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Study on mechanism of retrogressive slope failure using artificial rainfall

Ram Krishna Regmi [a,1], Kwansue Jung [b,*], Hajime Nakagawa [c], Jaewon Kang [a,1]

[a] International Water Resources Research Institute, Chungnam National University, Daejeon 305-764, Republic of Korea
[b] Department of Civil Engineering, Chungnam National University, Daejeon 305-764, Republic of Korea
[c] Disaster Prevention Research Institute, Kyoto University, Kyoto 612-8235, Japan

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ABSTRACT

Many slope failures have been observed in the mountainous environments of the world due to rainfall events. However, studies related to the correlation of rainfall intensity, sliding initiation time and the position of slip surface head are still lacking. Studies on the mechanisms of retrogressive slope failure that may occur in a series and the down-slope displacement of failure mass are also rare. In this study, slope failure experiments were performed using medium-grained silica sand S6 to prepare the model slope in a 5 m long, 30 cm wide and 50 cm deep rectangular flume. The experiments consisted of detailed observations of failure process consisting series of failures successively, with particular emphasis on the time of failure; shape, size and position of the slip surface; and final shape of the model slope after down-slope displacement of the failure masses. Moisture profiles at different points within the model slope soil domain and the profile of surface-water forefront were also reported. The observations showed that the slope failure initiating once at the region near the toe results in successive sliding failures in a series, thereby propagating an unstable zone toward the up-slope. When the slope failure initiates at the region toward the head reach, the successive failures may propagate toward the down-slope first, and then again toward the up-slope. This study also noticed a strong correlation between rainfall intensity, sliding initiation time and the position of its slip surface head. The relationship might depend on the shape and size of the model slope and the type of material used in the formation of the model slope. However, the results indicate the possibility of finding a relationship among rainfall intensity, sliding initiation time, and the position of its slip surface head in a natural slope failure prone zone. A landslide model test and application in real field, based on the similarity theory, may reveal the relationship more realistic. Then it would have a significant impact on policy making to mitigate the probable catastrophe during extreme rainfall-induced landslide disaster.

1. Introduction

The most common natural landslide-triggering processes include intense rainfall, rapid snow melt, water level changes in rivers or lakes at the foot of slopes, volcanic eruptions, and earthquakes (Wieczorek, 1996). However, intense rainfall is the most important trigger (Crosta and Frattini, 2008). In many mountain environments of the world, heavy rainfall and severe storms have caused many landslides and slope failures in a matter of seconds without warning. In a slope failure phenomenon, the slope collapses abruptly due to the weakened self-retainability of the earth under the influence of rainfall or an earthquake. If it occurs near the residential area, many people fail to escape and it results in higher fatalities. The impact of a landslide increases significantly with the velocity and the distance traveled. Slow and progressive movements are less dangerous to human life than sudden, rapid and intermittent movements. However, in either case, there is a large potential for damage to occur to infrastructure and property.

In general, rainfall-induced slope failures are caused by increased pore-pressure and seepage force during periods of intense rainfall (Anderson and Sitar, 1995; Sidle and Swanston, 1982; Sitar et al., 1992; Terzaghi, 1950; Wang and Sassa, 2003). The effective stress in the soil decreases due to increased pore-pressure, reducing the soil shear strength, and ultimately results in slope failure (Brand, 1981; Brenner et al., 1985). Slope failures occur as a result of rainfall events based on individual combinations of soil geometry, soil strength and infiltration parameters (Collins and Znidarcic, 2004). Many methodological approaches have been developed to reveal the occurrence of landslides in space and time, and to investigate processes acting within mass movements. However, the actual process of failure initiation is still not clear.

Sassa (1972, 1974) conducted a series of flume tests and concluded that the changes in rigidity of sand and the upper yield strain within a slope were essential to slope stability analyses. Fukuzono (1987) conducted an experiment to examine the conditions leading to slope failure

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[*] Corresponding author at: Department of Civil Engineering, Chungnam National University, 99 Daehangno, Yuseong-Gu, Daejeon, Korea 305-764. Tel.: +82 42 821 5675, +82 10 6327 2569 (Mobile); fax: +82 42 821 8994.
E-mail addresses: rkregmi@engineer.com (R.K. Regmi), ksjung@cnu.ac.kr (K. Jung).
[1] Tel.: +82 42 821 8958; fax: +82 42 821 8957.

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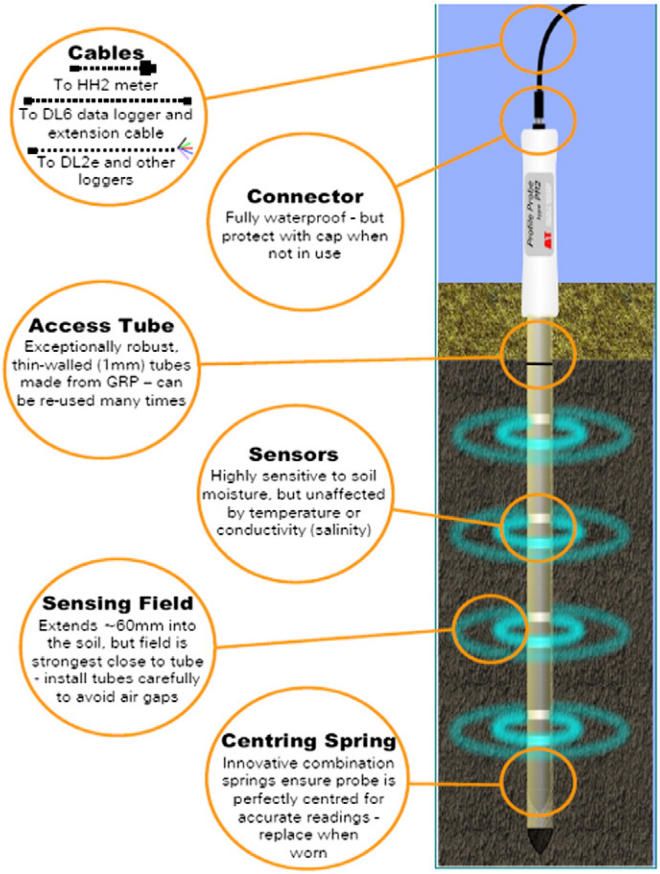

