Assessing slope stability and hydrological dynamics in different soil depths using a flume experiment

斜面実験による土壌深さの違いによる安定性と水文動態の評価

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1. Introduction

Hydrological processes related to soil depth significantly affect the timing and size of landslides (Sidle and Bogaard, 2016). Cogan and Gratchev (2019) found that rainfall infiltration causes pore pressure change from -4.00 kPa to -0.03 kPa and moisture content change from 7% to 26%, leading an experiment slope to failure based on a flume experiment. Soil thickness also affects hydrological dynamics, influencing water storage, pore water pressure distribution, and landslide dynamics. Tufano et al. (2021) revealed that soil depths of 1.0 m and 5.0 m experience pressure head changes from -1.0 m to -0.5 m and -2.5 m to -1.8 m, respectively, under 40 mm/hour rainfall. This indicated that thinner soils cause the soil water pressure head, thereby increasing the likelihood of slope failure. Bordoni et al. (2015) observed that shallow soils with 0.6 m depth undergo rapid changes in water content and pore pressure two times faster compared to the deep soil with a 1.0 m depth based on a field study in Northern Italy.

Despite our understanding of the soil depth and hydrological processes, the inter-relationship between soil depth and hydrological processes for the occurrence of landslides was not examined. Indeed, it is impossible to observe hydrological processes in actual landslides. To overcome these issues, the flume experiment is effective (Acharya et al., 2009). Therefore, the objectives of this study are to examine landslide initiation and the development of saturated zones in different soil depths.

2. Methodology

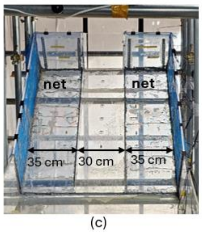
We developed a flume featuring an upper section of 1.3 meters long with a 35° slope to simulate the landslide area and a lower section of 2.0 meters in length with a 10° gradient to represent the runout area (Fig 1a). Flume bed surface was covered by a 0.5 cm mesh net to alter basal resistance between soil and acrylic surface. The center of hillslope was smooth surface with 30 cm for assuming zero-order basin (Fig 1c).

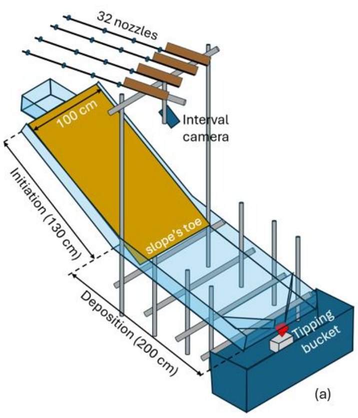
The area of hillslope was assumed to be 1/70 scale of surface to replicate geometric proportions based on actual landslides (width of 5 – 11 m and length of 15 – 35 m, based on Yamashita et al. (2017)). The flume depth was set at a scale of 1/10 to simulate shallow landslides which typically are less than 2 meters in natural environments (Sidle & Ochiai, 2006). We tested soil thicknesses of 10 cm and 20 cm to ensure a significant contrast in hydrologic behaviors and landslides.

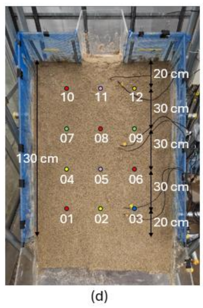
We selected Yahagi sand, with most of the grains having a diameter of 0.1 mm to 2.0 mm (D_{50}: 0.84 mm, D_{10}: 0.27 mm), to test the landside in granite geology. Using sand as a soil sample allows for controlled, reproducible conditions, especially to get similar density conditions for each sample, as coarse-grained material is less affected by water content. Three samples were used to measure the soil density at a 10 cm thickness, while six samples were utilized for the 20 cm thickness. The mean density of soil was 1.37 g/cm^3 (SD: 0.08) for 10 cm depth and 1.33 g/cm^3 (SD: 0.04) for 20 cm depth soil.

