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Geological and morphological study of the Jiufengershan landslide triggered by the Chi-Chi Taiwan earthquake

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Abstract

The Jiufengershan rock and soil avalanche is one of the largest landslides triggered by the Chi-Chi earthquake Taiwan 1999. The landslide destabilized the western limb of the Taanshan syncline along a weak stratigraphic layer. It involved a flatiron remnant, which was almost entirely mobilized during the earthquake. The avalanche was slowed down by NS trending ridges located downstream along the Jiutsaihu creek. The landslide affected a 60 m thick and 1.5 km long sedimentary pile composed of shales and sandstones, which dip ~22°SE toward a transverse valley. The triggering mechanism and the sliding process were analyzed by means of geological and morphological data from aerial photographs and observed in the field. A high-resolution airborne Light Detection and Ranging (LiDAR) image taken 2.5 years after the landslide allows the identification of morphological structures along the sliding surface and the landslide accumulation. The sliding surface shows several deformation structures such as fault scarps and folds. These structures are interpreted in terms of basal shear stresses created during the avalanche. Three major joint sets were identified at the sliding surface. The isopach map of the landslide was calculated from the comparison between elevation models before and after the earthquake. The coseismic volume of mobilized material and landslide deposit data are 42×10^6 m^3 and 50×10^6 m^3, respectively. The geometry of the landslide accumulation in the field has an irregular star shape. The morphology of the deposit area shows a sequence of smooth reliefs and depressions that contrast with the neighboring ridges.

Keywords: Landslide; Rock and soil avalanche; Chi-Chi earthquake; LiDAR image; Taiwan

1. Introduction

The 21st September 1999 Chi-Chi Taiwan earthquake (M_L=7.3, M_W=7.6) caused severe damage

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including 2412 deaths, more than 11,000 casualties, over US$11.8 billion capital lost (4% of Taiwan's GNP). This earthquake triggered 9272 landslides with sliding surfaces larger than 625 m^2 (Liao, 2000). The Jiufengershan landslide is one of the major mass wasting processes triggered by Chi-Chi earthquake. It occurred as a rock and soil avalanche that buried 39 persons.

The Jiufengershan landslide (120.84°E, 23.96°N) is located about 12 km to the north of the epicenter. Weathered, jointed rock and soil materials slid along the bedding plane creating a deep-seated rock and soil avalanche during the earthquake.

The volume of the landslide deposit comprises between 30 and 90×10^6 m^3, according to estimations published in literature (Kamai et al., 2000; Huang et al., 2002; Shou and Wang, 2003; Wang et al., 2003). The preliminary estimation of thickness of the displaced material is between 30 and 50 m (Huang et al., 2002). The rocks involved in the movement are Miocene in age and mainly composed of thick-bedded muddy sandstones with intercalated thin shale beds. Weathered rocks and soil were transported downslope for about 1 km. The rock and soil was avalanche deposited against several mountain slopes located downstream, infilling valley gorges and damming two small rivers.

This paper presents different approaches to describe the geological and morphological features of the Jiufengershan landslide. The geomorphological analysis is performed by means of the interpretation of aerial photos taken before and after the Chi-Chi earthquake. The topography of the landslide is studied by means of a high-resolution digital elevation model (DEM) from airborne laser altimetry data. The comparison between the topography before and after the slide allows precise calculation of the initial volume of rock and soil that was destabilized, as well as the geometry and isopach map of the landslide deposit. Field observations at different scales were performed along the sliding surface and the landslide deposit, which give new insights on the mechanical behavior of the landslide. The influence of large landslides on the erosion of the Taiwan western fold-and-thrust belt is discussed in the light of volume estimations of large landslide accumulations generated during the Chi-Chi earthquake.

2. Geological and morphological settings

Taiwan Island is located on the junction point of the Luzon Arc and the Ryukyu Arc, where the Philippine Sea Plate (PSP) converges toward the Eurasian Plate (EP) with a velocity of 8.2 cm/year in NW direction (Fig. 1) (Yu et al., 1997). Eastward of Taiwan the PSP subducts beneath the EP along the Ryukyu Trench. Southward of Taiwan the crust of the South China Sea (continental margin of the EP) subducts beneath the PSP along the Manila Trench. The crust of the Luzon arc (on the PSP) is overriding the Eurasian margin (Seno, 1977; Suppe, 1981; Seno et al., 1993; Malavieille et al., 2002).

The tectonic structure of west-central Taiwan can be subdivided into three major belts: the Western Coastal Plains, the Western Foothill Belt and the Hsuehshan Range Belt (Ho, 1975, 1976, 1986). The Western Foothill Belt is defined by an imbricated west vergent fold-and-thrust belt, bounded by the Chelungpu and Shuilikeng faults (Fig. 1) (Suppe and Namsom, 1979; Suppe, 1980, 1981; Hung and Wiltschko, 1993). It can be divided into an Outer Foothill zone and an Inner Foothill zone, which are delimited by the Shuangtung fault. The Outer Foothill zone consists of Pliocene and Pleistocene sedimentary rocks. The Inner Foothill zone consists of late Oligocene to Miocene sedimentary rocks (Huang, 1986; Mao et al., 2002).

The Jiufengershan landslide is located in the Inner Western Foothill zone and affected middle to late Miocene sandstones with interbedded shale layers. Fig. 2 shows the geological map of the sliding area, as well as a hill-shading model obtained from a high resolution DEM (details on the DEM are given in the following section). The stratigraphic formations from bottom to top in the study area are defined as follows: Tanliaoti Shale (TL), Shihmen Formation (SM), Changhukeng Shale (CHb, CHm, CHt) and Kueichulin Formation (KC) (Huang et al., 2000, 2002; Wang et al., 2003). The Tanliaoti Shale is an early Miocene formation composed mainly of thick shale beds and subordinate interbeds or laminations, overlain by alternations of shale and siltstone beds. This formation is exposed about 800 m toward the east of the sliding area and it is bounded by sub-metamorphic rocks of the Hsuehshan Range Belt located on the footwall of the