ARTICLE IN PRESS
ENGEO-04191; No of Pages 15
Engineering Geology xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Engineering Geology
journal homepage: www.elsevier.com/locate/enggeo

A physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows

H.X. Chen [a], S. Zhang [a], M. Peng [b], L.M. Zhang [a,]*

[a] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong
[b] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 4 December 2015
Accepted 10 December 2015
Available online xxxx

Keywords:
Slope stability
Landslide
Debris flow
Risk assessment
GIS
Wenchuan earthquake

ABSTRACT

Rainfall-induced slope failures and debris flows are two major hazards in mountainous areas. A physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows has been developed in this study. The platform enables prompt assessment of risks posed by regional rainfall-induced slope failures and debris flows across multiple catchments, which is required in landslide risk management in a large area. It considers the contribution of slope failures to debris flows and the scenario of a location impacted by multiple slope failures or debris flows or both. The contribution of slope failures to debris flows is considered by adding the increased amount of channel deposit from slope failures to the source material of debris flows. The platform is applied to a highway near the epicentre of the 2008 Wenchuan earthquake. The platform predicts the impact areas and runout distances of regional debris flows reasonably well. The risk assessment results indicate that both slope failures and debris flows pose a great danger to travellers along the road shortly after the earthquake due to the presence of a large amount of loose landslide deposits on steep terrains. The materials from the slope failures triggered during a storm substantially increase the channel deposit volume, leading to significantly increased debris flow volume and risk. A multi-hazard risk assessment approach is necessary to consider the scenario of a location impacted by multiple slope failures or debris flows or both, since assessing risks of slope failures and debris flows separately may underestimate the risk.

1. Introduction

Rainfall-induced slope failures and debris flows are mass movements driven by gravity, which can move rapidly for a long distance, posing a great danger to people and properties distributed within the impacted areas. Landslide risk can be defined as the expected number of lives lost, persons injured, damage to properties and disturbance of economic activities due to landslides in a given area and a reference period (Varnes, 1984). Risk analysis can be divided into qualitative analysis and quantitative analysis based on different levels of detail (e.g., Dai et al., 2002; Fell et al., 2008). For slopes that are amenable to conventional limit equilibrium analysis, real-time quantitative risk assessment (QRA) can be a powerful tool for hazard mitigation (Dai et al., 2002).

Great efforts have been made to assess the risks of slope failures and debris flows (e.g., Aleotti and Chowdhury, 1999; Australian Geomechanics Society, 2000; Guzzetti, 2000; Dai et al., 2002; Sassa et al., 2004; Nadim et al., 2006; Fell et al., 2008; van Westen et al., 2008; Li et al., 2009, 2014, 2015; Lin et al., 2011; Mousavi et al., 2011; Tang and Zhang, 2011; Zhang et al., 2012; Bhandary et al., 2013; Ali et al., 2014; Ngadisih et al., 2014; Sousa et al., 2014). Guidelines and procedures for hazard zoning and risk assessment have been proposed through these efforts. Aleotti and Chowdhury (1999) and Australian Geomechanics Society (2000) summarized the basic concepts of risk assessment. Dai et al. (2002) summarized several issues that should be addressed in landslide risk assessment and management: (a) probability of landslides, (b) runout behaviour of landslides, (c) vulnerability of property and people to landslides, (d) landslide risk to property and people, and (e) management strategies and decision-making.

For a large area where widespread rainfall-induced slope failures and debris flows may occur, the most challenging issue is to quantify the risks posed by multiple hazards efficiently and promptly. Extensive efforts have been made to assess the risks of regional rainfall-induced slope failures and debris flows (e.g., Lo and Cheung, 2004; Wong et al., 2004; Remondo et al., 2008; Jaiswal et al., 2010; Erener and Düzgün, 2013; Ngadisih et al., 2014; Vranken et al., 2014). While these methods are applicable to a large area, they do not include physical mechanisms of the hazards or determine the impact areas of the hazards accurately. Physically-based methods have been widely adopted for evaluating the susceptibility of slope failures (e.g., Crosta and Frattini, 2003; Frattini et al., 2004; Baum et al., 2008; Godt et al., 2008; Arnone et al., 2011; Zhang et al., 2014a). Great efforts have also been made to simulate the

* Corresponding author.
E-mail addresses: cechenhx@ust.hk (H.X. Chen), zhangs@ust.hk (S. Zhang), pengming@tongji.edu.cn (M. Peng), cezhangl@ust.hk (L.M. Zhang).

http://dx.doi.org/10.1016/j.enggeo.2015.12.009
0013-7952/

movement of debris flows (e.g., Hungr, 1995; Denlinger and Iverson, 2001; Pastor et al., 2009; Quan Luna et al., 2012; Chen et al., 2013; Ouyang et al., 2014; van Asch et al., 2014). However, limited studies were conducted to quantify the impact area and risk of slope failures and debris flows over a large area using physically-based methods. The detached material of slope failures often transforms to the source material of debris flows. An area may be impacted by multiple slope failures or debris flows or both during a certain period. Yet research on risk assessment considering relationships among hazards is still limited (Kappes et al., 2012; Marzocchi et al., 2012; Zhang et al., 2014b). In the literature, the risks of slope failures and debris flows are often evaluated separately. Therefore, efforts must be made to develop an integrated platform for efficiently assessing the risks of regional rainfall-induced slope failures and debris flows using physically-based methods.

The objective of this paper is to develop a physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows. The method is intended to be used in a real-time warning system for rainfall-induced slope failures and debris flows. In the paper, the term 'landslides' refers to both slope failures and debris flows.

