Occurrences and displacements of landslides by an earthquake with a subsequent rain: the 1999 Chi-chi earthquake in central Taiwan

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Abstract

Many landslides occurred during the Chi-chi earthquake (Ml=7.3) on 21 September 1999 in western central Taiwan. These landslides have been discerned from either aerial photographs or SPOT images, digitized, and coregistered with topographic maps at 1:25,000 scale. The data of the landslides were manipulated using ArcView GIS. Results indicate that the rock formation consisting of sandstone with shale interbeds in Miocene age was most susceptible to landslides, whether by the earthquake or by the rain. Most earthquake-induced landslides occurred on the upper part of the slopes and many transported displaced material to river channel. The average travel ratio of the earthquake-induced landslide was 1.2.

Study results indicate that the Toraji typhoon-related landslide in 2001 was a secondary disaster of the Chi-chi earthquake. Due to relatively high water content in the displaced material, the average travel ratio of the typhoon-related landslide reached 1.5, greater than the earthquake-induced one.

Key words: Chi-chi earthquake, Toraji typhoon, earthquake-induced landslide, typhoon-related landslide, travel ratio

1. Introduction

Landslide events are often fatal and damage engineering structures and other property. Rainfalls triggered most of the events and earthquakes did a few; therefore, the characteristics of a rain-induced landslide have been well studied to be capable of effectively mitigating the hazards. Unfortunately, damage from earthquake-induced landslides has sometimes exceeded that directly related to strong shaking. Estimating where and how far such landslides are most likely to occur and to travel are key elements in reducing damage in future earthquakes. However, we still have few data necessary to make such forecasts in a rigorous way. Jibson et al. (2000) suggested that regional analysis of a large group of landslides triggered in a well-documented earthquake is useful to estimate general conditions related to failure. The Chi-chi earthquake in Taiwan in 1999 presents an ideal case for such studies.

This study employed primarily by SPOT image and then aerial photo interpretations with subsequent field surveys. In the satellite or the aerial images, recent landslides, especially the disrupted type, often contribute their light-toned features for easily discerning them. A landslide could be divided into a failed area and an accumulated area, as shown in Fig.1. Practically, the boundary between the failed and the accumulated areas in an examined landslide is hardly determined from aerial photos or SPOT images; thus, a landslide area is considered to cover the failed area and the accumulated area in this study.

The perimeter of each landslide area was digitized, transferred to a digital map (1/25,000 in scale) and processed with MapInfo, software for GIS (geographic information system). Thus, the altitudes of the ridge, the head of the failure scar, the toe of the debris mass, and the river channel or the valley bottom can be easily read to calculate the slope height, the failure height, slope angle, and the travel distance of the landslide, as shown in Fig.1.

The earthquake-induced landslides for analyzing the distribution of size, slope angle, outbreak location and travel distance, were detected by aerial photograph in-

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Fig. 1 Schematic diagram showing morphometric measurement in a landslide
terpretation and mapped from the area centering the epicenter, as delimited by the box in Fig. 2. This mapped area was thought to be the most heavily affected region by the earthquake-induced landslides. The slopes being situated within a 20-km radius from epicenter have been supposed to be most vulnerable to seismic shocks (Inoue, 2000). Keefer (2000) also suggested that the seismic energy release that caused the landslides was concentrated near the epicenter rather than being uniformly distributed along the fault rupture.

Until the Chi-chi earthquake, no earthquake has damaged the study area for 30 years. Therefore, the landslides detected from the aerial photos taken in 1990-1998 are called rain-induced landslides, and those originated from the rain by the Toraji typhoon two years after the Chi-chi earthquake are called typhoon-related landslides in this study.

2. Physiography

Taiwan is situated on a collision zone where the Philippine Sea plate collides with the Eurasian plate. The Philippine Sea plate continues to move northwestward to the Eurasia plate at a rate of 7-8 cm/year (Ho, 1982). The uplift of the mountain range is estimated as 5 mm/year and the crustal shortening in western Taiwan at 2-4 cm/year (Yu & Chen, 1994). Frequent seismic activities (Tsai et al., 1987) indicate that the orogenic activity is still active.

