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Impacts of the Chi-Chi earthquake on subsequent rainfall-induced landslides in central Taiwan

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Abstract

The influence of the Chi-Chi earthquake on subsequent rainfall-induced landslides was evaluated by comparing the occurrence of landslides in the Choushui River watershed through eight SPOT images that covered the period from 1996 to 2001. The Chi-Chi earthquake not only triggered serious coseismic landslides itself but also extensively disturbed surface strata around the epicentral area. After surface strata have been highly disturbed heavy rainfalls in 2000 and 2001 have triggered more landslides than the earthquake itself. Compared with the data obtained from images before the earthquake, it is obvious that the density of rainfall-induced landslides increased significantly after the earthquake, and the places where landslides occurred changed, as well. Although typhoon Herb in 1996 brought more precipitation than typhoon Toraji in 2001, only 9.77 km^2 landslides were induced by Herb, while 48.8 km^2 landslides–almost five times larger than those caused by Herb–were triggered by Toraji. Besides, landslides induced by Herb were mainly distributed in mid-slope areas, with slopes of 20–30°. After the Chi-Chi earthquake, the rainfall-induced landslides occurred mainly in places with slopes between 40° and 50°.

Keywords: Chi-Chi earthquake; Landslide; SPOT image; Choushui River; Taiwan

1. Introduction

In mountainous areas, landslides and debris flows are major natural hazards and threats to both human lives and environmental ecology. Previous studies have shown that rainfall and earthquakes are two main mechanisms that trigger landslides (Keefer, 1984; Schuster et al., 1996; Crosta, 2004). For earthquake-induced landslides, many studies have been concerned with the identification and description of coseismic landslides, particularly those caused by catastrophic earthquakes (see, for example, Keefer, 1984; Harp et al., 1991; Jibson et al., 1994; Harp and Jibson, 1996; Khazai and Sitar, 2004). However, a catastrophic earthquake always intensively disturbs ground strata and affects the stability of slopes for a long period of time. Therefore, to predict the landslide behavior for a region that has suffered a catastrophic earthquake it is necessary to keep tracking the occurrences and density of rainfall-induced landslides for a longer period. Unfortunately, far less research work has been done on this topic.

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Located on an active mountain-building region and having experienced the catastrophic Chi-Chi earthquake in 1999, Taiwan provides an excellent opportunity to investigate how a catastrophic earthquake affects subsequent rainfall-induced landslides. In this study, the Choushui River watershed, located near the epicenter of the Chi-Chi earthquake, is selected as the study area. Landslides identified from eight SPOT images that cover the period 1996–2001 are used to differentiate the variations of landslide occurrence prior to and after the earthquake.

To understand the impact of the Chi-Chi earthquake on the occurrence of subsequent rainfall-induced landslides, this study mainly focuses on the variations in the characteristics of rainfall-induced landslides prior to and after the earthquake. We are especially concerned with (1) the variations in the density of landslides, (2) the variations in the places where landslides occurred, (3) the influence of lithology on the density and the places of landslide occurrence, and (4) the impact of ground motion on the occurrence of landslides.

2. Study area

The Choushui River watershed in central Taiwan, which is the largest drainage basin on the island, was selected as the study area (Fig. 1). Previous studies (Lin and Jeng, 2000, Lin et al., 2004) have shown that this watershed is one of the most susceptible areas for landslides and debris flow hazards on the island. In the Choushui watershed, the horizontal peak ground acceleration (PGA) induced by the Chi-Chi earthquake was in the range of 100 to 1200 gal, and over 70% of the area suffered horizontal PGA over 600 gal (Fig. 1). Thus, the Choushui River watershed suffered violent shaking, and the ground was highly disturbed during the earthquake. Besides coseismic landslides, serious landslides and debris flows were also triggered in the watershed during the heavy rainfall brought by typhoon Toraji after the earthquake. Therefore, the Choushui River watershed probably is one of the best places to study the impact of an earthquake on the occurrence of subsequent rainfall-induced landslides.

Before the Chi-Chi earthquake, severe landslides had been triggered by several major catastrophic earthquakes in the study area (Cheng et al., 1999). The 1906 Meishan earthquake (M_L=7.1; at 23.55°N, 120.45°E), with a focal depth of 6.0 km, generated surface ruptures of over 13 km and caused severe landslides in the southern part of the Choushui River watershed. The 1941 Chungpu earthquake (M_L=7.1; at 23.40°N, 120.47°E) induced intensive landslides in the watershed. The Tsaolien landslide, similar to the landslide that occurred at the same place in the Chi-Chi earthquake, is the most famous example. Over 1.5×10^8 m^3 of debris slid down to the Chinshui River and formed a debris dam during the earthquake. The 1998 Reili earthquake (M_L=6.2; at 23.5°N, 120.7°E) caused some landslides around the southern boundary of the study area that were also reported. However, no quantitative data were recorded for the 1906 and 1941 earthquakes, and landslides triggered by the 1998 earthquake only occurred in a small epicentral area near the southern boundary of the Choushui River watershed.

The physiography of the Choushui River watershed is primarily composed of a series of approximately N–S trending mountain ranges, including the Yushan and Central Range, the Chunda Range, and the Alishan Range, and some N–S trending tributaries, including the Chunda River, the Chenyulan River, and the Chinshui River (Fig. 2). The Central Range, with a maximum elevation of over 3900 m, forms the backbone ridge of the island. A series of E–W trending rivers initiate from the backbone range and join the N–S trending Chunta and Choushui Rivers when they meet the southern extension of the Hsuehshan Range and the Chunda Range. The Chenyulan River, which closely follows the Chenyulanchi fault line, is the major river flowing through the area between the Chunda Range and the Alishan Range (Fig. 2). The Chinshui River mainly flows through the area between the Alishan Range and the low hills of the Western Foothills.

Almost all important geological units in the Western Foothills and the Western Central Range are present in the study area. Four geologically distinct areas–the Western Central Range, the inner belt of the Western Foothills, the outer belt of the Western Foothills, and the Coastal Plain–can be differentiated in the Choushui River watershed (Fig. 3). For convenience of discussion, the exposed rocks in the study area are grouped (roughly according to their age and mechanical behavior) into six stratigraphic units, including, in ascending order, Oligocene–Eocene metamorphic sandstone, Miocene–Eocene slate, Miocene sedimentary rocks, Pliocene sedimentary rocks, Pleistocene sedimentary rocks, and Holocene–Pleistocene terrace and alluvium deposits (Table 1). The Western Central Range primarily consists of Miocene and Pre-Miocene dark gray, well-cleaved slates inter-bedded with lenticular, thick-bedded to massive metamorphic sandstone. The inner belt of the Western Foothills is the region bounded by the Chelungpu fault in the west and the metamorphic slate belt in the east, and it is mainly composed of well-cemented, Miocene sandstone and shale. The outer belt