Evaluating soil nails in slope stabilization: insights from a flume experiment

斜面安定化における土留め釘の評価: 水路実験からの知見

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1. Introduction

A non-frame soil nailing (NFN) system is an effective approach for improving stability and reducing slope deformation (Holtz and Schuster, 1996). NFN typically consists of nails with 1.5 to 3.0 m in depth, depending on soil and bedrock, with bearing plates at 2 m intervals (Iwasa et al., 2008). NFN systems have the advantage of flexibility, allowing installation under varying site conditions, while reinforcing slopes through passive resistance by mobilizing tensile strength (Bo et al., 2015). Consequently, soil nails increased the critical slope angle from 12° to 20°, with bending stress exceeding 1200 N/mm² at 35 mm displacement, while axial stress remained low (300 N/mm²) (Nakamura et al., 2001). Unlike frame systems with concrete covering hillslope surfaces, NFN allows infiltration and lateral water movement in soils. These hydrological processes possibly become a disadvantage by developing excess pore water pressures and leading to localized slope failures in between nails. To overcome the problems of internal hydrological processes of NFN systems, the primary objective of this study is to examine internal hydrological processes from rainfall initiation to landslide occurrence with the presence and absence of NFN systems. The specific objectives are (1) to investigate deformation processes and development of saturation and (2) to examine the timing and size of landslides with and without NFN systems.

2. Methodology

We developed a 1/70 scale flume (Fig. 1a) with a 1.0 m width flume consisting of 1.3 m length initiation area (35°). The soil thickness was 13 cm soil with 1.36 g/cm^3 of dry density. D_{50} of soil was 1 mm with C_u of 10 and C_c 1.2.

Rainfall intensity of 110 mm/h was applied using twenty 0.8 mm spray nozzles positioned 1.4 m above the slope. Volumetric water content (VWC), runoff, and slope deformation were monitored using soil moisture sensors (Onset S-SMC-M005), a tipping bucket with an event logger, and surface markers, respectively (Fig. 1a, 1b). Deformation was measured from marker displacement, using 1-second interval images captured by a camera located 1.4 m above and perpendicular to the slope. Marker positions were manually tracked in AutoCAD, and their displacements were calculated relative to initial coordinates. To correct image distortion and rectify the slope geometry, an affine transformation matrix was applied using the known initial coordinates of reference markers. This matrix was manually computed in Microsoft Excel, following the method described by Burger and Burge (2009), and was used to adjust marker coordinates during the displacement analysis.

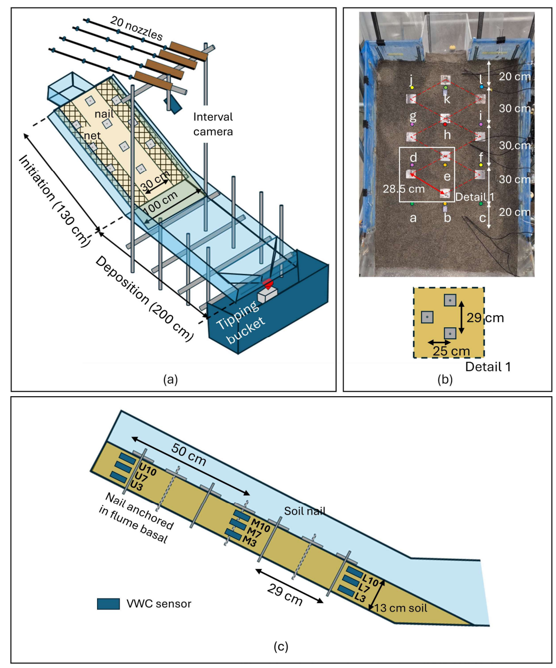

Figure 1 (a) Flume experiment set-up, (b) marker bead and nail spacing, (c) soil nail and VWC sensor configuration

A 1/70 scale aluminum rod with a diameter of 3 mm was used as a soil nail in NFN systems to avoid excessive quantity and impractically thin dimensions. The nails were installed at 28.5 cm intervals (Fig. 1b), corresponding to 2.0 m and 1.7 m spacing in the 1/7 scale model based on frame systems spacing. A 7 × 7 cm steel plate with a thickness of 0.5 cm was placed on the surface above each nail to represent head plate, distributing stress at the slope surface. The 19 cm-long nails were threaded at both ends for

Table 1 Experimental results for slopes with and without soil nails

Condition	Sample	Timing (min)		Volumetric Water Content (m^3/m^3)			Deformation (cm)		Saturated Length (cm)	Landslide Area (cm^2)
		First crack	Landslide	Initial	First Crack	Landslide	First Crack	Landslide		
Without Nail	1	7.5	12.3	0.146	0.157	0.235	0.2	1.1	85.9	8,797
	2	7.2	11.7	0.122	0.128	0.232	0.3	1.0	78.8	8,300
With Nail	1	11.2	17.3	0.100	0.175	0.198	0.1	0.8	78.8	7,799
	2	7.8	12.5	0.107	0.125	0.210	0.6	2.2	46.4	7,328
	3	8.3	12	0.103	0.166	0.227	0.6	2.0	72.2	7,143

anchorage into the acrylic flume base. The experiment was repeated two times without nails and three times with nails.

