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Title: Centrifuge modelling of root-reinforced soil slope subjected to rainfall infiltration

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Abstract:
Slope instability induced by heavy rainfall is a serious geotechnical hazard all over the world. The characteristics of water flow, pore water pressure changes and shear strength of the soil are the main factors involved in slope failure mechanisms. This paper describes soil slope failure induced by rainfall using a rainfall simulator in a geotechnical centrifuge. To study a soil-bioengineering slope stabilisation technique in a small centrifuge, a sloping rooted surface layer was simulated by mixing polyester fibres into the soil. The test results indicate that a rise in the groundwater table due to rainwater infiltration was responsible for slope failure and failure near the toe propagated upslope in a bare soil slope. On the other hand, a slope whose surface was reinforced with roots exhibited small deformation without failure under heavy rainfall (intensity of 20 mm/h) for a duration of 15 h at prototype scale. The test results also reveal that roots can help to reduce the infiltration of rainwater into the ground, delay a rise in groundwater table and increase the shear strength of the soil.

Keywords: Centrifuge modelling; Slopes; Vegetation

List of notation:

γ_d – maximum dry unit weight
γ_t – total unit weight
ACC – accelerometers
c – cohesion intercept
S_r – degree of saturation
e_{max} – maximum void ratio
e_{min} – minimum void ratio
G_s – specific gravity
k – coefficient of permeability
PWP – pore water pressure transducer
w_{opt} – optimum water content
ϕ - angle of shearing resistance

1. Introduction

In recent years, the occurrence of slope failure induced by rainfall has been increasing all around world especially in tropical region. To solve this problem, several mechanical methods have been used such as soil nail, retaining wall and geosynthetic reinforcement. All these methods are too expensive for the natural slope protection and they also require some maintenance. However, a soil-bioengineering approach is an alternative which is the use of live materials such as plants, vegetation and grasses in protection of the slope against failure. The roots of vegetation could enhance the slope stability by increasing the shear strength of soil (Gray and Sotir, 1996). Greenway (1978), Coppin and Richard (1990), and Wu (1995) have been researched on the role of vegetation in relation to the slope stability. Moreover, a vetiver grass had been promoted to control the soil erosion and water runoff or infiltration by the World Bank (Greenfield, 1996). Use of vetiver was proposed to be a soil-bioengineering because of its long root (2 – 3.5 m) and its very fast-growing (only 4 – 6 months). Since the shallow failures, typical failure mode of the slope usually occurs within 1 – 1.5 m depth from the surface in the regions with prolonged and heavy rainfall (Gray and Leiser, 1982), the rooting depth of the vetiver grass may be large enough to protect the slope from the shallow failure.

Previous researches have investigated on the mechanism of rainfall-induced slope instability based on the laboratory tests and field monitoring (Chen, *et al.*, 2004). To model soil slopes reinforced with vegetation, a few researchers recently have introduced the centrifuge (Sonnenberg, *et al.*, 2010, 2012, Askarinejad, 2013 and Takahashi, *et al.*, 2014). However, it is still difficult to model the effect of rainfall in a centrifuge. This paper therefore presents a series of centrifuge model tests on soil slopes reinforced with model roots using a rainfall simulator to demonstrate effectiveness of roots in the shallow depth against slope failure. The centrifuge model tests were performed at Tokyo Institute of Technology in Japan.

2. Experimental Method

In this study, the slope stability problem has been modelled using the centrifuge technique at a centrifugal acceleration of 50g. The brief summary of the experimental details is explained as follows.

