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Effect of seepage on shallow landslides in consideration of changes in topography: Case study including an experimental sandy slope with artificial rainfall

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A R T I C L E I N F O

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A B S T R A C T

Many studies on shallow landslides have focused on seepage mechanisms. However, most of these studies assumed that the hillslope was parallel to the seepage direction and force; they did not consider how the seepage was changed by the topography during failure. To investigate the seepage mechanism, particularly the influence of the topographic change during failure, flume experiments using a 30° sandy slope were performed with artificial rainfall. The factor of safety (FS) equation, which considers the seepage direction and force, and the numerical simulation were also applied to analyze the effect of topographic change on the seepage mechanism. The experiments were divided into two stages: rainfall-induced experiment (RIE) and seepage-induced experiment (SIE) with rainfall. In the RIE with a rainfall intensity of 80 mm/h, seepage erosion occurred followed by undercutting, which resulted from seepage erosion, to upward direction of sandy slope. The analysis of FS in RIE are showing an instability when seepage direction is be a slope parallel with theoretical value, i (*Hydraulic gradient*). In the numerical model, when topographic changes of the surface of the sandy flume were applied, seepage flow concentrated from failure surface of the toe of flume to middle part of flume, which is affected by saturation. In SIE, multiple failures caused by the seepage in the vertically upward direction occurred with a high seepage force, and the failure mass then moved in the downward direction with the seepage flow. FS for SIE showed a high instability than those of RIE when seepage direction with high force already changed from vertically downward seepage flow to increasing slope parallel seepage flow. Applying changed topography (more deep from sandy flume surface) in numerical model is showing concentrated seepage flow at the bottom of failures. This is one of mechanism developing failure mass to downward direction to the toe of flume because soil moisture sensors installed near failures (25 cm-depth) show high value than porosity value, indicating soil mobilization. Therefore, the seepage direction and force play important roles in landslide mechanism, and these factors should be considered in landslide studies.

1. Introduction

Shallow landslides, which occur in the soil mantle due to extreme rainfall, have been studied for practical and scientific reasons. Since shallow landslides often mobilize into rapidly moving debris flows (Iverson, 1997), they can present hazards to human life, property, and activities (e.g., Godt et al., 2012; Keefer and Larsen, 2007; Sidle and Ochiai, 2006). For example, on July 16, 2006, the total amount of rainfall and the maximum rainfall intensity in Jinbu-myeon, which is underlined by granite (over 90% sand), in the eastern part of the Republic of Korea were approximately 500 mm/day and 80 mm/h, respectively. This area consists mostly of mountainous areas with slope > 30° and elevations range from 430 to 1390 m, with an average of 736.1 m.

This region suffered considerable damage, including loss of human life, collapsed embankments, and flooding caused by the transport of sediment by the shallow landslides (Fig. 1a). Owing to this rainfall event, over 1200 shallow landslides (Park et al., 2013) occurred around variable source areas and failed mass sediment flowed to downward direction along the valley. Additionally, groundwater flow was detected at the exposed bedrock of the toes of the shallow landslide and the upward extension of the head of ephemeral channel also was occurred (Fig. 1b).

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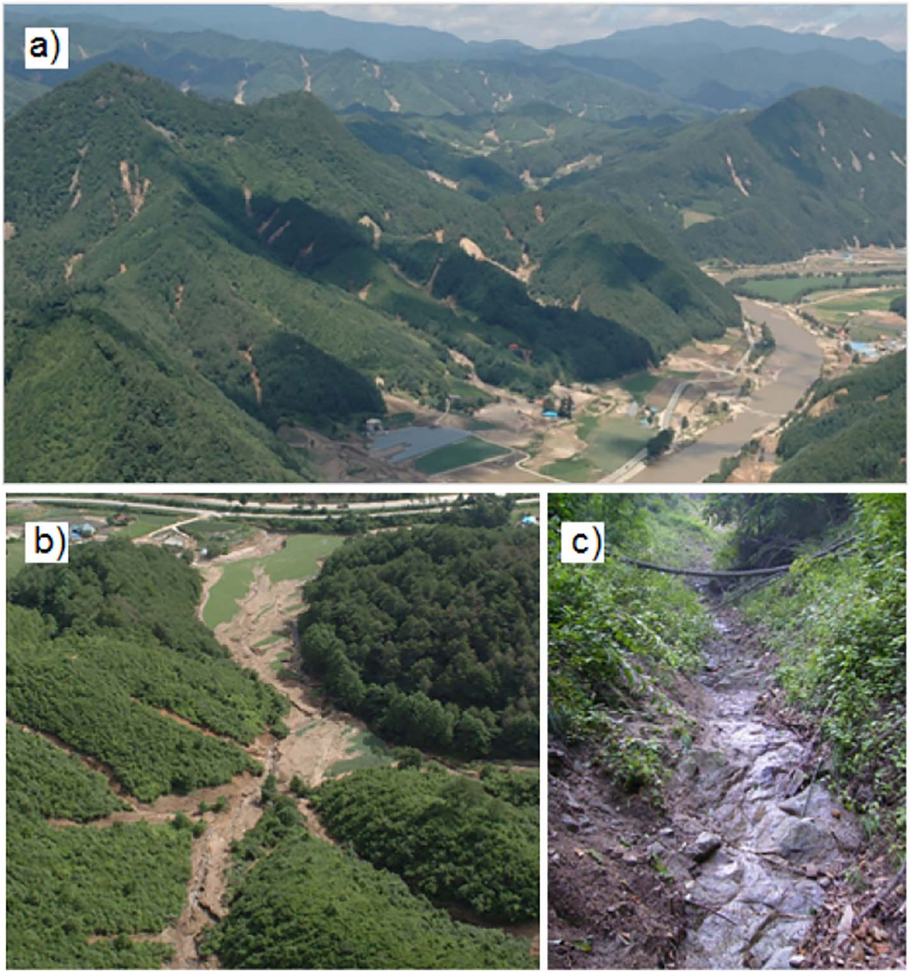

