令和8年度砂防学会研究発表会概要集

Effects of Soil Nails on Vegetated Slope During Rainfall-Induced Shallow Failures: Flume Experiment

降雨誘発浅層崩壊時における森林斜面への地山補強土の効果：斜面実験による評価

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1. Introduction

Rainfall-induced shallow failure can still occur on vegetated slopes (McGuire et al., 2016), underscoring the importance of reinforcement such as nails to improve slope stability. Under rainfall infiltration, numerical analyses showed that soil nails reduced the maximum displacement from 5.2 m in the unreinforced slope to 0.4 m, indicating delayed failure development (Cheuk et al., 2005). Landslide timing is controlled by hydrological processes that determine how incoming water is partitioned between runoff and temporary subsurface storage (Bogaard and Greco, 2016). For instance, a GIS-validated modeling showed that incoming water was partitioned between surface runoff and temporary subsurface storage, delaying wetting from 1 h at 50 cm to 24-312 h at 100-200 cm depth and postponing instability on a 40° slope from 5 h to 16 h (Baum et al., 2010). Storage development influences local wetting and saturation, which in turn affect deformation, fissure initiation, and final failure; in vegetated flume slopes, rainfall-driven storage rose to 50-78% of maximum storage, with mean VWC increasing from 0.03-0.07 to 0.08-0.21 m^3/m^3, followed by upper-slope fissuring and landslide initiation (Noviandi et al., 2026). However, the effect of soil nails on vegetated slopes under rainfall through hydrological indicators has not been examined. Therefore, this study investigates vegetated slopes with and without soil nails under controlled rainfall, with the objectives of (1) evaluating how soil nails affect rainfall-runoff-based relative storage development, and (2) clarifying how this relative storage development is related to deformation processes leading to shallow failure in vegetated slopes.

2. Methodology

A 1/70-scale laboratory flume (1.0 m wide) was prepared to simulate shallow landslide (Fig. 1a). The flume comprised an upper initiation section (1.3 m long, 35°) and a lower runout section (2.0 m long, 10°). The initiation section was packed with a 13 cm-thick soil layer at a dry density of 1.36 g/cm^3, using soil with a median grain size (D_{50}) of 1 mm, a coefficient of uniformity (Cu) of 10, and a coefficient of curvature (Cc) of 1.2.

Two vegetated treatments were prepared: a vegetated slope without nails (VS) and a vegetated slope reinforced with nails (VS-N). *Pisum sativum* (microgreen pea) was used as model vegetation and planted at 10 cm spacing (100 stems/m^2; Fig. 1b). In the reinforced treatment, 3 mm-diameter aluminum rods were used as 1/70-scale soil nails. The nails were installed at 28.5 cm intervals (Fig. 1b). A 7 × 7 cm, 0.5 cm-thick steel plate was placed at the slope surface for each nail to simulate the head plate and distribute stress around the nail head. Each nail was 19 cm long and threaded to ensure anchorage into the acrylic flume base.

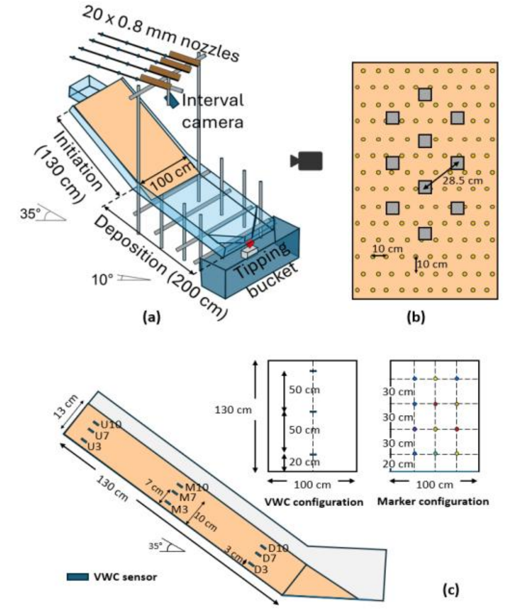

Figure 1 (a) Flume set-up, (b) vegetation and nail spacing, (c) VWC sensor and marker bead configuration.

Constant intensity of rainfall (110 mm/hr) was simulated using 20 spray nozzles (0.8 mm diameter, 1.4 m height) (Fig. 1a). Rainfall input was measured by a flow meter at 30 s intervals and corrected for losses (water falling outside the flume and hose leakage). Volumetric water content (VWC) was measured at 3, 6, and 10 cm below the slope surface (Fig. 1c) using soil moisture sensors (Onset S-SMC-M005) with a 30-s interval, whereas surface runoff was recorded with a 50 mL tipping bucket connected to an event logger. Evapotranspiration was assumed to be negligible because the aboveground biomass was cut before each test. Temporal change in a rainfall-runoff-based relative storage proxy was estimated for each 30-s interval using simple water balance, $\Delta S(t) = P(t) - Q(t)$, where $P(t)$ is rainfall input and $Q(t)$ is runoff output during the same interval. The cumulative storage series ($S(t)$) was obtained by summing $\Delta S(t)$, represents the relative accumulation and release of water within the slope rather than absolute total storage.

Slope deformation was evaluated from the displacement of 12 surface markers on the slope (Fig. 1c), using images captured at 1-s intervals. Marker positions were manually tracked in AutoCAD, and their displacements relative to the initial coordinates were calculated. Saturation-zone development was interpreted from the temporal VWC response. The storage record was then compared with VWC responses, deformation, fissure, and landslide initiation time.