Thirty-two 0.8 mm water spray nozzles were placed at 1.4 m above the lower edge of the hillslope to simulate rainfall. An average flow rate of 1.9 L/min replicating a rainfall of approximately 90 mm/h. Volumetric water content (VWC) was monitored using the soil moisture sensor (Onset S-SMC-M005) at depths of 3 and 7 cm for the 10 cm sand sample and at 5, 13, and 17 cm for the 20 cm sand sample, with 1-minute intervals (Fig 1b). Runoff was measured using a 50 mL tipping bucket connected with an Onset event pendant logger. Twelve deformation markers were placed on the soil slope surface (Fig 1d). We recorded video from the front of the flume setup and captured 0.5-second time-lapse images from above to measure the deformation (Fig 1a). The experiment was replicated three times for each soil thickness, resulting in a total of six experiments in this study.

Thickness	soil used	ρ_d (gr/cm^3)	n
10 cm	Yahagi sand	1.23	0.532
20 cm	Yahagi sand	1.20	0.537







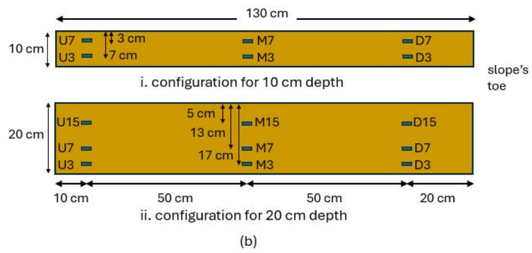


Figure 1 (a) Flume experiment set-up, (b) soil moisture installation location, (c) detail of net installation at initiation segment, (d) marker beads spacing.

3. Results

At a 10 cm soil depth, initial crack occurred at centre of the top part of the slope 7.0 min (SD: 0.9) after rainfall was started. Mean VWC of hillslope at the first crack was 0.065 m^3/m^3. The saturated zone began from the bottom of hillslope after an average of 16.7 (SD: 3.5). Landslide occurred after 20.5 min (SD: 9.7) with mean VWC of 0.186 m^3/m^3. Landslide occurred with mean landslide areas of 0.57 m^2 (SD: 0.1). Nonetheless, the second test did not result in a landslide, possibly due to the high density of the soil sample (ρ_d: 1.3 g/cm^3) alter soil hydrologic properties. Estimated saturated areas were 147.6 cm^2 (SD: 122.2), extend for 22.3 cm (SD: 21.7) in length. Runoff rate prior to collapse ranged from 10.5 to 14.5 L per 10 min. The total runoff was 14.8 m^3 (SD: 10.5) with storage capacity at 65.3% (SD: 7.3%).

For the 20 cm depth, first crack occurred after 9.3 min (SD: 1.2) at the slope's top center. Mean VWC of hillslope at the first crack was 0.082 m^3/m^3. Then landslides occurred after 30.7 min (SD: 15.9). Landslide area of 1.10 to 1.23 m^2 (mean: 1.18 m^2, SD: 0.1) moved entire hillslope with mean VWC of 0.185 m^3/m^3. The saturated zone began to form after 18.5 min (SD: 0.7). The saturated zone area is 167.9 cm^2 (SD: 97.2), extend for 32.3 cm (SD: 5.1) in length. Runoff flow before landslides ranged from 8.5 to 9.5 L per 10 min, with the total runoff volume of 13.0 m^3 (SD: 9.3). Estimated soil storage capacity was 72.0 % (SD: 17.6).

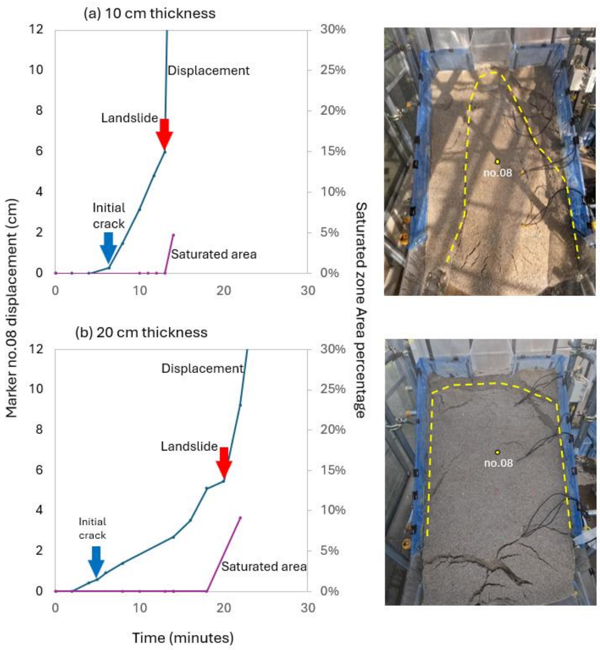


Figure 2 Alteration of slope surface displacement (marker no. 08) to saturated area development.

