Topographical Changes Due to Heavy Rainfall in the Chiu-Fen-Erh-Shan Landslide Triggered by the Chi-Chi Earthquake in Taiwan

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Abstract

This paper reports on topographical changes in the sediment area in the Chiu-fen-erh-shan landslide located in Nantou County, central Taiwan. This landslide was triggered by the Chi-Chi earthquake ($M_L = 7.3$) on September 21st, 1999. Field work-surveys conducted from 1999 immediately after the earthquake, to 2005. This landslide is a huge dip-slope slide, and about 1 km wide, 2 km long and 80m deep. The landslide buried several valleys on the lower slope, reaching a maximum depth of about 80m, and yielding four natural dams. The maximum depth of the water in these dams reaches about 30m. After the Chi-Chi earthquake, the heavy rainfalls accompanying the Toraji and the Nari typhoons in 2001 followed by the Mindulle and the Aere typhoons in 2004, greatly changed the topographical features of the landslide sediment area. The most dramatic changes in the sediment area mainly occurred along a main spill way which was constructed as a countermeasure against flooding. Groundsel and revetment works were severely damaged due to these changes. In particular, downstream of the main spill way from the confluence where the tributary comprises the basin of the slope of the Chiu-fen-erh-shan landslide, the facilities damage, river bed degradation and occurrences of landslides along the main spill way were remarkable. Erosion of the initial ground surface after the earthquake reaching up to about 30 m provided an earthflow to the downstream area. The landslides which occurred along the main spill way were generated on slopes covering the initial valleys before the occurrence of the earthquake, and the area of these landslides likely spread due to heavy rainfalls which followed after the earthquake. Investigation into the topographical changes in the Chiu-fen-erh-shan landslide provided valuable information about phenomena seen after occurrence of a huge landslide.

Keywords: Chiu-fen-erh-shan landslide, Chi-Chi earthquake, Topographical change, Sediment area, Typhoon

Introduction

The Chi-Chi earthquake ($M_L 7.3$) which occurred on September 21st 1999 caused numerous landslides in the mountainous region of central Taiwan (Kondo *et al.*, 2003; Kawabe *et al.*, 2003; Hayashi *et al.*, 2004; Numamoto *et al.*, 2004; Hayashi *et al.*, 2005; Kondo *et al.*, 2005). A huge landslide having about 1 km wide yielding natural dams occurred at the Chue-fen-erh-shan district in Nantou County (Hayashi *et al.*, 2004).

In general, the topography of landslide sediment areas changes due to rainfall after an earthquake. Rapid topographical change may be generated by the collapse of a natural dam. Though the frequency of such massive landslides occurring is low, a lot of damages is caused to a region, and the effects of a slide of this magnitude continues into future. The sediment area of the Chue-fen-erh-shan landslide was affected by topographical changes caused by heavy rainfalls following the earthquake. These topographical changes observed here provide useful information about applying methods to countermeasures against landslide occurrence in the future.

This paper reports on topographical changes in the sediment area of the Chue-fen-erh-shan landslide area. The findings are based on field study and surveys which examine the factors yielding degradation, sedimentation and landslide.

Outline of Chue-fen-erh-shan landslide

The Chue-fen-erh-shan landslide, locates at Chang-shih- siang, Nankang Village in the Kou-hsing township of Nantou County, occurred in the left basin of Chiutsaihu creek which flows into the Peishankeng

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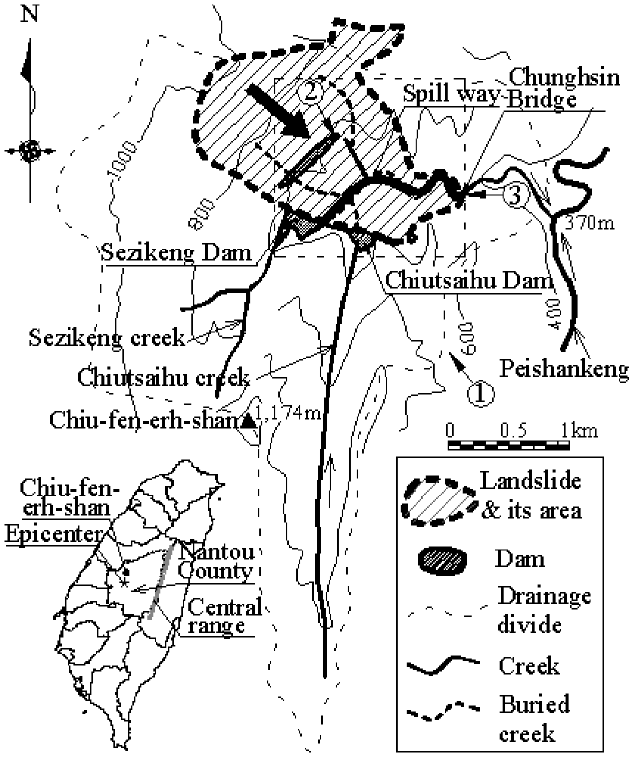

