



Forecasting landslide hazard by the 3D discrete element method: A case study of the unstable slope in the Lushan hot spring district, central Taiwan



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ABSTRACT

Catastrophic landslides and related phenomena are commonly facilitated by the subtropical climate with frequent typhoons and recurrent earthquakes in Taiwan's mountainous areas. One area susceptible to potentially catastrophic landslides is located at Lushan in central Taiwan, which is famous for its hot springs and tourism. The northern slope above the hot spring district slips gradually and frequently due to heavy rainfall. For safety reasons, the slip-affected area has been under constant borehole monitoring by government agencies, and a controversial public debate has arisen over permanent evacuation of the hot spring district. In this study, we attempt to simulate possible scenarios of catastrophic slope failure using slip geometries derived from the monitoring data, and assess potential landslide impact areas by a discrete element method using the PFC3D code. In the worst case scenario, the Lushan hot spring district is predicted to be destroyed by debris in 20 s. Besides, the planned regional emergency refuge is rapidly jeopardized by flooding resulted from landslide-dammed lakes. This study addresses catastrophic slope failure under heavy rainfall conditions given a range of friction coefficients and varied continuity of the failure surfaces. It is noted that the PFC3D code has limitations in modeling all complex mechanisms of landslide, particularly in modeling loss of material shear strength due to increases in pore pressure. Nevertheless, the numerical simulation results by the 3D discrete element method provide scenario-based runout paths, particle velocities and landslide-affected areas, which are useful information for decision support and future landslide hazard assessment.

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1. Introduction

Extremely rapid landslides, such as debris and rock avalanches, are the most obvious and major geological hazards in mountainous areas. They have caused extensive infrastructure damage and threatened human lives through the centuries (Eisbacher and Clague, 1984; Turner and Schuster, 1996; Dai et al., 2002; Nadim et al., 2006; Keefer and Larsen, 2007; Highland and Bobrowsky, 2008). According to the World Disaster Report (IFRC, 2011), there were more than 200 landslides and about ten thousand people killed by landslides during the last ten years (2001–2010) around the world. Taiwan has a subtropical climate and an annual average of four typhoons. Active orogeny due to the collision between the Eurasian and Philippine Sea plates has also produced both mountainous terrain and frequent earthquakes (e.g.

Dadson et al., 2003). Taiwan is therefore one of the landslide-hazard hotspots of the world (Nadim et al., 2006).

Large earthquakes and torrential rainfall are considered to be the main agents generating catastrophic landslides (e.g., Keefer, 1984, 2000; Terlien, 1998; Crozier, 1999; Van Asch et al., 1999; Lin et al., 2004; Jibson, 2007; Crosta and Frattini, 2008). The basic physics of triggering and initiation of landslides such as gravity, strength of material, external forces due to seismic shaking and pore-water pressure have been well investigated for decades (Erismann, 1979; Campbell, 1989; Iverson, 2000; Legros, 2002; Guzzetti et al., 2007; Wasowski et al., 2011). However, more progress in forecasting and understanding of catastrophic landslides is needed to reduce casualties and property losses.

Catastrophic failures can involve slopes in metamorphic rocks with well-developed foliation, following long-term mass rock creep that tends to change the orientation of foliation (Chigira, 1992). Mass rock creep or the so-called deep-seated gravitational slope deformations can evolve from continuous and very slow displacements to catastrophic and rapid movement (Chigira, 1992, 2009; Dramis and Sorriso-Valvo, 1994; Kilburna and Petley, 2003; Petley et al., 2005). The deformation

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and fragmentation of the rock mass through the creep process may further lead to the occurrence of landslides (Giraud et al., 1990). Therefore, the phenomenon of mass rock creep offers a clue to forecasting potential sites of catastrophic landslides.

Several studies have improved our understanding of the effects of topography and geological structures on landslide occurrence and probability (e.g., Chigira et al., 2003; Sidle and Ochiai, 2006; Lee et al., 2008; Wasowski et al., 2011). The most frequently used empirical method for the runout analysis is derived from the correlations between landslide volume and the angle of reach (Heim, 1932; Scheidegger, 1973; Nicoletti and Sorriso-Valvo, 1991; Corominas, 1996; Legros, 2002). The relationship between landslide volume and deposition area has also been discussed (Hungr, 1990; Inverson et al., 1998). In addition to empirical methods, numerical methods can simulate the runout behavior of landslide debris through the time-stepping algorithms that have been developed over the past decade (McDougall et al., 2012). The numerical methods for modeling landslides mainly include the continuum method and the discrete element method (DEM).

The continuum method models the runout of landslides by analyzing the flow of fluids in channels. Savage and Hutter (1989) developed the continuum model from depth-averaged (shallow flow) equations to simulate the flow of dry sand. Hungr (1995) used DAN2D (dynamic analysis 2D), which is a meshless Lagrangian model, to take different fluid rheology into consideration. DAN3D, a 3D extension of the existing 2D model, was later used to simulate the 1855–1856 Rubble Creek landslide in British Columbia by McDougall (2006). A similar approach, RASH3D, a fixed-mesh Eulerian model, has also been developed and applied (Pirulli, 2005).