3. Results

The vegetated slope with nails (VS-N) reached higher rainfall-runoff-based relative storage proxy values than the vegetated slope without nails (VS) at fissure initiation and landslide occurrence (Fig. 2a; Table 1). At fissure initiation, VS fissured at 8.0 min under 14.5 L of cumulative rainfall and 3.4 L of cumulative runoff, corresponding to a relative storage proxy of 11.1 L, whereas VS-N fissured at 9.1 min under 17.1 L of cumulative rainfall and 2.2 L of cumulative runoff, corresponding to a relative storage proxy of 14.9 L. Similarly, at landslide, VS failed at 12.4 min under 22.8 L of cumulative rainfall, 6.6 L of cumulative runoff, and a relative storage proxy of 16.2 L, whereas VS-N failed at 21.6 min under 38.6 L of cumulative rainfall, 8.6 L of cumulative runoff, and a relative storage proxy of 29.9 L.

Table 1 Summary of experimental result

Condition		∑P (L)	∑Q (L)	S (L)	Mean VWC (m^3/m^3)			Mean Deformation (cm)	Timing (min)
VS	Initial fissure	14.5	3.4	11.1	0.179	Upper	0.128	0.5	8.0
						Midle	0.196		
						Lower	0.208		
	Landslide	22.8	6.6	16.2	0.227	Upper	0.126	4.3	12.4
						Midle	0.242		
						Lower	0.287		
VS-N	Initial fissure	17.1	2.2	14.9	0.197	Upper	0.133	0.7	9.1
						Midle	0.213		
						Lower	0.217		
	Landslide	38.6	8.6	29.9	0.249	Upper	0.159	4.2	21.6
						Midle	0.236		
						Lower	0.249		

VWC and deformation showed similar overall increases with rainfall-runoff-based relative storage proxy in both VS and VS-N, although their rates and VWC distribution patterns differed (Fig. 2b; Table 1). At fissure initiation, mean VWC was 0.179 m^3/m^3 in VS and 0.197 m^3/m^3 in VS-N, while mean deformation was 0.5 and 0.7 cm, respectively; at landslide occurrence, mean VWC increased to 0.227 and 0.249 m^3/m^3, and mean deformation to 4.3 and 4.2 cm, respectively. In VS, VWC increased mainly in the middle and lower slope positions, from 0.196 and 0.208 m^3/m^3 to 0.242 and 0.287 m^3/m^3, whereas in VS-N, VWC increased more evenly across positions, from 0.133, 0.213, and 0.217 m^3/m^3 to 0.159, 0.236, and 0.249 m^3/m^3. Saturation-zone development began after 11 min in VS and after 10 min in VS-N, and the saturation-zone area at landslide occurrence was 14.2% in VS and 15.7% in VS-N.

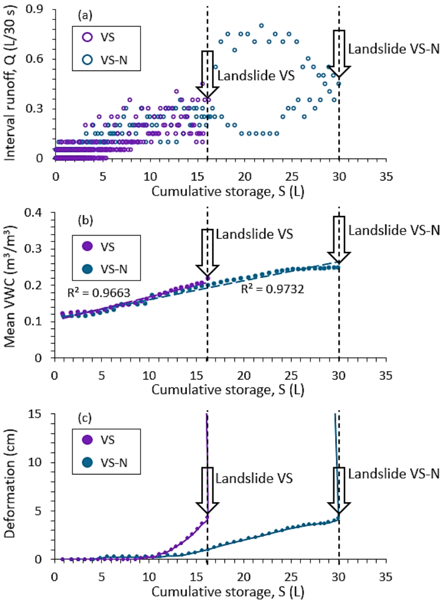

Figure 2 (a) Storage-runoff, (b) storage-VWC, and (c) storage-deformation relations for vegetated slopes with and without soil nails.

4. Discussion

We found that soil nails affected rainfall-runoff-based relative storage development associated with landslide occurrence in vegetated slopes. At fissure initiation and landslide occurrence, the rainfall-runoff-based relative storage proxy in the nailed slope was 1.3 and 1.8 times that in the slope without nails, accompanied by delays of 1.1 and 1.7 times, respectively. A larger reinforcement response was reported in a numerical study of forested slopes with steel bars, where the reinforced slope remained stable under groundwater rise from 0.5 to 1.0 m (Nghiem et al., 2004). The smaller response in our study may reflect rainfall-driven wetting, which can reduce rooted-soil shear strength by 17-23% (Zhou et al., 2024).

We also found that soil nails altered the spatial wetting pattern and allowed failure under a greater hydrological state. As the rainfall-runoff-based relative storage proxy increased from fissure initiation to landslide occurrence, mean VWC and deformation increased in both treatments. This is physically reasonable because rainfall infiltration can cause toe-focused wetting and pore-pressure buildup (Lehmann et al., 2013). However, VS-N showed a more distributed VWC pattern at landslide occurrence, with a smaller upper-to-lower VWC spread (0.090) than VS (0.161), suggesting that soil nails limited deformation after fissure initiation, preserved slope structure, and thereby delayed the concentration of infiltration toward the toe (Liang, 2020).

5. Conclusion

The vegetated slope reinforced with soil nails required higher rainfall-runoff-based relative storage proxy values before fissure initiation and landslide occurrence than the slope without nails. Therefore, practical assessment and design of soil-nailed vegetated slopes under rainfall should integrate hydrological indicators in addition to conventional mechanical reinforcement criteria.

6. References

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