Fig. 1. Outline figure of the Chiu-fen-erh-shan landslide

Photo. 1. View of the Chiu-fen-erh-shan landslide (taken on Dec. 17, 2000)

Photo. 2. Four dams produced by the landslide (taken on Dec. 16, 2000). Bottom side: Dam at toe of the landslide, Up-right side: Sezikeng Dam, Up-middle side: Chiutsaihu Dam, Up-left side: Dam in right tributary

tributary that is to the left of the Wushi River. This landslide is far about 13 km north-northeast of the Chi-Chi earthquakes' epicenter. The seismological station (TCU089) nearest the Chue-fen-erh-shan landslide, recorded 225 gal in the N-S, 348 gal in the E-W and 190 gal in the U-D as the peak accelerations. A vast slope to the left of the confluence of the Chiutsaihu and the Sezikeng creeks has slid due to the Chi-Chi earthquake as shown in Fig.1, killing 41 residents. The sliding body created two big natural dams by filling the Chiutsaihu and Sezikeng creeks over 1,600 m. The dam in the lower side in Photo 1 will hereafter be referred to as the Chiutsaihu dam and the other one is called the Sezikeng dam. Two smaller natural dams can be also seen in Photo 2. The dam in the upper left corner in Photo 2 is a part of the right creek among the Chiutsaihu creeks. Another small dam in the lower right corner in Photo 2, produced a boundary between the upper part of the sediment area and lower part of the slope of the Chue-fen-erh-shan landslide.

Table 1. Main rainfalls causing degradation, sedimentation and landslide in the sediment area

	2001		2004	
Monitoring Stations	Peishan primary school		Chiu-fen-erh-shan	
Terms	July 29-30	Sep. 16-19	July 1-5	Aug. 24-30
Names of Typhoons	Toraji	Nari	Mindulle	Aere
cumulate rainfalls	360.5 mm	70.0 mm	1,158 mm	612.0 mm
Maximum daily rainfalls	357.5 mm (30th)	49.0 mm (17th)	464.5 mm (4th)	430.0 mm (25th)
Maximum hourly rainfalls	95.0 mm (9:00)	7.5 mm (2:00)	98.5 mm (8:00)	43.5 mm (2:00)

* Parenthesis indicates day and time of occurrences
Maximum hourly rainfall occurred at the same day
when maximum daily rainfall occurred

The Chue-fen-erh-shan landslide (hereafter referred to as the main landslide) occurred at the southeast slope of the Chiutsaihu basin. The main landslide has an average width of about 1 km, a length of about 2 km, an area of about 195 hectares and a sediment volume of about 35 million cubic meters (Hayashi *et al.*, 2004). The depth of the slip surface of the main landslide reached a maximum size of about 74 m, with an average size of about 45 m(Hayashi *et al.*, 2003). The average angle of inclination is 22 degrees at the upper part of the slope and 27 degrees at the lower part of the slope (Kondo *et al.*, 2001). The basin of the Chiutsaihu creek exhibits a slender shape influenced strongly by an axis of syncline in a north-south direction, as shown in Fig.1. The Soil and Water Conservation Bureau of Taiwan has constructed countermeasures such as a spill way, groundsel works, and revetment works to combat the erosion of sediment area caused by water flow over the natural dams.

