Developing an Experimental Method to Evaluate the Effect of Root Network on Shallow Landslides by Using a Flume Experiment

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1. INTRODUCTION

Vegetation cover has a strong influence on the vulnerability towards slope instabilities, particularly shallow landslides (*Cohen and Schwarz, 2017*). In general, vegetation roots system is capable to modify soil structures, influencing mechanical and hydrological processes of the slope that alter slope stabilities (*Bordoni et al., 2020*). Previous studies reported the significance of root systems on slope stability. For instance, Swanson and Dyrness (*1975*) found that the frequency of landslide in clear-cut areas was 2.8 times greater than ones in forested areas of the Western Cascades in Oregon. Similarly, Imaizumi et al. (*2007*) found that landslide occurrence around 5-15 years after forest cutting remained 10-fold greater compared to non-cutting areas.

Various experimental methods have been developed for the measurement of root strength (*Giadrossich et al., 2017*). Most of these studies have focused on determining the tensile strength of individual roots using a pulling device until it breaks. Other studies determined the shear-strength of rooted soils and compared them with non-rooted soils in a shear-box and triaxial test. Yet, an evaluation of root strength is still challenging because the complex features of roots consisted of both lateral and vertical root networks (*Yildiz et al., 2018*). The contribution of the roots system to slope stability depends not only on individual root strength and soil-root interaction but also on the complete root system architecture (*Reubens et al., 2007*).

Root geometry, particularly the orientation of root mass (i.e., vertical, lateral), plays a significant role in defining the reinforcement mechanism on soils (e.g., *Cohen and Schwarz, 2017*). Many studies have mentioned the importance of these vertical and lateral root mass on slope stabilization (e.g., *Schwarz et al., 2015*). Vertical root mass may act on the basal shear surface enhancing shear resistance. While lateral root mass may prevent lateral deformation on the slope. Because of difficulties in measuring the actual root condition without dissection, evaluating root strength for slope stability by considering the entire root mass is also difficult to perform. To overcome the problem, a laboratory slope stability experiment with vegetation can be effective. Yet, methods for laboratory experiments have not been established.

Therefore, the objectives of this study are to: (1) develop an experimental method to quantify the effect of the root network on slope stability; and (2) evaluate the significance of the vegetation root network in stabilizing the slope. Findings of this study can be useful for developing parameters for predicting slope stability using root mass on slopes.

2. METHODOLOGY

[1] Experimental slope

We developed a flume apparatus with a 1:70 geometric scale made of 1-cm thick acrylic material, consisting of an initiation and deposition segment (**Fig. 1**). The initiation segment was 120 cm long with a 35° inclination representing the slope for landslide initiation, while the deposition segment was 50 cm long and inclined at 10°, reflecting the deposition zone. Eight nozzles were installed 2 m above the flume to apply surface water as rainfall. Since the edge of the deposition segment was open, water from the slope flowed freely on this segment. Hence, we placed a sediment box at the end of the deposition segment to capture water and collapsed sediment from the slope. Material used for all conditions was low cohesion sand with 1.4 g/cm^3 dry density, D_{50} = 0.23 mm and porosity = 55.4%. Sand was placed in the initiation segment to a depth of 10 cm.

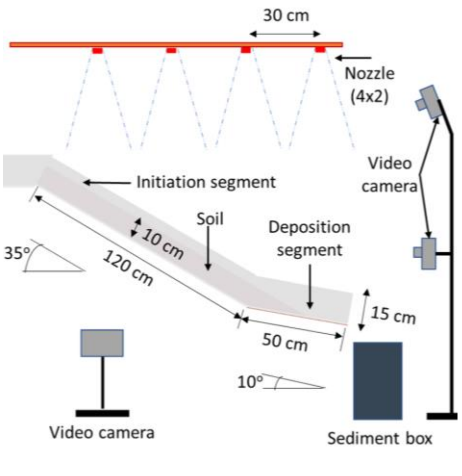

Fig. 1 Schematic illustration of flume apparatus

2] Application of vegetation

For conditions with vegetation (V), we grow pea (*Pisum sativum L.*) bean sprouts in the soil to simulate the root reinforcement effect on the slope. Beans were placed at 3 cm intervals. After 2 weeks, beans reached 25-30 cm in height with vertical roots extending to 10 cm depth and 3-4 cm of lateral root extension. This condition of the experiment plot with beans was assumed to be forest stand with 2200 stem/ha of density and 17.5-21 m height (i.e., Japanese cedar plantation).

[3] Measurement and analysis

We applied rainfall at an intensity of 60 mm/h. When the landslide initiated, we measured the time (from surface water application to landslide initiation) and water content. Ten TDR (Time Domain Reflectometer) sensors were placed at 3 and 7 cm depths to monitor soil-water content. Nine displacement markers were located on the soil surface to measure the velocity and displacement. The time when the first crack developed was also measured. Three video cameras were placed in front, side, and above the flume to capture sediment motion (**Fig. 1**). Landslide area, velocity, and displacement were estimated from video cameras using AutoCAD 2014 student version. The saturated zone was estimated based on TDR readings using interpolation on Phyton.

