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Risk analysis and emergency actions for Hongshiyan barrier lake

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Abstract This paper presents the emergency response to the barrier lake created by the *Mw* 6.5 earthquake on August 3, 2014, in Niulan River which is situated in Yunnan Province, southwest China. The lake, behind 83- to 103-m-high landslide dam, has a storage capacity of 260 million m^3. The Hongshiyan hydropower station, situated just upstream of the landslide dam, was submerged by the lake water. The rescue actions include building an 8-m-deep drainage channel in the flood season, draining the lake water via a water release tunnel and rebuilding the landslide dam as a permanent structure. This paper presents the considerations and processes in deciding on the emergency actions. One major consideration is to minimize the hazards caused by a possible dam break flood induced by Hongshiyan barrier lake in the flood season. It was found that the barrier lake is classified as "grade I: extremely high risk" in which the 5- and 20-year floods should be used for design and check purposes of emergency works, respectively. The dam break flood evaluations indicated that an 8-m-deep diversion channel should be constructed in order to reduce the total amount of the released reservoir storage and to prevent possible overtopping of the downstream Huangjiaoshu rockfill dam. This study was based on an improved analytical approach to dam break flood modeling and a handy spread sheet developed by the authors. The considerations on various risks and the key analytical

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technology for dam break flood predictions described in this paper may be useful for other similar cases.

1 Introduction

On August 3, 2014, an earthquake of magnitude 6.5 occurred at Ludian, Yunnan Province, in southwest China. As a consequence of the earthquake, a barrier lake was formed in the Niulan River. This river is a tributary on the right bank of the Jinsha River. The landslide debris formed an 83- to 103-m-high barrier dam, which can hold a maximum water storage of 260 million m^3. The landslide is located 600 m downstream of Hongshiyan hydropower dam that was completely submerged by the rising water of the barrier lake. Downstream of the landslide dam, there exist a 90-m-high concrete arch dam and a 65-m-high concrete face rockfill dam, which are located at 18.8 and 57.6 km from the landslide dam, respectively. Break of the landslide dam not only poses a threat to the downstream residents but also has a risk of overtopping the two downstream existing dams. This barrier lake also has a special feature in that once the impounding pool water reaches the elevation of 1174 m (which is approximately 48 m below the dam crest), the water stops rising under normal conditions because the water level reaches the elevation of the surge tank crest of the submerged Hongshiyan hydropower station. Thus, the water in the river flows through the water supply tunnel, overflows the surge tank and then flows downstream. This means that the dam will stay unless it is destabilized by piping or overtopping with a huge flood whose flowrate is much greater than the discharge capacity of the water supply tunnel. In view of the situation, it is necessary to ask the following questions:

1. What is the dam break flood if ever the dam is overtopped due to an extraordinary huge flood in the Niulan River?
2. What is the flood standard to be adopted for the dam break flood analysis?
3. If the predicted dam break flood exceeds the mitigation standards, what are the possible engineering measures that could lower the flood peak to a level that is safe for the downstream residents and structures?

Occurrences of landslide dams are common. Strong earthquakes are a main triggering factor (Keefer 1984, 2002; Evans et al. 2011). Typical examples of earthquake-induced barrier lakes can be referred to the Tsao-Ling landslide dam formed by Chi-Chi earthquake on September 21, 1999, in Taiwan (M_w 7.6; Li et al. 2002; Khazai and Sitar 2003), the EI Desagüe and Jiboa landslide dams in El Salvador on February 13, 2001 (M_w 6.6; Baum et al. 2001), the Higashitakezawa barrier lake formed by Niigata-ken Chuetsu earthquake on October 23, 2004, in Japan (M_w 6.6; Furumura and Hayakawa 2007), HattianBala landslide dam formed by Kashmir earthquake on October 8, 2008, in Pakistan (M_w 7.6; Sato et al. 2007; Schneider et al. 2013). In China, the M_w 8.0 Wenchuan earthquake triggered approximately 60,000 landslides (Dai et al. 2011; Gorum et al. 2011) and formed more than 800 landslide dams (Fan et al. 2012). The Tangjiashan barrier lake had the highest risk among them, and fortunately, it was successfully drained in time (Liu et al. 2010).

