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Presenting regional shallow landslide movement on three-dimensional digital terrain

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ABSTRACT

A storm can trigger numerous shallow landslides on hilly terrains. This paper presents a distributed cell model for presenting regional shallow landslide movement on a three-dimensional digital terrain. The model consists of five components; namely, a digital terrain module, a spatial rainfall distribution module, an infiltration analysis module, a slope stability evaluation module, and a movement prediction module. The locations and volumes of landslides are analyzed first through rainfall infiltration and slope stability analyses. The detached material is assumed to move along the steepest path from one cell to a lower cell. Empirical equations that are developed based on local landslide inventories are adopted as a landslide movement cessation criterion. The effect of landslide size on travel distance is considered by grouping unstable cells that are bounded at least at one side or corner. The uncertainties in soil shear strength parameters and the landslide movement process are considered in determining the possible bounds of travel distance. The movement analysis method is applied to a 164.5 km^2 hilly terrain in the Wenchuan earthquake zone to test its performance in presenting regional shallow landslide movement. The method predicts the volume of landslides reasonably well. The observed and computed movement traces and deposition locations of the detached material also agree reasonably well. The volume of individual landslide and travel distance may be substantially underestimated if the size effect is not considered.

1. Introduction

Shallow landslides are one of the most common hazards in mountainous areas. The detached material can pose great danger to the people and properties along the movement path. In order to assess the risk posed by such landslides, delimiting the extent of endangered areas is essential. The hazard impact area entails the source zone, the movement path and the deposition zone. Assessing the impact area of the shallow landslides is always not an easy task.

Evaluation of the landslide location and volume is the basis for movement analysis. The methods for slope instability mapping can be classified into qualitative factor overlay (e.g., Anbalagan, 1992; Pachauri and Pant, 1992), statistical models (e.g., Carrara et al., 1991; Wang et al., 2005), and geotechnical process models (e.g., Montgomery and Dietrich, 1994; Crosta and Frattini, 2003; Godt et al., 2008; Chen and Zhang, 2014).

The methods for predicting the landslide movement path and deposition zone can be classified into three types; namely, empirical methods (e.g., Scheidegger, 1973; Corominas, 1996; Finlay et al., 1999; Rickenmann, 1999; Hunter and Fell, 2003; Budetta and de Riso, 2004; Tang et al., 2012), analytical methods (e.g., Hungr et al., 1984; Sassa, 1988; Takahashi, 1991), and numerical methods (e.g., O'Brien et al., 1993; Hungr, 1995; Chen and Lee, 2003; Crosta et al., 2003a; Pastor et al., 2009; Huang et al., 2012; Li et al., 2012; Chen et al., 2013). Empirical methods often relate the travel distance/runout distance of the landslide material with the landslide volume and fall height, which are simple and easily applicable. The empirical approach, however, cannot explicitly consider the mechanics and material rheology. Analytical methods include lumped mass methods (e.g., Sassa, 1988) and momentum conservation based methods (e.g., Hungr et al., 1984; Takahashi, 1991), which can reflect the material rheology and kinetic mechanics to a certain extent, but cannot describe the mass motion in detail. Numerical methods include continuum methods (e.g., O'Brien et al., 1993), the finite element method (e.g., Chen and Lee, 2003), the distinct element method (e.g., Li et al., 2012), the smoothed particle hydrodynamics method (e.g., Pastor et al, 2009) and others, which can consider the material rheology and mechanical processes. However, numerical analysis requires a large amount of accurate site data when applied to a large area where widespread landslides may occur.

Two problems arise in evaluating the movement of shallow landslides in a regional landslide study. The first problem is how to properly determine the locations and volumes of potential landslides. Geotechnical process models are preferred since they can account for the mechanisms and process of the potential landslide and compute the volume of the landslide. The second problem is how to properly and efficiently assess the movement of the detached material on a large area of three-

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dimensional natural terrain. An empirical model is a viable option if adequate field data is available. Burton and Bathurst (1998) and Arnone et al. (2011) successfully adopted empirical methods to predict the travel distance of landslides in a large area. The travel distance in their work is assumed to be governed by the fall height while the size effect of the landslide is not considered. In reality, a landslide with a larger volume can move farther if other conditions are the same. Legros (2002) further found that the travel distance of a landslide depends primarily on the volume instead of the fall height. In addition, most empirical equations for estimating travel distance are simply regression trend lines; the uncertainties in travel distance are rarely considered in the existing work. How to properly consider the landslide size effect and the uncertainties in travel distance when evaluating the movement of detached material on natural terrain should be explored further.

The objective of this study is to develop a distributed model to properly present the movement of regional rainfall-induced shallow landslides on a three-dimensional digital terrain including the landslide size effect and the uncertainties in the movement analysis.

