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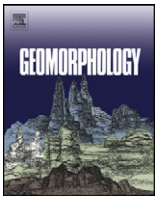

Effects of soil depth and subsurface flow along the subsurface topography on shallow landslide predictions at the site of a small granitic hillslope

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ABSTRACT

Shallow landslides are affected by various conditions, including soil depth and subsurface flow via an increase in the pore water pressure. In this study, we evaluate the effect of soil depth and subsurface flow on shallow landslide prediction using the shallow landslide stability (SHALSTAB) model. Three detailed soil depth data—the average soil depth, weathered soil depth, and bedrock soil depth—were collected using a knocking pole test at a small hillslope site composed of granite in the Republic of Korea. The SHALSTAB model was applied to a ground surface topographic digital elevation model (DEM) using the three soil depths and upslope contributing area (SCA) assuming subsurface flow calculated from four DEMs: a ground surface topography (GSTO) DEM, weathered soil topography (WSTO) DEM, bedrock topography (BSTO) DEM, and low-level bedrock topography (EBSTO) DEM. The model performance was measured using a receiver operating characteristic (ROC) analysis. While evaluating the effect of the soil depth with SCA using GSTO DEM, it was found that the bedrock soil depth had higher prediction accuracy compared to that of the average soil depth or weathered soil depth. To evaluate the saturated subsurface flow between the soil and bedrock, SCAs calculated using WSTO and BSTO DEMs were applied. From these simulations, we found that SCA from BSTO DEM and the bedrock soil depth affect the shallow landslide prediction; however, these prediction effects are not significantly increased by large differences in the elevation (between the lowest and highest elevation values). Therefore, we considered the influence of the bedrock depression and SCA from EBSTO DEM. In applying SCA from EBSTO, the prediction accuracy was significantly increased compared to the other predictions. Our results demonstrate that the influence of the bedrock topography on the prediction of shallow landslides may be particularly significant at the scale of a hillslope.

1. Introduction

Shallow landslides are one of the most common geomorphological processes, occurring over large areas and in different soils in various climatic zones (Kirkby, 1987; Benda and Cundy, 1990; Selby, 1993; Antronico et al., 2004; Borrelli et al., 2015a,b; Cascini et al., 2015). They can cause environmental and economic damage in locations worldwide depending on the intensity and duration of the rainfall (Caine, 1980; Crozier, 2005; Glade et al., 2005; Guzzetti et al., 2007, 2008; Cascini et al., 2015). Shallow landslides have different morphometric features depending on their localization along the slope and have widths ranging from 3 to 15 m and lengths ranging from 10 to 100 m. The sliding surface can reach depths varying from a few centimeters to 3 m (Rogers and Selby, 1980; Gullà et al., 2004; Crozier, 2005; Cascini et al., 2015).

The spatial distribution of the soil depth is controlled by complex interactions of multiple factors, such as topography, parent material, climate, and chemical and physical processes (Borrelli et al., 2007; Pelletier and Rasmussen, 2009; Nicótina et al., 2011; Lanni et al., 2012). Soil depth is a particularly important input parameter in hillslope hydrology (Tromp-van Meerveld and McDonnell, 2006); however, its estimation is often overlooked in landslide literature, where a soil of uniform depth is often assumed to overlie an impermeable bedrock (Lanni et al., 2012).

Recent hillslope hydrology studies considering subsurface flow processes occurring during shallow landslides have shown that subsurface topography has a strong impact on controlling the connectivity of saturated areas at the soil–bedrock interface (e.g., Freer et al., 2002; Uchida et al., 2011; Lanni et al., 2013). Because subsurface flow in steep forested hillslopes plays an important role in stormflow generation, the landslide

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slip surface can also be strongly affected by its relationship with the pore water pressure and the bedrock surface topography (e.g., Hewlett and Hibbert, 1963, 1967; Anderson and Burt, 1978; Onda et al., 2004; Uchida et al., 2005).

In addition, several studies have identified topography as being a significant factor in subsurface flow (e.g., Anderson and Burt, 1978; McDonnell, 1990; Onda et al., 2004; Uchida et al., 2011; Lanni et al., 2013). Both field studies (e.g., Freer et al., 2002; Onda et al., 2004; Tromp-van Meerveld and McDonnell, 2006) and numerical studies (e.g., Hopp and McDonnell, 2009; Lanni et al., 2012) have shown that subsurface topography has a strong impact on the connectivity of saturated zones at the soil–bedrock interface and the timing and positioning of shallow landslide initiation.

For shallow landslide predictions, increasingly complex shallow landslide occurrence processes have been incorporated into physically based models to predict the spatial patterns of the shallow landslide susceptibility (e.g., Hiramatsu et al., 1990; Wu and Sidle, 1995; Rosso et al., 2006; Talebi et al., 2008; Uchida et al., 2011), such as SHALSTAB (Montgomery and Dietrich, 1994), SHETRAN (Ewen et al., 2000), GEOtop FS+ (Simoni et al., 2008), TRIGRS (Baum et al., 2010), and H-slider (Uchida et al., 2011).