2.1 Properties of soil and fiber used in the model

Edosaki Sand, a fine sand according to JGS0051 (Japan Geotechnical Society Standard), was used in the model slopes. Fig. 1 shows the grain size distribution curve of the Edosaki sand. Only the sizes below 2mm were used in this study. Table 1 summary the engineering properties of the Edosaki sand. The polyester fibers (Teijin RA04FN, approximately 39μm in diameter and 10mm in length) were used to model the fiber root. In the model tests, the 2% by mass of polyester fibers were mixed with the sandy soil for the vegetated slope surface cases. It is noted that the 2% fiber mixing by mass is approximately 7% by volume, which is slightly higher than typical values of the root area ratio of 3 - 5% for small vegetation observed in literatures (Gary and Sotir, 1996). Figure 2 presents photos of the polyester fibers before and after mixed with the sandy soil. The engineering properties of soil mixed with 2% of polyester fiber are summarised in Table 1.

2.2 Shear strength of soils

The shear strength of the soils was examined by a 60-mm diameter direct shear box apparatus. In the tests, Edosaki sand with a water content of 15% was compacted to achieve a degree of compaction of 80%. For the case with the model fiber roots, water content of 17% was needed to mix with the fibers 2% to reach the final water content of 15%. The direct shear tests were carried out to obtain the angle of shearing resistance (ϕ) and the cohesion intercept (c) of the soils both with and without fibers and the results were shown in Fig. 3a. By adding 2% of polyester fiber into the sand has increased the cohesion around 14 kPa and the friction angle around 3^{o} as summarised in Table.1. This result can be compared to Vangbunkong et al. (2013) and Ali & Osman (2008). For example, Vangbunkong et al. (2013) carried out the large direct shear box test on the reinforcing effect of the soil-root matrix with vetiver grass and its result exhibits that the fiber roots could increase the shear strength which mainly arises from the cohesion (Fig. 3b). Regarding the hydraulic conductivity of the soils, the coefficient of permeability of the soil with fibers was slightly smaller than that of the soil without fibers (see Table 1).

2.3 Rainfall simulation

In this study, the rainfall intensity classified as heavy rainfall (Llasat, 2001) was selected. To simulate the heavy rainfall in the centrifuge, nine pneumatic spray nozzles were chosen for spraying water over the model slope. Fig. 4 shows the schematic of a rainfall simulation system for the centrifuge tests. The rainfall simulator was placed above the steel box at a distance of 80 mm. The small tank was installed in the left side of the steel box as water storage tank and it was used as a rain gauge to estimate precipitation on the slope.

2.4 Slope model and testing procedure

The slope model was constructed inside a 450mm×150mm×270mm steel box. A side view of the experimental system is schematically illustrated in Fig. 4a. Three model cases, i.e., Case 1: without reinforcement, Case 2: with 20-mm fiber reinforcement and Case 3 with 40-mm fiber reinforcement, were conducted as summarised in Table 2 and depicted in Fig. 4.

To examine the reinforcing effect of the roots against slope failure, the rooting depth is selected as a parameter. The slope model consists of bedrock and soil slope. The bedrock with 165 mm in length, 76 mm in height and slope angle of 25^{o} was made of aluminum plates and placed on a 10 mm-thick acrylic plate. The surface of bedrock was roughened by attaching a sand paper. The soil slope consists of four layers of Edosaki sand with a total thickness of 80 mm. Pore water pressure transducers (PWPs) and accelerometers (ACCs) were installed in the soil layers during the compaction to measure the pore water pressure and the soil slope displacement. The soil displacements were measured by both the accelerometers and a video record through the front transparent window.

3. Test Results and Discussion

3.1 Test Results

Figure 5 shows variations of phreatic surface within the soil slope. Fig. 5a depicts the location of the PWPs used for determination of the phreatic surface location. Calculated slope displacements at the upslope and mid-slope using the ACCs at relevant times are plotted in Figs. 6 – 8 in all cases. Side views of the model slope after rainfall are shown in Fig. 6b, 7b and 8b for all the cases.

