Evaluating the Effect of Forest Density on Root Reinforcement by Using a Flume Experiment

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1. INTRODUCTION

Vegetation cover is the key factor for slope stabilization in forested hillslopes (*Sidle, 1991*). Vegetation root systems reinforce soil structures and thereby improve slope stability (*Schwarz et al., 2010*). This reinforcement depends on many contributing factors but is mainly affected by the characteristics of the root system architecture including root orientation and mass. Root orientation defines the reinforcement mechanisms, in which vertical roots enhance basal shear resistance while lateral roots moderate slope deformation (*Cohen and Schwarz, 2017*). Root mass including root size and distribution then controls the magnitude of root reinforcement (*Wu et al., 1979*).

In the hillslope, root reinforcement depends not only on the characteristics of root systems architecture but also on the root connections between neighboring trees. Such connections are complex but may be largely affected by the length of the connections (hereinafter referred to as root overlapping length). The overlapping length may not only control the continuity of root reinforcement within the slope but also the capability of the slope to resist deformation. Nevertheless, the effect of root overlapping length on root reinforcement has never been studied in any studies because of the difficulties in measuring the actual overlapping length even with dissection.

Forest density and distance between vegetation greatly influence the overlapping length (e.g., *Babi et al., 2019*), affecting root reinforcement on the slope. Indeed, previous study suggested that the change in forest density from 400 to 1000 stems/ha elevated root reinforcement by 1.6 times because of more overlapping roots (*Schwarz et al., 2010*). Since root reinforcement affects slope stability, the change in forest density consequently alters landslide frequency (e.g., *Imaizumi et al., 2007*). Thus, evaluating the effect of forest density on root reinforcement is the key point for landslide risk assessment in forested hillslopes. However, such evaluation has been remaining a challenge since forest conditions are spatially and temporally complex.

Flume experiment with vegetation can be effective to evaluate the effect of forest density on root reinforcement. Indeed, previous study mentioned the effectiveness of the flume experiment in evaluating the effect of vegetation root systems on slope stability (*Noviandi et al., 2021*). Therefore, the objectives of this study are to (1) evaluate the effect of forest density on slope stability by using a flume experiment and (2) elucidate the effect of root overlapping length on root reinforcement. Findings of this study provide insight for improving landslide risk assessment in forested hillslopes.

2. METHODOLOGY

[1] Experimental slope

A flume constructed at a 1:70 scale was used to evaluate the effect of forest density on root reinforcement (**Fig. 1**). The flume consisted of two segments representing landslide initiation (120 cm long, 35° inclination) and deposition (150 cm long, 35° inclination). All segments were 80 cm wide, 15 cm high, and constructed with 1-cm thick acrylic material. 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 tipping bucket at the end of the deposition segment to measure the outflow discharge. Sand (density = 1.4 g/cm^3, D_{50} = 0.23 mm) was placed in the initiation segment to a depth of 10 cm.

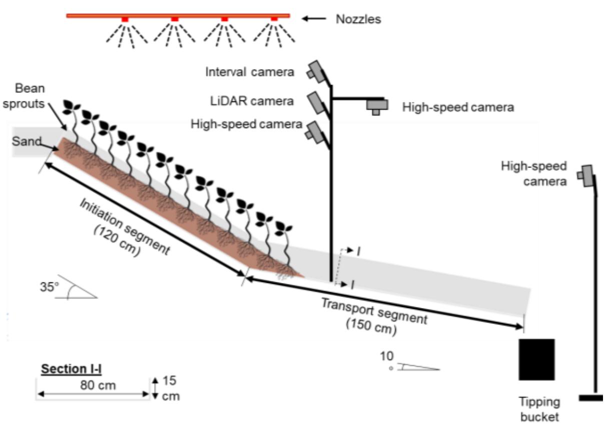

Fig. 1 Schematic illustration of flume apparatus

2] Application of vegetation

We grew pea (*Pisum sativum L.*) bean sprouts in the sand to simulate the root reinforcement effect on the slope. Beans were placed at 3, 5, and 7 cm intervals to represent a forest with 2,200, 800, and 400 stems/ha of density. After 2 weeks of planting, the sprouts reached 25-30 cm in height that representing 17.5-21 m height of Japanese Cedar plantation.

[3] Measurement and analysis

We applied rainfall at an intensity of 90 mm/h. When the landslide was initiated, we measured the time from surface water application to landslide initiation. Mean volumetric water content was estimated based on 10 TDR (Time Domain Reflectometer) sensors placed at 3 and 7 cm depths from soil surface. Nine intact root system samples (individual vegetation) were taken from each experiment to measure the fresh individual root mass and the maximum root radius. Total root mass was estimated on the basis of the mean individual root mass multiplied by the total number of vegetation per unit area. Root overlapping length was then estimated based on the mean root radius and vegetation intervals, assuming 60° of lateral root inclination on pea beans (e.g., *Rubio et al., 2003*).

