Evaluation of Remedial Works for a Spillway on Landslide-dammed Lakes by an Earthquake, a Case Study in the Jiufengershan Landslide

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ABSTRACT: This paper applied digital elevation models of different periods and long-term field monitoring data to compare elevation changes of a spillway for remedial works of landslide-dammed lakes in the Jiufengershan landslide. Digital aerial photogrammetry and LiDAR techniques were used to rebuild orthophotos and digital elevation models in the area from 1998 to 2015 in order to review the changes of deposit and erosion in topographies and profiles of the spillway. Through many torrential rainfalls in the past, it was particularly effective for related spillway remedial works to suppress the production and flow of collapse debris from the bed and bank of the spillway channel. It is the most important for spillway remedial works to remain the stabilization of two dammed lakes.
Keywords: Landslide-dammed lake, spillway, remedial works, digital elevation model.

1. INTRODUCTION

This paper employed digital elevation models (DEMs) of different periods and long-term field monitoring data to compare elevation changes of a spillway and water-level variations of landslide-dammed lakes in the Jiufengershan landslide by the 1999 Chichi earthquake. Schuster (1986) argued that many landslide-dammed lakes were often transitory to keep their integrity because the flow of water in a dammed lake could easily spill over the top of a landslide dam in which unconsolidated debris may rapidly be eroded and cut; then, it could cause the dam to break down in a few hours so that occurred a catastrophic flood disaster. The author indicated 91% of landslide dams failed within 1 year of formation based on 63 cases from literature and past experience. Thus, it is necessary for the safety of residents in the downstream to remediate the dammed lakes against failure disasters.

For emergency treatments of landslide-dammed lakes, excavated spillway is a fast and simple method which is used for the overflow discharge of a dammed-lake and the mitigation of potential disasters caused by the breakage of landslide dams (Schuster, 1986; Li et al. 1986; Chen, et al., 2011). Other methods include drainage by intake structure, siphon pipes, pump systems, tunnel excavation and diversions (Sager and Chambers 1986; Code and Sirhindi, 1986; Hansen and Morgan, 1986).

The case study of the research is in the Jiufengershan landslide by the Chichi earthquake in September 1999 in Taiwan, which caused two landslide-dammed lakes. There are two main emergency measures for the landslide and two dammed lakes. Firstly, one of emergency mitigative measures was an innovative method, namely temporary geotextile dams of debris-filled shipping containers, in the end part of deposit area in order to increase strength of the slope stable and avoid headward erosion. The other emergency measure was an excavated spillway of dammed lakes that was an emergency drainage channel so as to discharge the overflow of dammed lakes and decrease the storage volume of two lakes. After emergency mitigative measures for dammed lakes, Remedial works of a permanent spillway needed to be undertaken so as to retain the two dammed lakes. There were a slit-type sabo dam, several columnar-type submerged dams, groundsill works and some check dams in the spillway from 2000 to 2008.

For the performance evaluation of the spillway, digital aerial photogrammetry and LiDAR techniques were used to rebuild orthophotos and DEMs in the area from 1998 to 2015 in order to review the changes of deposit and erosion by profiles of the spillway and to evaluate lake-surface variations of dammed lakes by long-term monitoring data.

2. JIUFENGERSHAN LANDSLIDE

A case study is located at the Jiufengershan landslide in Taiwan by the Chichi earthquake in September 1999, as shown in Figure 1. The area of the landslide is 195 ha and the amount of the collapse is 35 million cubic meters that blocked two creeks, namely Jiutsaihu and Sezaikeng streams, and caused two dammed lakes. The area of the Jiutsaihu and Sezaikeng dammed lakes is 4.4 ha and 6.4 ha, respectively. Since 2003, there has been a monitoring landslide project in the Jiufengershan landslide with some monitoring equipment, including extensometers, inclinometers, groundwater lever gauges, etc.

Figure 1 Geographic Map of the Jiufengershan Landslide

The geology of the landslide is underlain mainly by Miocene sedimentary rocks where the strike is N36° E and the dip is 21° SE with an N-S trending synclinal axis of Daanshan syncline in the eastern part; the geologic formation of the syncline axis is the Kueichulin Formation which unconformably contacted with the underlain Changhukeng Shale; the lower formations include Miocene strata of Shihmen Formation (Shou & Wang, 2003), as shown in Figure 2.

