer using the wet tamping method. Each layer was of 20 mm thickness. During the construction, porewater pressure transducers (PPT) were buried in the respective locations as shown in Fig. 1. Unfortunately, the available PPTs can only measure changes in the positive porewater pressure. Further, markers were placed in a way that it is possible to discuss the deformation behavior of the slope during landslide progression as shown in Fig 3.

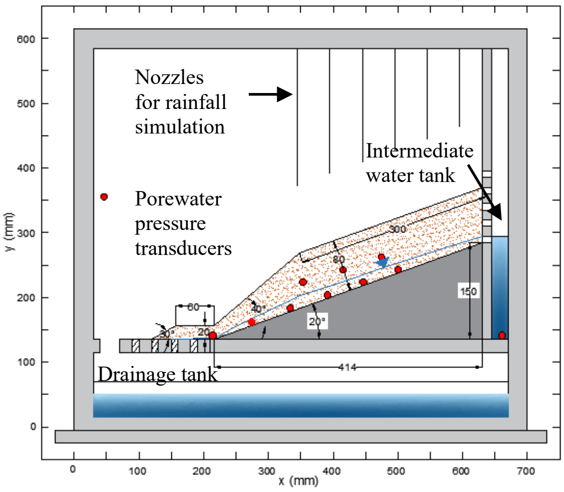

Fig. 1 Schematic diagram of the centrifuge container

Table 1. Scaling factors relevant to the study

Parameter	Model/Prototype
Stress	1
Length	1/N
Time (diffusion)	$1/N^2$
Rainfall intensity	N
Suction	1
Hydraulic Conductivity	N

2.3 Slope material

A silty sand soil which is available in Japan under the commercial name “Masado soil” was used in the experiments. The index properties together with the soil water characteristic curve (SWCC) parameters were determined. SWCC parameters were established by van Genuchten (1980) [5]. The material properties are shown in Table 2.

2.4 Test cases

Two cases are discussed here in order to present the difference in unsaturated soil slope behavior with and without the presence of phreatic surface during the time of rainfall.

Case 01 – rainfall only (no phreatic surface) (Fig. 2)

The first case investigated how slope failure occurs only under the applied rainfall without groundwater conditions. The rainfall intensity was calibrated to 25 mm/Hr in the prototype scale.

Case 02 – groundwater simulation followed by application of rainfall (Fig. 2)

The second case investigated how an unsaturated slope with a pre-existing groundwater table behaves during a rainfall condition. The slope was first subjected to a water head from the right edge boundary of the slope via the intermediate water tank. This process was continued until PPT along the soil-bed rock interface shows positive and constant. Then the rainfall (25mm/Hr in prototype scale) was applied on the slope until the failure.

Table 2. Material properties of Masado soil

Parameter and unit	Value
D_{60}, D_{30}, D_{10} (mm)	0.83, 0.32, 0.15
Particle density (G_s) (g/cm^3)	2.6
Max dry density (g/cm^3)	1.76
Optimum moisture content (%)	15.5
Sat. hydraulic conductivity (m/s)	4×10^{-5}
SWCC parameters (wetting) (α, n, m)	0.41,2.2,0.55
Friction angle ($\varphi°$) and cohesion (c) (kPa)	40, 0