In these shallow landslide models, a topographic wetness index, defined by the ratio between the specific upslope contributing area and the local slope, is used as a surrogate for the lateral subsurface flow processes. In general, most models use a digital elevation model (DEM) of the ground surface to compute the steady-state wetness index (Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Pack et al., 1998) or a “quasi-dynamic” wetness index (Barling et al., 1994; Borga et al., 1998; Casadei et al., 2003), where it is assumed that the specific upslope area derived from the surface topography is a surrogate measure of the subsurface flow in response to a rainfall event of a specified duration. The subsurface flow paths (i.e., the drainage directions) are then derived from the DEM analysis, and the land surface slope is used as a substitute for the slope of the subsurface hydraulic gradients (Lanni et al., 2013).

The slope stability component (i.e., the infinite slope stability model) uses this topographic index to analyze the stability of each topographic element. While hydrological models have been coupled to infinite slope stability models (Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Pack et al., 1998; Borga et al., 2002; Casadei et al., 2003; Uchida et al., 2011), nearly all such models assume that the soil–bedrock interface is a simple topographic surface paralleling the soil surface.

However, saturated and unsaturated water movements on hillslopes or catchments are affected by topography, soil depth, and hydraulic properties in a complex manner. These properties serve as input data for numerical simulations and have significant implications for the simulation's accuracy; however, the effect of the flow path at different soil depths on the slope stability is not clearly understood (Schmidt et al., 2001). As many researchers have observed, the soil depth and subsurface flow are very important in shallow landslide predictions.

Therefore, the aim of this study was to investigate (1) the impact of the three soil depths and (2) the effect of the subsurface flow at the weathered soil layer and at the bedrock interface on shallow landslide predictions. To determine the soil depth, we used a knocking pole test in a small study area in Korea, and two high-resolution soil depth data sets were collected.

2. Study area

The specific hillslope study area was located in the Jinbu-Myeon, Pyeongchang-gun, Kangwon Prefecture in the Republic of Korea and has a subtropical climate with year-round precipitation. The average annual precipitation from 1978 to 2008 was 1400 mm. The rainfall occurs primarily in the summer season (June–September) as a result of the East Asian monsoon, during which time the territory of Korea is also

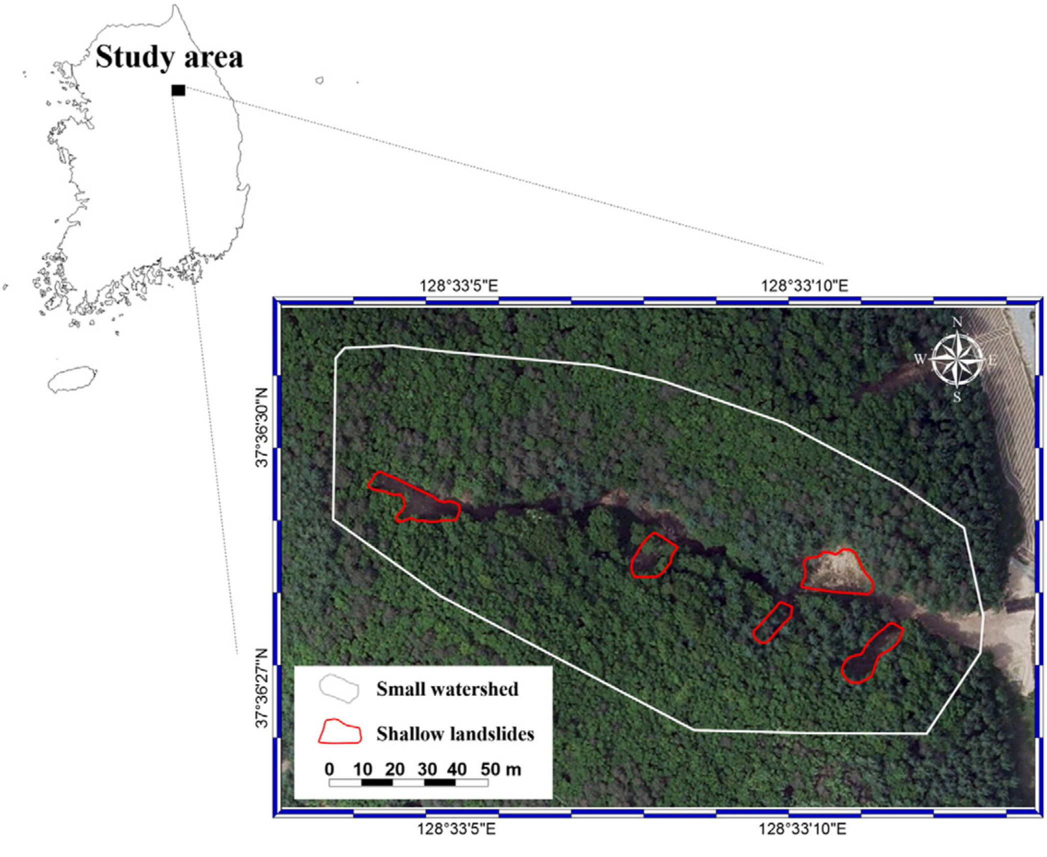

Fig. 1. Location of the study site in South Korea.