Dam-break flood risk assessment and mitigation measures for the Hongshiyan landslide-dammed lake triggered by the 2014 Ludian earthquake

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ABSTRACT
Landslide-dammed lake is a typical geological hazard induced by earthquakes in mountainous river areas that pose a great threat to human lives and property for reservoirs and downstream areas. In this paper, the 3 August 2014, Hongshiyan landslide-dammed lake induced by the Ludian earthquake (Mw 6.5) was taken as an example to study the dam-break risk and flood routing process. The fuzzy mathematics method was used to evaluate the risk level of the Hongshiyan landslide-dammed lake, and six main indicators were developed to classify its risk level. The assessment results indicated that the Hongshiyan landslide-dammed lake had an extremely high risk and very serious possible disaster consequences. Then, we analyzed the possible dam-break flood routing process by numerical simulation. The simulated results showed that a dam-break flood would pose a great threat to the downstream Tianhuaban Hydropower Station. Therefore, some effective artificial measures must be taken to control the scale of the disaster. The artificial measures included upstream interception, middle grooming, downstream emissions and subsequent treatments. Some emergency measures were implemented and prevented the failure of the landslide-dammed lake through 19:00, October 4 2014, and subsequent treatment even turned the potential harm into a benefit.

1. Introduction
Southwest China has become the most active area in China for geological disasters because of fragile geological conditions and frequent geological movements. This region is characterized by distinct topographical relief, high mountains, steep valleys, and many hills and mountains (Wu et al. 2013; Zhou et al. 2013; Chen et al. 2015a). Moreover, seismic activity is frequent in this area, and several strong earthquakes with magnitudes larger than 6.0 have occurred in recent years such as the 2008 Wenchuan earthquake (Mw 8.0), the 2013 Lushan earthquake (Mw 7.0) and the 2014 Ludian earthquake (Mw 6.5) (Fan et al. 2012; Zhang et al. 2015). Strong earthquakes can not only cause directly damage to the structures (such as houses, roads and bridges) and human beings, and may also produce a large number of secondary geological disasters in mountainous area, such as landslides (collapse, rock slides, rock avalanches and debris avalanches) and landslide-dammed lakes (Bergman et al. 2014). Among these secondary geological disasters, landslide-dammed lakes have become important and cannot be ignored in the process of earthquake relief in mountainous areas because...
of their characteristics of wide range, long duration and serious consequence (Xu et al. 2013; Sun et al. 2014).

Several catastrophic landslide-dammed lake events were occurred at southwest China in the past time (Wang et al. 2008; Peng & Zhang 2013; Xu et al. 2013; Dong et al. 2014). For example, on 25 August 1933, the Diexi strong earthquake (Mw 7.5) was happened at the Sichuan province and triggered a large number of landslides, and among these landslides some blocked the Minjiang River and formed three landslide-dammed lakes, which broke out after 45 days and resulted in a huge loss of lives and properties. The flood routing reached more than 1,000 km downstream of Yibin City, and there were more than 20,000 casualties and 50,000 acres of farmland destroyed (Xu et al. 2013). On 17 June 1967, the Tanggudong landslide-dammed lake broke out on the ninth day after formation; the maximum discharge of the outburst flood exceeded 57,000 m$^3$/s and has a large affected area for the downstream, which even affected the Chongqing city (1700 km far away from the dam site). The Tangjiashan landslide-dammed lake induced by the Wenchuan earthquake broke on 10 June 2008, and the dam-break flood posed a great threat to the 1 million inhabitants of central Mianyang City (Chanson 2005). Previous studies have shown that the abundant material sources on both sides of the deep and steep valley and the sufficient external loads (earthquake or rainfall) were the two triggering factors for these catastrophic landslide-dammed lakes (Ermini & Casagli 2003; Zhou et al. 2016b). The threat to life and property came not only from the landslides themselves but also from the dam-break floods (Dong et al. 2014; Tang et al. 2015). Therefore, it is very important to study the dam-break flood process and other related problems for hazard prevention and mitigation of reservoir landslides.