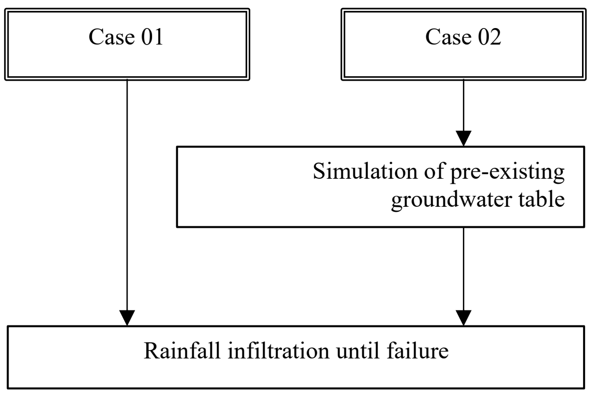

Fig. 2 Test cases used in the experiments

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3 Results and Discussion

3.1 Failure surface

Fig. 3 (a) and (b) present the failure surfaces (marked in red dashed line) resulted from Case 01 and 02. From observation alone, Case 01 where only rainfall was applied resulted a semi-circular failure. The failure happened here slid the soil in the steeper slope as a thick slice and soil slope above the failure surface was less affected. In contrast, case 02 showed more of a translational failure and distinct differences in the failure surface such as deeper and wider area of instability. This failure included both steeper slope and gentle slope in the sliding. The landslide depths measured at the time of failure initiation were 60 mm (Case 01) and 70 mm (Case 02). These observations implied that volume of landslide of Case 01 is lesser compared to Case 02.

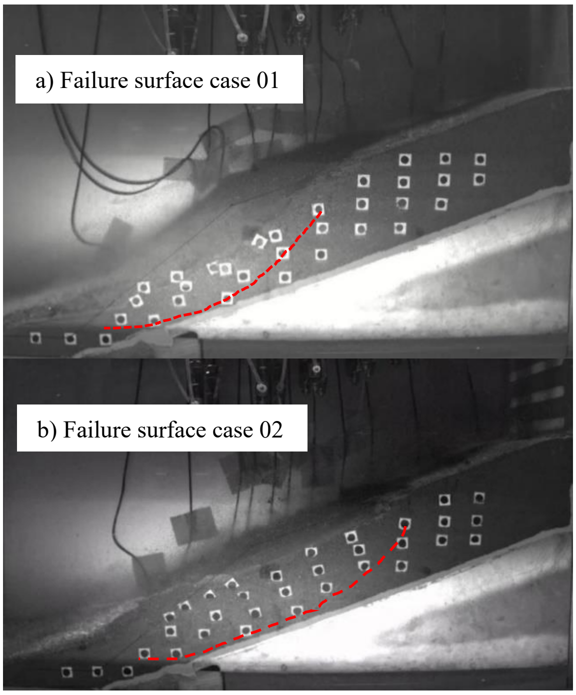

Fig. 3 Failure surface of a) Case 01 and b) Case 02

3.2 Porewater pressure (PWP) distribution

Fig. 4 illustrates the recorded porewater pressure development of PPT 03, 04 and 05 upon the rainfall infiltration of Case 01. After the rainfall was applied, PPTs began to respond starting from PPT 01. With the continuing rainfall, the advancement of the wetting front continued, leading the other PPTs to respond with respect to their location. The failure time was recorded as 175 s.

Fig. 4 further depicts the porewater pressure response of Case 02. During the initial groundwater simulation with continuing flow from the slope end, PPTs started to respond to the groundwater flow. The rainfall was applied on the slope when the PPTs showed a constant value with time even if PPTs did not show a parallel PWP distribution along the soil-bed rock interface. In contrast to the PWP response of Case 01, PPT 03, 04, and 05 responded to the rainfall simultaneously. The slope failed after 100 s of rainfall duration.

The differences in the failure surfaces, volume, and the time for slope failure between Case 01 and 02 could be explained from the variations in the PWP responses. In Case 02, soil slope along the soil-bed rock interface were adequately saturated prior to the rainfall infiltration. The time taken to create a seepage path connection between the rainfall infiltration through the unsaturated soil layer and groundwater flow was only 45 s. Thereafter, PPTs started responding to the positive PWP quickly, and hence strain localization towards the steep part of the soil slope was inevitable. Under these conditions shear induced excess PWP were generated, and as shown in Fig. 3 (b), a shear plane was created. However, Case 01 took more time to create a seepage path and hence saturated transmission of water flow. PPT 03 showed higher PWP generation compared to other PPTs thus only the steeper part of the soil slope was deformed under rainfall infiltration. This resulted in sliding of the thick soil layer out of the whole plane in Case 01.