In Case 1 (Fig. 5b), the rain was provided for 26s in the model scale ($\equiv$ 26s $\times$ 50^2 = 65,000s $\equiv$ 18hr in the prototype scale). Since the model slope was partially saturated before rainfall, the initial pore water pressure was negative due to suction. It is observed that the pore water pressure at PWP13 starts increasing around 1mm (5cm) at 13s in the model scale (9hrs in the prototype scale). The slope starts showing the movement based on the ACCs reading (Fig. 6a). At the time of 22s (15hr), the general failure of the slope has occurred at the toe slope with the pressure head around 30mm (1.5m) at PWP13. Once the pressure head reaches around 40mm at PWP13, the slope was collapsed with a relatively deep slip surface as shown in Fig. 6b. According to the accelerometer reading (Fig. 6a) and the video observation has shown that the slope has started to collapse from the toe of the slope and progressively moves upward.

In the cases with the model vegetation (Cases 2 and 3), at PWP13 the pore water pressure started showing change around 14s (10hr) for Case 2 (Fig. 5c) with 1.5mm (0.075m) of water head while Case

3 (Fig. 5d) is 1.3mm (0.065m) at this time and there is a very small change of the slope displacement in both cases (Fig. 7a and 8a). At the time 22s (15hr), the water head at PWP13 reached to 15mm (0.75m) for Case 2 and 14mm (0.7m) for Case 3. It was observed that once the phreatic surface reaches at 28mm (1.4m) for Case 2 and 25mm (1.25m) for Case 3 and the slope has deformed with small displacement (Fig. 7a and 8a) with time 36s (25hr). In this stage, the water head of Case 3 was slowly raised up due to the fibers mixing. Based on the permeability test shown that the infiltration of rainwater could be delayed by the fibers (see Table 1) and Rahardjo, *et al*. (2012) also mentioned on the effectiveness of the vetiver roots in minimising the infiltration into greater depth. At the end of the precipitation, the pressure head is reached to 33mm at 50s (35hr) and 33mm at 58s (40hr) for Case 2 and 3, respectively. The displacement in this stage has shown that the soil displacement is moderate for Case 2 (see Fig. 7) and limited around the toe slope for Case 3 (see Fig. 8), compared to Case 1. There is no collapse in Cases 2 and 3. This is caused by the effect of the model roots, which tie up the soil particles and prevent formation of the crack on the slope surface. Rather uniform deformation of the slope in Cases 2 and 3 (see Figs. 7b and 8b) supports this effect of the fibers.

3.2 Result Discussion

The results indicate that the bare soil slope was failed by raising the groundwater table, in which cracking started from the toe of the slope and progressively moved to the upslope. On the other hand, in the presence of the surface layer reinforced with fibers, the slopes deformed uniformly without collapse. This marked reinforcing effect is attributed to the surfficient reinforcement around the toe, otherwise the noticeable contribution of the reinforcement cannot be expected (e.g., Sonnenberg, et al., 2010, 2012).

Figure 9 plots changes of average water pressure head and displacement at the toe for all cases. Based on Fig. 9a, the pressure head in Case 1 has reached to 1.2m at time 18hr while Case 2 is 1.3m at 35hr and Case 3 is 0.9m at 40hr. Hence, the pressure head of Case 1 is higher than the other two cases by comparing with time. Fig. 9b, the displacement in Case 1 is shown a large displacement around 0.8m at time of 18hr and the other two cases just 0.3m at 35hr for Case 2 and 0.1m at 40hr for Case 3. According to the results, the tests have revealed that the fibers, i.e. the roots, could help to increase the soil strength of soil slope to prevent the failure and reduce the infiltration of rainfall into the ground to delay the groundwater table raising. These results are comparable to Rahardjo, *et al*. (2012). Table 3 summarises the test results.

4. Conclusions

Two main conclusions are as follows:

- The slope started to deform from the toe. This deformation is caused by rising of the water table, which decreased the effective stress and shear strength of the soil. The results also reveal that a slope with a high water content is more inclined to fail with a shallow slip surface washed out due to changes in pore water pressure and soil permeability during heavy rain.
- Roots in the surface of a slope tie the soil particles together and prevent the formation of cracks on the slope surface. This effect is more pronounced for larger rooting depths. In addition, roots delay the ground infiltration of rainfall and delay the rise in groundwater table. In other words, roots can delay slope failure and slow movement of a soil slope could provide a first early warning of failure.