Risk assessment and flood routing analysis were always used to study the flood scale and disaster mitigation measures for dam-break floods (Bergman et al. 2014; Shi et al. 2016). Risk assessment was a comprehensive consideration of the occurrence probability and the possible consequences of risk events, including qualitative evaluation, quantitative evaluation and the combination of the two; it laid the foundation for reasonable disaster prevention plans (Alexandra & Davis 2012; Kelman et al. 2015). Li et al. (2014) analyzed the flood risk from the dam-break of the Muyu Reservoir based on the causes for possible dam-break flood occurrence, the geometric data and the dam-break mode. Yang et al. (2013) used the fuzzy comprehensive evaluation method for the risk analysis of dam breaks and the risk grades of dam-break consequences. Flood routing was the inevitable result of the dam-break at high water level and determined the flood inundation area and the loss degree of a disaster directly (Duman 2009; Dong et al. 2014). With the development of computing technology, numerical simulation has been widely used for dam-break flood analysis (Xia et al. 2010). Carbon et al. (2014) simulated dam break flood routing by the NWS-FLDVAV data (US National Weather Service flood routing program), which replaced the existing HEC-RAS (US Army Corps of Engineers Hydraulic Engineering Center River Analysis System). Zhu et al. (2015) focused on the construction of the virtual geographic environment (VGE) system and the scale effect analysis developed to support dam-break simulation and risk analysis of the Xiaojiaoqiao landslide-dammed lake.

In this paper, the 3 August 2014, Hongshiyan landslide-dammed lake induced by the 2014 Ludian earthquake (Mw 6.5) at Yunnan, China, was taken as an example to study the dam-break flood process. The dam-break risk of this landslide-dammed lake was studied by using the analytic hierarchy process and the fuzzy membership function. A hydraulic calculation model was used to simulate the dynamic process of the dam-break flood. Disaster preparedness measures were proposed. The conclusions we present were useful for forecasting the risk of the dam-break and disaster prevention and mitigation measures.

2. The Hongshiyan landslide-dammed lake

2.1. Hazard overview

At 16:30, 3 August 2014, the Mw 6.5 Ludian earthquake (27.189°N, 103.409°E) suddenly occurred in Ludian County, Yunnan Province, southwest China; the earthquake had a focal depth of 12 km and
a maximum seismic intensity of IX degree (Chen et al. 2015b). Moreover, it produced a total of 1335 recorded aftershocks until 00:00, 11 August 2014. As a result of the high magnitude and a dense population, the earthquake caused significant casualties and economic loss. According to official data reported as of a month after the earthquake, more than 1,080,000 people were affected; there were 617 deaths, 112 people missing and 3143 people injured. Moreover, it caused the relocation of 229,700 people and economic loss of more than 460 million Chinese yuan (Hu et al. 2015). Figure 1 shows the damaged houses induced by the Ludian earthquake, obtained from the Geographic Information of Surveying and Mapping Bureau of Yunnan Province.

The complex geological conditions and the rainfall followed resulted in a large number of secondary geological hazards in the epicentre area, such as landslides, debris flows and landslide-dammed lakes. Among the secondary hazards, a large landslide event (Hongshiyan landslide) was induced by this earthquake, which is located at the Hongshiyan Village and about 600 m far away from the Hongshiyan Hydropower Station. The Hongshiyan landslide blocked the Niulan River and formed a large dammed lake (Hongshiyan landslide-dammed lake), as shown in Figure 2. The Hongshiyan landslide-dammed lake was the second largest earthquake-induced landslide-dammed lake known in China. It had a catchment area of 11,832 km² and a total capacity of approximately 260 million m³, the capacity was two times as large as the Tangjiashan landslide-dammed lake (145 million m³) and the water level difference was larger than the Tangjiashan (Zhou et al. 2016a). The Hongshiyan landslide-dammed lake had a direct impact on the safety of the population of 9000 and the cultivated land of 8500 acres in the upstream Huize County and also on the population of 30,000 and the cultivated land of 33,000 acres in Ludian County, Qiaojia County and Zhaoyang County (Chen et al. 2015b). At the same time, it posed a great threat to the Hongshiyan dam, the Xiaoyantou dam upstream, the Tianhuaban dam and the Huangjiaoshu dam.
2.2. Topography and geology