The experts involved in this emergency response work were mainly the key members who successfully carried out the rescue work of Tangjiashan barrier lake. They carefully reviewed all the related concerns and came to the following conclusions that were put into action:

1. According to the code "Standard for Classification of Risk Grade of Landslide Lake (SL 450-2009)" published by the Ministry of Water Resources of China, the Hongshiyan barrier lake belongs to risk grade I and the 5- and 20-year floods should be used for design and check purposes of emergency works, respectively, because the rescue work was carried out during the flood season of this river.
2. The dam break analysis indicates a flood with a peak discharge of 8368 m^3/s associated with the 20-year flood. This would cause overtopping of both Tianhuaban and Huangjiaoshu dams.
3. A decision was made that an 8-m-deep diversion channel be constructed in the right embankment in order to reduce the total amount of the released reservoir storage by 1.2×10^7 m^3 and the peak dam break discharge to 8163 m^3/s. This measure would ensure that the possible dam break flood would not overtop Huangjiaoshu rockfill dam.
4. As a matter of fact, the 20-year flood did not occur in the 2014 flood season and the diversion channel was not used. The reservoir was subsequently emptied by a new diversion tunnel. This landslide dam is being upgraded to a permanent dam replacing the submerged Hongshiyan concrete dam.

These emergency actions are considered appropriate in view of the huge disaster that could happen if the dam were to break. As members of the working team on the dam flood evaluation for the Headquarters of Hongshiyan Emergency Action, authors of this paper present the various aspects that were studied during the emergency response period which led to the final hazard reduction decisions.

2 Characteristics of river basin and Hongshiyan barrier lake

2.1 Hydrology of the Niulan River

The Niulan River, where the landslide dam happened, is a main tributary of the Jinsha River. It is located in Yunnan Province, China, as shown in Fig. 1. Its total length is 440 km with a catchment area of 13,672 km^2. The average bed slope is approximately 4.4 ‰. According to the historical data from 1953 to 2012, the average annual runoff was approximately 4.9×10^9 m^3, and the average flow at Hongshiyan hydropower dam was approximately 128 m^3/s. In the typical year of 1968, the peak discharge at Hongshiyan hydropower station was measured to be 2740 m^3/s. Figure 2 shows the design flood hydrographs of different return periods (solid lines) and the 1968 flood hydrograph (dashed line).

The Niulan River has rich water resources with four hydropower stations that are located in the vicinity of the landslide. Figure 3 shows the locations of the four cascade hydropower stations and the landslide dam. The Hongshiyan hydropower station is submerged completely, and the downstream hydropower stations (Tianhuaban and Huangjiaoshu) face the risk of overtopping if the landslide dam breaks. The main technical parameters of the downstream hydropower stations are shown in Table 1.

2.2 Hydropower projects

2.2.1 Hongshiyan hydropower station

The Hongshiyan hydropower station has its dam located just 600 m upstream of the landslide and was completely submerged by the barrier lake. The Xiaoyantou project has a
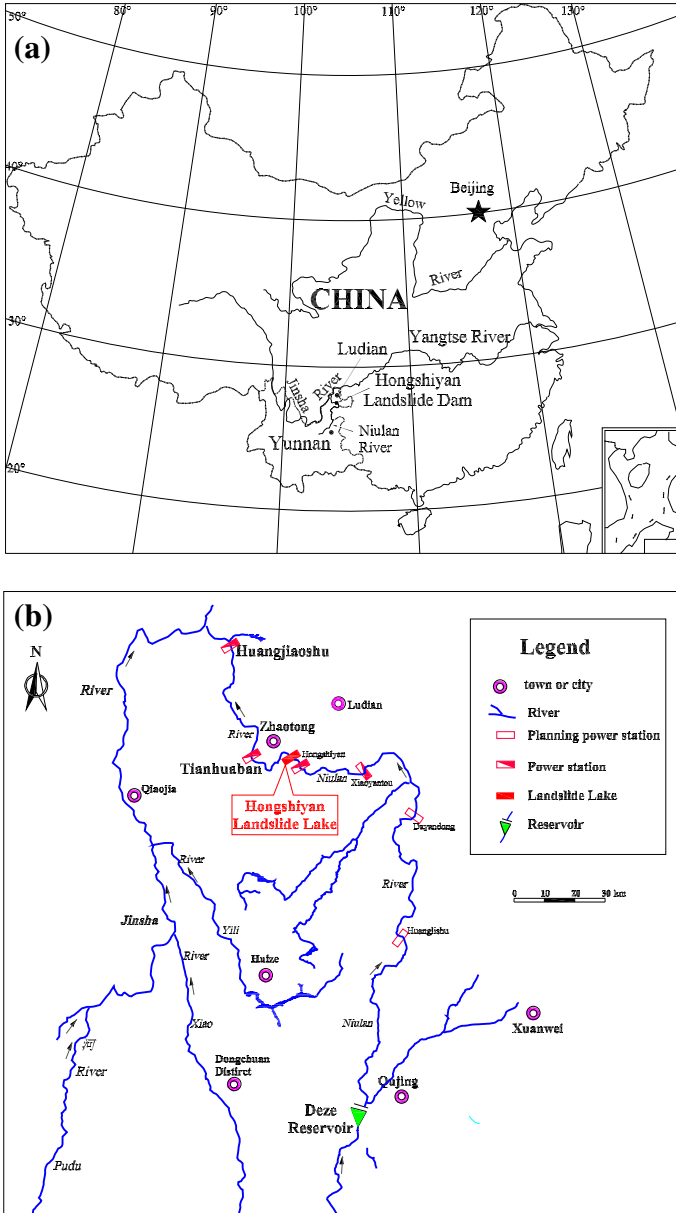