3. RESULTS

For the non-vegetated condition (NV; n = 3), the first crack developed at t = 120 to 300 s (mean = 220 s; SD = 90 s). Landslides initiated at t = 1750 to 1820 s (mean = 1790 s; SD = 36 s). Regarding the maximum water content when landslides initiated, NV had a volumetric water content of 34 to 35% (mean = 34.6%; SD = 0.6%) with an estimated saturated zone of 6200-8000 cm^3 (mean = 7100 cm^3; SD = 900 cm^3). Landslide area on NV was 4300-4700 cm^2 (mean = 4600 cm^2; SD = 260 cm^2). The peak velocity of these landslides was 30 to 35 cm/min (mean = 33 cm/min; SD = 2.6 cm/min) with total displacement of 60 to 67 cm (mean = 63.3 cm; SD = 3.5 cm).

The landslide with vegetation (V; n = 1) was different from than for NV. The first crack was developed at t = 1500 s. The landslide initiated at t = 3600 s with a maximum water content of 40%. The estimated saturated zone was 15000 cm^3 and the landslide had an area of 3200 cm^2. The landslide with vegetation had a peak velocity of 22 cm/min. Nevertheless, this landslide had a total displacement of 64 cm, similar to that for non-vegetated conditions.

4. DISCUSSION

We successfully developed a flume experiment for testing the effects of vegetation root networks on slope stability. The effect of root networks on slope stability includes basal reinforcement by vertical root mass and lateral reinforcement by lateral root mass. Basal reinforcement is the most effective mechanism for slope stabilization due to its anchoring effect (*Schwarz et al., 2015*). In many cases, however, this mechanism is absent because the position of the slip surface is deeper than the rooting zone (*Cohen and Schwarz, 2017*). Similarly, because the vertical root mass did not penetrate the flume bed, and all landslides in our experiment slipped over the flume bed, the basal reinforcement may be zero. Thus, we assume that lateral reinforcement by lateral root mass is the main contributor altering landslides on non-vegetated and vegetated conditions in our experiment.

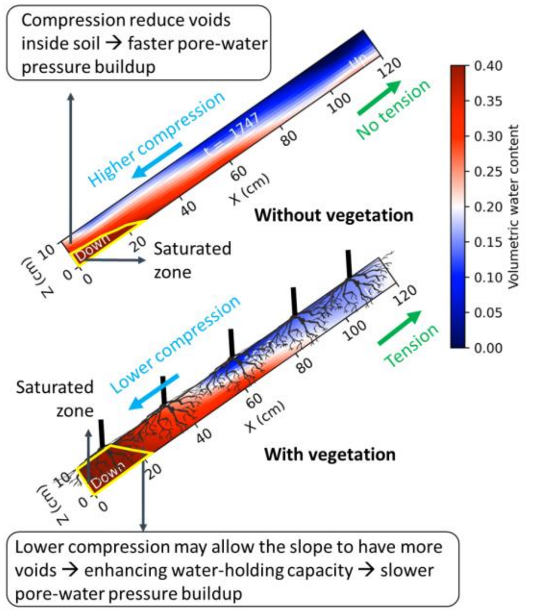

Fig. 2 Schematic illustration of the effect of lateral force redistribution on hydrologic processes of slope

The mechanical contribution of lateral root mass in slope stability is due to lateral force redistribution by root tension (*Cohen and Schwarz, 2017*). This reduces the compression force downslope that prevents crack formation. Indeed, as found in our study, the vegetated condition (V) delayed the first crack formation about 5 times longer compared to non-vegetated conditions (NV). Landslide with vegetation also had 25-31% smaller area since lateral root tension at the edge of stable and unstable zones began to take and redistribute some loads to resist the downslope movement (*Cohen and Schwarz, 2017*). The reduction in the unstable area then reduces landslide mass and momentum (e.g., *Guo et al., 2020*). This therefore reduces the velocity of V by 26-37% compared to NV. Thus, V is more stable than NV.

The lateral force redistribution by root tension may also alter the hydrologic processes on the slope (**Fig. 2**). As compression force is reduced by lateral root tension, the slope may have more space to hold water. Indeed, when landslide was initiated, we found that V had 14-17% higher water content and 88-109% wider saturated zone compared to NV. This may indicate higher water-holding capacity on V compared to NV. Thus, we highlight that the significant contribution of root network in slope stabilization is not only by providing mechanical reinforcement, but also by altering hydrologic processes that enhance water-holding capacity of the slope. This then elevates the threshold of rainfall (i.e., intensity and duration) for landslide initiation.

5. CONCLUSION

Flume experiments are effective to evaluate the effects of complex root networks on slope stability. As found in our experiment, the presence of root networks reduces slope instabilities not only via mechanical reinforcement by root strength, but also by modifying hydrologic processes through lateral force redistribution. Based on these findings, possible land use management for mitigation measures against landslide hazards can be implemented. We plan to conduct further experiments for vegetated conditions, including investigating the effect of different root densities on shallow landslides.

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