The study area is located in western central Taiwan. Topography in the area ranges from basin plain and rolling hills on the west and the steep slopes of high mountains on the east. Geologically, the area is composed of Tertiary sedimentary and metamorphic rocks and a few Quaternary sediments (Table 1), of which strata age and rock induration increase eastward (Fig. 2). Four longitudinal faults, called the Chelungpu
fault, the Shuangtung fault, the Shuili fault, and the Lishan fault, divide the area into the outer foothill zone, the inner foothill zone, the Hsuehshan range, and the Backbone range (Ho, 1986). The outer foothill zone is a series of rolling hills; rocks formations including P1, P2, Ptk1, and Ptk2, as shown in Table 1. The inner foothill zone is expressed by slightly high relief landforms to distinguish from the outer foothill zone; it consists of a thick succession of alternating sandstone and shale, mainly Ms, Mj, and My. The Hsuehshan range and the Backbone range constitute the Central range of Taiwan, they consist of a great sequence of indurated and metamorphosed rocks, including O1, O2, EO, E1, E2, and M1.

3. Setting of the Chi-chi earthquake

The Chi-chi earthquake with ML=7.3 or MS=7.7 took place in western central Taiwan on September 21, 1999. Its focal depth was about 10km. This shallow earthquake killed about 2,400 persons, injured 8,700, destroyed over 6,000 buildings, and made 100,000 people homeless. Surface faulting extended for about 100 km along the north-south trending Chelungpu fault (Fig.2). The faulting dipping 25°-30° toward the east raised the hanging wall up to 3-10m.

About 10,000 Chi-chi earthquake-induced landslides in an area of 3,750km² were discerned from SPOT images (Wang et al., 2002). The earthquake-induced landslides were mostly distributed in the region between the Chelungpu and the Lishan faults; to the east of the Lishan fault, the Backbone range, the landslides were few. The Chi-chi-erh-shan landslide complex (1,140 ha in area), the Chi-chi-feng landslide (180ha), and the Tsao-ling landslide (620ha) were special landslides caused by this earthquake (Fig.2).

Mean annual precipitation varies from about 2,000 mm in the foothill zone to 3,000mm in the Central range; generally, the season from May to September is rainy. The rainfall in 1999 was less than annual mean precipitation, and that in the September of 1999 was cumulated to 79.5mm, which was 150.1mm less than a mean value, showing that the Chi-chi earthquake occurred in a relatively dry year. The Chi-chi earthquake-induced landslides seemed to be hardly correlated to precipitation causes.

4. Characteristics of the earthquake-induced landslide

4.1 Types of landslides

The landslides induced by an earthquake can be categorized into disrupted landslides, coherent landslides, and lateral spreads and flows on the basis of movement, internal disruption, and geological environments (Keefer, 1984; 2002). Parise and Jibson (2000) suggested that coherent landslides mostly have aspect ratios (L/W as indicated in Fig.1) close to 1; disrupted landslides are shown with greater aspect ratios to express their elongated shapes. The Chi-chi earthquake-induced landslides were mainly disrupted slides with some coherent ones, few lateral spreads were also