3. Results

Deformation behavior under rainfall differed between slopes with and without soil nails (Table 1). In slopes without nails, first fissure occurred after 7.4 minutes (SD: 0.2), forming at 8.4 cm from top part of hillslope with a mean VWC of 0.143 m^3/m^3 and 0.3 cm mean surface deformation from the bead marker reading. Saturation started to develop after 9 minutes at the bottom of the hillslope. Just before failure at 12 minutes, mean surface deformation was 1.0 cm with 2 - 4 numbers of fissures (total fissure length: 69.1 – 108.7 cm). Saturation area at the time of failure extended for 82.3 cm with an area of 645.0 cm^2 (SD: 28.0). The average of landslide area was 8,548 cm^2 (SD: 352.0), distributed as 1,587 cm^2 in the upper zone, 3,077 cm^2 in the middle, and 3,884 cm^2 in the bottom zone (Fig. 2). Runoff rate prior to collapse ranged from 2.4 to 3.8 L per 10 min. The total runoff was 3.3 m^3 (SD: 0.8) with storage capacity at 87.6% (SD: 2.4).

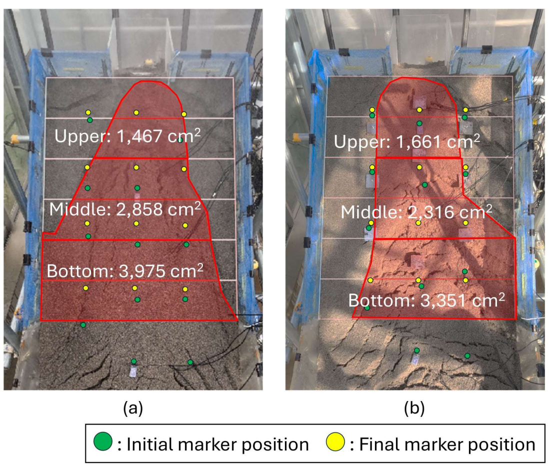

Figure 2 Landslide area in different zones for (a) slope without NFN, (b) slope with NFN

First fissure development at NFN systems was 9.1 minutes (SD: 1.8) with mean VWC 0.155 m^3/m^3. Saturation area started developing at 11 minutes. Saturation area was extended with 65.8 cm in length and 430.8 cm^2 in area (SD: 108.8) at the time of failure. Right before landslide occurrence, 13.9 minutes after rainfall, the mean deformation was 1.7 cm with 5 - 7 numbers of fissures (total fissure length: 102.5 - 120.0 cm). The landslide area was 74,23 cm^2, SD: 338.0), and consisted of 1,604 cm^2 in the upper zone, 2,241 cm^2 in the middle, and 3,578 cm^2 in the bottom. The slope sith nail exhibited 2.9 to 5.0 L per 10 minutes of runoff flow prior to failure, with a total runoff volume of 3.6 m^3 (SD: 1.5) and storage capacity of 84.7% (SD: 4.1).

4. Discussion

Our study revealed that soil nails slightly affected the hydrologic and geomorphic processes during rainfall-induced landslides, with a 1.2-fold delay in crack initiation, a 1.2-fold delay in saturation zone development, and a 1.1-fold delay in landslide occurrence. For comparison, Nakamura et al. (2005) reported a pronounced delay in slope displacement, from 135 to 300 seconds, in experiments using a wax-coated sliding surface to simulate failure. This difference is likely due to the coarser and less dense soil used in our experiment (D_{50} = 1 mm, dry density = 1.36 g/cm^3) compared to the finer volcanic sand (maximum particle size of 0.85 mm) with higher density (1.84 g/cm^3) in their study, as well as the shallower moving soil layer in our setup (13 cm versus 20 cm), both of which may have reduced the effectiveness of soil nail reinforcement. Nevertheless, we still found that soil nails contributed to a reduction in the landslide-affected area, particularly in the middle part of the slope, showing that soil nails possibly reduce lateral deformation and help confine the sliding mass.

We also found that slopes with NFN systems experienced landslides governed by the same mechanism as non-reinforced slopes, primarily driven by hydrological processes. A consistent pattern was observed where saturation developed shortly after the first crack, and the difference in landslide timing was minimal, with similar storage capacity. In the absence of surface protection, rainfall infiltrated into the soil, leading to saturation in the toe area, possibly leading to localized rises in pore water pressure and triggering failure through fluidization, consistent with the observations of Okura et al. (2002).

5. Conclusion

To improve NFN systems in slope stabilization, future applications should incorporate designs that address internal pore water pressure buildup, such as integrating subsurface drainage layers, and enhancing soil cohesion through the introduction or preservation of plant root systems.

6. References

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