With regards of two dammed lakes, the surface elevation of the Jiutsaihu and Sezaikeng lake was 585 m and 577.5, respectively, as the earthquake occurred. The detailed data of two lakes is shown in Table 1. Furthermore, the greatest depth of the Jiutsaihu and Sezaikeng lake was estimated about 29 m and 37.5 m, respectively, before completed spillway.

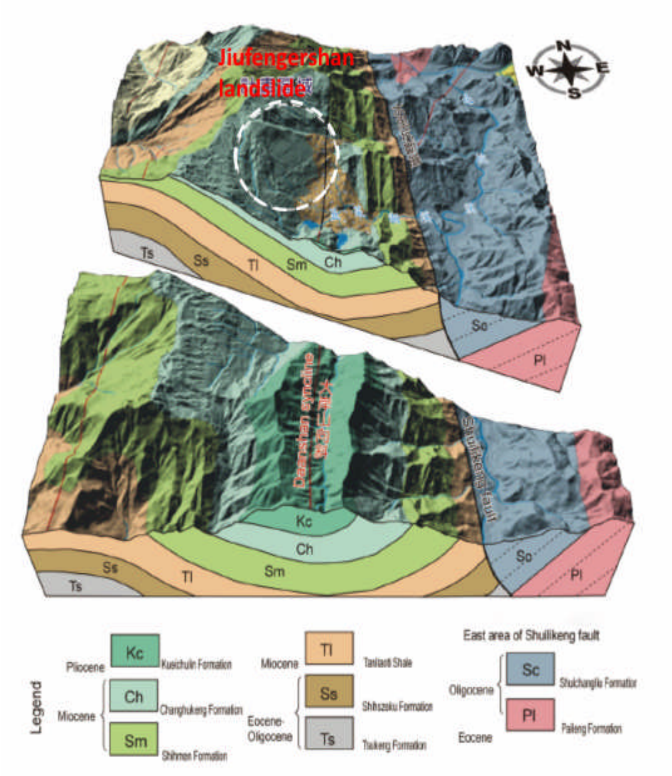

Figure 2 3D Geological Structure in the Jiufengershan landslide

Table 1 Relative elevations, depths and volumes of two landslide-dammed lakes

	Jiutsaihu dammed lake	Sezaikeng dammed lake
Area (ha)	4.43	6.48
	Before completed spillway	
Elevation (m)	585	577.5
Max lake depth (m)	29	37.5
Storage volume (m3)	678,000	1,089,700
	After completed spillway	
Elevation (m)	575.89	570.05
Max lake depth (m)	15	29
Max lake-level rise as a heavy rainfall (m)	1.2	4

For long-time monitoring the lake surfaces of the Jiutsaihu and Sezaikeng lakes in Figure 3 and Figure 4, the elevations of lake surfaces dropped to 575.89 m and 570.05 m, respectively, after completed spillway. From rainfall and lake-surface monitoring data of typhoon events in September 2015, the highest water levels of the Jiutsaihu and Sezaikeng lakes was 577.1 m and 574 m which went up approximately 1.2 m and 4 m, respectively. As a result, it is successful to control the water surfaces of two dammed lakes while the spillway completed.

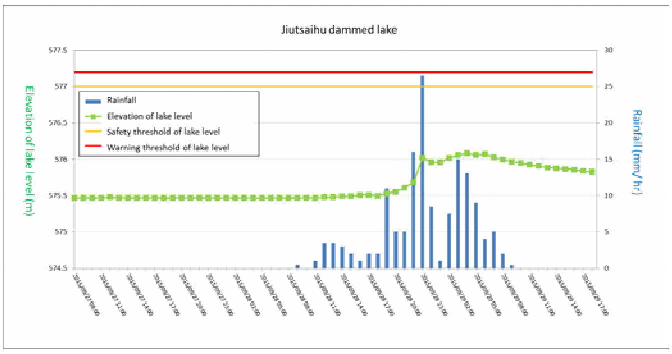

Figure 3 Relationship between rainfall and elevation of lake level in the Jiutsaihu dammed lake