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Table 1. Properties of compacted soils

Soil type	Edosaki Sand	Edosaki Sand + 2% by mass of polyester fibre
Specific gravity, G_s	2.65	-
Maximum dry unit weight, γ_d (kN/m^3)	12.94	12.94
Optimum water content, w_{opt} (%)	15.19	17.28
Degree of saturation, S_r (%)	39.85	-
Total unit weight, γ_t (kN/m^3)	14.91	15.18
Void ratio, e	1.01	-
Maximum void ratio, e_{max}	1.29	-
Minimum void ratio, e_{min}	0.87	-
Coefficient of permeability, k (cm/s)	3.25×10^{-5}	3.08×10^{-5}
Cohesion intercept, c (kPa)	4.8	18.9
Angle of shearing resistance, ϕ (^{o})	28.58	31.45

Table 2. Summary of centrifuge tests

Case No.	Model case	Real case	Average of pressure head (m)	Total rainfall depth (mm)	Duration of rainfall (hr)	Slope deformation
1	Without reinforcement	Bare soil	1.2	293.22	18	Collapsed
2	With 20-mm thick of fiber-reinforced surface layer	1-m depth of vegetation root (6 months growth of vetiver)	1.3	610.4	35	Moderate deformation (Uncollapsed)
3	40-mm thick of fiber-reinforced surface layer	2-m depth of vegetation root (a year growth of vetiver)	0.9	835.2	40	Small deformation (Uncollapsed)