The study area was a typical upland-valley area with a maximum height of more than 800 m. The original slope was between 35° and 50° with a bank height of approximately 200 m on the left bank and was between 50° and 60°, even 70° locally, with a bank height of approximately 600 m on the right bank, which provided the necessary topographical conditions for the formation of landslides (Zhou et al. 2016a). The slope material was hard on the upper slope (mainly limestone and dolomite) and soft on the lower part (mainly mudstone and shale). The Hongshiyan landslide was located in the fault zone of Zhaotong-Lianfeng, which had the typical characteristics of high geostress and high-weathered rock masses that provided the necessary material sources for the occurrence of landslides, as shown in Figure 3.

The Ludian earthquake triggered a large number of geological disasters, such as the collapse of shallow surfaces, landslides and rockfalls, which mainly occurred in the neighbouring area of the focal zone (Lin et al. 2015). The largest geological disaster was the Hongshiyan landslide that mainly collapsed on the upper slope and slid along the layers of the lower part of the slope. After the earthquake, the stability of the rock mass was greatly reduced and the safety factor dropped from 1.450 before the earthquake to 0.962 after the earthquake, as calculated by Geo-Studio software, which resulted in the failure of the Hongshiyan slope directly (Chen et al. 2015b).
The serious collapse occurred on both sides of the river, and most of the sliding masses were run into the Niulan River. The landslide deposits with huge volume about 12 million m³ cut off the river and formed a landslide dam. The maximum elevation of the landslide deposits was 1680 m and the width was approximately 200 m; the elevation was approximately 1350 m after sliding and the vertical distance was 330 m (Zhang et al. 2015). The landslide dam had a length of approximately 753 m along the river, a width of approximately 286 m and a height of approximately 103 m (Figure 4).

As shown in Figure 4, the landslide dam generally was an asymmetric saddle; the elevation of the dam crest (EL) was 1,222 m and the average slope was 1:2.5 upstream and 1:5.5 downstream. Approximately 70% of the dam materials came from the right bank. Stones larger than 1 m accounted for approximately 10% of the dam materials, particles larger than 30 cm accounted for approximately 30%, particles between 10 cm and 30 cm accounted for approximately 40%, and particles smaller than 10 cm accounted for approximately 20%. Surface materials were uniform.

2.3. Hydrology

For the hazard assessment of a landslide-dammed lake, the change in the water level was the problem of most concern during the disaster and provided an important basis for emergency management. However, the landslide-dammed lake was mostly located in an inaccessible mountain area and there was a relatively short time available for access, which made it difficult to monitor water level change in real time. During the Hongshiyan lake process, manual observations were used during the early period between August 3 and August 7, 2014, and a pressure-type stage gauge was used later, between August 7 and October 4 when the dam collapsed. The lowest water level was 1,137.5 m, the highest was 1,182.56 m and the maximum water-level change was 45.06 m, which was 1.85 times that of the Tangjiashan dammed lake.
During the formation of the landslide-dammed lake, the Niulan River was in main flood season and the upstream inflow accumulated in the reservoir area at a rate of 270 m$^3$/s (Figure 5(b)). At the same time, the flow of approximately 80 m$^3$/s was discharged along the tunnel drainage of the Hongshiyan Hydropower Station. The water level reached 1174.60 m at 12:00, 5 August, which was 16.17 m higher than the day before; 1,350 acres of farmland and 368 houses were flooded, and the water level continued to rise gradually at a speed of 0.16 m/h. If the Hongshiyan landslide dam broke out, the dam-break flood would have had great impacts on people and property downstream. There were mainly seven growth periods at the water level (Figure 5(c)), which rose 39.37 m within the first 92 hours (Zhou et al. 2015). Moreover, the water level rose 7.68 m within 83 hours from September 18 due to the influence of the typhoon ‘Seagull’. During the growth process of water level, the inundated area increased and a large number of houses and roads were flooded. Figure 6 shows photographs of the reservoir submergence; the water level was low after the formation of the landslide but then rose because the inlet discharge was larger than that of outlet discharge.