Fig. 1 Location of Hongshiyan landslide lake and its nearby cities and towns. **a** Location, **b** the tributary

Fig. 2 Design flood hydrographs (*solid lines*) and measured flood hydrograph in 1968 (*dashed line*) at Hongshiyan hydropower station
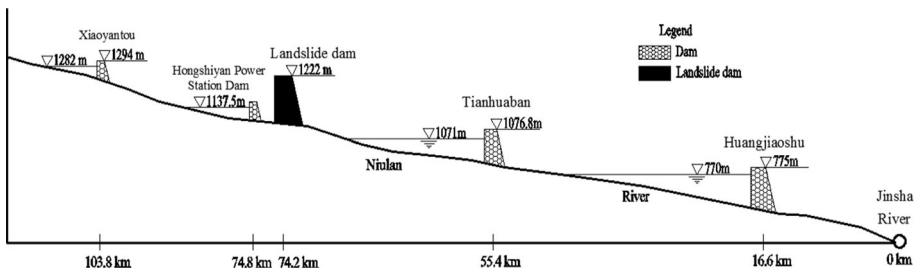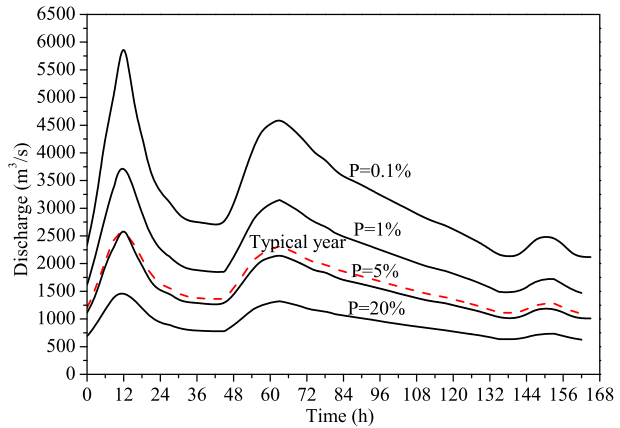

Fig. 3 Geographic relationship of the cascade dams and the landslide dam

concrete arch dam located 29.6 km upstream of the barrier lake, which was not damaged during the earthquake. Hence, it was not part of the rescue work for Hongshiyan barrier lake. The project has a water supply tunnel in the right abutment that leads to the power station. Figure 4 shows the layout along the diversion channel of Hongshiyan station. After the earthquake, in the afternoon of August 4, 2014, the water in the surge tank of the Hongshiyan station started to overflow (refer to Fig. 5). This happened when the water level rose to 1171.80 m, which is the elevation of the surge tank crest. The relationship between the overflow discharge of the surge tank and the bulkhead gate and the water level of the lake is presented in Fig. 6. However, there is still a risk of the landslide dam to be overtopped if the river encounters a huge flood in the flood season. Figure 7 shows the relationship between the water storage and the elevation of the water level in the landslide lake.