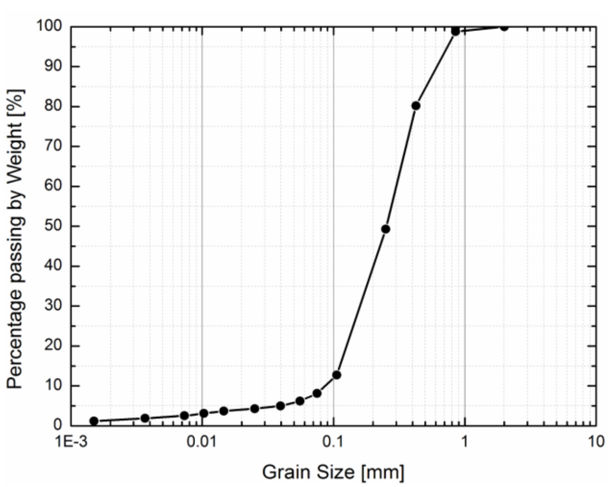

Figure 1. Grain size distribution curve of Edosaki Sand

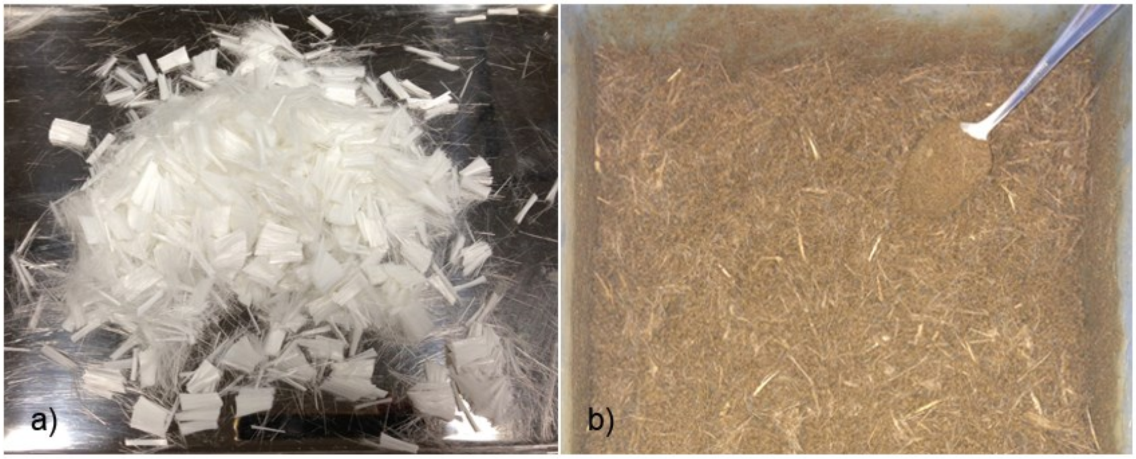

Figure 2. Polyester fibers before and after mixed with Edosaki sand at 2% by mass: a) Before mixing and b) After mixing

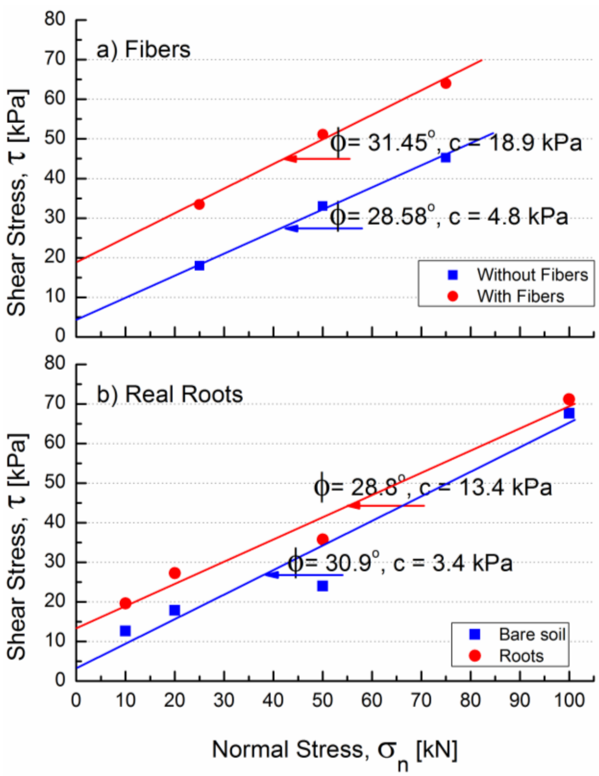

Figure 3. Direct shear box test results: a) Edosaki sand specimens with and without 2% of polyester fibers and b) Real roots of vetiver grass

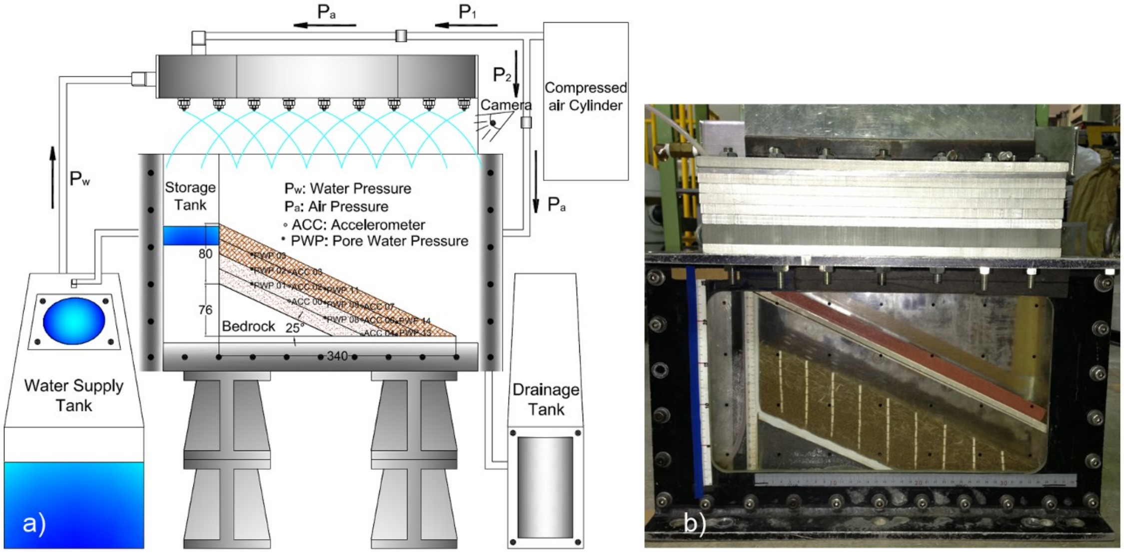

Figure 4. Typical centrifuge model test with a rainfall simulator system: a) Schematic model system and b) Model preparation before testing