3. Dam-break flood risk assessment

The dam-break process was characterized by a sudden outbreak, a long duration and a wide influence range that posed a great threat to human life and property downstream. Therefore, it was necessary to make a risk assessment of the disaster and forecast the risk level before proposing reasonable prevention measures to reduce disaster losses.

3.1. Evaluation parameters

Based on the theory of risk, the fuzzy mathematics method was used to evaluate the risk level of the Hongshiyan dammed-lake failure. The specific steps included: (a) identify the related indicators and establish an evaluation index system; (b) determine the scope of the qualitative and quantitative indicators of all levels; (c) determine the weight of the relevant indicators $a_i (i = 1, 2, 3, \ldots n; n$ is the index number) based on the engineering experience and related literature summary results;
(d) determine the value of each index and represent the upper and lower values of all levels with $b_i$ ($i = 1, 2, 3, \ldots, n$), and divide the risk based on the criteria of risk rank of the landslide-dammed lake; (e) calculate the corresponding risk membership grade by Equation (1) and obtain the evaluation matrix $R$ of the different indicators by Equation (2); (f) calculate the risk grade by Equation (3) based on the weight and the judgment matrix obtained; and (g) defined as processing at the same level as long as it meets one of the largest indicators based on the maximum record, and set the maximum number of the $B$ series as the result of fuzzy evaluation as shown in Equation (4). For

Figure 5. Hydrological conditions of the study area: (a) curve relationship between the storage and the capacity; (b) annual average flow at the Hongshiyan landslide dam site and (c) water level change of the Hongshiyan landslide-dammed lake.
example, if $B_2 = \max(B_1, B_2, B_3, B_4)$, then $G = 2$ and the risk grade is the second level, high risk.

$$
\begin{align*}
r_{in}(x_i) &= \begin{cases} 
0, & x_i \geq b_{6-m} \\
\frac{b_{6-m} - b_{5-m}}{b_{5-m} - b_{4-m}} - x_i, & b_{5-m} < x_i < b_{6-m} \\
1, & x_i = b_{5-m} \\
\frac{x_i - b_{4-m}}{b_{5-m} - b_{4-m}}, & b_{4-m} < x_i < b_{5-m} \\
0, & x_i \leq b_{4-m}
\end{cases} \\
&\quad (m = 1, 2, 3, 4; i = 1, 2, 3, \ldots, n) \tag{1}
\end{align*}
$$

where $x_i$ is the index $i$ value and $b_{4-m} = 0$ when $m = 4$.

$$
R = \begin{bmatrix}
  r_{11} & r_{12} & r_{13} & r_{14} \\
  r_{21} & r_{22} & r_{23} & r_{24} \\
  \vdots & \vdots & \vdots & \vdots \\
  r_{n1} & r_{n2} & r_{n3} & r_{n4}
\end{bmatrix} \tag{2}
$$

$$
B = A \cdot R \tag{3}
$$

IF $B_i = \max(B_1, B_2, B_3, B_4)$, then $G = i \tag{4}$

The risk level of the landslide-dammed lake was affected by many factors; therefore, we focused on the main factors and also considered the general parameters in the process of evaluation. Six indicators were proposed: the social development along the coast $I_1$, mainly the population downstream, which can reflect the economic development state to some extent; dam material $I_2$, mainly the grain size distribution of the dam material and the boulder size, the more uniformity the grain size distribution, and the greater the dam structure strength is, and the more stable the dam is. At the same time, the greater the boulder size, the more stable the dam is, too, which has been verified by the experiment; landslide-dam volume parameters $I_3$ ($DBI = \lg(AH/V)$), where $H$ is the dam height, $V$ is the volume of the dam body and $A$ is the catchment area; water level growth rate in the reservoir $I_4$; the mountain stability on both sides of the reservoir $I_5$; and the river channel river $I_6$.

Among the indicators, $I_1$ and $I_6$ directly reflect the extent of economic losses and $I_2, I_3, I_4, I_5$ reflect the risk degree of the dam failure.