2.2.2 Tianhuaban hydropower station

The water-retaining structure of Tianhuaban hydropower station is a concrete arch dam. The dam is 107 m high. The elevation and the length of the dam crest are 1076.8 and 159.87 m, respectively. The discharge structures include three surface spillways, two middle orifices and a sediment bottom sluice. The inlet elevations of surface spillway and middle orifice are 1260.5 and 1020 m, respectively. The elevations of the check and

Table 1 Main parameters of cascade hydropower stations

Name	Unit	Value	
		Tianhuaban	Huangjiaoshu
Dam		Concrete arch dam	Rockfill dam
Elevation of dam crest	m	1076.80	775
Maximum height of dam	m	107.00	65
Length of dam crest	m	159.87	217.72
Water level			
Check flood water level	m	1076.61 ($P = 0.2$ %)	774.37 ($P = 0.05$ %)
Design flood water level	m	1070.91 ($P = 2$ %)	770 ($P = 1$ %)
Normal water level	m	1071.00	770
Dead water level	m	1050	746
Capacity of reservoir			
Total storage	10^4 m^3	7871	4046
Dead storage	10^4 m^3	2949	885
Discharge			
The maximum discharge in check flood water level	m^3/s	5046 ($P = 0.2$ %)	6781 ($P = 0.05$ %)
The maximum discharge in design flood water level	m^3/s	3152 ($P = 2$ %)	4300 ($P = 1$ %)
Discharge structures			
The upper outlet			Spillway tunnel
The elevation of practical weir crest	m	1062.50	750
Design flood flow	m^3/s	1455 ($P = 2$ %)	2366 ($P = 1$ %)
Check flood flow	m^3/s	3246 ($P = 0.2$ %)	3250 ($P = 0.05$ %)
The middle outlet		Radial gate	Diversion tunnel
The elevation of gate bottom	m	1020.00	716
Design flood flow	m^3/s	1697 ($P = 2$ %)	1934 ($P = 1$ %)
Check flood flow	m^3/s	1800 ($P = 0.2$ %)	3531 ($P = 0.05$ %)

normal flood levels are 1076.61 and 1070.91 m, corresponding to the reservoir capacities of 7.87×10^7 and 6.57×10^7 m^3, respectively. The maximum discharge is approximately 5046 m^3/s through all discharge structures, and the discharge would be 3152 m^3/s if the water level is at the design flood level (1070.91 m). The storage–elevation curve and the discharge curves are shown in Figs. 8 and 9, respectively.

2.2.3 Huangjiaoshu hydropower station

Downstream of Tianhuaban hydropower project, there is a concrete face rockfill dam for the Huangjiaoshu hydropower station. The safety of this dam is of prime concern because the consequence of this dam being overtopped due to the breaking of the barrier lake is unacceptable. The dam is 65 m high. The elevation and the length of the dam crest are 775 and 217.72 m, respectively. The elevations of the check and normal water levels are 774.37 and 770 m, corresponding to the reservoir capacities of 4.05×10^7 and
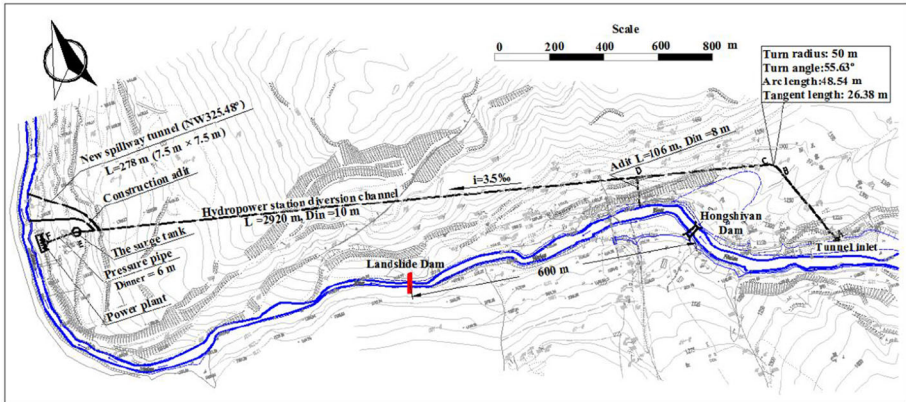
Fig. 4 Layout along the division tunnel of Hongshiyan station

