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A physically-based distributed cell model for predicting regional rainfall-induced shallow slope failures

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ABSTRACT

Rainfall-induced slope failures are one of the most frequent hazards on hilly terrains. This paper proposes a physically-based distributed cell model to predict regional rainfall-induced shallow slope failures in two-layer soils under realistic rainfall conditions. The model consists of four components; namely, a digital terrain model, a spatial rainfall distribution model, an infiltration analysis model, and a slope stability and reliability evaluation model. The digital terrain is discretized into a grid of numerous cells first, with the properties of the soils in each cell assigned. Universal kriging is then adopted to interpolate the spatial rainfall distribution. Afterwards, the infiltration analysis model is used to analyze the infiltration process in two-layer soils under realistic rainfall conditions. The slope stability and reliability evaluation model is finally adopted to assess the regional slope stability and reliability. The distributed cell model is applied to evaluate the spatial and temporal response of a 164.5 km^2 area to rainfall near the epicenter of the 2008 Wenchuan earthquake zone. Comparison between the predicted and observed slope failures triggered by the 13 August 2010 storm shows that this model is capable of predicting the locations of rainfall-induced slope failures reasonably well. The model is intended for use as a module in a real-time warning system for rainfall-induced slope failures.

1. Introduction

Rainfall-induced slope failures are one of the most frequent hazards on hilly terrains. For a large area where widespread slope failures may be triggered by rainfall, a distributed model for predicting rainfall-induced slope failures at regional scale is necessary, and one that is physically-based is preferred, because such a model is able to explicitly consider site-specific conditions.

It is generally recognized that rainfall-induced slope failures are caused by changes in pore water pressures and seepage forces (e.g., Zhu and Anderson, 1998; Gerscovich et al., 2006; Zhao and Zhang, 2014). The failure mechanisms can be classified into two types; namely the generation of sufficient positive pore-water pressure and the dissipation of matric suction (e.g., Au, 1998; Chen et al., 2004; Collins and Znidarcic, 2004; Zhang et al., 2011). These two mechanisms lead to the decrease of shear strength or the increase of driving forces. Hence, changes in pore-water pressure provide basic information for the analysis of slope stability and reliability under rainfall infiltration.

Both empirical models (e.g., Au, 1993; Aleotti, 2004; Chang et al., 2011a; Lee et al., 2013) and physically-based models (e.g., Montgomery and Dietrich, 1994; Wu and Sidle, 1995; Dietrich and Montgomery, 1998; Crosta and Frattini, 2003; Zhou et al., 2003; Frattini et al., 2004; Baum et al., 2008; Godt et al., 2008; Arnone et al., 2011; Shuin et al., 2012; Park et al., 2013; Jiang et al., 2014; Zhang et al., 2014a) have been adopted to predict the occurrence of rainfall-induced slope failures. An empirical model does not need detailed information regarding the physical, mechanical, and hydrological properties of the soil or rock mass and the geometry of the slopes (Lee et al., 2013), but needs careful verification when being used in another area. A physically-based model can predict the slope failure accurately and explicitly considering site specific conditions. However, the physically-based model requires detailed investigations to obtain accurate site data.

Physically-based distributed models account for the mechanisms and process of the rainfall-induced slope failures and have been adopted by many researchers. Each model typically consists of a hydrological module and a geotechnical module. The hydrological module is used to analyze the infiltration process and changes in the groundwater table. The geotechnical module is used to compute the slope factor of safety, and an infinite slope model is most widely used due to its simplicity. The above distributed models can predict widespread rainfall-induce slope failures in homogeneous soils. However, for a large area with layered soils, a new physically-based distributed cell model that can predict regional rainfall-induced slope failures in layered soils under realistic rainfall conditions is desired.

To facilitate real-time warning of rainfall-induced slope failures, it is necessary to obtain the spatial and temporal response of the terrain to rainfall. Infiltration analysis can be conducted to investigate the rainfall infiltration process and obtain pore-water pressure profiles. The governing equation for infiltration analysis which considers the most

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realistic situation is the Richards equation. Several analytical solutions (e.g., Srivastava and Yeh, 1991; Basha, 1999; Iverson, 2000; Chen et al., 2001; Yuan and Lu, 2005; Wu and Zhang, 2009; Wu et al., 2012; Zhan et al., 2013) and approximate solutions (e.g., Cho, 2009) to the equation have been proposed, and some of them have been adopted in physically-based distributed models (e.g., Crosta and Frattini, 2003; Frattini et al., 2004; Baum et al., 2008; Godt et al., 2008). A few of these solutions can describe infiltration in layered soils under a constant rainfall condition (e.g., Srivastava and Yeh, 1991; Cho, 2009; Zhan et al., 2013). Some can describe the infiltration process in homogeneous soils under arbitrary rainfall conditions (Basha, 1999; Iverson, 2000; Chen et al., 2001; Yuan and Lu, 2005). Yet a method that is capable of analyzing the infiltration process in layered soils under arbitrary rainfall conditions, which are most common on natural terrains, is still not available.

The objective of this paper is to develop a new physically-based distributed cell model for predicting regional rainfall-induced slope failures in layered soils under arbitrary rainfall conditions. The method is intended for use in a real-time warning system for rainfall-induced slope failures.