The risk level and the division criteria of the landslide-dammed lake were proposed by referencing related literature, as shown in Table 1. The risk level was divided into four categories: extremely high risk, high risk, middle risk and low risk. Indices without the maximum value, such as the
volume parameters $I_3$, were derived by the arithmetic method. The critical values $b_i$ of the four levels for the different indices are as shown in Equation (5).

\[
 b_i = \begin{pmatrix}
 b_1 \\
 b_2 \\
 b_3 \\
 b_4 \\
 b_5 \\
\end{pmatrix} = \begin{pmatrix}
 0 & 1 & 10 & 100 & 1000 \\
 0 & 0.25 & 0.50 & 0.75 & 1.00 \\
 0 & 2.75 & 2.91 & 3.08 & 3.25 \\
 0 & 2.8 & 4.7 & 6.7 & 8.6 \\
 0 & 0.25 & 0.50 & 0.75 & 1.00 \\
 0 & 0.25 & 0.50 & 0.75 & 1.00 \\
\end{pmatrix}
\] (5)

The evaluation indicators used here were referred to the statistical results from several landslide-dammed lakes triggered by the 2008 Wenchuan earthquake, which have made some improvement for the influencing factors from the Chinese Standard: Classification of risk grade of landslide dammed lake. Then the initial weight distribution of the six indicators was obtained, as shown in Table 2.

### 3.2. Evaluation results

Based on the actual situation of the Hongshiyan landslide-dammed lake, the risk assessment indicators were as follows: for the social development $I_1$, the disaster had a direct impact on Ludian County, Zhaoyang County and Huize County, affecting a population of 30,000 and 33,000 acres of farmland; for dam material $I_2$, the material was mainly strongly weathered dolomite with some stones and a fuzzy score of 40; for volume parameters $I_3$, the dam height was 103 m, the volume was 12 million $m^3$ and the catchment area was 11,832 $km^2$, which produced a DBI of 5.01, more than the maximum value of the index; for water level growth rate $I_4$, the water level increased 39.37 m within 92 hours after the formation, 10.27 m/d, and then increased another 7.68 m within the next 83 hours because of the influence of the typhoon ‘seagull’; for mountain stability $I_5$, many loose rock bodies remained, recurrence of a large and medium-sized landslide was possible, and the Fuzzy score was 60; for River channel river $I_6$, the dam-break flood peak was expected to reach tens of thousands of cubic metres per second, although the river is relatively meandering, which could delay...
the peak, and the fuzzy score was 70. The evaluation matrix $R$ was obtained by Equations (1) and (2). Then, the results of fuzzy evaluation were obtained by Equation (4).

\[
R = \begin{bmatrix}
0 & 0 & 0.3 & 0.7 \\
0 & 0.6 & 0.4 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0.4 & 0.6 & 0 & 0 \\
0.8 & 0.2 & 0 & 0
\end{bmatrix}
\]  

\[
B = (0.30, 0.25, 0.25, 0.10, 0.05, 0.05) = (0.32, 0.19, 0.19, 0.21)
\]  

Regard to the maximum record $B_1 = \max(0.32, 0.19, 0.19, 0.21)$ and $0.32 > 0.21 > 0.19$, $G = 1$, that is, the risk grade for the Hongshiyan landslide-dammed lake was level I and belonged to the extremely high risk class.

4. Dam-break flood routing process

To further understand the characteristics of flood routing and submergence after a Hongshiyan landslide-dammed lake failure, the dam-break flood routing process was analyzed by the numerical simulation.

4.1. Numerical method, model and parameters

We selected a 20 km-wide study area and obtained the terrain and contours by using Google Earth. As shown in Figure 7, the maximum elevation was 2,700 m and the minimum elevation is 900 m. The landslide-dam was located in the southeast. The area was imported into the numerical software with the STL format and then was simulated. Figure 8 shows the numerical model and boundary conditions for the dam-break flood analysis of the Hongshiyan landslide dam.