Fig. 5 Overflowing through the surge tank

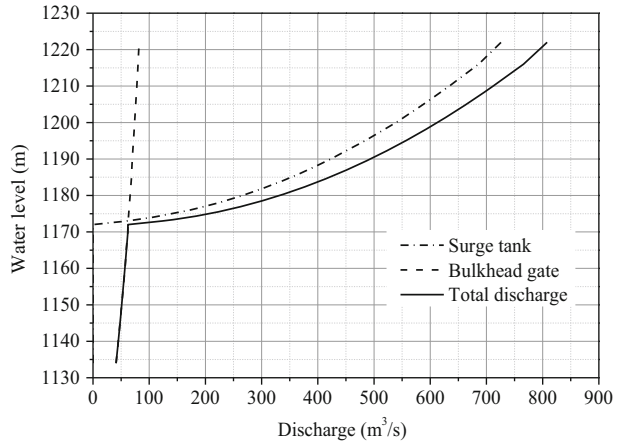**Fig. 6** Discharge curves of surge tank and bulkhead gate

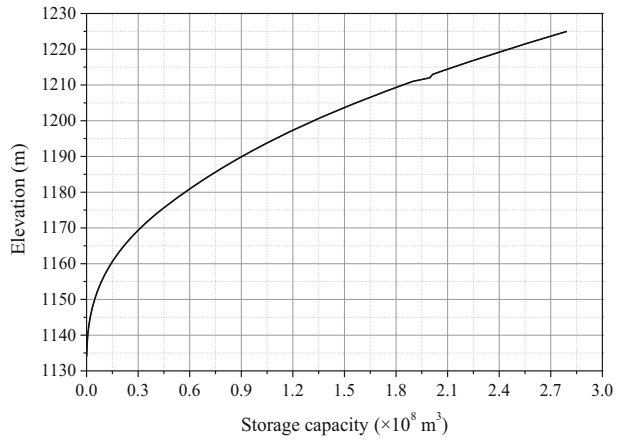**Fig. 7** Relationship between water storage and elevation of the landslide lake

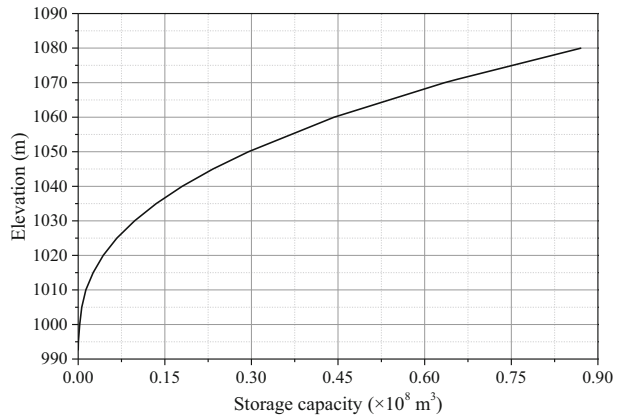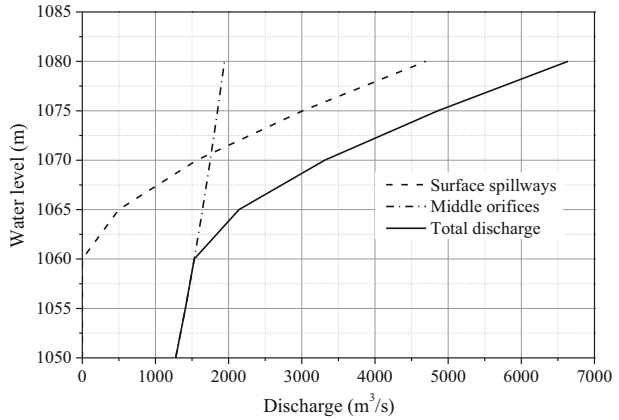**Fig. 8** Relationship between water storage and elevation of Tianhuaban

Fig. 9 Discharges of the flood release facilities of Tianhuaban

3.29×10^7 m³, respectively. The discharge structures include a spillway tunnel and a sediment diversion tunnel. The respective inlet elevations of the two tunnels are 750 and 716 m. The maximum discharge is approximately 6691 m³/s through both tunnels, and the discharge would be 5744 m³/s if the water level is at the design flood level (i.e., 770 m). The storage–elevation curve and discharge curves are shown in Figs. 10 and 11, respectively.