| Table 1 Rocks exposed in the studied area (revised from Ho et al., 1956; Ho and Tan, 1960; Ho, 1986) |
|---|---|---|---|
| Age | Formation | Symbol | Character |
| Recent | Alluvium | Qa | Boulders, cobbles, sand, silt, and clay. |
| Pleistocene | Terrace deposits | Qt | Loosely consolidated gravel, sand, and clay. |
| Plio-Pleistocene | Tougoshan Formation: | Ptk2 | Conglomerate with few thin sandy beds. |
| | Sandstone facies | Ptk1 | Loosely fine-grained to siltly sandstone. |
| Pliocene | Cholan Formation | P2 | Thick-bedded sandstone with thin shale. |
| | Chinshui Shale | P1 | Shale with thin siltstone interbeds. |
| Miocene | Kueichulin Formation | Ms | Sandstone and shale in alternation |
| | Shuilieng Formation | Mj | Muddy sandstone with shale interbeds. |
| | Takeng Formation | My | Dark gray shale with sandstone interbeds. |
| | Lushan Formation | M1 | Slate, phyllite, and little sandstone. |
| Oligocene | Shuichangliu Formation | O2 | Arglilite or slaty shale. |
| | Paileng Formation | O1 | Grayish white quartzitic sandstone. |
| Eocene-Oligocene | Chiayang Formation | EO | Slate with quartzitic sandstone interbeds. |
| Eocene | Tachien Sandstone | E2 | Quartzitic sandstone with slate interbeds. |
| | Shihpachungchi Formation | E1 | Slate with quartzite interbeds. |
Almost the landslides induced by the Chi-chi earthquake were disrupted. They were restricted to the weathered zone in bedrock; their failure depths ranging 1-5m (Lin et al., 2003). The disrupted landslides commonly occurred on the slopes steeper than 30°; sometimes they were found on the gentle dip slopes (less than 30°) where the rock was weakly cemented or well jointed across bedding planes, such as those found in the Cholan formation and the Sandstone facies of the Toukoshan formation. The disrupted slides were generally easy to recognize, whether on field or from aerial photographs, because of bare horseshoe-shape scarps or serrate scares tapering uphill at their heads and irregular rock fragments sloping downhill from source area, leading to show an elongated appearance of light tones on the photographs. The aspect ratios for the disrupted slides mostly ranged from 3 to 6. Some individual disrupted landslides might have small areas in size, but they originated from closely spaced sources and coalesced to form a landslide complex, which could possess an aspect ratio less than 1.

About 200 earthquake-induced coherent landslides in central Taiwan have been interpreted from aerial photographs; parts of them were checked on field. They mostly occurred on the slopes gentler than 30° in the foothill zone. These slides had a slid mass bounded by a bare main scarp and flanks; the slid mass could be broken into several blocks with tilting trees. Depressions or grabens were occasionally found on the head of the slid mass. About 70 coherent slides were measured their aspect ratios ranging between 0.8 and 2, as shown in Fig.3. Several localities, where correspond to the coherent slides discerned from the post-earthquake aerial photographs, illustrated horseshoe-shaped scarp with hummocky topography in the pre-earthquake topographic maps, implying that the Chi-chi earthquake reactivated several old landslides.

Few spreads were found on the alluvium areas nearby the Chelungpu fault. They developed on the gentle slopes, less than 3°, beside creeks. It seemed to result from liquefaction of underlying sand and silt and spreading of the surficial material.

No flow was found during the Chi-chi earthquake.

4.2 Size of landslide

About 1,200 landslides, excluding those less than 50 m in width and gigantic ones (the Tsao-ling landslide and the Chiu-fen-erh-shan landslide), from aerial photographs were analyzed. The earthquake-induced landslide ranged from slightly less than 0.2ha to about 30ha in size (Fig.4); the average area of the landslides was 1.6ha. About 50% of landslides were smaller than 1ha; the greatest frequency, 27% of the total landslides analyzed, appeared at the range of 0.5-1ha, then exponentially decreases with increasing landslide area.

The size of the disrupted landslides caused by the Chi-chi earthquake widely varied, from a 0.1ha one to a 30ha landslide complex; the coherent landslides were generally larger than 2ha.

4.3 Slope angle and height

The slope angle exerts a significant influence on the
a steep slope is generally more susceptible to the failure than a gentle one. The slope angles that the earthquake-induced landslides occurred on ranged from 5° to 80° (Fig.5), and the slope heights \( H_r \) as indicated in Fig.1) varied between 10m and 1,000m. More than 80% of the landslides distributed on the slopes steeper than 30° with slope heights between 50 m and 1,000m, and they were chiefly disrupted landslides.