As shown in Figure 8(a), the study area was divided into a grid with a cell size of 100 m and the river above the Tianhuaban Hydropower Station, the main affected area, was then subdivided to the

Figure 7. Simulation area: (a) 3D stereogram map and (b) floor plan.
cell size of 5 m. Here, we assumed that the landslide dam would break instantly after the water level overtopped the dam crest and the reservoir water would be discharged, which is the most dangerous situation (an extreme case), and it is beneficial to improve security defence. Therefore, the maximum water level was set equal to the dam crest elevation (1,222 m), and the water depth was 103 m. However, the model failed to fully reflect the capacity because part of the capacity was outside the model area; therefore, the calculated depth was increased to reflect the dam-break flood volume truly. Assuming the channel section was basically constant, the maximum water level in the model was increased to 1,281 m and the water depth to 162 m (Figure 8(b)). The upstream flow was set to 270 m$^3$/s, which was the annual flood discharge in August appropriately based on hydrological statistics. The river was blocked by the landslide dam and the water level downstream was smaller than the upstream; at the same time, the downstream 19 km was blocked by the Tianhuaban Hydropower

Figure 8. Numerical model and boundary condition for the dam-break flood analysis of the Hongshiyian landslide dam: (a) numerical mesh by using Hypermesh; (b) assumption of water depth in the numerical model and (c) the river section along the Niulan River.
Station, which has a large dam-crest elevation, producing a large reservoir depth (Figure 8(c)). Then, we assumed that the river was relatively static and the water level kept at a normal water level of 1,071 m during the calculation process, without additional water supply.

During the setting of boundary conditions, the upstream boundary was set as the Volume flow rate boundary with an inflow of 270 m³/s, the two neighbour sides and the bottom were set as the Wall boundary, the downstream boundary was set as the outflow boundary and the top was set as the Specified pressure boundary. The channel roughness coefficient n was set to 0.05, which is basically similar to the numerical parameter used for the simulation of water discharge problem of the Tangjia Shan landslide-dammed lake, and the calculation time was 60 min. Four monitoring points were laid out in different parts, as shown in Figure 10(b); ‘1’ was located in the dam upstream, ‘2’ was located in the first corner, ‘3’ was located in the midstream and ‘4’ was located in the Tianhuaban reservoir.

4.2. Simulation results

The elevation of the actual channel was uneven; part was protruding (convex) and part was concave. Therefore, the water depth was small in the convex parts and was large in concave parts for the calculation results. Figure 9 shows the simulated results of the dam-break flood evolution distance at different times. At the first corner, the water level rose and some water flowed into the ditch.

As shown in Figure 9, the maximum flow movement distance was 8,896 m with an average speed of 14.8 m/s at the simulation time of 10 minutes, which corresponded to the first large bend. The movement distance was 13,068 m with an average speed of 10.89 m/s at the 20 minutes, when the contact was made with the downstream reservoir water. The movement distance was 16,860 m with an average speed of 9.4 m/s at the 30 minutes, when the flow had basically reached the downstream

Figure 9. Simulated results of the dam-break flood evolution distance at different times: (a) 10 min; (b) 20 min; (c) 30 min and (d) 40 min.
reservoir and was delayed by the original hydrostatic pressure. At the 40 minutes, the movement distance was 19,874 m with an average speed of 8.3 m/s, which raised the reservoir water level and allowed some water to the branch. At that time, the water moved with a larger kinetic energy to the Tianhuaban dam. Figure 10 shows the simulated results of the dam-break flood depth at the different times. Reservoir water moved because of its own weight, and the water level would reduce by the continuous discharge of the water in the reservoir. The downstream water level would also rise because the downstream structures intercepted the discharged water.

As shown in Figure 10, the water level had significantly reduced at the dam site in 10 minutes; however, the movement distance of the precipitation wave was limited and the water level had less change at the partial upstream position, resulting in a water depth between 130 m and 150 m. The water level rose greatly downstream when the flood arrived, although the water level at the reservoir in 10 minutes was almost unchanged because the flood had not reached the original downstream reservoir. After 20 minutes, the flood arrived at the downstream reservoir. After 30 minutes, the water level had greatly increased in the downstream reservoir and was larger than 100 m; then, the water level decreased steadily in the upstream reservoir and increased downstream, although there was little difference at 40 minutes compared with 30 minutes.