3 The Hongshiyan barrier lake

3.1 Hongshiyan landslide dam

Hongshiyan landslide dam is formed by the collapsed strongly weathered dolomite on both sides of the Niulan River. The volume of the landslide deposit is approximately 1.2×10^7 m³ with the deposit on the right of the landslide accounting for 70 % of the total. Some of the deposits in the dam body are larger than 50 cm, and the maximum diameter of rock is between 5 and 10 m. The crest elevation of Hongshiyan landslide dam

Fig. 10 Relationship between water storage and elevation of Huangjiaoshu
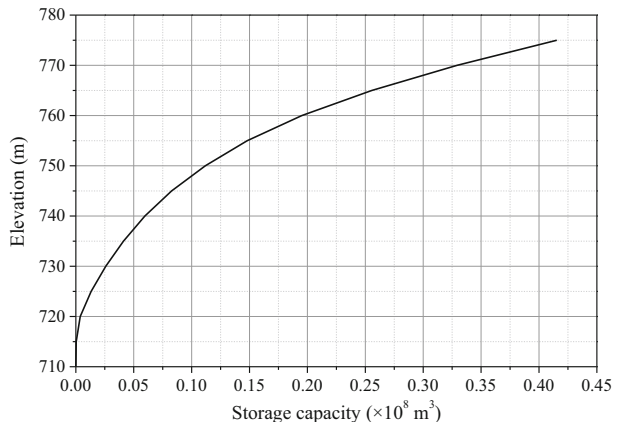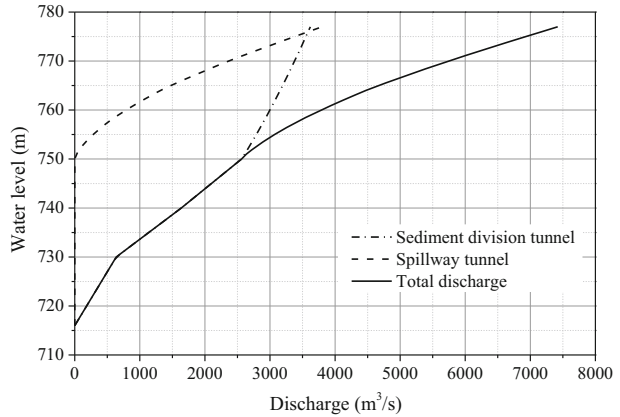
Fig. 11 Discharges of the flood release facilities of Huangjiaoshu

is 1222 m. Its height is between 83 and 103 m. The storage capacity of barrier lake is 2.6×10^8 m^3, and the length of upstream backwater is 25 km when the water level is at the crest elevation of landslide dam (i.e., 1222 m). Table 2 and Fig. 12 show the main characteristic parameters and topography of the landslide dam.

3.2 Assessment of the level for risk control

The risk classification of a landslide dam depends on the hazard level and the severity of the consequential loss. The Ministry of Water Resources of China published a code entitled "Standard for classification of risk grade of landslide lake (SL 450-2009)." According to the size of barrier lake, a dam can be classified into one of the four categories: "large" ($V \geq 1.0 \times 10^8$ m^3), "medium" (1.0×10^8 m$^3 > V \geq 0.1 \times 10^8$ m^3), "small (1)" (1.0×10^8 m$^3 > V \geq 0.1 \times 10^8$ m^3) and "small (2)" ($V < 0.01 \times 10^8$ m^3), where V is the water storage of the lake. Further, according to the size, material composition and the height (designated H), the risk of landslide dam can be classified into "very high" ($H > 70$ m), "high" (30 m $> H \geq 70$ m), "significant" (15 m $> H \geq 30$ m) and "low"