In general, the slope angles increase with the slopes heightening; the landslides on low slope angles were mostly small in size and located on the top or near the base of the medium slopes. The landslides on slope angles greater than 50°, but slope heights less than 150m, were concentrated on the outer foothill zone; especially, twice of the average density of this kind of landslide \( (0.1 \text{ landslide/km}^2) \) was found in the Ptk2, and local geology was considered to have relation to their distribution.

4.4 **Outbreak and stop locations**

A relative failure location is used to represent an outbreak location where a landslide occurred on a hillslope. A relative failure location is expressed by the ratio of the vertical distance between the crown and the ridge to the slope height (Fig.1). The value for the relative failure location shown as 0-0.3, 0.4-0.7, and 0.8-1 signifies a location at the upper, the middle, and the lower part of a slope, respectively.

Fig.6 illustrates about 70% of the Chi-chi earthquake-induced landslides occurring on the upper part of slopes and a few on the lower part. The landslides at the lower part of slopes mainly distributed on the slopes higher than 300m and none on the slopes lower than 100m (Fig.7).

A relative accumulation location is used to define a location where displaced materials stopped. It is represented by the ratio of the vertical distance between the toe and the valley bottom to the slope height \( \text{Ht/Hr} \) as shown in Fig.1): the value for the relative accumulation location equals 0 indicating a location at the valley bottom.

40% of the Chi-chi earthquake-induced landslides showed the relative accumulation location between 0.2 and 0.8 (Fig.8), implying that their displaced materials were still accumulated on the slopes after the Chi-chi earthquake calmed down.

4.5 **Gigantic rock avalanche**

Two gigantic rockslides, the Chiu-fen-erh-shan landslide and the Tsao-ling landslide, on dip slopes resulted in devastating rock avalanches during the Chi-chi earthquake: they killed 39 and 19 persons, respectively.

The Tsao-ling landslide is located in a mountainous area about 30km southwest of the epicenter (Fig.2). The slid debris reached \( 1.2 \times 10^8 \text{m}^3 \) in volume. The source slope was 800m high with an average slope angle of 20°. 5° steeper than the bedding plane’s dip angle. The slope has suffered catastrophic rockslide events, by either an earthquake or a heavy rainfall, four times before the Chi-chi earthquake. Apparently, this source slope can be referred to a highly potential rock avalanche slope as suggested by Keefer (1984). Chigira et al. (2003), Hsu and Leung (1977), Huang et al. (1983), Hung (1980), and Hung et al. (2002) have ex-

The Chiu-fen-erh-shan landslide is located at about 10 km northeast of the epicenter (Fig. 2). The peak ground acceleration recorded by a CWB (Central Weather Bureau in Taiwan) seismic monitoring station about 6 km north of this landslide was 465.3 gal in east-west component, 370.5 gal in north-south component, and 274.7 gal in vertical component during the Chi-chi earthquake. The mass moved along the bedding plane with a strike/dip of N30°-50°E/SE20°-36° (Wang et al., 2003). The materials slid chiefly composed of thick-bedded muddy sandstone with subordinate shale, estimating a volume of 3.5 × 10^7 m^3. The slid materials buried 39 persons and 289 Asiatic deer, and blocked a confluence of two streams leading to the formation of two ponds. One pond was 4.4 ha in size and 18 m in depth, and the other was 6.4 ha and 31 m. The Chiu-fen-erh-shan landslide possessed a 102 ha failed area and a 92.5 ha deposited area.

The gigantic landslide deposit is often characterized by its constituent pieces being not far removed from their original positions relative to each other (Davies, 1982). Fig. 9 shows the distribution of the wreckage of the houses, which originally located at the upslope before the Chiu-fen-erh-shan landslide event. The distribution of the houses can be detected from the pre-earthquake aerial photos and 1/5,000 scale topographic maps; the houses' wreckage and/or the victims found are located with the GPS. Though the displaced material of this landslide traveled for about one kilometer with a high speed, its constituent pieces, including damaged houses and victims, were not widely separated to deposit. It seemed that the shallow part of the displaced material was subjected to little disturbance. The slope seemingly started to fail at the lower part (Wang et al., 2003) and extend toward the up-slope instantly, leading that the displaced materials were moved along for several hundreds meters as if sitting on a magic carpet.