Rainfalls after the Chi-Chi earthquake

Several topographical changes such as degradation, sedimentation and landslide in the sediment area after the Chi-Chi earthquake were caused mainly by heavy rainfall in 2001 and 2004. Though the Nari typhoon during the 16th to 19th, September, 2001 did not bring much precipitation, the Toraji typhoon during the 29th to 30th, October, 2001 produced heavy rainfall over the Chue-fen-erh-shan district, as shown in Table 1 and Fig.2. The precipitation station located at the Peishan primary school far about 6 kilometers north-northeast of the main landslide, recorded a maximum hourly rainfall of 95.0 mm and daily rainfall of 357.5 mm during the Toraji typhoon. The heavy rainfalls brought by these typhoons caused much damage throughout Taiwan (Kondo *et al.*, 2003). In 2004, the Mindulle typhoon during the 1st to 5th, July brought a maximum hourly rainfall of 98.5 mm and an accumulated rainfall of 1,158 mm at the monitoring station of the Chiu-fen-erh-shan district, which was founded after the occurrence of the main landslide. The event caused by this heavy rainfall is called the 72 Water Induced Disaster in Taiwan. Following this, the Aere typhoon during the 23rd to 25th, August brought a maximum hourly rainfall of 43.5 mm and an accumulated rainfall of 430 mm at the same monitoring station. This typhoon also struck Taiwan directly.

Degradation in the sediment area

Survey of topography

The authors had been investigating continuously from December, 1999 after the earthquake to December, 2005. Surveying of the topography twice a year from 2002 after the Toraji typhoon to 2004 and once a year in 2005 were performed, and clear topographical changes mainly in a main spill way and its slope in the sediment area have been observed. Longitudinal and crossing sections of the main spill way and locations of some features such as groundsel works, were surveyed using a non-prism laser range finder with compass function based on azimuth. Water depths of the Chiutsaihu and Sezikeng dams were measured by survey rope with a weight at its end lowered from a boat. The positions of the boat were specified by the non-prism laser range finder giving distance, azimuth and inclination angle, installed at a fixed point.

The plan which was drawn based on the survey is shown in Fig.3. The location of this plan throughout the basin area of the Chiutsaihu creek is indicated in Fig.1 by a square of broken line. In this plan, the suffix 'D' indicates a numeral of the groundsel works constructed of concrete piles. Numeral suffixes are numbered from upstream to downstream. Broken lines indicating buried creeks are drawn based on a topographical map

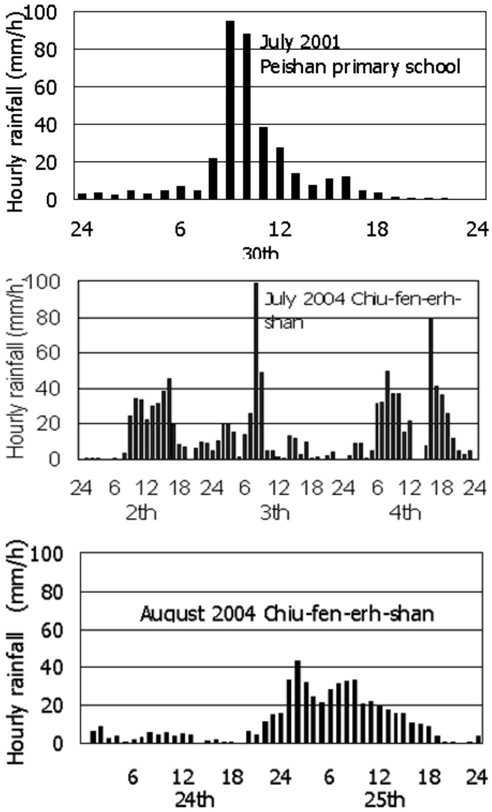

Fig. 2. Main rainfalls causing degradation, sedimentation and landslide in the sediment area

1/25,000 in scale. Ends of the traverse line D and lower part of line A in Fig.3 are connected with base-GPS-point and GPS-point at the right wing of a slit dam at the downstream-end of the main spill way. The ends of line D, and the upper parts of line A and C are connected with the base-GPS-point and the GPS-point at the slope in the main landslide. Errors of the former line are 9.6m in horizontal distance and 2.6m in vertical height. Errors of the later line are 12.6m in horizontal distance and −0.4m in vertical height. The closing ratios are 1/150 and 1/120, respectively.

