Evaluation of the influence of the soil-bedrock interface and physical properties of soil in the landslide prediction model

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1. INTRODUCTION

Landslides are natural hazards that have the potential to exert either an extreme impact on humans and/or the natural environment (Sidle et al., 2021). Prediction models is a tool used to reduce the negative impacts caused by landslides. Landslide susceptibility assessment methods can be classified into qualitative (inventory-based and knowledge driven methods) and quantitative (data-driven methods and physically based models), (Coraminas et al., 2014). Physically based models attempt to replicate soil behavior in nature and are useful for many aspects for understanding processes and characteristics of landslides.

Many prediction models have been proposed since the 1980s, models incorporating a wide variety of parameters have been developed. Some physically based models, such as SHALSTAB (shallow landsliding stability model - Montgomery and Dietrich, 1994) and SINMAP (stability index mapping - Pack et al., 1999) have been applied to shallow landslides. SHALSTAB and SINMAP consider a simple steady-state hydrogeological process under constant rainfall. This means that both models are used to predict a spatially distributed slope stability (Chae et al., 2017). Despite the advancement of model, models assumed that steady-state description of hydrological fluxes and the adoption of the hydraulic gradient equals the slope of the terrain.

Soil depth and hydrological gradient varies spatially depending on the topographic characteristics and long-term geomorphic processes. Liang and Uchida (2014) showed that soil depth was shallower in valleys and deeper on hillslopes in an intensively measured site in Hiroshima, Japan, where soil depth on some hillslopes are > 3.5 m. In contrast, Ho et al. (2012) found that soil depth ranged from 0.4 to 2 m within the 26.5 km² Tung-An watershed, Taiwan, where thin soils occurred along narrow ridges and thick colluvium accumulated in valley bottoms. Hence, these models do not consider the spatial variability of soil characteristics such as soil depth and soil hydrological conditions. Although detailed surface topographic data can usually be readily obtained from DEMs, the soil depth and hydraulic properties for an entire hillslope or catchment are often lacking (Kim et al., 2015).

Combination of topography and soil thickness need to be included in the physical model because it increases the current capacity to determine the moment and areas of initiation of landslides. In this research, we showed entry conditions are obtained by a field survey and laboratory analysis and is restricted to only those that can be obtained, and the water table level is considered stationary. Therefore, objective of this study is measure the depth of the soil and its properties and establishes the influence of the spatial distribution of these parameters in the modeling processes. For achieving the objective, we will use H-SLIDER (Hillslope scale shallow landslide-induced debris flow risk evaluation method) developed by Public Works Research Institute, Japan (Uchida et al., 2009).

2. METHODOLOGY

We used H-SLIDER because this approach has the advantage of being driven by field survey and have adequacy for analyzing landslide because they predict critical rainfall data that occurring shallow landslide. H-SLIDER model can be useful for evaluating shallow landslides caused by rainfall. H-SLIDER is based on the infinite slope form of the Mohr-Coulomb failure law expressed by the ratio of stabilizing forces (shear strength) to destabilizing forces (shear stress) on a failure plane parallel to the ground surface (Uchida et al., 2009). H-SLIDER method is a distributed model that restricts entry conditions to those that can be captured by on-site inspection. Even if a hydrological model assuming a steady state and stability analysis of an infinite slope are used, the location of surface collapse can be predicted with considerable accuracy by appropriately inputting field conditions such as measuring the spatial variability of soil layer thickness. Assuming that: (1) steady state (2) groundwater flow follows Darcy's law (3) surface collapse occurs when the safety factor becomes 1.0 in the infinite slope stability analysis, and (4) erosion due to groundwater will not occur, the minimum rainfall intensity (r_c) at which surface collapse may occur is calculated:

$$r_c = \frac{K_s \tan\emptyset \cos\theta \,\{c\, \gamma_t\, h \cos\theta\, (sin\theta - \cos\theta\ \tan\emptyset)\}}{A\,\{\gamma_w\ \cos\theta\ \tan\emptyset + (\gamma_{sat} - \gamma_t)(sin\theta - \cos\theta\ \tan\emptyset)\}} \quad [1]$$

Where, r_c = critical steady-state rainfall intensity required to cause landslide, θ = Slope angle (°); A = Catchment area (m²/m); h = Soil layer thickness (cm); c = Soil cohension (kN/m²); $\emptyset$= Friction angle (°); K_s = Saturated hydraulic conductivity of soil layer (cm/s); γ_{sat} = Unit volume weight of soil layer at saturation (kN/m³); γ_t = Unit volume weight of soil layer at unsaturated (kN/m³); γ_w = Unit volume weight of water (kN/m³). Thus, the critical steady-state rainfall intensity required to cause landslide r_c is calculated by Equation-1.