Figure 11 shows the simulated results for the variation of the monitoring points’ water depth. For monitoring point 1 (at the dam site), the water level decreased steadily from 162 m to 90 m within the calculated 50 minutes. For monitoring point 2 (at the first corner), the water level rose rapidly when the flood arrived and then decreased slowly; the water level gradually became similar to the dam site, as did the water depth because of the lower elevation of the river-bed compared with the dam site. The changes at monitoring point 3 (the middle of the river) were similar to those at monitoring point 2. For monitoring point 4 (at the downstream reservoir), the water level rose from its original depth when the flood arrived, although the growth rate was small because of the large water surface. During the reservoir water discharge process, the water velocity decreased gradually because

Figure 10. Simulated results of the dam-break flood depth at different times: (a) 10 min; (b) 20 min; (c) 30 min and (d) 40 min.
of the decrease of the water level difference and the frictional resistance. Figure 12 shows the simulated results of the dam-break flood velocity at different times.

As shown in Figure 12, the maximum velocity was 37 m/s and located at the forward position in 10 minutes, when the flood arrived at the first corner. Velocity lessened to 34 m/s at 20 minutes and the flood reached the downstream reservoir at 30 minutes; the residual energy gradually disappeared because of the interaction process of water and the water surface shock. At 40 minutes, the velocity decreased further to a maximum value of approximately 20 m/s. The large kinetic energy would make a huge impact on the Tianhuaban dam and greatly affect its safety.

Figure 12. Simulated results of the dam-break flood velocity at different times: (a) 10 min; (b) 20 min; (c) 30 min and (d) 40 min.
Figure 13 shows the simulated results for the variation of the flow velocity of the monitoring points. For monitoring point 1 (at the dam site), the water velocity rose rapidly under the action of gravity to a maximum of 34 m/s. Then, it decreased gradually because of the decrease of the water level difference. For monitoring point 2 (at the first corner), the water velocity rose rapidly when the flood arrived and then decreased slowly. The middle of the river bed (monitoring point 3) was similar to point 2. For monitoring point 4 (at the downstream reservoir), the water velocity was small in general because of the retarding effects of the original water.

5. Hazard mitigation

During the process of the occurrence, development and demise of the Hongshiyan landslide-dammed lake disaster, the main damage shown by the simulation was mainly concentrated in the reservoir submersion and dam-break flood, especially the dam-break flood. According to the results of the risk evaluation, the Hongshiyan landslide-dammed lake was at the great risk and the disaster consequence would be very serious. Therefore, it was necessary to take effective measures to reduce the risk. The measures included emergency treatment and subsequent treatment.

5.1. Emergency measures

After the landslide occurred, the water level rose sharply in the reservoir area, lead to a great inundation in the reservoir upstream and the outburst risk increasing substantially. It was the primary problem to reduce the reservoir water level in a timely and effective manner. The main method included upstream interception, middle grooming and downstream emissions, and paid attention to the mountain stability on both sides of the reservoir.

Upstream interception reduced the reservoir water by intercepting the upstream runoff and delaying the rise of the reservoir water level. There were many dams upstream of the Hongshiyan landslide-dammed lake, such as the Deze reservoir, located in Zhanyi County, Qujing City, approximately 300 km upstream. The Deze reservoir was fully closed at 4 o’clock on 4 August 2014, and the intercepted water exceeded $6 \times 10^7$ m$^3$ until 8:00, 12 August, equal to the maximum storage capacity that occurred at Hongshiyan, which produced much time for the emergency risk management.