4. Discussion

Our study revealed soil depth affected the internal hydrological processes and resultant soil volumetric water for landslides occurences. Development of saturated area was 1.1 times slower, resulting in 1.5 times longer delay in landslide initiation. These findings differed to the previous study by Sammori et al. (1995), who found that the increases in soil depth from 20 cm to 60 cm delayed landslide time from 13 to 49 min using sandy soil (most of the grains having a diameter of 0.1 to 1.0 mm, D_{50}: 0.32 mm, D_{10}: 0.14 mm ρ_d: 1.3 g/cm^3). Our different responses may associate with soil particle size distribution. Soils with larger particle sizes have large pore spaces between particles, allowing water to infiltrate and percolate through the soil more rapidly (Mazaheri and Mahmoodabadi, 2012).

We also revealed the depth affected the size of landslides because the depth of soil affected the development of saturated areas and saturated length between soil and flume surface. The longer the saturated area persists, the more extensive the affected area becomes, contributing to the potential size of a landslide. These findings agreed to the findings by Bellugi et al. (2021).

5. Conclusion

Our findings showed that incorporating soil depth into landslide prediction models is essential for improving the timing and size of landslides. Therefore, methods for measurement of soil depth, such as soil probes or penetrometers and geophysical methods, need to be incorporated for estimating soil depth in the field and GIS.

6. References

Acharya, G., Cochrane, T. A., Davies, T., & Bowman, E. (2009). The influence of shallow landslides on sediment supply: A flume-based investigation using sandy soil. Engineering Geology, 109, 161–169.

Bellugi, D. G., Milledge, D. G., Cuffey, K. M., Dietrich, W. E., & Larsen, L. G. (2021). Controls on the size distributions of shallow landslides. Proceedings of the National Academy of Sciences, 118, e2021855118.

Bordoni, M., Meisina, C., Valentino, R., Lu, N., Bittelli, M., & Chersich, S. (2015). Hydrological factors affecting rainfall-induced shallow landslides: From the field monitoring to a simplified slope stability analysis. Engineering Geology, 193, 19–37.

Cogan, J., & Gratchev, I. (2019). A study on the effect of rainfall and slope characteristics on landslide initiation by means of flume tests. Landslides, 16, 2369–2379.

Mazaheri, M. R., & Mahmoodabadi, M. (2012). Study on infiltration rate based on primary particle size distribution data in arid and semiarid region soils. Arabian Journal of Geosciences, 5, 1039–1046.

Sammori, T., OHKURA, Y., Ochiai, H., & KITAHARA, H. (1995). Effects of Soil Depth on Rain-induced Landslide. 砂防学会誌, 12–23.

Sidle, R. C., & Bogaard, T. A. (2016). Dynamic earth system and ecological controls of rainfall-initiated landslides. Earth-Science Reviews, 159, 275–291.

Sidle, R. C., & Ochiai, H. (2006). Landslides: Processes, prediction, and land use. American Geophysical Union.

Tufano, R., Formetta, G., Calcaterra, D., & De Vita, P. (2021). Hydrological control of soil thickness spatial variability on the initiation of rainfall-induced shallow landslides using a three-dimensional model. Landslides, 18, 3367–3380.

Yamashita, K., Hattanji, T., Tanaka, Y., Doshida, S., & Matsushima, T. (2017). Topographic characteristics of rainfall-induced shallow landslides on granitic hillslopes: A case study in Hofu City, Yamaguchi Prefecture, Japan. Tsukuba Geoenvironmental Sciences, 13, 23–29.

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