Table 2 Main characteristics of the landslide dam and lake

| Item	Parameters	Magnitude
Landslide dam	Volume of the landslide deposit	1.2×10^7 m^3
	Elevations of crest/toe, measured at the lowest crest surface of the right deposit	1222/1119 m
	Length along the river valley (top of the deposit)	17 m
	Length along the river valley (bottom of the deposit)	911 m
	Length across the river valley of the deposit (1222 m)	301 m
	Average slope ration of upstream/downstream	1:2.5/1:5.5
Lake	Potential highest water level	1222 m
	Potential storage of water	2.6×10^8 m^3
	Elevation of the original river bed	1119 m
	Backwater length	25 km
	The catchment area of barrier lake	11,832 km^2
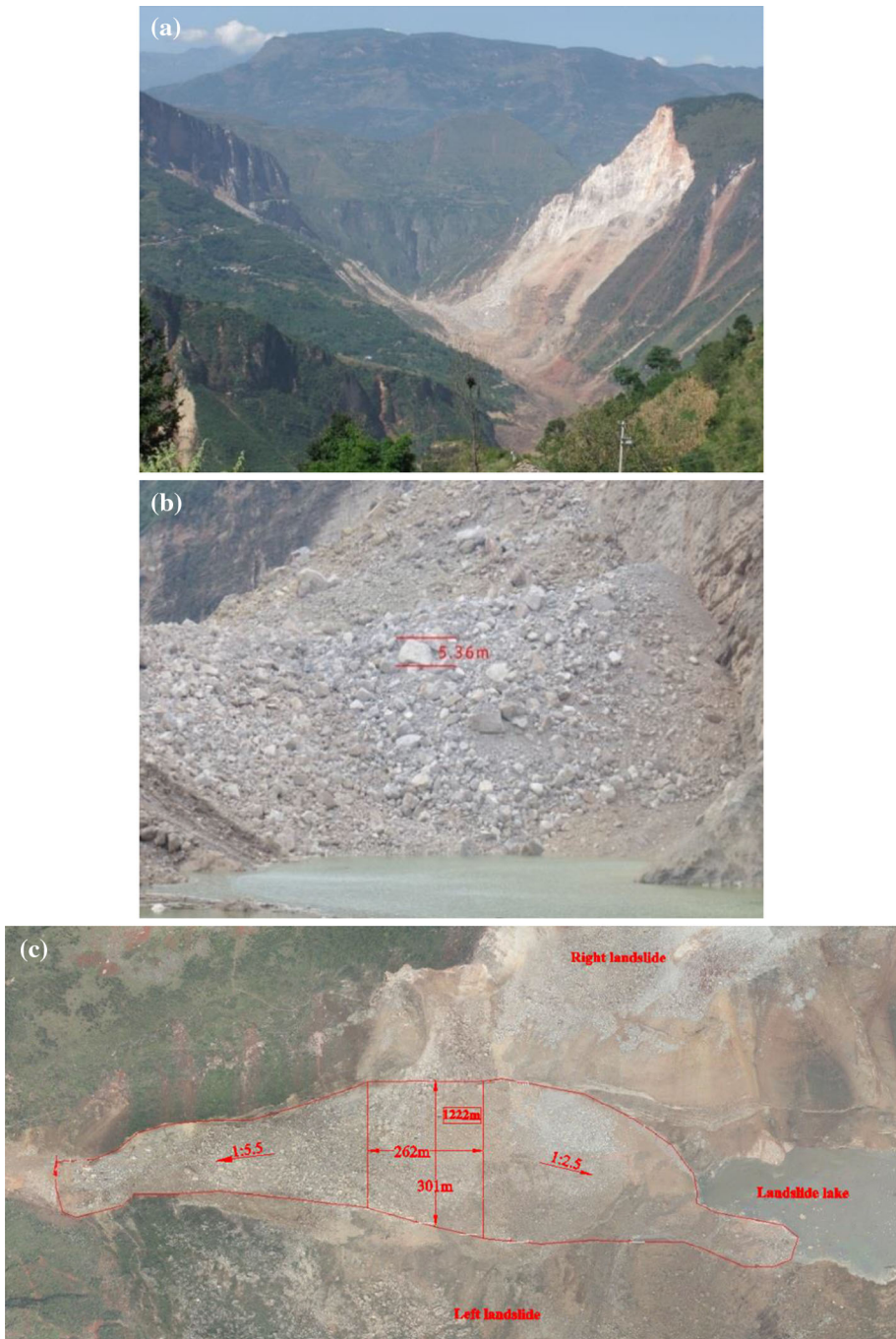
Fig. 12 Hongshiyan landslide dam. **a** The overall view, **b** the dam surface, **c** the size of dam (from Kunming Engineering Corporation Limited)

($H < 15$ m). The severity of consequential loss due to breaking of landslide dam is directly dependent on the number of people at risk (PAR), and the importance and values of the towns and its installations. It can be classified into four levels: "extremely serious" (PAR $\geq 10^6$), "serious" ($10^5 >$ PAR $\geq 10^6$), "relatively serious" ($10^4 >$ PAR $\geq 10^3$) and "general" (PAR $< 10^4$).