Middle grooming was the most important task for emergency risk management; it controlled the growth rate of the water level by accelerating the discharge of reservoir water. A landslide dam was located between the Hongshiyan Hydropower Station Dam and its powerhouse; there was a 9 m ×
8 m water diversion tunnel hole in the middle of the landslide dam. By removing the access door, the tunnel was transformed into an emergency spillway channel; the maximum discharge reached 60–90 m$^3$/s, which provided the conditions for the water discharge. At the same time, a diversion channel was built on the crest; the bottom width was 5 m, the depth was 8 m, the slope ratio was 1:1.5 and the excavation volume was 103,000 m$^3$, as shown in Figure 14. Excavation of the diversion channel began on 8 August 2014, and was completed on 12 August 2014. The reservoir water discharged through the emergency diversion channel on 3 October and the maximum flow reached 600 m$^3$/s. The reservoir water discharge ended roughly at 19:00 of the next day after a discharge of 47.522 million m$^3$ of water over 28 hours.

The downstream emissions component was the early release of the downstream reservoir to avoid the superposition of the water caused by the dam-break on the water in the downstream reservoir, which would cause a large burst. Some hydropower stations existed downstream of the Hongshiyan landslide-dammed lake, including the Tianhuaban Hydropower Station (approximately 19 km downstream) and the Huangjiaoshu hydropower station (approximately 59 km). A burst would have a devastating effect; therefore, it was very necessary to discharge the water in downstream reservoirs to accept and delay the dam-break flood. The two reservoirs could maintain discharge to the dead water level below the reservoirs, and the redundant total capacity was more than $1 \times 10^8$ m$^3$. At the same time, some other emergency measures can be made to avoid recurring cross-strait residual slope landslides, such as shifting the population and property.

After a series of engineering and non-engineering measures, the evolution of the landslide-dammed lake was maintained in the expected direction and a large dam-break flood was avoided. The reservoir discharged to basically empty at 19:00, 4 October 2014 and the disasters of the landslide-dammed lake were prevented, as shown in Figure 15.

### 5.2. Subsequent treatment

Emergency treatment was a temporary treatment and it could only meet requirements against flooding of a perennial flood standard, which was essentially not the elimination of disaster risks. A large
number of accumulation bodies remained on the river-bank and river, and it would again be disaster if they were mismanaged. Therefore, it was necessary to make some subsequent treatments for which the treatment time was relatively abundant compared with the emergency treatment.

There were two types of treatment methods to address the accumulation bodies of 12 million m³: one was full excavation and the other was artificial reinforcement. The full excavation method required much work and the cost was very high; moreover, it was hard to find a large enough place to hold the excavated materials, which could cause further disasters. The second method, artificial reinforcement, was a water conservancy project that could provide water for irrigation, human life and hydropower resources for downstream areas; however, it would be necessary to solve the problems of seepage prevention, the stability of high slopes and the restoration of the coastal highway. By site visits, some engineering reinforcement measures could completely develop the landslide dam for irrigation, power generation, flood control and tourism.

Because of subsequent transformations, new large-scale landslides did not occur for the residual slopes and floods were successfully experienced in 2015. Moreover, the landslide lake had been further treated, forming a comprehensive hydropower project with a total capacity of 1.6 billion m³ and an installed capacity of 200 MW.

6. Conclusions

Landslide-dammed lakes were typical geological hazards induced by earthquakes in mountainous river areas that expanded the time-space influence of earthquake disasters. Studies of the dam-break risk and the mitigation measures were very important for hazard prevention and the mitigation of reservoir landslides. In this paper, the 3 August 2014, Hongshiyan landslide-dammed lake induced by the Mw 6.5 Ludian earthquake was used as an example to study the dam-break risk and the flood routing process.

The fuzzy mathematics method was used to evaluate the risk level of the Hongshiyan dammed-lake and to propose six main indicators. The results showed that the Hongshiyan landslide-dammed
lake had an extremely high risk and very serious disaster consequences; effective artificial measures were required to reduce the scale of possible disasters. Emergency measures and subsequent treatments were used in the process of disaster reduction. The emergency measures included upstream interception, middle grooming and downstream emissions; these measures avoided a large dam-break flood and basically prevented landslide-dammed lake disasters through 19:00, 4 October 2014. Based on the emergency measures, subsequent treatments included some engineering reinforcement measures to completely open up the landslide dam’s development for irrigation, power generation, flood control and tourism.

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Disclosure statement

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