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Analysis of landsliding by earthquake shaking using a block-on-slope thermo-mechanical model: Example of Jiufengershan landslide, central Taiwan

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Abstract

The Jiufengershan rock-and-soil avalanche is one of the largest landslides triggered by the Chi-Chi Taiwan earthquake (September 21, 1999). In order to study landslide triggering and propagation by seismic shaking, we propose a method that combines features of the classic Newmark approach with mechanical relations involving Mohr-Coulomb failure criteria, pore-water pressure and shear heating during the sliding process. The effective shear strength is affected by shear heating and by pore-pressure variations during the sliding process. The shaking process was simulated using strong-motion accelerograms of the three nearest free-field stations, which surrounded the landslide. The initiation and propagation of earthquake-induced landslides are mainly controlled by the peak and residual shear strengths, respectively. The increase in temperature in the shear zone increases the pore-water pressure and weakens the shear strength. Rock avalanches are generated when mechanical parameters achieve critical threshold values, such that the residual shear strength is less than the tangential projection of body forces.

Keywords: Thermo-mechanical model; Newmark's method; Jiufengershan rock-and-soil avalanche; Earthquake-triggered landslide; Chi-Chi earthquake

1. Introduction

Landslides are one of the most destructive natural hazards associated with earthquakes, as shown by the 21 September 1999 Chi-Chi Taiwan earthquake (M_L=7.3), which triggered 9272 landslides having areas larger than 625 m^2 (Liao, 2000). This earthquake occurred on the Chelungpu fault, a shallow, low-angle thrust located in west-central Taiwan. It caused 2400 deaths, more than 8000 casualties and over US$ 10 billion in damages.

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In this paper, we study the mechanical process of the Jiufengershan landslide, which is one of the major slides triggered by Chi-Chi earthquake. This landslide is located about 12 km to the north of the epicenter (120.84°E, 23.96°N). The slide affected weathered, jointed rock and soil materials, which slid along the bedding plane, generating a rock-and-soil avalanche during the earthquake. The volume of the sliding debris is roughly 50×10^6 m^3 and consists of ~50–60 m of thick-bedded muddy sandstones with thin shale beds, covered by weathered rock and soil. These materials were transported downslope for about 1 km. The avalanche created a debris deposit with maximum thickness of 110 m, which dammed two small rivers and created three small lakes located upstream.

Earthquake-induced landslides are commonly analyzed using the Newmark's (1965) method, which allows estimation of the co-seismic inertial displacement from seismic records (Lee, 2001; Huang et al., 2001) and the seismic stability of a slope (Miles and Ho, 1999; Jibson et al., 2000). Huang et al. (2001) studied the Jiufengershan landslide using Newmark's method in an attempt to estimate the critical displacement required for a loss of strength sufficient to allow large-scale failure (Wilson and Keefer, 1983). These authors estimated a co-seismic displacement for the sliding material of 0.2–19.2 cm, considering a cohesion value of 14.4 kPa and friction angles between 20 and 25°. In this study, we introduce a block-on-slope thermo-mechanical method, in order to analyze the propagation of the landslide and initiation of the avalanche. The velocity and displacement of the sliding block are calculated taking into consideration the effect of the strong motion accelerations, the Mohr-Coulomb failure criterion (for peak and residual shear strength) and the influence of pore-pressure and frictional heating. This method is applied to the Jiufengershan landslide, using three strong-motion acceleration records from nearby stations.

2. Tectonic and geological setting

Taiwan Island is located at the junction of the Luzon Arc and the Ryukyu Arc, where the Philippine Sea Plate converges toward the Eurasian Plate with a velocity of 8.2 cm/yr in NW direction (Yu et al., 1997). The tectonic structure of west-central Taiwan can be divided into three major belts: the Western Coastal Plains, the Western Foothill Belt and the Hsuehshan Range Belt (Ho, 1975, 1976, 1986), bounded by the Chelungpu and Shuilikeng faults. The Western Foothill Belt consists of Late Oligocene to Pleistocene sedimentary rocks (Huang, 1986; Wu, 1986; Huang et al., 2000; Mao et al., 2002) structured along an imbricated west-vergent fold-and-thrust belt (Suppe and Namson, 1979; Suppe, 1980, 1981; Hung and Wiltschko, 1993).

The Jiufengershan area is characterized by an asymmetric fold (Taanshan syncline), which plunges gently toward the south. The stratigraphic formations from bottom to top in the study area are defined as follows: Tanliaoti Shale (TL), Shihmen Formation (SM), Changhukeng Shale (CH) and Kueichulin Formation (KC) (Fig. 1). The Changhukeng Shale is composed mainly of shale and sandstone. The Jiufengershan landslide destabilized the western limb of the Taanshan syncline, affecting rocks belonging to the Changhukeng formation (Huang et al., 2002; Wang et al., 2003). The dip angle of the western limb is about 15–25° in the study area. The sliding surface was characterized by striations parallel to the dip of the bedding, as well as shear folds generated by the rock avalanche. Near the main shear zone, we observed mud injections infilling preexisting fractures and joints. These structures were created during the sliding process and they are probably linked to the fluidization of saturated clay levels subjected to high pore-water pressure. A thin layer of pseudotachylyte (glass or cryptocrystalline material associated with cataclasites) was also observed along some areas of the basal shear surface, in particular in the upper zone of the sliding surface. We suggest that this material was formed by frictional heating during the sliding process. Note that the minimum estimated temperature for pseudotachylyte formation is 1100–1600 °C for dry rocks (Lin et al., 2001). These observations suggest that the sliding process occurred at high velocities.

The landslide accumulation is mainly located within a kilometric scale depression that was filled by the rock and soil avalanche. The geometry of the landslide accumulation in the field has an irregular star shape, which follows roughly a topographic contour line. The landslide deposit shows a chaotic mix-