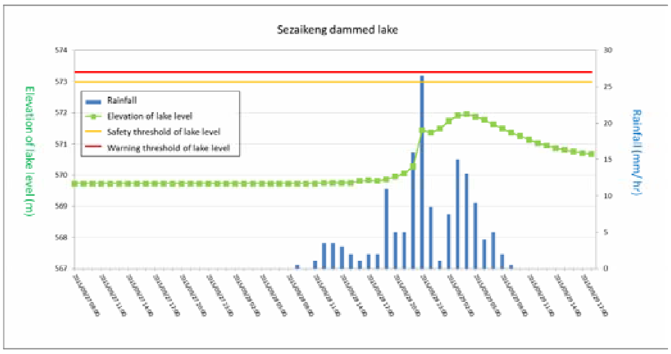

Figure 4 Relationship between rainfall and elevation of lake level in the Sezaikeng dammed lake

3. REMEDIAL WORKS OF THE LANDSLIDE AND DAMMED LAKES

3.1 Emergency treatment

Dammed lakes were vulnerable to catastrophic failure by overtopping and breach, landslide emergency treatments involved in the potential failure of these dams need to be carried out for protection of relative people's living and property. Thus, there were two items of remedial works for the landslide and two dammed lakes.

Firstly, one of emergency mitigative measures was an innovative method, namely temporary geotextile dams of debris-filled shipping containers, in the end part of accumulation area in order to increase strength of slope stable and avoid headward erosion. The measure of debris-filled shipping containers was the first for the slope toe loading of a landslide in Taiwan whose height, width and height were 122.7 m, 8.2 m and 7.5m, respectively, and the aims of the measure were for four functions as marked in Figure 5(1) (they are: ①slope stable, ②slope toe loading, ③headward erosion control, ④ protection of stream bank).

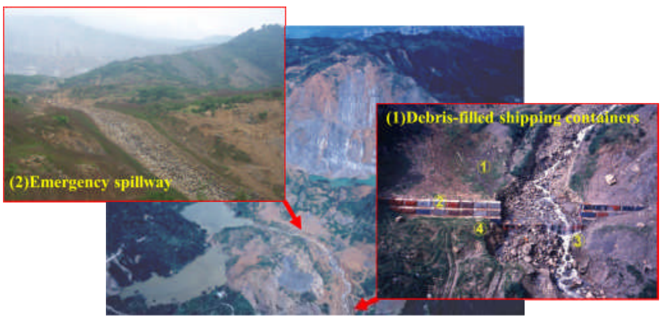

Figure 5 Locations and photos of emergency treatments in the landslide

The other emergency measure is a spillway of dammed lakes that is an emergency drainage channel with 1450 m in length and 8 m in depth in order to discharge the overtopping of dammed lakes and decease the storage volume of two lakes in October 1999, as shown in Figure 5(2).

3.2 Soil and water conservation treatment

After emergency mitigative measures of dammed lakes, it is important for remedial works of a permanent spillway so as to avoid severely incised channel, losing a lot of debris and dammed-lake failure. One of the remedial works was a slit-type sabo dam that was located at 1K+230 m from the overflow outlet of the spillway in 2000. The aim of the dam was for a direct barrier to debris flows which could occur. The location is shown in Figure 6.

Figure 6 Location of spillway works in the landslide

The slit-type sabo dam divided two constructions including a main dam and auxiliary dam, of which the lengths and heights were 131 m and 15.5 m, and 84 m and 8 m, respectively. The sabo dam that categorized as a permeable structure is one of popular methods currently used for debris flow prevention. The dam can effectively block huge boulder as well as debris from upstream while allow smaller-grain debris and stream flow to be released into downstream channel.

The other remedial works were 20 columnar-type submerged dams on the spillway so as to increase the stabilization of channel bed and decrease fast headward erosion of the spillway in 2003 (see Figure 6). The size of a single submerged dam is 42 m in length and 5 in height. The column diameter is 1 m and the spacing in 3 rows is all 1m. In contrast with traditional dams, this dam was more permeable from its bottom to all other parts which was suitable for the special geology in the Jiufengershan landslide, so 20 columnar-type submerged dams were immediately designed and implemented by a local government. After that, remedial works of check dams was performed to enhance the bed stability of the spillway from 2008 to 2013, as can be seen in Figure 6.