5. Comparison with Toraji typhoon-related landslide

Taiwan is averagely attacked by 3.2 typhoons per year; and the typhoons often bring high precipitation to damage the slopes in this island.

After the Chi-chi earthquake, Taiwan had been attacked by 17 typhoons, of which the Toraji typhoon on 30 July 2001 brought heavy rainfall, 230-714 mm/day, to central Taiwan. The hourly rainfall, 130 mm/hr, by the Toraji typhoon broke the record for the last 20 years. Consequently, the Toraji typhoon triggered more than 10,000 landslides, which were delineated from SPOT images, in central and eastern Taiwan. This event killed 230 and wounded 189, leading to the most serious rain-induced disaster during the last 35 years in Taiwan.

5.1 Comparison in landslide size

More than 6,000 typhoon-related landslides were found in central Taiwan. These landslides were summed up to 13,500 ha; about 60% of the landslides were less than 1 ha, and 36% between 1 and 10 ha (Fig. 10). The averaged area of the typhoon-related landslide is 2.8 ha/landslide, larger than that of the earthquake-induced. The aerial photo interpretation shows that about 30% of the typhoon-related landslides were derived from outward widening the earthquake-induced landslides, inferring that the strata near the earthquake-induced have been shattered by the Chi-chi earthquake shake.
5.2 Comparison in landslide type

The typhoon-related landslides were mainly disrupted slides and some debris flows that have not been reported during the Chi-chi earthquake. The debris flows found before the Chi-chi earthquake generally occurred in the gullies with catchment area greater than 0.1 km². The Toraji typhoon-related debris flows took place in the gullies with catchment area less than 0.03 km² (Lin et al., 2003), and some even in the areas without significant gully topography. The accumulation of the earthquake-induced landslides’ debris at valley bottoms and on slopes, as shown in Fig. 8, seemed to greatly affect the occurrence of the typhoon-related debris flow.

5.3 Comparison in location on slope

Fig. 11 illustrates that the rain-induced landslides mostly occurred on the lower part of slopes in contrast to the earthquake-induced mainly on the upper part. In addition, the earthquake-induced landslides were concentrated on the slope angle with 40°, while the rain-induced shifted to the slopes dipping about 30°, as shown in Fig. 12. These observations might result from the ground motion amplified on the higher and steeper slopes and the rainwater concentrated on the lower and gentler.

The typhoon-related landslides showed similar distribution results to the earthquake-induced (Figs. 11 and 12). Tension cracks on up-slopes and failed materials on mid-slopes were obviously found by field reconnaissance after the Chi-chi earthquake. Apparently, the distribution of the Toraji typhoon-related landslides had relation to the Chi-chi earthquake event.

5.4 Comparison in geology

The failure rate in a stratum or a rock formation is expressed by the percentage of the landslide area to the stratum area.

Fig. 13 shows that the rain-induced failure rates commonly decreased from the Central range to the foothill zone; it could result from more precipitation in the Central range than the foothill zone. Moreover, the typhoon-related failure rates were mostly greater than the earthquake-induced ones in the same stratum, implying that many earthquake-induced landslides could be widened during the Toraji typhoon.

The uniquely great failure rate in the Ptk2 seemed to be mainly caused by the strong ground motion on the ridges in the Chi-chiu-feng hilly area during the Chi-chi earthquake (Hayashi et al., 2002).

All kinds of failure rate were great in the Ms (Fig. 13). It could result from well-developed bedding planes and joints in the alternate layers of sandstone and shale of which the Ms is composed. This type of stratum seems to be highly susceptible to landslides, whether by earthquakes or by rains.

