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Review

The Tsaoling landslide triggered by the Chi-Chi earthquake, Taiwan: Insights from a discrete element simulation

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ABSTRACT

In the village of Tsaoling (in Yunlin County, Taiwan), a major landslide was triggered by the Chi-Chi earthquake in 1999 with more than 125×10^6 m^3 of rock displaced. The kinematic behaviour of this landslide is simulated using a 2D discrete element model (PFC2D code). Our numerical model is composed of discs bonded together. The initial boundary conditions are applied along the ball-wall contacts by using derived velocities integrated from the strong motion data with a duration of 160 s including the peak acceleration near Tsaoling. The constraints are mainly issued from the final geometry of the landslide including its capacity to cross the river valley and reach a significant elevation on the opposite mountain flank. They also result from a variety of geological and hydrological observations, including the local levels of material disruption and the location of survivors. Our modelling thus indicates that a low-friction coefficient (about 0.15) and a medium strength are required to account for the actual landslide characteristics. A self-lubrication mechanism probably accounts for the low residual friction. Our model also suggests that the maximum velocity of sliding reached 50 m/s, a result that cannot be checked in the absence of actual measurements. In addition to friction, the strength of sliding block is of special importance because it controlled the possibility for the upper layer fragments to roll and get buried, and hence the probability of survival.

Contents

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1. Introduction

Earthquake shaking is considered to be one of the main agents of the generation of a landslide with the largest earthquakes capable of triggering thousands of landslides throughout areas of more than 100,000 km^2 (Keefer, 1984, 2000; Keefer and Larsen, 2007). In Taiwan, landslide hazard reaches high levels in the mountainous part of the island where argillaceous slate lithology, earthquakes, typhoons and heavy rainfall facilitate to favour gravitational sliding (Hsu and Leung, 1977; Hung, 2000). Thus the basic physics governing the initiation of landslides such as material strength, gravitational stress, external forces due to seismic shaking and pore-fluid pressure have been well studied for decades (e.g., Crosta, 1998; Legros, 2002; Crosta et al., 2003; Keefer and Larsen, 2007).

1.1. The 1999 Tsaoling landslide

Numerous landslides have been observed in the mountain terrain adjacent to the epicentral area of the Chi-Chi earthquake which occurred on September 21st, 1999 (CGS, 1999). Based on the study of SPOT images, Liao (2000) pointed out that the Chi-Chi earthquake had triggered 9272 landslides and the total area of the landslides is 128 km^2.

Among the many catastrophic landslides of West-Central Taiwan where the disastrous Chi-Chi earthquake occurred in 1999 (Fig. 1a), the most impressive is located in Tsaoling on the northern side of the Chingshui River valley (Fig. 1b). The shape of the detachment and accumulation areas of the landslide is shown in Fig. 1c. At least five major dip slope failures occurred at Tsaoling during the 19th and 20th centuries (Hung, 2000; Hung et al., 2002) with the last triggered by the 1999 Chi-Chi Earthquake (Table 1). The estimated volume of the Tsaoling landslide is about 125×10^6 m^3 (Hung et al., 2002). The volume of fill is about 150×10^6 m^3, based on integration of aerial photogrammetry and digital terrain model analyses within the frame of a GIS (Geographic Information System) with 10 m pixel size resolution (Liao, 2000). As Fig. 2 shows, about 20% of the sliding mass accumulated in the Chingshui River valley (Fig. 2), creating a 5-km-long dam and a lake (Hung et al., 2002) which was deeply incised by the river erosion over the next few years (Chen et al., 2005, 2006). Moreover, significant portions of this mass “flied” over the valley and accumulated in the lower portion of the opposite mountain flank.

1.2. Deformation and friction in landslides

Although strong and pervasive disruption occurred inside the sliding terrain, as can be observed in the landslide mass, the moving components of many large landslides show a remarkable tendency to remain in a more or less unchanged, sequential order and shows that the main landslide mass undergoes severe fracturing and disruption but relatively limited deformation during the event. Observations in sedimentary terrain often show that the original order of the strata is preserved in the landslide (Johnson, 1979). This suggests that whereas the rock masses experience sufficient stress to induce dense fracturing of rock layers, stresses are applied during a very short time span, thus inhibiting large internal deformation and significant rearrangement of the deposit. As a consequence, most of the deformation often remains confined to narrow basal regions of landslide mass (Cleary and Campbell, 1993) where simple shear prevails.

In addition, for massive catastrophic long runout landslides, the apparent friction coefficient, defined as the ratio between the total vertical and horizontal displacements as proposed by Heim (1932), is many times smaller than the friction coefficient indicated by standard tests of material mechanical properties. For the largest landslides this parameter may fall below 0.1. The largest landslide on planet Mars, estimated to have a volume of 17,880 km^3, moved with an apparent friction coefficient of 0.06 (Lucchitta, 1979; McEwen, 1989). The dynamics of Valles Marineris are controversial: either the landslides are interpreted as dry rock avalanches or as gigantic debris flow. Lucchitta (1978) have proposed that the Valles Marineris landslide were probably gigantic wet debris flows. These fluidization mechanisms are also suggested based on the morphology and geometry of Valles Marineris landslides (Quantin et al., 2004) and a dynamic finite-difference model (Harrison and Grimm, 2003). In comparison with the power-law relationship between the volume and run-out distance of landslide on Earth and those in Valles Marineris, Soukhovitskaya and Manga (2006) argued that water did not play a significant role in the dynamics of martian landslides. The exponent of the power-law for martian landslides is similar to that for dry landslides and volcanic flows on Earth. Furthermore, the apparent friction decreases as the volume of slide increases (Heim, 1932).

Many interpretations have been proposed to explain the low apparent friction of long runout landslides. For instance, it has been considered that the basal area of the slide is lubricated by a layer of trapped air (Shreve, 1968). The material may be liquified by a flow of air through its mass (Kent, 1966). A similar concept was also proposed to explain the disastrous Vaiont landslide of October 9th, 1963, in north Italy (Habib, 1967, 1975). The low apparent friction resulted from partial melting of part of the constituent minerals that resulted from the large energy dissipation of the slide (Erismann, 1979; Voight and Faust, 1982). In the deposits of the Köfels landslide, melted rock (frictionite) was observed (Eriscmann, 1986). Melosh (1979, 1986) has proposed the idea of ‘acoustic fluidization’, meaning that the low friction is explained by acoustic energy stored in the constituent rocks, forcing intermittent contact and low-friction slip between the constituent rocks. Hsü (1975, 1978) proposed that the apparently excess travel distance of many sturzstroms might be related to a reduction of frictional resistance of colliding blocks dispersed in a dust