4. PERFORMANCE EVALUATION OF SPILLWAY WORKS

The landslide blocked two streams which caused two landslide-dammed lakes so a spillway was built to discharge water volume of the two lakes. Thus, it is important to evaluate remedial works of the spillway. The paper applied DEMs for different periods and long-term monitoring data to compare elevation changes of the spillway and water surfaces of dammed lakes. Digital aerial photogrammetry and Light Detection and Ranging (LiDAR) techniques were used to rebuild orthophotos and DEMs in the area from 1998 to 2015 in order to review the change of accumulation and erosion in profiles of the spillway.

4.1. Landform changes with photogrammetry and LiDAR survey

Digital aerial photogrammetry and analysis tools of ERDAS IMAGINE were used to rebuild orthophotos and DEMs for different periods before and after the 1999 Chichi earthquake. The result is shown in Figure 7. According to the topographic analysis (see Table 2), the average depth of the landslide is 34 m with a collapse volume of 34.92 million cubic meters and a deposit volume of 36.58 million cubic meters.

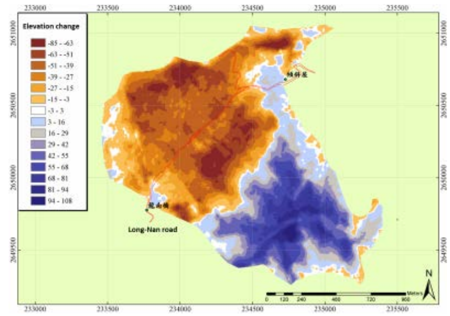

Figure 7 Landform change between 1998 and 2002 (collapse is in brown color; deposit is in blue color)

Table 2 Relative areas and volumes of collapse and deposit in the landslide

Type	Area (ha)	Debris volume (m3)	Maximum elevation change (m)
Collapse	102.5	34,923,400	-85
Deposit	92.5	36,585,000	+108
Sum	195		

There was LiDAR data to make DEM for this area after 2004. The data of DEMs in 2004, 2011 and 2015 for the landslide can be compared with ground surface changes in three dimensions and help to understand area and volume changes.

The data of DEMs was built in 2004, 2011 and 2015. The results of elevation changes illustrate the differences in elevations from 2004 to 2015 in the landslide, as shown in Figure 8(1). The figure shows that erosion area is in blue color and deposit area is in red color between 2004 and 2015 in which the landslide volume is estimated about 267,000m3 with a maximum erosion depth of 27 m and maximum deposit depth of 24 m. However, the elevation variation was smaller from 2011 to 2015 in Figure 8(2).

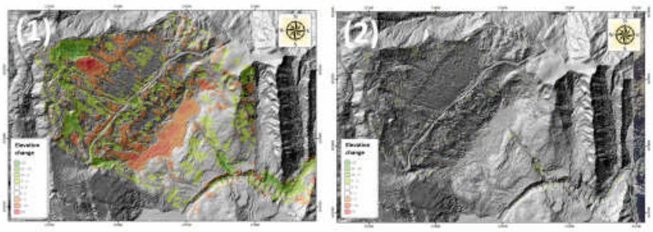

Figure 8 (1) Landslide change between 2004 and 2015; (2) Landslide change between 2011 and 2015. (Erosion area is in green color and deposit area is in orange color.)

4.2 Profile changes of the spillway with photogrammetry and LiDAR data

DEMs of the area were built by the data of photogrammetry in 1998, 2002 and 2005. Then, profiles of the Jiutsaihu stream before and after the 1999 Chichi earthquake were drawn in Figure 9 by using the data of DEMs. The graph of profiles in the figure shows elevation changes of the stream bed before and after the earthquake in which the maximum landslide depth is 87 m at 2K+250 of the profile line. It is clear for the profiles that there was an erosion phenomenon at 3K+500 of the upstream and a deposit area occurred from 0K+775 to 1K+365 at the downstream that was possibly caused by excavated spillway or collapsed debris of the upstream.