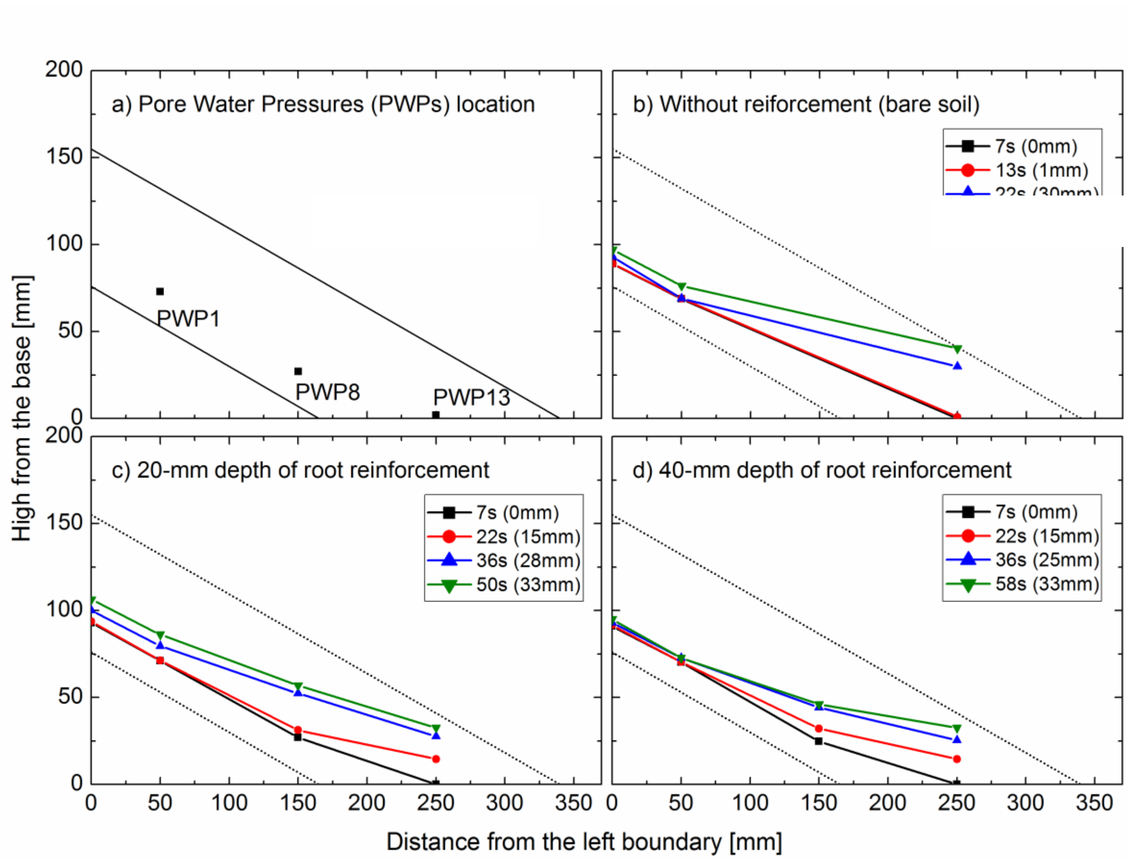

Figure 5. Variation of phreatic surface and location of pore water pressure gauges used: a) Pore water pressure location, b) Case 1: Without reinforcement, c) Case 2: With 20-mm thick of fiber-reinforced surface layer, and d) Case 3: With 40-mm thick of fiber-reinforced surface layer