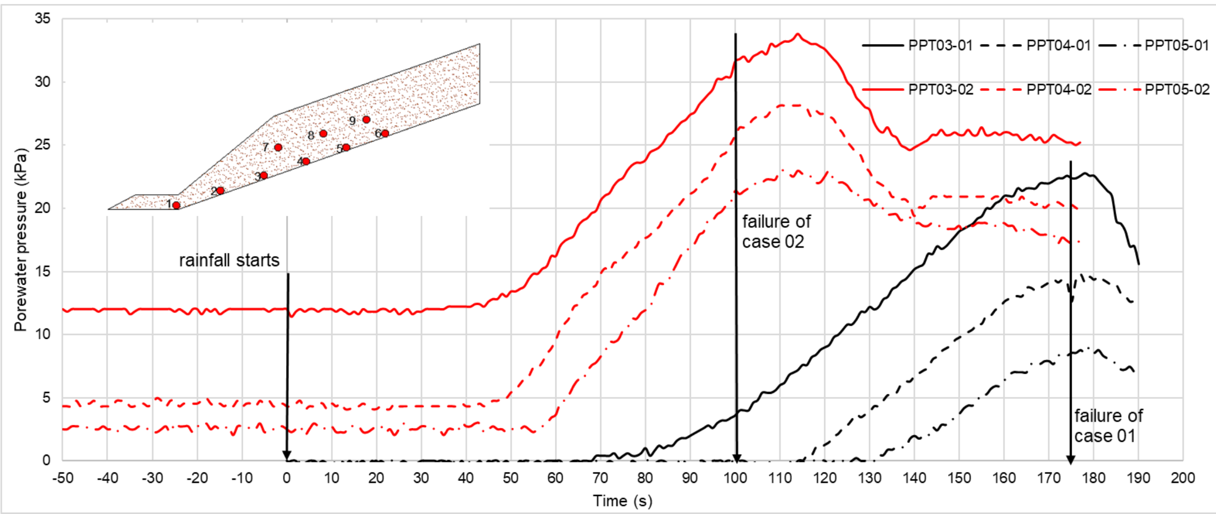

Fig. 4. Recorded PWP development of Case 01 (black) and Case 02 (red)

Further analysis was carried out to discuss the possibility of generating a surcharge flow over the pre-existing groundwater table. The rate of change in porewater pressure $(\dot{u})$ was calculated and it showed that $\dot{u}$ for Case 02 was around 0.35 to 0.4 whereas for Case 01 it was around 0.2 to 0.25. This suggested that the likelihood of generating a surcharge flow over the groundwater table is high. Therefore, the time taken for failure would be drastically reduced under these circumstances.

3.3 Slope failure

Slope failure mechanisms were assessed and compared under two cases using infinite slope stability equation presented by Iverson (2000). Equation (1) has the capacity of calculating the factor of safety (FoS) catering both groundwater flow (steady component) and time-dependent rainfall infiltration to assess the stability of unsaturated slopes. When steady groundwater pressure $(\psi_0(Z))$ is known, steady state factor of safety $(FS_o(Z))$ can be estimated by equation (2). The time dependent factor of safety $(FS'(Z,t))$ which varies upon rainfall infiltration is given by equation (3).

$$FoS(Z,t) = FS_o(Z) + FS'(Z,t) \quad (1)$$

$$FS_o(Z) = \frac{tan\varphi}{tan\alpha} + \frac{c}{\gamma_S \cdot sin\alpha \cdot cos\alpha} - \frac{\psi_0(Z)\gamma_w tan\varphi}{\gamma_S \cdot Z \cdot sin\alpha \cdot cos\alpha} \quad (2)$$

$$FS'(Z,t) = -\frac{\gamma_w}{\gamma_S} \cdot \frac{tan\varphi}{sin\alpha \cdot cos\alpha} \cdot \frac{I_z}{K_z} \cdot [R(t^*)] \quad (3)$$

in which

$R(t^*)=\sqrt{t^*/\Pi}e^{(-\frac{1}{t^*})}\text{-erfc}(1/\sqrt{t^*})$,

$t^*=\frac{t}{Z^2/\hat{D}}$, and $\hat{D}=4D_0\cos^2\alpha$

where the symbols have the following meanings as given in Table 3.

