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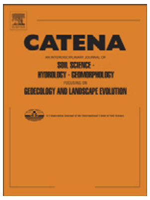

Numerical analysis of multiple slope failure due to rainfall: Based on laboratory experiments

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ABSTRACT

The investigation of mechanisms of multiple slope failure and the displacement of the resulting failure mass is highly important for the safety of the mountainous environments of the world. This study attempts to investigate such phenomena through numerical analysis. A one-dimensional (1D) surface flow and erosion/deposition model, a two-dimensional (2D) seepage flow model, a 2D slope stability model (the Spencer method of slope stability analysis), and a 1D sliding block model were combined as a single unit such that the developed model can also successfully analyze the surface water flow and erosion/deposition on the model slope soil surface, seepage-flow phenomena within the soil domain, and stability of the model slope during the movement of the sliding mass by updating the shape of the model slope according to the new position of the sliding mass. The Spencer method of slope stability analysis was incorporated into dynamic programming to predict the time of a slope failure and the shape of the failure surface. The data obtained from the numerical simulation results were compared with the experimental data obtained from Regmi et al. (2014) for validation. The application of the model in the real field would have significant impact for appropriate mitigation measures against probable disasters that may be caused by rainfall-induced landslides and slope failures.

1. Introduction

Extreme rainfall events have caused landslides and slope failures in mountainous environments worldwide. Increased pore pressure and seepage flow during periods of intense rainfall cause landslides and slope failures in general (Terzaghi, 1950; Sidle and Swanston, 1982; Sitar et al., 1992; Anderson and Sitar, 1995; Wang and Sassa, 2003). During rainfall, a wetting front moves downward into the soil, resulting in an increase in water content and an increase in pore pressure. The increase in pore pressure results in a decrease in effective stress, reducing the shear strength of the soil and ultimately resulting in landslide/slope failure (Brand, 1981; Brenner et al., 1985).

Various methodological approaches have been developed for the investigation of landslide and slope failure processes. A series of flume tests were conducted by Sassa (1972, 1974), and it was 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 using near-actual-scale slope models providing heavy rainfall to examine the conditions leading to slope failure. A rainfall-based landslide-triggering model was developed from landslide episodes in Wellington, New Zealand, termed the ‘Antecedent Water Status Model,’ to predict landslide occurrence by providing a 24-h forecast (Crozier, 1999). A physical model was developed using the complete Richards' equation, which measures the effect of the slope angle (Tsai et al., 2008), and the extended Mohr-Coulomb failure criterion of Fredlund et al. (1978) was also adopted to describe the unsaturated shear strength. A numerical model was developed to estimate the extent of rain-water infiltration into an unsaturated slope, the formation of a saturated zone, and the change in slope stability (Mukhlisin and Taha, 2009). Then, the model was used to analyze the effects of soil thickness on the occurrence of slope failure. Numerical simulations and flume experiments were performed by Regmi et al. (2012) to investigate the mechanism of slope failure due to rainfall events. However, these works are not applicable to multiple slope failures.

Tsutsumi and Fujita (2008) investigated several landslide sites and used physical experiments and numerical simulations with a combination of rainwater infiltration for their slope stability analysis, which was applicable to represent multi-stage failure. After a failure, the failure mass slides slowly down along a well-defined slip surface as long as

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the slope gradient is steep enough, and it stops sliding when it arrives at a flatter area. This mass also supports the remaining soil mass such that the remaining mass does not immediately lose its stability. However, in their analysis, they did not consider the presence of such a failure mass. In the stability analysis, they used Janbu's simplified method, which satisfies only the force equilibrium. However, it would be better to use a method that satisfies both force and moment equilibria to obtain more accurate results.

Regmi et al. (2012) performed numerical simulations and flume experiments to investigate the mechanism of slope failure due to rainfall events. A three-dimensional (3D) seepage-flow numerical model was coupled with a 2D surface-flow and erosion/deposition model for seepage analysis. Janbu's simplified 3D method of slope-stability analysis, as well as the extended Spencer method of slope-stability analysis, was incorporated into dynamic programming to locate the critical slip surface of a single failure event. However, these works did not examine the movement of the failure mass along the failure surface that may occur on the slope and probable multiple failures. Regmi et al. (2014) performed slope failure experiments consisting of a series of successive failures, with particular emphasis on the time of failure; the shape, size and position of the slip surface; and the final shape of the model slope after the displacement of the failure masses. However, numerical analysis of these phenomena is still lacking.