Fig. 1. Shallow landslide area in South Korea. a) Shallow landslide area in Jinbu-myeon, b) landslides occurred along the valley, c) the exposed bedrock.

To better understand landslide mechanisms, many researchers have applied various approaches such as flume experiment and numerical modeling to test specific hypotheses aimed at understanding the behavior of landslides, debris flows, and other geomorphic phenomena in many fields (Iverson, 2015). Previous studies on shallow landslides have shown that the movement of groundwater in the soil mantle markedly affects slope stability on steep slopes (e.g., Anderson and Sitar, 1995; Dunne, 1990; Fox and Felice, 2014; Iverson et al., 2000; Kosugi et al., 2008; Onda et al., 2004; Reid et al., 2008; Torres et al., 1998; Wang and Sassa, 2003). For example, Iverson and Major (1986) and Reid and Iverson (1992) showed that ascending subsurface flows at the toes of slopes or at geological boundaries are involved in the initiation of shallow landslides and subsequent debris flows. Reid et al. (2008) performed three types of large physical experiments under different water flow conditions (i.e., rainfall and groundwater inflow). They found that groundwater inflow and high-intensity sprinkling led to abrupt, complete failure, whereas moderate-intensity sprinkling led to retrogressive, partial failure. Ochiai et al. (2004) conducted an experiment with 80 mm/h of rainfall on a natural slope for 7 h and found that the landslide mass first slid, then fluidized, and finally transformed into a debris flow by the seepage.

Many researchers, however, have found that bedrock exfiltration may elevate groundwater levels and thereby play an important role in landslide triggering (e.g., Baum et al., 2005; Brand et al., 1986; Ebel et al., 2008; Jenkins et al., 1988; Ohta et al., 1981; Onda et al., 2004; Selby, 1993). Recent studies on shallow landslide initiation have suggested that the seepage mechanism (i.e., seepage force and direction) of the subsurface flow (e.g., bedrock flow and piping) may contribute substantially to the rapid transfer of storm water (e.g., Dunne, 1990; Fox and Wilson, 2010; Iverson et al., 2000; Kirkby, 1988; McDonnell, 1990; Mirus et al., 2007; Mosely, 1982; Tanaka et al., 1988; Tsukamoto and Ohta, 1988). Others have reported theoretically for the movement of soil particles within slopes in the presence of emerging subsurface flow (Chu-Agor et al., 2008; Fox and Wilson, 2010; Gabet and Dunne, 2002; Iverson and Major, 1986; Kochel et al., 1985; Kohno et al., 1987; Kosugi and Katsuyama, 2004; O'Loughlin and Pearce, 1976; Selby, 1993; Terajima and Sakura, 1993; Terajima et al., 1997, 2001; Terajima et al., 2014; Wu et al., 1979; Zaslavsky and Kassiff, 1965).

As indicated by many of these previous studies, the subsurface flow markedly affects shallow landslide initiation; however, they have just considered slope parallel subsurface flow. It is, therefore, important to consider the subsurface flow when attempting to understand the processes involved in the initiation of shallow landslides (Anderson and Sitar, 1995; Gabet and Mudd, 2006; Hewlett, 1961; Iverson, 1997; Terajima et al., 2014). Further experiments are needed to better understand subsurface flow such as change of seepage mechanism occurring shallow landslide initiation.

In the studies on effect of seepage mechanism for landslides, Crosta and di Prisco (1998) reported that the seepage direction can be changed due to failure and flow convergence can occur at the failure surface. Fox and Wilson (2010) pointed out that failure is the final result of a complex chain of events that occurs during a certain time period. Furthermore, Fox and Felice (2014) studied the seepage mechanism using a small experiment and numerical modeling. They found that the seepage leads to two commonly observed failure mechanisms in channel banks and hillslopes: (i) tension or “pop-out” failure and (ii) undercutting and eventual slope failure (Chu-Agor et al., 2008; Fox and Wilson, 2010).