The longitudinal figure of the main spill way (line A) based on the survey is shown in Fig.4. The elevation in water level in the Sezikeng dam is set to 572 m and an origin of horizontal distance is set at the Chung-hsin bridge. Broken lines directly above the river bed lines indicate the intended river bed lines which would comply with the structure of the groundsel works. This figure also shows the river bed of the buried creek as a broken line. Longitudinal figures shown later are also arranged in the same way. The maximum thickness of the sediment is around 75 m at the D1 section and the maximum depth of the Sezikeng dam reached 30m. The figure of line B that is a section along the buried Chiutsaihu creek is shown in Fig.5. The figure for downstream from the D1 section is omitted because of overlapping with line A. Sediment along line B is about 80 m deep. The altitude of the water level of the Chiutsaihu dam at 20 m deep is higher than that of the Sezikeng dam at 7 m. Fig.6 shows the figure of the line C that covers from the left spill way to the slope of the main landslide. The depth of the sediment at point E is about 65 m.

Outline of degradation to understand from photographs

The greatest topographical changes have been generated in the sediment area. Photo 3 shows the degradation along the spill way from December, 1999 after the earthquake to December, 2005. The positions and the directions of photographs are marked in Fig.1. Photo 3 in 1999 shows the spill way excavated without timbering by the Soil and Water Conservation Bureau to deal with floods from the Sezikeng dam. Photo 3 in 2000 shows that the main spill way having 20 m wide and 2 m deep, was protected by dry pitching work, using coarse stones (Hayashi *et al.*, 2003).

However, as shown in Photo 3 taken in September, 2001, the main spill way suffered greatly from river bed degradation caused by heavy rainfall mainly accompanying the Toraji typhoon which struck in July, 2001. To prevent further degradation, groundsel work had been carrying out in steps in our investigation done in

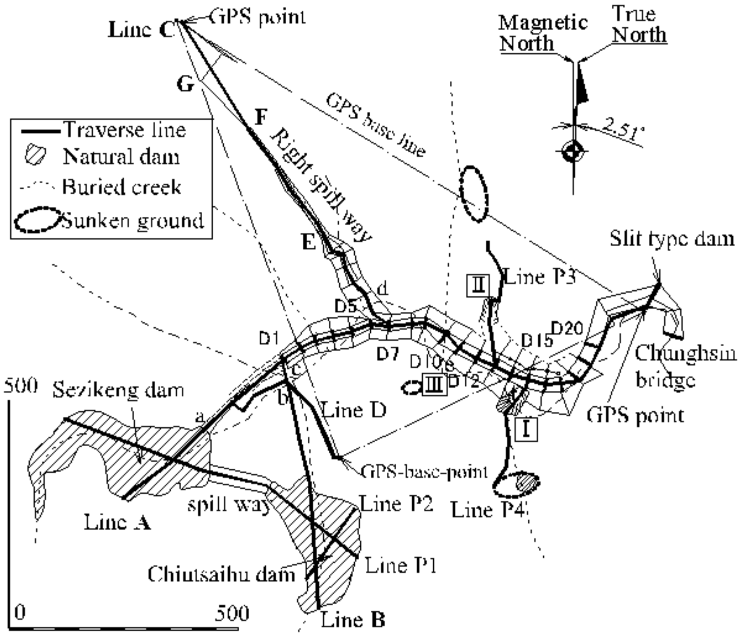

Fig. 3. Plan based on survey

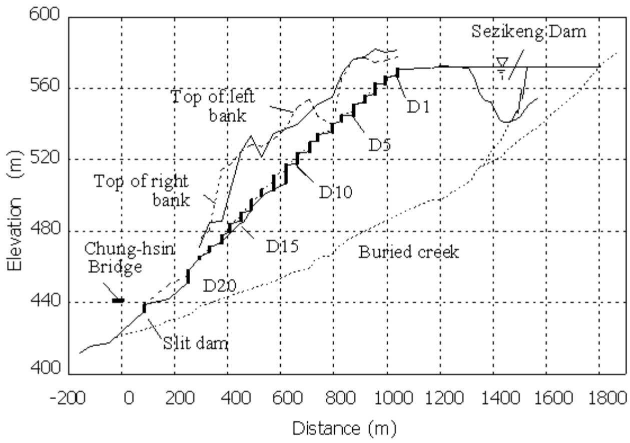

Fig. 4. Longitudinal figure of the main spill way (line A)

September, 2002. As indicated by Photo 3 taken in September, 2003, 20 groundsel works in steps were near completion and wet masonry work using coarse stones between the groundsel works and slope vegetation had been under construction.