3. RESULTS

Root distribution differed depending on vegetation interval (**Fig. 2a**). The individual root mass was the highest for 7 cm (n = 18, mean = 0.58 g, SD = 0.07 g), followed by 5 cm (n = 27, mean = 0.48 g, SD = 0.07 g) and 3 cm intervals (n = 27, mean = 0.33 g, SD = 0.06 g). In contrast, total root mass was the highest for 3 cm (mean = 371 g/m^2, SD = 73 g/m^2), followed by 5 cm (mean = 192 g/m^2, SD = 29 g/m^2) and 7 cm intervals (mean = 119 g/m^2, SD = 15 g/m^2). Root overlapping length was the highest for 3 cm (mean = 65 mm, SD = 18 mm), while that in 5 cm (mean = 51 mm, SD = 11 mm) and 7 cm intervals (mean = 50 mm, SD = 18 mm) was almost similar.

Differences in root distribution affects landslide characteristics (**Fig. 2b**). Indeed, condition with 3 cm interval had the gratest capability to delay landslide initiation (n = 3, mean = 924 s, SD = 41 s), while landslides in 5 cm (n = 3, mean = 810 s, SD = 113 s) and 7 cm intervals (n = 3, mean = 820 s, SD = 58 s) were initiated at almost the same time. Similarly, mean volumetric water content during landslide initiation was the highest for 3 cm interval (mean = 0.22, SD = 0.01), followed by 7 cm (mean = 0.19, SD = 0.01) and 5 cm (mean = 0.18, SD = 0.01).

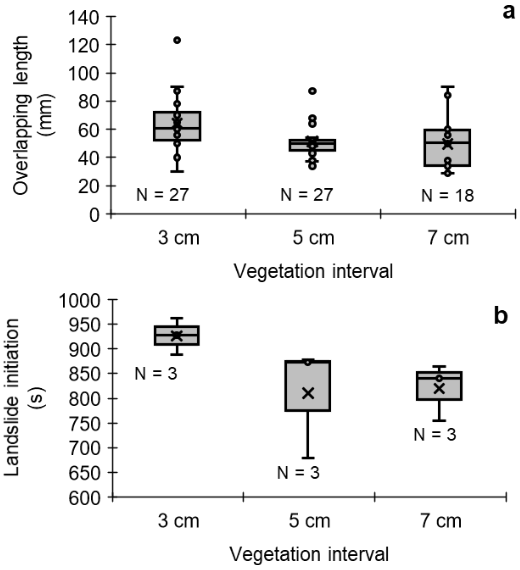

Fig. 2 (a) Root overlapping length and (b) timing for landslide initiation for different vegetation intervals

4. DISCUSSION

Forest density greatly influences root mass since tree spacing affects the competition between trees for getting light, water, and minerals (*Babi et al., 2019*). Indeed, we found that the highest individual root mass was for 7 cm since less vegetation spacing promoted more root growth, whereas the lowest one was for 3 cm interval. In contrast, total root mass was the highest for 3 cm interval because it produced the greatest amount of vegetation. Similarly, root overlapping length was the longest for 3 cm intervals because less vegetation spacing resulted in more overlapping length. Nevertheless, the overlapping length for 5 cm and 7 cm intervals was almost similar (**Fig. 2a**). Since less spatial competition promoted more root growth, whereas less vegetation spacing resulted in more overlapping, conditions with 5 cm and 7 cm intervals generated similar values of overlapping length.

Previous studies mentioned the effect of root mass on root reinforcement (*Wu et al., 1979*). In general, the larger root mass generated greater reinforcement effects (e.g., *Wu et al., 1997*; *Sakals and Sidle, 2004*; *Genet et al., 2008*). Indeed, we found that 3 cm interval, having the largest total root mass among other conditions, had the greatest capability to delay landslide initiation. Nevertheless, we found a similar response on landslide initiation timing for 5 cm and 7 cm intervals even though they produced a dissimilar total root mass (**Fig. 2b**). Instead of total root mass, root reinforcement under these conditions is likely influenced by the overlapping length since they produced a similar value of this parameter.

Roots at overlapping zone may fail under pull-out because of nonintact root connections, unlike an individual intact root. Since root length controls root pullout resistance (*Schwarz et al., 2010*), root overlapping length thereby influences root failure within the overlapping zone. Thus, the longer overlapping length may generate greater reinforcement and capability to accommodate deformation because of the larger pull-out resistance. Such condition consequently alters the rainfall threshold (e.g., duration) for landslide initiation. Indeed, we found that 3 cm interval with the longest overlapping length had the longest duration for landslide initiation, whereas that for 5 and 7 cm intervals was similar since these intervals generated similar values of overlapping length. Thus, our findings concur with previous studies that root mass influences root reinforcement. However, we highlight that root overlapping length is also a key parameter for controlling root reinforcement in forested hillslopes.

5. CONCLUSION

We suggested that root overlapping length is also influential for root reinforcement in addition to root mass. Since forest density affects the overlapping length, forest density greatly influences the vulnerability toward slope instabilities, particularly shallow landslides. Based on these findings, possible land use management for mitigation measures against landslide hazards can be implemented. We plan to estimate root reinforcement under various forest densities in future studies.

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