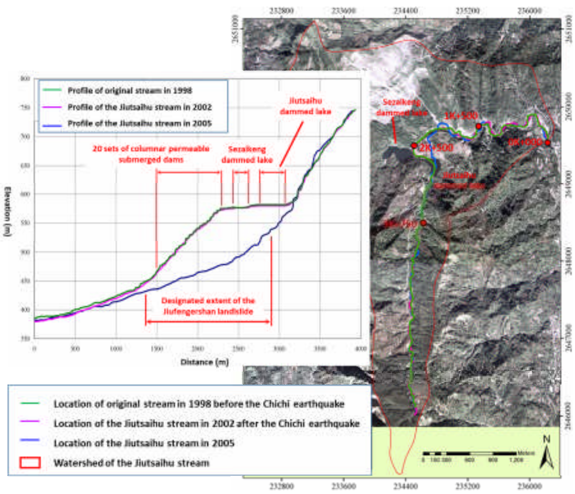

Figure 9 Location and profile of the Jiutsaihu stream before and after the Chichi earthquake

Other DEMs of the area were built by the data of LiDAR in 2004, 2011 and 2015 with the grid precise of 5 m. Then, profiles of the spillway were drawn by using the data of DEMs in the three periods, as shown in Figure 10. Meanwhile, the locations of remedial works, including a sabo dam, 20 columnar-type submerged dams and check dams, are plotted in the figure.

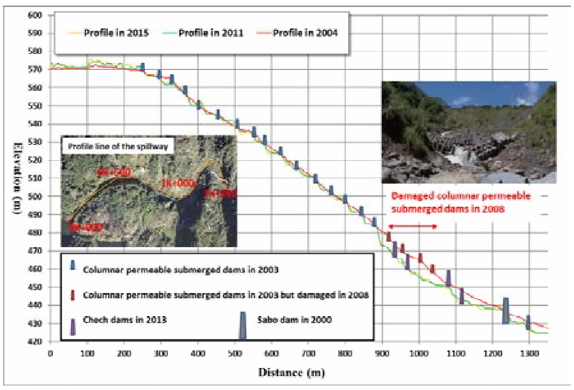

Figure 10 Elevation changes of the spillway for different periods

Figure 10 illustrates that there was a significant downcutting in the elevation change by 20 meters between 0K+870 m and 1K+80 m in the spillway from 2004 to 2011, which caused falling and damage of some columnar-type submerged dams. Nevertheless, the elevation changes gradually remained stable from 2011 to 2015 after remedial check dams and groundsills from 2008. The other point is that the sabo dam effectively blocked the massive debris against its flowing to downstream. All spillway works could have a capacity of debris pool by 6 million cubic meters. Dammed-lake failure and debris flow did not occur in the landslide area while all spillway works completed.

Overall, through many torrential rainfalls and typhoons from 2004 to 2015, related remedial works which have cost about 12 million USD were particularly effective suppress the production and flow of collapse debris in the bed and bank of the spillway channel. The most important performance is to remain the stabilization of two dammed lakes.

5. CONCLUSION

From the lake-surface monitoring data of two dammed lakes, an average drop of the lake surface in the Jiutsaihu and Sezaikeng dammed lakes was 8.28 m after completed spillway works in 2000. Through some heavy rainfall events from 2004 to 2015, the highest lake surface went up approximately 1~4 meters, which means that it is successful for the spillway to control the changes of lake surfaces in two dammed lakes. According to Schuster (1986), 91% of 63 global barrier lakes broke down within a year after having formed. As a result, it is valuable for the spillway in the landslide that two dammed lakes can be maintained and there was no severe disaster in the past.

Compared to elevation changes of the spillway by DEMs of different periods with photogrammetry and LiDAR techniques, there are some results of the analysis. Firstly, the average depth of the landslide is 34 m with a collapse volume of 34.92 million cubic meters and a deposit volume of 36.58 million cubic meters while the Chichi earthquake occurred. Secondly, the data of DEMs in 2004, 2011 and 2015 shows that landform changes in the landslide were nonstop in which the landslide volume is estimated about 267,000 m^3 with a maximum erosion depth of 27 m and maximum deposit depth of 24 m. Then, there was a significant downcutting in the elevation change by 20 m between 0K+870m and 1K+80m in the spillway from 2004 to 2011, which caused some submerged dams damaged but the changes gradually decreased from 2011 to 2015 after some check dams were completed from 2008. Finally, the most important performance is to remain the stabilization of two dammed lakes after emergency treatment and a series of spillway remedial works.

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