In spite of these works, as shown in Photo 3, taken in September, 2004, the foundations of the groundsel works were greatly scored by torrents and landslides which occurred at the slopes along the main spill way following the Aere and Mindulle typhoons, striking one after the other in July then in August in 2004. These situations will be further described later.

Though countermeasures against damage to the groundsel foundation had been performed, as indicated in Photo 3, taken in December, 2005, other groundsel works had been scored. Not reported in photographs in this paper, sediment control dams were erected downstream of the Chung-hsin bridge at the edge of the spill way to control reflowing of sediment that was flowing down from upstream caused by the heavy rainfalls of 2004.

Degradation in the main spill way

In 1) and 2) of Photo 3 taken before the disaster after the earthquake, the relative height between the sediment surface and the river bed of the main spill way must have been small. By contrast, in Fig.4, the

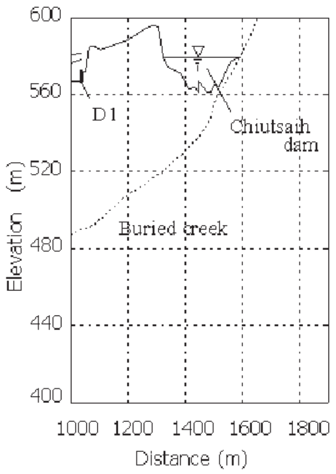

Fig. 5. Longitudinal figure of traverse line B

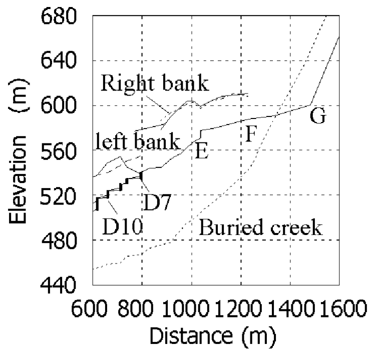

Fig. 6. Longitudinal figure of the left spill way (line C)

relative height between the tops of the slope on both sides of the main spill way and the crowns of flood way of groundsel, are range from 20 m to 30 m. This is presumed to be resulted by the degradation due to the heavy rainfalls in 2001.

In Fig.4, the average stream gradient having around 1/7.1 from D1 to the Chung-hsin bridge, decreased to 1/12.0 as influenced by 21 groundsel works. The groundsel works as countermeasure to prevent degradation are composed of concrete piles 1 m in diameter staggered in arrangements of 3 rows on concrete footings 1.8 m thick and 7 m wide. The piles are driven into a foundation from the bottom of the footing to protect subsidence and to maintain bearing capacity. Clearances between the piles are filled by boulders. The dam at the downstream edge (on the right upstream of the Chung-hsin bridge) in Fig.3 has a slit type gravitational concrete structure.

Degradation in the left spill way

As mentioned previously, the natural dam, shown as a white circle in Photo 2, extending from the northeast to the southwest had been formed immediately after the occurrence of the main landslide between the points F and G in Fig.6 which are located around the foot of the main landslide. The left spill way from D7 to point F in Fig.6 has been excavated. Tributaries which had a basin consisting of the slope before the occurrence of the main landslide had jointed the Chiutsaihu creek spanning from the crest of the Sezikeng dam to D7. Due to the occurrence of the main landslide, outlet of the basins of these tributaries have moved, flowing into the left spill way. The left spill way has jointed the main spill way to the D7. The natural dam, shown as white line in Photo 2 located at the foot of the main landslide, disappeared due to flowing down of residual soil on the main landslide slope.

Knick point can be seen at point E in Fig.6. The gradient of the lower reaches from the point E reveals a steep stream with a gradient of about 1/6. The upper reaches from point E reveals a gentle stream with a gradient of about 1/19.

Factors causing degradation, sedimentation and landslide

The main trigger causing topographical changes is a runoff caused by heavy rainfalls. In this chapter, other factors causing **degradation and sedimentation** in the main spill way including landslides on the slope along the main spill way, will be discussed.