We applied H-SLIDER model to a 6.4 ha sub-catchment (131°33'E and 34°05'N) of the Tsurugi basin in the northern part of Hofu City, Yamaguchi Prefecture, Japan. On July 21, 2009, many shallow landslides occurred in this region, which triggered debris flows. Eight of these shallow landslides occurred in the study catchment. The landslides initiated in a narrow altitudinal band from 200 to 230 m a.s.l. The landslides and debris flows were triggered by 24 h rainfall of 275 mm, with a maximum hourly rainfall of 63.5 mm measured at the Hofu rainfall observatory 5 km from the study area.

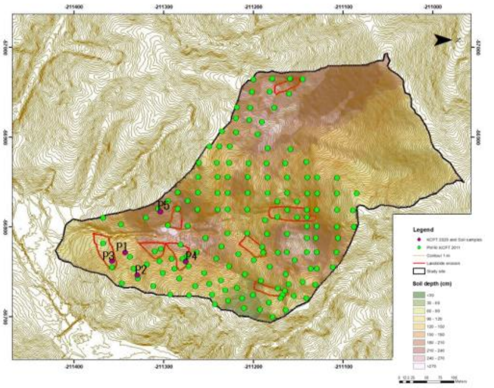


Figure 1: Soil depth distribution map of study area.

We developed methods for analyzing depth of soil-bedrock interface and soil properties using the Knocking Cone Penetration Test (KCPT). Soil depth data measured using KCPT were conducted at intervals of about 10–15 m in 2011 (two years after the disaster) and at 151 points, 27 of which were inside the collapsed area. Thus, the point density became 0.0023 point/m^2. Moreover, on February 2020, five soil pits were selected in the study site: three outside the collapsed zone and two inside the collapsed zone and soil samples were collected as undisturbed samples at 10 to 100 cm depth intervals for obtaining specific weight of the saturated soil, specific weight of the unsaturated soil and soil-saturated conductivity. The friction angle and cohesion were extracted by Public

Works Research Institute in 2010. Topography was measured using a 5-m digital elevation model (DEM) of the ground surface using the after disaster LIDAR data. Then, we used an interpolation by cone penetration tests to calculated the soil depth distribution (Figure 1). Also, we calculated the Slope angle and Catchment area using the D-infinity Flow Direction method, (Tarboton, 1997).

The minimum rainfall intensity occurring at steady-state collapse (r_c) of each (151) mesh in the study area was calculated from Eq. (1). The model begins with the loading of the elevation and landslide map. The next step was the analysis of the topographic data. In this step, the elevation raster was worked to remove the sinks and plans and calculate the upslope area and slope area. The soil depth was reported by raster files. In fact, hydraulic conductivity and soil resistance are considered to vary spatially on slopes. On the other hand, in this study, the values were constant within the target area, which depend on the measurement density of the thickness of the soil layer. After all these analyzes, the result of the H-SLIDER is the critical rainfall intensity (r_c) required for the collapse, as an index to assess susceptibility to shallow landslides. According to Uchida et al. (2011), the grid cells with lower r_c values to be more susceptible to shallow landsliding, and those with higher r_c to be more stable, because the higher the r_c value was, the less frequent would be the occurrence of a rainfall event sufficient to cause shallow landsliding.

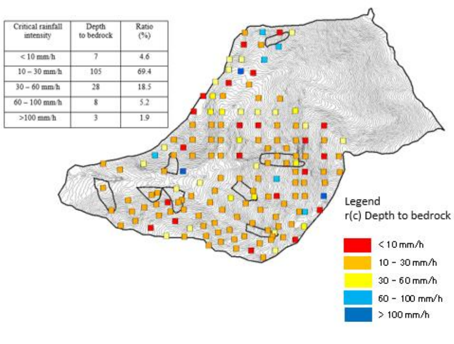
3. RESULTS AND DISCUSSION

3.1) Parameters setting

The measured soil thickness based on the Nc < 30 criteria in the five profiles ranged from 0.5 to 1.8 m. Based on KCPT, depth of soil-bedrock interface ranged from 0.3 to 3.3 m, with thin soils along narrow ridges and thicker soils accumulated at backslope and valley bottom. 25% of soil depth ranged from 0.6 to 0.9, while 10% of them was more than 2.0 m (Figure 1). Based on field pits and KCPT data in 2020, we confirmed that soil with Nc > 10 was presence of "saprolitic zone". This zone appears to exert a strong influence on vertical heterogeneity in these soil profiles. Based on soil analysis, we obtained the weight of the volume of the saturated unit γs: 14 kN/m³, the weight of the volume of the wet unit γt: 16 kN/m³, the saturated hydraulic conductivity K_s: 5E-02 cm/s and the weight of the volume of the water unit γw: 9.8 kN/m³. The internal friction angle was ø: 35°, soil cohesion was c: 6 kN/m² and the calculation was performed for each grid at intervals of 5 m.