In the discrete element method (DEM), a group of individual particles interact with each other by sliding, falling and rolling on the ground surface, to simulate the cracks and the subsequent large-scale displacement of a catastrophic landslide. Itasca Consulting Group, Inc. (Cundall and Strack, 1979) developed the Particle Flow Code (PFC) model based on the DEM. In the PFC model, particles can be bonded together or separated during the simulation process (Poisel and Roth, 2004). There have been several studies that simulate real landslide cases by using the PFC (Poisel and Preh, 2008; Chang and Taboada, 2009; Tang et al., 2009, 2013; Lo et al., 2011). Because large displaced fractures can be simulated by the discrete element method, the method is appropriate for modeling the kinematic processes of landslide events.

However, from the viewpoint of landslide hazard assessment, not only the potential landslide source but also the runout path and the landslide-affected area are crucial targets for investigation. Through simulating landslide scenarios, it will help in better assessing landslide hazards and eventually decreasing casualties and property losses. While numerical modeling has often been used to analyze past events (Crosta et al., 2003; Stead et al., 2006; Poisel et al., 2008; Chang and Taboada, 2009; Crosta et al., 2009; Kuo et al., 2009; Tang et al., 2009), few attempts have been carried out to forecast scenarios of potential catastrophic slope failures, possibly due to limited spatial and temporal field observational data (Crosta et al., 2006; Poisel et al., 2009).

With the aforementioned motivation, we applied the program PFC3D (Particle Flow Code 3D) to simulate the potentially catastrophic slope failure of an unstable rock mass and its impact in the Lushan hot spring district, where field observational data have been accumulated for the past decade. The northern slope of the district was among the few potential landslide areas in Taiwan that show strong evidence of mass rock creep by monitoring data. Abundant data have been collected which indicate that the slope slid several to tens of centimeters during recent torrential rainfall events (Soil and Water Conservation Bureau, 2006, 2008; Central Geological Survey, 2011). Because of the noticeable creep events, a controversial public debate has arisen concerning whether or not the Lushan hot spring district should be evacuated permanently for safety reasons. The present work intends to model and forecast detailed 3D landslide occurrence, specifically, the landslide transportation and deposition in the famous resort

area. Although the 3D discrete element method has limitations in modeling landslides, the work demonstrates that it can provide useful insights for mapping areas susceptible to potentially catastrophic slope failures.

2. Characteristics of the Lushan hot spring district

2.1. Geographical and geological setting

The Lushan hot spring district is located at Jin-Yin Village, Ren-Ai Township, Nan-Tou County at the western side of the central mountain range of Taiwan, and is famous for its hot spring tourism (Figure 1). The Tai-14 highway, N87 highway, and the village roadways are used by the residents and tourists traveling between the Lushan district and western Taiwan. The drainage system of the study area belongs to the Jhuo-Shuei River, and the Lushan district is located at the confluence of the Ta-Lou-Wan and Ma-Hai-Pu rivers. Most hotel buildings in Lushan are distributed along or near the Ta-Lou-Wan River reach, where the northern valley slope often slides following torrential rainfall events.

The Lushan Formation, the major unit in the study area, is mainly composed of Miocene slate and sandy slate (Figure 2). Based on previous investigations (Soil and Water Conservation Bureau, 2006, 2008; Central Geological Survey, 2011), the slope is composed of surface colluvium with complex subsurface geology and ground water conditions. The elevation of the slope susceptible to failure varies from 1085 to 1495 m with an average gradient of about 22°.

2.2. Recorded failures at the Lushan district

During pouring rain or typhoon seasons, the torrential rainfall frequently destroyed the roads, split the retaining walls, and caused structure tilting and subsidence at the northern valley slope of the Lushan hot spring district. The 25 creep monitoring systems (mainly borehole inclinometers) installed by SWCB (Soil and Water Conservation Bureau) and CGS (Central Geological Survey) (Figure 3), recorded the slip phenomena at different depths during the 2005–2011 period. The measured surface displacements were about 10 cm during typhoon Matsa in August 2005, more than 50 cm during the torrential rainfall in June 2006 and 25 cm during typhoon Sinlarku in September 2008.

The recorded failures in the Tai-14 highway and other roadways, as well as the distribution of damaged buildings, enable the potential sliding areas to be reliably defined. According to the records of the Lushan rain station of the Central Weather Bureau (CWB) between 1952 and 2004, the rainy season begins from April to September, with an average annual rainfall about 2500 mm. A potential sliding area labeled as SA1 (Figure 2) in the Lushan district is about 19 hectares. Another potential larger sliding area labeled as SA2 (Figure 2), which also encompasses the SA1 area, is nearly 30 hectares. After several typhoon events in recent years, the sliding phenomena become more notable, which led to more installations of monitoring systems by the government agencies. The slide phenomena raised safety concerns not only for the lives and properties of local residents, but also for the hot spring visitors at the toe of the unstable slope.

2.3. Failure mechanisms at the northern slope of Lushan

Rock-boring samples from the northern slope of the Lushan district show well-developed, high-angle slaty cleavage, as well as deformation interpreted to be indicative of creeping or sliding at different depths. Furthermore, the inclinometer monitoring data demonstrate that deep-seated creep deformation involves depths down to 108 meters. According to the aforementioned field observations, the creep phenomena conform to type I deformation, i.e., buckling folds, in the classification proposed by Chigira (1992). Buckling occurs whenever a foliated rock moves downslope on a gentler slope than the foliation, and the sliding rock mass is constrained by the stationary rock at the foot of

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