Natural basin and landslide basin

The whole of the basin area of the Chiutsaihu creek is 10.6 km^2. The relative height from the peak of the Chue-fen-erh-shan mountain to the confluence with the Peishankeng river downstream of the Chiutsaihu creek is about 800 m. The slopes in the basin, in general, are steep but are relatively gentle in the upper part of the slopes near the watershed divide. The Chiutsaihu creek before the occurrence of the main landslide met with the Sezikeng creek at point b in Fig.7 (Fig.3).

The water of the Chiutsaihu dam flows into the Sezikeng dam through the spill way connecting them.

Photo. 3. Degradation of the main spill way (The slope behind the main spill way is the main landslide)

Therefore, rain water from both the basins flows over the flood way of the Sezikeng dam. In the upstream basin of the both dams, no large sacle landslides have occurred, thus forest has been permitted to grow. The basin of the Sezikeng dam could be called the "natural basin" (area = 6.64 km^2).

The main landslide caused by the earthquake had occurred in the basins flowing into the Chiutsaihu creek at points b, c and d. By the occurrence of the main landslide, rain water in all these basins began to flow into the main spill way at point d (D7) through the left spill way. The main landslide area almost covers these basins. Throughout the whole basin consisting of the dip slope, the terrain is exposed rock, thus, rain water quickly runs off as surface flow. This basin could be called the "landslide basin" (area = 1.40 km^2).

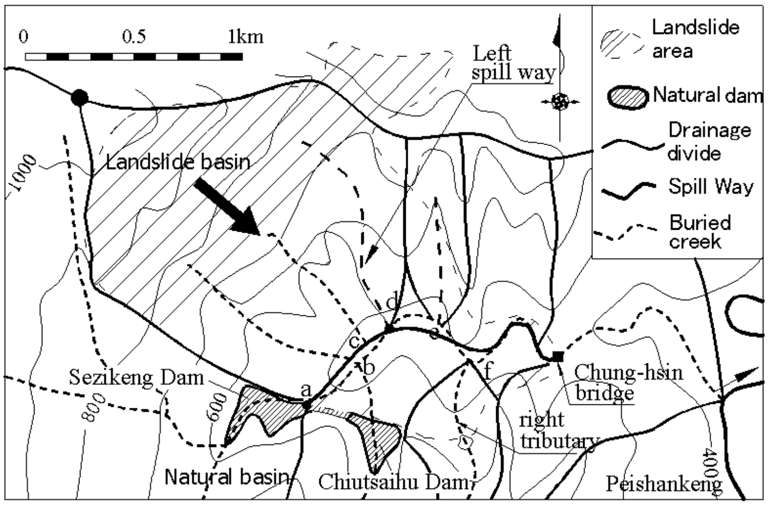

Fig. 7. Outline of the buried creek and its basin

Photo. 4. Comparatively stable main spill way at D2 Downstream direction taken from D2 (Sep. 4, 2004)

Photo. 5. Downstream of knick point E taken on Dec. 27, 2004

The runoff-characteristic of the landslide basin has changed due to the depletion of forest that grew before the occurrence of the main landslide. As a consequence, the increasing runoff coefficient and shortened time of flood concentration have been produced. Sediment runoff from the main landslide slope and consequent deepening of the river bed of the left spill way are likely to be induced by a greater flood discharge, when compared with flooding in the natural basin.

On the contrary, the upper reaches from D1 to D7, that is the upstream section of the confluence with the left spill way have been maintaining a stable situation as shown in Photo 4, though the occurrence of some small landslides on the slope along the main spill way and somewhat scoring of the foundation of the groundsel works can be seen. The natural basin produces floods with little sediment, and the two natural dams interrupt sediment runoff if it does occur. Under these conditions, the reaches from D1 to D7 are maintaining a relatively stable situation when compared to the area downstream of the main spill way, as mention below.

Protecting degradation by big rocks in the left spill way

In the left spill way, no countermeasure to prevent scoring of the river bed have been employed. In Fig.6, the river bed from D7 to E (knick point), where the gradient is steeper ($i = 1/6.0$) than that of the main spill way, has greatly suffered from scoring, as shown in Photo 5. At the knick point E, there is a group of big rocks as shown in Photo 6 that had existed and transported within the body of the main landslide. The group of rocks is protecting a degradation in the upstream of point E in which gradient of the river bed is relatively

Photo. 6. Group of rocks at the knick point E (Spring water can be seen, taken on Dec. 27, 2004)

Photo. 7. Sediment upstream of the knick point E (Direction to left spill way from on the landslide slope taken on Dec. 27, 2004)

Photo. 8. Sedimentation from the left spill way taken on Sep. 4, 2004

gentle ($i = 1/19$). However, spring water can be observed at downstream of point E. Erosion or collapse of this group of rocks will increase the probability that enormous sediment in the upstream, as shown in Photo 7, would run off downstream.