Table 3. Properties used in the FoS calculation

Symbol, property, and unit	Value
α, slope angle (deg)	20
Z, Landslide depth (prototype scale) (m)	Case 01 – 3 Case 02 – 3.5
γ_s, γ_w soil and water unit weight (kN/m^3)	16.2, 9.8
D_0, Hydraulic diffusivity (m^2/s)	6×10^{-3}
$\frac{I_z}{K_z}$, Normalized vertical infiltration rate	0.045
$\psi_0(Z)$, steady groundwater pressure head (prototype scale) (m)	Case 02 – 0.75

In this assessment, modifications made to Iverson model considering ponding conditions were not considered [6]. Since runoff was visible due to the geometry used in the experiments, the assumption that total rainfall would infiltrate was not realistic. Therefore, infiltration rate (Iz) was firstly calibrated to Case 01.Fig. 5 demonstrates the variation of FoS with time, and a rational prediction for Case 01 was given at *Iz/Kz=0.045*. Then the variation of FoS for Case 02 was estimated and exhibited in Fig.5. Even though the prediction was reasonable, the slope was still on the verge of failure by the time it actually failed in the experiment. Therefore, the presence of a pre-existing groundwater table increases the probability of slope failure. This implies that an unsaturated slope with a pre-existing groundwater table has a higher tendency to failure compared to a slope without a pre-existing groundwater table. However, the validity of assumptions such as groundwater table keeps constant without any surcharge flow from the upper slope during the rainfall infiltration remains doubtful. Additionally, the occurrence of a potential surcharge flow parallel to the slope would be more significant when a groundwater level pre-exists. Hence more accurate predictions could be attained if FoS calculation are incorporated with the effects of surcharge flow.

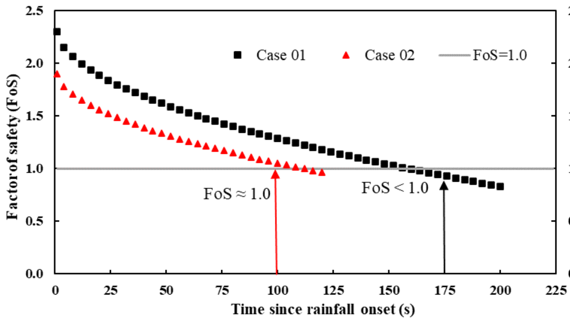

Fig. 5. FoS variation with time

4 Conclusions

The significance of unsaturated slopes with pre-existing groundwater table was discussed using the centrifuge model testing technique. The failure surface, PWP development and FoS were assessed and compared. The observed slope behavior of the two cases showed a complete distinction. Case 01 resulted a thick slice of slope slid whereas Case 02 lead to a comparatively large translational failure. PWP distribution demonstrated that PPTs in Case 01 responded to advancement of wetting front and thereafter saturated transmission of water flow. However, in Case 02 advancement of wetting front happened quicker and the rate of increase in PWP was much higher than that in Case 01. FoS calculated using the infinite slope equations portrayed a slight mismatch of failure timing compared to the experimental results. These results suggested i) a higher risk of slope failure under pre-existing groundwater flow and ii) acceleration of the progression of a landslide due to a potential surcharge flow. Further, it is expected to conduct more studies to assess the generation and the effect of surcharge flow in unsaturated slopes subjecting to a pre-existing groundwater flow.

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