Fig. 1. Profile probe type PR2. (Image courtesy of Delta-T Devices Ltd, 2004).

using near-actual-scale slope models providing heavy rainfall. Crozier (1999) tested a rainfall-based landslide-triggering model developed from landslide episodes in Wellington, New Zealand, termed the ‘Antecedent Water Status Model,’ to predict landslide occurrence by providing a 24-h forecast. Tsai et al. (2008) developed a physical model using the complete Richards' equation that measures the effect of the slope angle and also adopted the extended Mohr–Coulomb failure criterion of Fredlund et al. (1978) to describe unsaturated shear strength. Mukhlisin and Taha (2009) developed a numerical model to estimate the extent of rain-water-infiltration into an unsaturated slope, the formation of a saturated zone, and the change in slope stability. Then, the model was used to analyze the effects of soil thickness on the occurrence of slope failure. Regmi et al. (2012) performed numerical simulations and flume experiments to investigate the mechanism of slope failure due to rainfall events. However, these works are not applicable to successive failures in a series and the down-slope movements of the failure mass that may occur on the slope.

A lot of landslide research has been analyzed and has monitored rainfall and slope hydrology as an important factor in landslide-triggering. Yagi and Yatabe (1987), Kitamura et al. (1999), Yokota et al. (2000) and Sasahara (2001) monitored pore-water pressure, soil suction, groundwater depth and slope deformation, at critical locations within a slope, as a basis for the prediction of slope failure. Groundwater conditions such as pore-pressures, soil-water suction and volumetric soil-water contents are usually measured by using piezometers, tensiometers and Time Domain Reflectometry (TDR). A considerable amount of research has been conducted under controlled laboratory conditions. Sassa (1984) conducted liquefied landslide experiments and showed that rapid increases in pore-pressure, due to localized subsidence, occur suddenly before a landslide is triggered. Okura et al. (2002) performed laboratory flume experiments and noticed the slope collapsing by volumetric compaction with shear, a rise in pore-pressure in the saturated zone and rapid shearing around the slip surface. Orense et al. (2004) and Tohari et al. (2007) conducted a series of laboratory experiments on model slopes and showed that slope failure is always induced when the soil moisture content within a certain region near the toe of the slope reaches nearly full saturation, even though other parts of the sliding mass are still in a partially saturated state.

Although a significant amount of studies have been conducted to investigate the mechanism of landslide and slope failure, a study related to the correlation of rainfall intensity, sliding initiation time and position of the slip surface head is still lacking. A study on the mechanism of slope failure that may occur in a series and the down-slope displacement of the

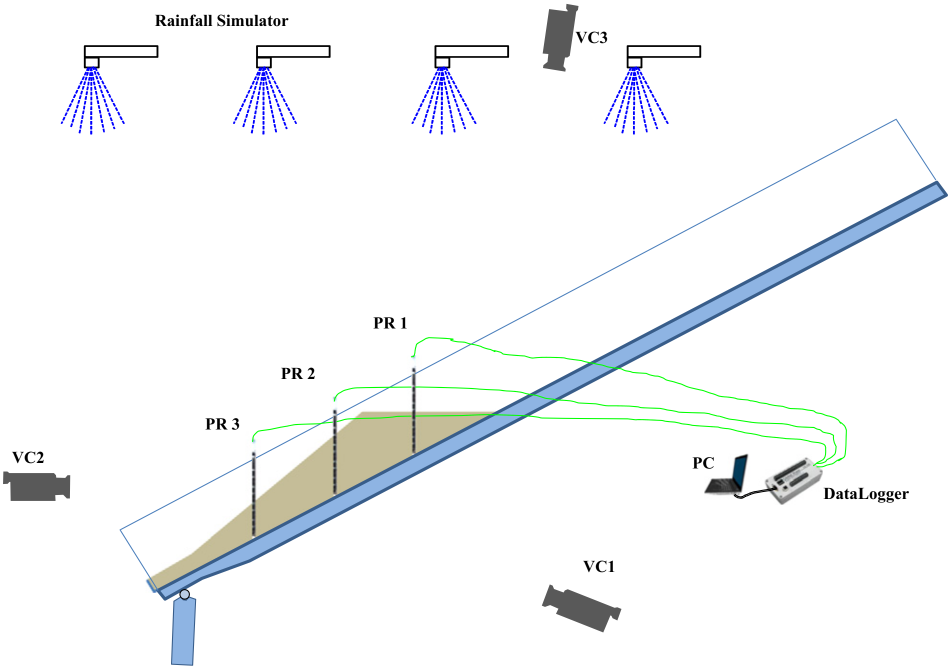

Fig. 2. Experimental setup in Ujigawa Open Laboratory, DPRI, Kyoto University, Japan.