Landslide causing sedimentation and degradation in middle reaches of the main spill way

Photo 8 shows the situation of a section in the main spill way just downstream of the confluence involving the left spill way. Enormous soil from the landslide basin through the left spill way is deposited. Erosion, scoring and sediment runoff in the downstream reaches of the left spill way have become increasingly prevalent (see Photo 5). The piles of the groundsel works were worn away and partially damaged by the flood which carried much stone and rock.

Fig.8 is an expanded figure of the longitudinal figure from D10 to D17 in Fig.4. In this figure, vertical lines indicate the groundsel works and the broken line indicates the intended river bed. The solid line below indicates the lowest section of river bed running behind the wing of the groundsel. Its location is shown in Fig.3 from D12 to D17 in the left bank of the main spill way. Fig.8 shows that a section of river bed from D10 to D17 suffered a lot of scoring. The level of the foundation of D11, as shown in Photo 9, was degraded up to 10 m from the intended river bed. This groundsel has controlled the height of the upstream river bed of the main spill way. If it becomes damaged, the possibility of further degradation of the river bed increases

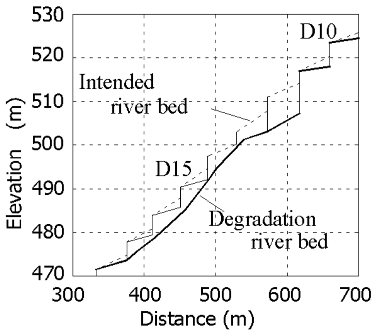

Fig. 8. Longitudinal figure from D10 to D17 of the main spill way

Photo. 9. River bed degradation of apron of groundsel taken on Sep. 4, 2004

Photo. 10. New water way in the left of D12 taken on Sep. 4, 2004

upstream. The lowering of the river bed generates a new water way behind the wing of the groundsel as shown in Photo 10. Generating a new water way promotes degradation of the river bed because of weaknesses in the sediment soil. Therefore, one of integral causal factors promoting degradation of the river bed is certain to be a formidable landslide (Ls. II) in the slope along the main spill way, as will be mention later.

Old topography causing landslides in the slope along the main spill way

Presently, the fundamental form of the slope along the main spill way has been generated by scored river bed produced by heavy rainfall accompanying the typhoon in 2001. After these events, groundsel and revetment works against erosion were constructed, and simple vegetation on the slope was planted. However, no further countermeasures against the slope such as cutting down the slope to stabilize, has been conducted.

The slope under this situation suffered two big landslides and one small one as shown in Fig.3 caused by heavy rainfall which accompanied two typhoons in 2004. These landslides are hereafter called Ls. I, Ls. II and Ls. III in ascending order. The shapes of the landslides in Fig.3 are based on conducted surveys. These landslides occurred along the main spill way downstream of the confluence with the left spill way as shown in Fig.3. The situations of each landslide are shown in Photo 11. In Ls. I, spring water from the slope could be seen from our investigations done in September 4th, 2004. A wet zone at the toe of the slope could also be seen in December 24th, 2005. Traces of spring water in Ls. III were recognized in our investigation done in September 4th, 2004. Ls. II having a large scale valley configuration had caused the degradation of the river bed, as shown in Photo 9 and Photo 10. Fig.9 shows the longitudinal figures for Ls. I and Ls. II. Ls. I has a steep slope of about 35 degrees in inclination. Ls. II dissected comparatively, has a gentle slope of about 25 degrees.