3.2) Simulation results of H-SLIDER

Figure 2 shows the calculation result (r_c) distribution map in the study area. Unstable points were found in the 7 collapsed areas and in points adjacent in the study area. On the other hand, in the collapsed area without unstable points, the intensity of rain required for the minimum collapse in each collapsed area is 60 mm/h or more, which coincides with the actual maximum hourly precipitation (63.5 mm/h). Here, we found that 74% of the possible occurrences of shallow landslides were in the rainfall intensity of less than 30 mm/h and distributed evenly on the simulated area. Uchida et al. (2011) demonstrated the conditions of unconditionally stable and potentially unstable grid cells are strongly affected by the soil depth. They applied two soil thicknesses to shallow landslide prediction and the results showed that using bedrock soil thickness produced higher prediction results than when using weathered soil thickness. These results indicate that if we ignore the spatial variability of soil depth, the precision of distinguishing between unconditionally stable and potentially unstable grid cells becomes worse. For instance, Kim et al., 2015 applied the H-SLIDER model to the Republic of Korea, which is similar to our study site. Comparing with our results, they found that the results of the spatial distribution of simulated critical rainfall intensity (mm/h) based on the ground surface and bedrock surface using the distribution of weathered soil thickness from the knocking pole tests (Nc < 20) was ≈25% of the possible occurrences of shallow landslides were in the rainfall intensity of less than 20 mm/h and ≈60% of the possible occurrences of shallow landslides were in the rainfall intensity of more than 80 mm/h. These results indicate that the H-SLIDER can reproduce the relationship between the location of the surface collapse and the amount of rainfall intensity required to cause surface collapse.



Critical rainfall intensity	Depth to bedrock	Ratio (%)
< 10 mm/h	7	4.6
10 – 30 mm/h	105	69.4
30 – 60 mm/h	28	18.5
60 – 100 mm/h	8	5.2
>100 mm/h	3	1.9

Figure 2: Spatial variability of calculated critical steady state rainfall intensity (depth to bedrock).

4. CONCLUSIONS

The study presents the results obtained from the index for assessing shallow landslide susceptibility by implementing the H-SLIDER model. The results obtained showed less conservative values of critical rainfall intensity (r_c) in the small catchment area. The results showed that the use of KCPT to measure the spatial variability of the soil depth and the physical properties are very important to improve the performance of the model. As a future step, we will discuss the effects of topography and the average soil thickness and colluvium material to define better values in different geoenvironments.

REFERENCES

Chae, B., Catani, F., Simoni, A., Berti, M. (2017). Landslide prediction, monitoring and early warning: a concise review of state-of-the-art. Geosciences Journal. Vol. 21, No. 6, p. 1033-1070, December 2017 http://dx.doi.org/10.1007/s12303-017-0034-4 pISSN 1226-4806 eISSN 1598-747

Corominas, J., Van Westen, C., Frattini, P.., Cascini, L., Malet, J.P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M.G., Pastor, M., Ferlisi, S., Tofani, V., Herva, J., Smith, J.T. (2014). Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and the Environment 73:209–263 DOI 10.1007/s10064-013-0538-8 Montgomery, D. and Dietrich, W. (1994). A physically based model for the topographic control of shallow landsliding, Water Resour. Res.,30, 1153–1171, 1994.

Ho J-Y, Lee KT, Chang T-C, Wang Z-Y and Liao Y-H. (2012) Influences of spatial distribution of soil thickness on shallow landslide prediction. Engineering Geology 124:38-46. doi:10.1016/j.enggeo.2011.09.013

Kim, M.S., Onda, Y., Uchida, T., Kim, J.K. (2015). Effects of soil depth and subsurface flow along the subsurface topography on shallow landslide predictions at the site of a small granitic hillslope. Geomorphology, 271, 40-54.

Liang W-L and Uchida T. (2014) Effects of topography and soil depth on saturated-zone dynamics in steep hillslopes explored using the three-dimensional Richards' equation. Journal of Hydrology 510:124–136. doi:10.1016/j.jhydrol.2013.12.029

Montgomery DR and Dietrich WE. (1994) A physically based model for the topographic control on shallow landsliding. Water Resources Research 30:1153-1171. doi:10.1029/93wr02979

Pack, R. T., Tarboton, D. G., and Goodwin, C. N. (1998). Terrain Stability Mapping with SINMAP, technical description and users guide for version 1.00. Report Number 4114-0, Terratech ConsultingLtd., Salmon Arm, B.C., Canada, 1998.

Sidle, R.C. (2021). Module 1 - Introduction to Natural Hazards and Concepts of Risk and Vulnerability. Introductory course: Natural Hazards and Risk Management in Mountain Regions. University of Central Asia, February 2021. 67p.

Tarboton, D.G. (1997): A new method for the determination of flow directions and upslope areas in grid digital elevation models, Water Resources Research, Vol.33, pp.309-319.

Uchida, T., Mori, N., Tamura, K., Takiguchi, S., Kamee, K. (2009). The role of data preparation on shallow landslide prediction. Journal of Japan Society of Erosion Control. Eng. 62, 23–31 (in Japanese).

Uchida, T., Tamur, K., Akiyama, K.(2011). The role of grid cell size, flow routing Algorithm and spatial variability of soil depth on shallow landslide prediction. Italian Journal of Engineering Geology and Environment. http://dx.doi.org/ 10.4408/IJEGE.2011-03.B-018.