2. Methodology of the distributed cell model

2.1. Framework of the distributed cell model

The framework of the new physically-based distributed cell model is shown in Fig. 1. The framework consists of four components; namely, a digital terrain model, a spatial rainfall distribution model, an infiltration analysis model, and a slope stability and reliability evaluation model.

The digital terrain of a sample study area is shown in Fig. 2, which includes a section of Provincial Road 303 (PR303) from milestone K0 to K18 and its vicinity near the epicenter of the Wenchuan earthquake, Yingxiu, which is located in Sichuan Province, southwest China. The study area is discretized into a grid first with information for each cell assigned (e.g., elevation, slope gradient, surface geological type, rainfall information, soil depth, groundwater level, and soil properties). Each cell is a computational unit. All the analyses are based on the concept of cell.

Rainfall is the triggering factor for slope failures; hence it is essential to obtain the spatial rainfall distribution. Very often only a limited number of rain gauges are installed in a certain area. Universal kriging has been widely applied to obtain the spatial rainfall distribution (e.g., Ali et al., 2005; Haylock et al., 2008; Ly et al., 2011), which is also adopted in this study. The cumulative rainfall at each cell in the study area is obtained through interpolation using rainfall records from nearby rain gauges. The real-time hourly rainfall intensity at each cell can be then obtained.

Based on the obtained rainfall information, infiltration analysis is performed to provide the pore-water pressure profile in the ground of each cell. An infiltration analysis model for two-layer soils under arbitrary rainfall conditions is developed in the study. Considering the runoff process under arbitrary rainfall conditions, the unsteady infiltration rate at each cell can be obtained.

The stability and reliability of the slope in each cell are finally assessed through the slope stability and reliability evaluation model. The hydrological conditions in the ground are evaluated using the aforementioned rainfall infiltration analysis method. Hence, the spatial and temporal responses of the terrain to rainfall can be analyzed, and the regional slope failures can be predicted.

2.2. Universal kriging interpolation

Universal kriging is adopted here because the rainfall distribution in the study area is not uniform due to the complex topographic conditions. The basic principles of universal kriging have been introduced by Olea (1999). Let $R(\boldsymbol{u_i})$ be the measured rainfall value at location $\boldsymbol{u_i}$ (i.e., a sampled point) and $R(\boldsymbol{u_0})$ be the rainfall value at $\boldsymbol{u_0}$ where the rainfall information is unknown (i.e., an unsampled point). $R(\boldsymbol{u_0})$ can be represented by a linear combination of $R(\boldsymbol{u_i})$:

$$R(\boldsymbol{u_0}) = \sum_{i=1}^{n_r} \lambda_i R(\boldsymbol{u_i}) \tag{1}$$

where n_r is the number of rain gauges; λ_i is the optimal weight, the sum of the n_r weights being 1.0. The rainfall value at each cell is represented by that at the center of the cell. A schematic grid for universal kriging is shown in Fig. 3. In real applications, the grid can contain much more cells. The rainfall information for each cell can be obtained by setting the center of the cell as an unsampled point.

A linear rainfall trend is adopted in this study:

$$m(\mathbf{u}) = a_0 + a_1 x + a_2 y \tag{2}$$

where a_0, a_1, and a_2 are regression coefficients; x and y are coordinates. The residual, $Y(\boldsymbol{u})$, of the rainfall is the difference between the random rainfall function, $R(\boldsymbol{u})$, and the trend, $m(\boldsymbol{u})$ (i.e., mean):

$$Y(\mathbf{u}) = m(\mathbf{u}) - R(\mathbf{u}). \tag{3}$$

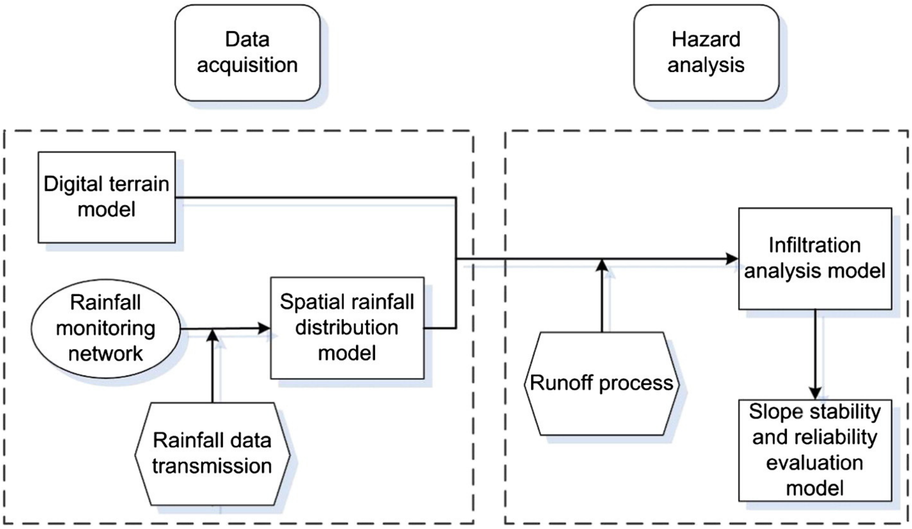

Fig. 1. Framework of the physically-based distributed cell model.