学 位 論 文 要 旨

Evaluating catchment-scale soil depth characteristics for improvement of landslide prediction model

斜面崩壊予測モデルの改良に向けた集水域スケールの土壌深度特性の評価

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Landslides have been causing serious damage to society and environment. Occurrence of landslides have been increased because of extreme climate conditions. For instance, the number of landslides from 1968 to 2020 years in Japan is about one thousand per year on average. In Brazil, number of landslides occurred from 1966 to 2020 years was 100 per year on average. Because rapid economic growth and population development in Brazil, land use changes in steep terrain causes much more damage of natural hazards such as landslides, debris flow, and landslide dam formation. Consequently, economic loss, properly and infrastructure damage and number of fatalities has been evaluated. Thus, understating the occurrence and predicting landslides is one of key components for developing appropriate land use planning and zonation of natural hazard area for sediment control structures and evacuation practices.

Soil depth is one of important characteristic to understand the occurrence of landslides and prediction of landslides because it controls subsurface flow paths and water holding capacity. In addition to soil depth, soil proprieties such as bulk density, hydraulic conductivity and soil particle size distribution alter movements of water within the soil matrix. Thus, both soil depth and soil physical properties are key factor for improving the predictability of landslides. Hence, soil properties are not fully incorporated into the most of prediction model of landslides. Furthermore, soil depth and soil properties can be spatially differed depending on the long term weathering processes and gravitational deformation and movement of soils. For overcome the problems, development of methodology for examining the spatial variability of soil depth and properties is essential. Given the importance of soil depth and the distribution of soil properties on hydrogeomorphic processes that affect landslide initiation, this study was consisted by (1) examining soil characteristics such as soil depth distribution and physical properties and bedrock and soil interface, and (2) application of spatial variability of parameters for improving a numerical landslides model.

For examining the spatial variability of soil depth and soil physical properties, field investigation was conducted in a 6.4-ha small catchment of the Tsurugi basin in the northern part of Hofu City, Yamaguchi Prefecture, Japan. On July 21, 2009, shallow landslides with 70.8/ km^2 in density was occurred mostly area with granite. Eight of these shallow landslides occurred within the study catchment with 0.2 to 2 m depth ranging from 200 to 230 m interval in elevation. Soil depth data measured using Knocking Cone Penetration Test (KCPT) with 10–15 m interval in 2011 and at 151 points (Density: 0.0023 point/m^2). Additional KCPT and soil pits and soil samplings were conducted in five soil profiles in 2020. At five soil profiles, soil samples with 5 cm interval in depth were collected as disturbed samples from surface to 2 m in depth for measuring bulk density, water content and particle size. Other samples were collected as undisturbed samples using a 100 cc cylinder for measuring saturated hydraulic conductivity. The hydraulic conductivity test was performed for at 3 different depths (≈ 0.1, 0.5 and 1.0 m) using, in the laboratory, falling head method.

Based on the data by soil profiles and KCPT data, three soil layers was identified. Number of knocks for penetration (Nc) was used as indicator of the hardness of soil. Layer I was topsoil and subsoil or availability colluvium material in soil matrix with Nc value less than 10, while Layer III was the hardest soil with Nc value more than 30 indicating soil-bedrock interface. Layer II with Nc value ranging from 10 to 30 was weathered layer with the moderate hardness including rocks and boulders between mineral soil. Mean soil depth defined as Nc < 30 within the entire catchment was 0.90 m ranging from 0.30 to 3.00 m. The depth of weathered soil layer (Layer II) ranged from 0.15 or less to 0.75 m or more. Deep weathered soil layer with 0.60 m and 0.75 m or more in depth was located at ridge line and upper dissected slopes within the catchment and, while thin weathered soil with 0.15 m or less and 0.30 m in depth was located at valley bottom. Weathered soil layer (mean thickness: 0.35 m) had low saturated hydraulic conductivity (10^{-3} cm/s), likely inducing a hydrological discontinuity in the soil and affect the stability of hillslope.

Spatial variability of soil depth and properties was incorporated into H-SLIDER model (Hillslope scale shallow landslide-induced debris flow risk evaluation) developed by Public Works Research Institute, Japan. This analysis permits for understanding how soil depth and its proprieties affects landslides occurrence as well as which area is sensitive for the potential occurrence of landslides within a small catchment. The spatial distribution of critical steady-state precipitation r_c for initiation of landslides was used as an indication for susceptibility of landslides using H-SLIDER model. Under low rainfall amounts, grid cells with lower r_c values denote areas unstable for shallow landslide while those with higher r_c values indicate stable areas. Catchment area and slope angle were calculated based on a 5-m digital elevation model (DEM) of LiDAR data. For testing the effects of soil properties of soil, two scenario of soil properties and depth with (1) mean properties of total soil with 0.30 and 3.00 m in depth were applied, and (2) properties of weathered soil with 0.15 and 0.75 m in depth. r_c with case (1) and case (2) tended to be correlated to each other, while some outlier occurred. r_c values with case (2) > case (1) suggested low probability of landslide which occurred at upslope area within catchment. r_c value with case (2) < case (1) suggested that high probability of landslide. Because thick weathered soil layer with 0.60 and 0.75 m or more in depth caused slow water movement and developed water table for elevating the probability of landslides.

Finding of this study showed that measuring spatial variability and soil discontinuities and their thicknesses to improve the performance of landslide prediction models. The applicability of this research can be translated into a guideline to support the decision-making of public managers and professionals who work by promoting identification, prevention and recovery actions in the management of disaster risks. It is expected that countries with a high number of natural hazards per year, especially related to landslides, such as Brazil and Japan, consider adopting this approach to improve their practices.