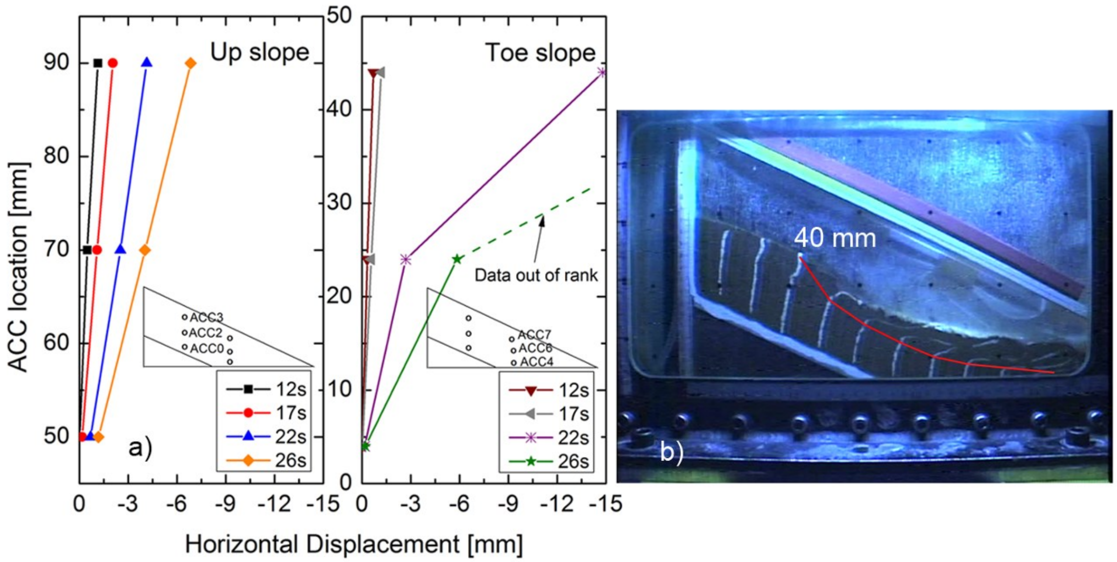

Figure 6. Slope displacement for Case 1 without reinforcement: a) Displacement calculated from ACCs and b) Slip surface of soil slope at 26s