2. Methodology

2.1. Framework of the multi-hazard risk assessment platform

The physically-based multi-hazard risk assessment platform is based on a grid system, which discretizes the computation area into a large number of cells. The physical processes within each cell and the material exchange between adjacent cells can be analysed efficiently. The grid system is applicable to both slope failures and debris flows.

There are five components in the proposed multi-hazard risk assessment platform (Fig. 1); namely, a digital terrain module, a spatial rainfall distribution module, a slope failure prediction module, a debris flow simulation module, and a multi-hazard quantitative risk assessment module. The first four components have been introduced in detail by Chen and Zhang (2014, 2015) and Chen et al. (2015), and the focus of this study is to present the multi-hazard quantitative risk assessment module. The cell-based platform is used for data acquisition, hazard analysis and risk assessment.

Quantitative risk assessment for regional rainfall-induced slope failures and debris flows can be conducted for both loss of lives and loss of properties. In this paper, the study area includes a section of Provincial Road 303 (PR303) from milestone K0 to K7 and its vicinity near the epicentre of the Wenchuan earthquake, Yingxiu, Sichuan Province, China (Fig. 2). Since there are only a limited number of buildings and infrastructural structures in the study area, only the risk to the travellers in vehicles along the road is considered in this study.

The procedure for rapid risk assessment in the cell-based platform is introduced step by step as follows (Fig. 1):

(1) The digital terrain of the study area is discretized into a grid first, with properties in each cell assigned, such as geology, topography, soil properties, hydrological parameters, and groundwater table. The cell size must satisfy the requirement that the plane dimensions are much larger than the depth of the potential slip surface of slopes. A too large cell size is not preferred either since it is difficult to accurately identify slope failures, debris flows and road features.
(2) The monitored rainfall data by automatic rain gauges is transferred to a data processing centre via a wireless network. An antecedent infiltration rate, q_A, before the storm is introduced to consider the antecedent rainfall effect, which is used to determine the initial pore-water pressure profile (Chen and Zhang, 2014). The rainfall information for each cell during the storm is obtained by the spatial rainfall distribution module based on universal Kriging interpolation.
(3) Given the spatial rainfall distribution, the runoff and infiltration processes can be analysed, providing spatial and temporal pore-water pressure profiles of each cell. The stability and reliability of each cell, and the movement trace and deposition location of the detached material in each unstable cell can then be

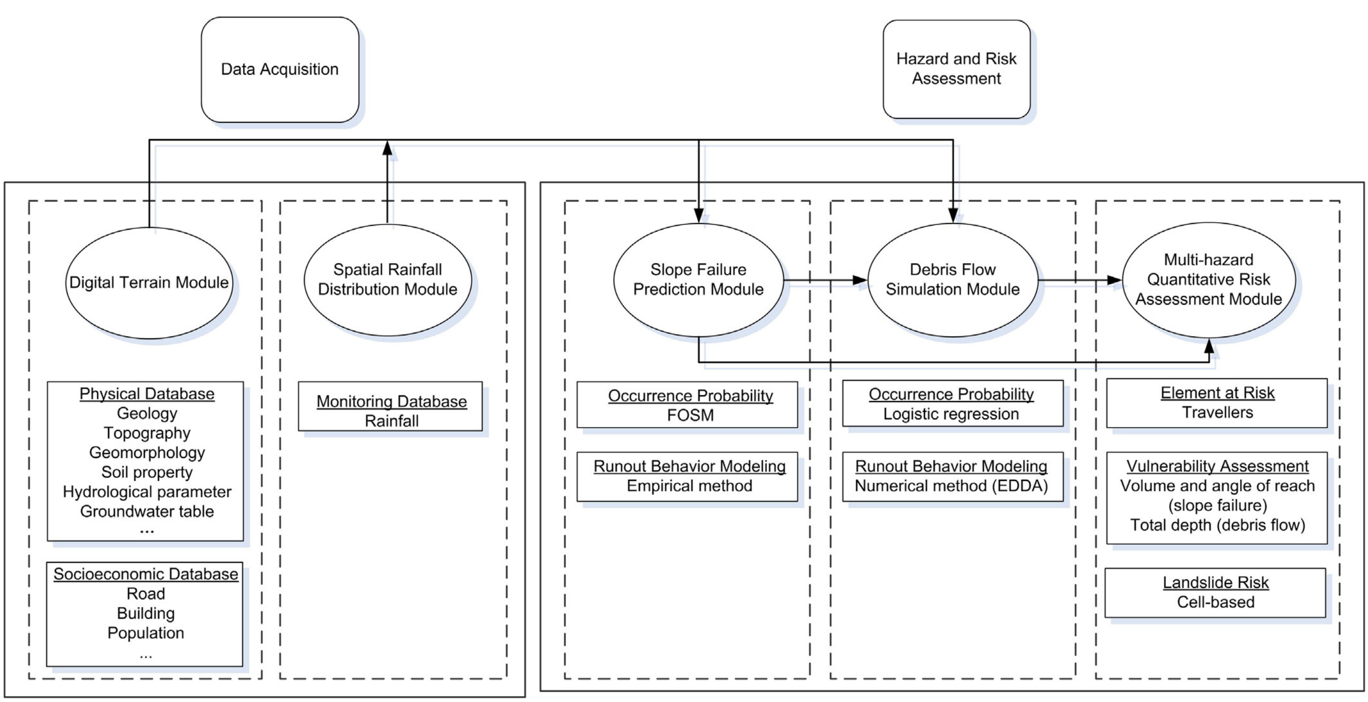

Fig. 1. Framework of the multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows.

Please cite this article as: Chen, H.X., et al., A physically-based multi-hazard risk assessment platform for regional rainfall-induced slope failures and debris flows, Eng. Geol. (2015), http://dx.doi.org/10.1016/j.enggeo.2015.12.009