The O1 and the E2 are formations consisting mainly of quartzite. However, the O2, the EO, and the El are chiefly a thick series of slate. The O1 and the O2 are distributed in the western part of the Hsuehshan range, and the O1 had a greater earthquake-induced failure rate (1.2%) than the O2 (0.7%). Similarly, the EO, the E2, and the EI occupy the eastern part of the
Hsuehshan range, and E2 had a greater earthquake-induced failure rate than the others. It could be attributed to a ductile character in argillaceous rocks.

The M1 is almost consists of slate. Due to the ductile character and a long distance from the epicenter, the Chi-chi earthquake caused few landslides in the M1 and might have left some fractures, which resulted in a great Toraji typhoon-related failure rate in the M1.

5.5 Comparison in travel distance

The travel distance of displaced material is an important factor for evaluating the landslide risk. The failure length is defined as the maximum plane length of the failed mass from head to foot; it is thought to be equivalent to the travel distance in this study. The ratio of the travel distance to the failure height, \( L/H \) as shown in Fig.1, is called travel ratio.

The travel ratios of the earthquake-induced landslides, excluding those less than 50m in width and gigantic rockslides, distributed from less than 0.5 to slightly greater than 7 (Fig.14); 94% of the earthquake-induceslandsides were equal to or less than 2.5 in travel ratio. The average travel ratio of the Chi-chi earthquake-induced landslide was 1.2. The travel ratio may decrease with steepening the slope. The travel ratios less than 0.5 were originated from the disrupted slides on the slopes steeper than 65°. Few coherent slides on slope angle about 10° with low failure heights could result in travel ratios up to 7.

The greatest travel ratio for the typhoon-related landslide reaches 3, and 99.7% of the landslides had their travel ratios equal to or less than 2.5 (Fig.15). The horizontal travel distance of the Toraji typhoon-related landslide is averagely 1.4 times of the failure height. The travel ratio for the Toraji typhoon-related landslide was greater than that for the Chi-chi earthquake-induced, apparently being due to relatively high water content in the displaced material of the typhoon-related landslide.

6. Conclusion

The Chi-chi earthquake-induced landslides mainly distribute in the area between the Chelungpu fault and the Lishan fault in western central Taiwan, basically coincided with the region of major aftershocks. Because of a relatively dry year, these landslides seem to have little relation to precipitation causes.

The earthquake-induced landslides are mainly disrupted slides with a few coherent slides. The disrupted slides mostly occurred on the slopes steeper than 30°; the coherent slides commonly occurred on gentler slopes. Several coherent slides might be resulted from the reactivation of old landslides by seismic shaking.

The average area of the earthquake-induced landslide is 1.6ha, which is less than the Toraji typhoon-related landslide's (2.8ha). An aerial photo interpretation result shows the earthquake-induced landslides being enlarged during the Toraji typhoon. Besides, the typhoon-related failure rates are mostly greater than the earthquake-induced ones in the same rock formation, indicating that the strata near the earthquake-induced have been shattered by the Chi-chi earthquake shake.

The Toraji typhoon triggered some unique debris flows, which have never been found on the slopes without significant gully topography in Taiwan before. Much earthquake-induced landslide debris accumulated on the slopes seems to be responsible for these unique debris flows.

About 70% of the earthquake-induced landslides originate on the upper part of slopes in contrast to the rain-induced mainly on the lower part. Furthermore, the earthquake-induced landslides are concentrated on the slope angle with 40°, while the rain-induced shift to about 30°. The typhoon-related landslides show similar distribution results to the earthquake-induced and can
be considered as a secondary disaster of the Chi-chi earthquake.

Comparing with the arenaceous strata, the argilaceous strata are more resistant to earthquake shakes, but less resistant to rains. A stratum composed of well-developed bedding planes and joints in the alternated layers of sandstone and shale, such as the Ms, is highly susceptible to landslides, whether by earthquakes or by rains.

The average travel ratio for the earthquake-induced landslide is 1.2, while that for the typhoon-related is 1.4; it seems to result from relatively high water content in the displaced material of the typhoon-related landslide.

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