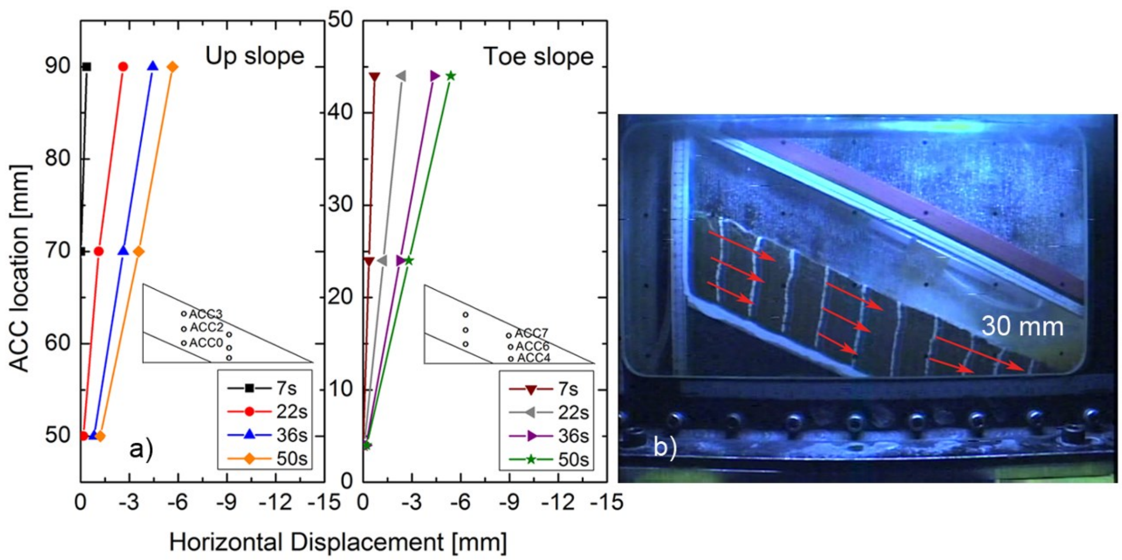

Figure 7. Slope displacement for Case 2 with 20-mm thick of fiber-reinforced surface layer: a) Displacement calculated from ACCs and b) Exaggerated displacement vector at 50s

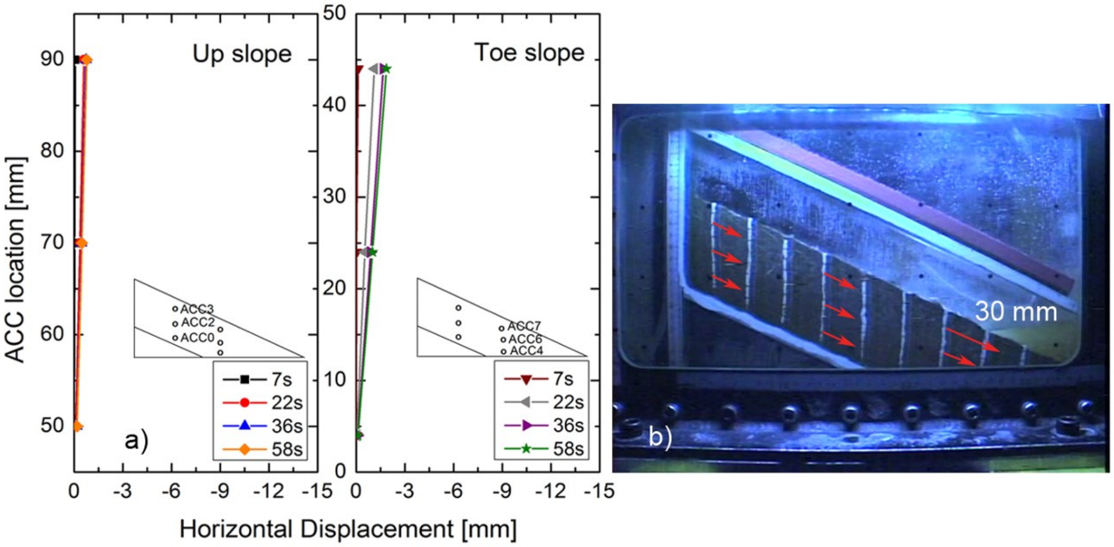

Figure 8. Slope displacement for Case 3 with 40-mm thick of fiber-reinforced surface layer: a) Displacement calculated from ACCs and b) Vector displacement at 58s

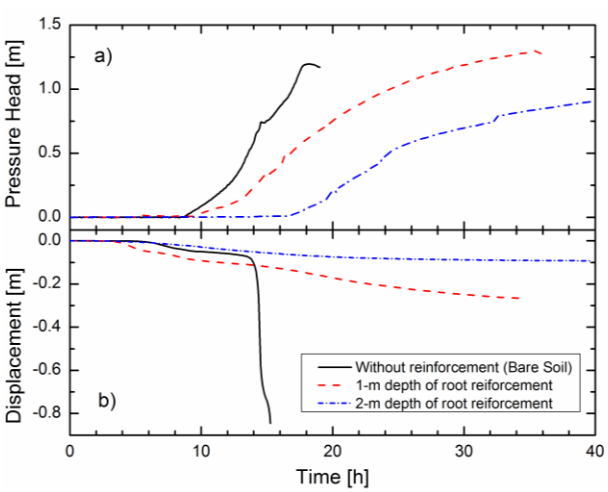

Figure 9. Evolutions of a) average water pressure head; b) displacement at toe slope