2. Methodology

2.1. Model framework

The framework of the distributed model is shown in Fig. 1. The model consists of five components; namely, a digital terrain module, a spatial rainfall distribution module, an infiltration analysis module, a slope stability evaluation module, and a movement prediction module. The first four components have been described in detail by Chen and Zhang (2014). The last component is the key part of this study and will be introduced in detail.

The movement analysis is built on a three-dimensional digital elevation model, which includes the information of plane coordinates and the respective elevation data. An example 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, Sichuan Province, China (Chen and Zhang, 2014). 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). Elevation and slope gradient are obtained using a digital elevation model on a GIS platform. Surface geological type, soil depth, and groundwater level are determined based on field investigations and interpretation of satellite images. Soil properties are determined using field and laboratory tests. The rainfall information is interpolated using universal kriging based on measurements from a limited number of rain gauges. The detailed information has been reported by Chen and Zhang (2014).

Each cell is a computational unit. All the analyses are based on the concept of cell. The real-time hourly rainfall intensity at each cell can be obtained through universal kriging interpolation based rainfall records at a limited number nearby rain gauges. Infiltration analysis is then performed to provide the pore-water pressure information at each cell in the ground. Afterwards, the stability of the slope in each cell is assessed through the slope stability evaluation module, which provides the time, location, and volume of the potential shallow landslides. Once the location of a landslide is identified, the detached material is routed down the hill slope. An empirical movement prediction model is adopted as a movement cessation criterion. The empirical relationship is developed based on previous landslide data in the study area. The movement prediction module gives the movement traces and deposition zones of the detached material, which are essential for landslide risk assessment.

2.2. Development of empirical relationships for movement prediction

The empirical approach for movement prediction refers to actual landslide data and in accordance with proper classification of the modes of landslide movements (e.g., Chen and Lee, 2004). The most widely used empirical approach for shallow landslides includes the angle of reach method and the direct statistical method.

The angle of reach is defined as the angle of the line connecting the highest point of landslide source to the distal margin of displaced mass, which reflects the mobility of landslide material and is closely related to the landslide volume. The method is suitable for all types of landslides, for example, rockfall, earth flows, debris flows, and transitional slides (Corominas, 1996), but a specific relation can only be used to where the data is gathered. Scheidegger (1973) found that the angle of reach decreases with increasing landslide volume, which indicates that the landslide mobility increases with landslide volume. The direct statistical method is to obtain a regression equation to directly estimate the runout indices (e.g., travel distance or runout distance) based on inventory data. This method is also suitable for all kinds of landslides and has been applied extensively (e.g., Iverson et al., 1998; Rickenmann, 1999; Li et al., 2011; Chen et al., 2012; Zhang et al., 2013).

The most widely used movement indices for delineating movement path and deposition zone include travel distance, L, runout distance, L_f, and planimetric area inundated by the deposit materials, B. Travel

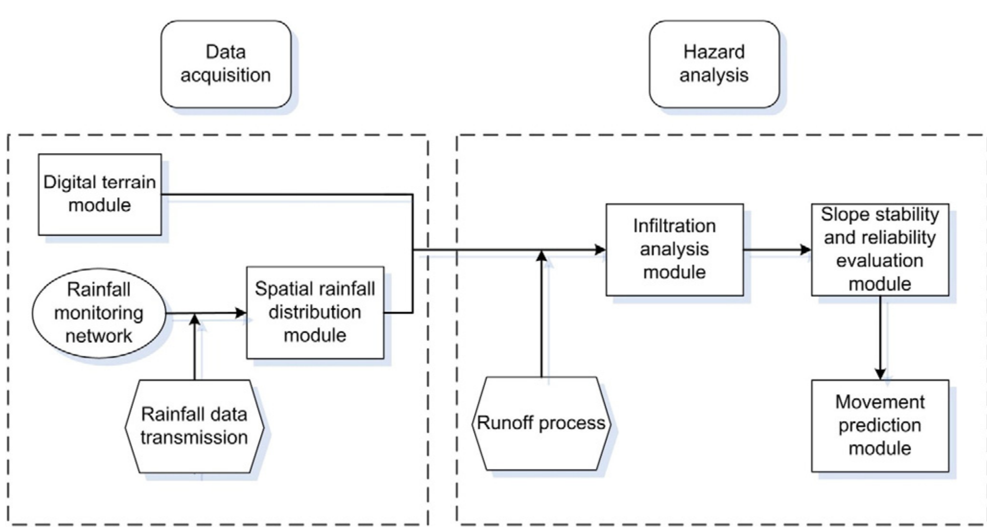

Fig. 1. Framework of the distributed cell model.