Several researchers have proposed physically based models, which correlate the movement of landslide masses along slip surfaces to one or more variables controlling the slide behavior. Hong et al. (2005) used a statistical approach to correlate the relationship between intense rainfall and landslide movement. Leroueil (2001) proposed a physically based model to take into account the complexity of the hydrological and mechanical responses of the soil for the movement of landslide masses along pre-existing slip surfaces due to rainfall-triggered pore pressure fluctuations. Calvello et al. (2008, 2009) developed a numerical model to predict the movement of landslide masses along pre-existing slip surfaces. The model is comprised of the following: a transient seepage finite-element analysis to compute the variations of pore-water pressures from rainfall; a limit equilibrium stability analysis to compute the factors of safety along the slip surface associated with transient pore pressure conditions; an empirical relationship between the factor of safety and the rate of displacement of the slide along the slip surface; and an optimization algorithm for the calibration of analyses and relationships based on the available monitoring data. Although the other researchers, besides Hong et al. (2005), used physically based model to evaluate the movement of landslide masses along pre-existing slip surfaces, their works are also not applicable for multiple failure.

If a landslide occurs due to the rise of the saturated zone, at least in the neighborhood of the slip surface, the void-rich soil structure will be destroyed, forming a liquefied layer (Takahashi, 2007). Suwa et al. (1985) emphasized the role of the liquefied layer beneath the landslide mass, categorizing it as a significant cause of its movement. Many authors (e.g., Iverson et al., 1997; Sassa, 1997; Hutchinson, 1988; Okura et al., 2002; Wang and Sassa, 2002; van Asch et al., 2006) discussed the importance of liquefaction within the saturated zone as the cause of the rapid motion of the landslide mass. The nature of the movement of landslide masses is essentially viscous (Savage and Chleborad, 1982; Leroueil and Marques, 1996; Corominas et al., 2005), and the displacement rate is related to the changing saturated zones, which affect the shear stress level along the slip surface. In such cases, Vulliet and Hutter (1988) stated that “the slope is neither still nor ruptured but simply moves.” They proposed several phenomenological relationships between the displacement rate and the shear stress acting along the slip

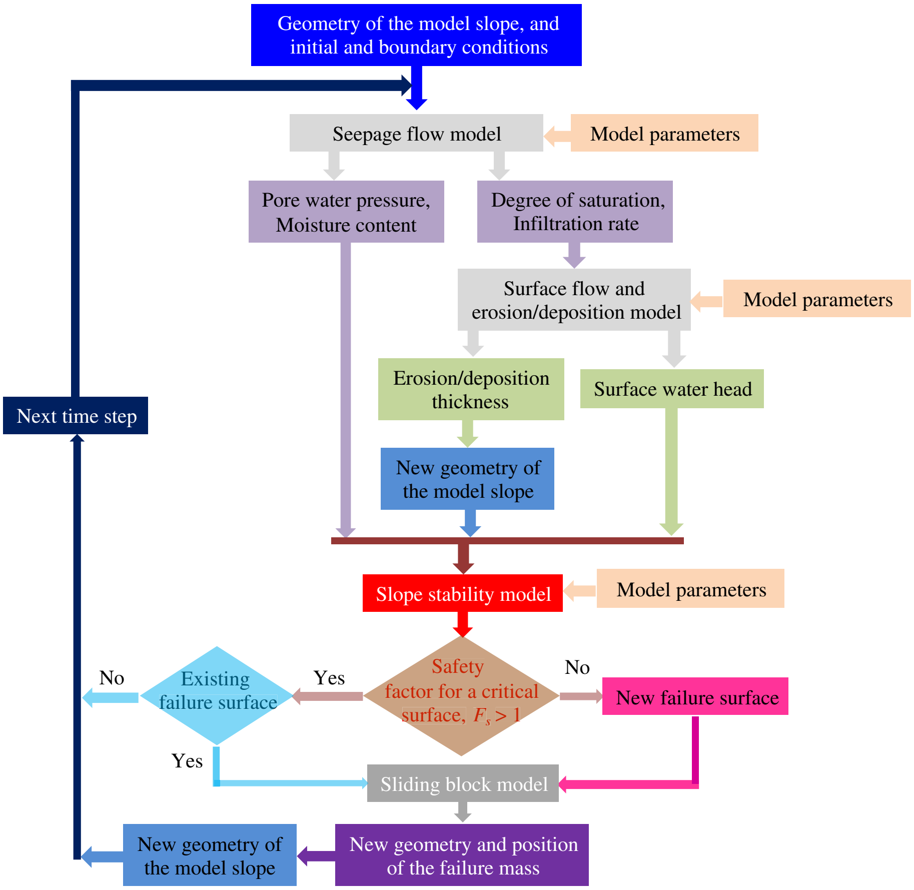

Fig. 1. General flow chart of the coupled numerical simulation model.