Ls. I and Ls. II occurred in the region where the buried creeks meet with the main spill way. There are sunken grounds in the upper part of the slopes behind the landslides indicated by the circle marks in Fig.3. Small natural dam, indicated in the upper left in Photo 2, was generated in the slope behind Ls. I. Though

Photo. 11. Landslides along the main spill way

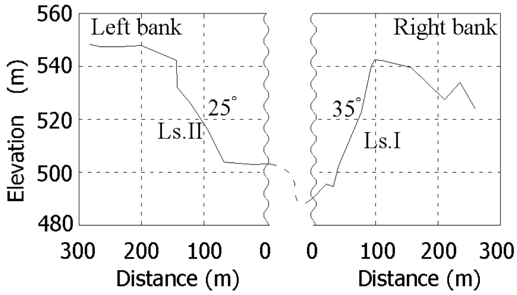

Fig. 9. Longitudinal figure of Ls. I (left of D13) and Ls. II (right of D15)

the buried creek cannot be clearly seen behind Ls. III, the configuration of the valley before the main landslide occurred can be distinguished in the map 1/ 25,000 in scale. Sunken ground indicated in the figure as a circle, can be seen after the main landslide due to the influence of old topographical features. In this manner, the landslides along the main spill way which occurred along the slope, correspond with buried creeks and old configuration of the valley where sunken grounds exist. The landslides along the main spill way have been creating their original own basin as is illustrated in Fig.7. Water from heavy rainfall concentrates in these places even after the topographical configuration of the creek and valley have been buried by landslides. Water seepage into the sediment area of the main landslide easily flows into the buried Chiutsaihu creek located at the main spill way, as was restricted by the old configuration. The seepage of water generated a slope that is susceptible to landslides.

Natural dams are often produced by landslides. However, huge landslides like the Chue-fen-erh-shan landslide which buried several valleys and produced big natural dams seldom occurs. This case proved that water from rainfall and seepage water restricted by the old configuration inevitably triggers landslides. It is likely that heavy rainfall even in the future, will produce and expand landslide on the same slope. Though countermeasure against big natural dam must be taken, landslides as shown here occurred at toe of the sediment area, needs to be recognized as a danger to making entire sediment area unstable.

Conclusion

We have investigated the topographical changes of the Chiu-fen-erh-shan landslide for about 6 years ending in 2005, after the occurrence of the Chi-Chi earthquake in September 1999. In 2002, the main spill way eroded by floods due to heavy rainfall triggered by the Toraji typhoon and the sediment area changed remarkably. In 2004, the 72 Water Induced Disaster and other factors yielded the topographical changes such as the erosion of the spill ways and the landslides. It is very likely that a heavy rainfall in the future will produce topographical changes mainly in the sediment area. Though huge landslides seldom occur, formidable damage arises if it does occur. Such a large scale phenomenon of sediment involves continuous damages after the occurrence of a landslide, and the Chiu-fen-erh-shan landslide is no exception to this fact. The case of the Chiu-fen-erh-shan landslide is providing precious and instructive information for us to reduce damage after the occurrence of a huge landslide. Conclusions are listed in the following.

(1) The main spill way constructed to control floods from the natural dams was eroded about 20 m to 30 m

in depth by the heavy rainfall due to the Toraji typhoon in 2001.

(2) The groundsel works, revetment works and so on were constructed to prevent vertical and lateral erosion at 21 points along the main spill way after the striking of the Toraji typhoon. However, the heavy rainfall in 2004 (mainly by the 72 Water Induced Disaster) eroded the river bed up to about 10 m in depth and landslides occurred along the main spill way.

(3) Remarkable damage was observed as caused by the typhoons, downstream from the confluence with the left spill way that incorporated the basin of the main landslide due to the earthquake.

(4) The groundsel of D11 controlled the height of the upstream river bed of the main spill way. If this groundsel is damaged, the possibility of further degradation of the river bed increases.

(5) Sediment runoff from the left spill way that has tendency to erode river bed has been remarkable. The group of rocks has controlled the height of the upstream river bed. Erosion or collapse of the group of rocks will increase the probability that enormous sediment in the upstream runs off downstream.

(6) The positions of the landslides in the slope along the main spill way correspond to the confluence of the tributaries with the Chiutsaihu creek before the occurrence of the main landslide. On the slope behind the landslides along the spill way, sunken grounds were observed. The remaining basin of the tributaries and sunken ground operate a concentration of surface flow, and the buried creek restricts seepage flow in the sediment area and provides a run-off way for water produced by rainfall. Thus, landslides on such a slope along the spill way were induced.

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