The risk of landslide lake can be classified into four categories based on the hazard level and the severity of consequential loss in the case of a dam break. Using the risk matrix method, Table 3 shows the risk classifications.

3.3 Selection of design flood for emergency mitigation civil work

For any structure that is to be constructed on a river, it is a common practice to design it based on a flood of a certain return period (Fernández and Salas 1999). Similarly, the code specifies flood return periods for landslide lakes associated with their risk classifications, which are shown in Table 4.

Based on Table 3, the Hongshiyan barrier lake belongs to grade I risk classification. Based on Table 4, the corresponding design flood for grade I risk classification is associated with a return period "$\geq$5 year." However, the code did not clearly specify what a particular year of return period is suitable for a specific grade I barrier lake. After a careful study, it was decided that for Hongshiyan barrier lake, the 5- and 20-year floods should be used as design and check cases, respectively. The main reasons are as follows:

1. From Table 3, one can find that under the "grade I" risk classification, there are two subgrades which are "serious" and "extremely serious." In view of the possible impact on the two existing dams downstream, Hongshiyan barrier lake is considered to belong to the subgrade "extremely serious" and the upper bound of the specification of "$\geq$5 year" should be adopted.

2. A back analysis for a similar emergency disposal work on the design flood return period for the Tangjiashan Barrier Lake has been recently carried out by the authors' research group (Zhou et al. 2015). It was concluded that the overtopping of this landslide dam in conjunction with a 20-year flood would create a flood of 17,583 m^3/s at Mianyang, a downstream very important city with 1.2 million residents, while the dike of this city can only resist a flood of 15,600 m^3/s. A 13-m-deep diversion channel

Table 3 Risk classification of landslide lake

Risk classification	Hazard level of landslide dam	Severity of consequential loss
I	Extremely high risk	Serious
	High risk, medium risk	Extremely serious
II	Extremely high risk	Relatively serious, generally serious
	High risk	Serious, relatively serious
	Medium risk	Serious
	Low risk	Relatively serious, serious
III	High risk	Generally serious
	Medium risk	Relatively serious, generally serious
	Low risk	Relatively serious
IV	Low risk	Generally serious

Table 4 Flood standard of landslide lake in emergency stage

Risk classification	Flood return period/year
I	≥5
II	3–5
III	2–3
IV	<2

was actually excavated. The back analysis showed that this work would reduce the dam breach flood at Mianyang to a magnitude of 15,464 m^3/s for an overtopping combined with a 20-year flood. This case history represents an experience of engineering practice that adopts a flood standard of one in 20-year flood.

After determining the design and check floods, the next question is to select an appropriate emergency mitigation civil work that can meet the requirement of these standards. The feasibility studies include the alternatives of excavating a diversion channel with depth of 8, 14 and 22 m, respectively. It was finally concluded that an 8-m-deep channel would make the downstream Huangjiaoshu rockfill dam survive without being overtopped by the landslide dam breach combined with a 20-year flood. The remaining part of this paper is mainly focused on the alternative with an 8-m-deep diversion channel.

4 Dam break and flood routing analysis

4.1 Method of analysis

Predicting the dam break flood due to overtopping of the Hongshiyan landslide dam, either in its original geometry or in the alternative geometry with an 8-m-deep diversion channel, is an essential part of the emergency mitigation study. There are two parts in this study: (1) estimation of flood hydrographs at the breach and (2) routing of the flood hydrographs along the downstream river until they reach Huangjiaoshu rockfill dam.

There are many publications on the numerical simulation of the dam break process (e.g., Fread 1984, 1988; Singh et al. 1988) and the associated computer programs, such as DAMBRK, BREACH (Fread 1984), BEED (Singh et al. 1988), MIKE11 (Havnø et al. 1995) and HEC-RAS (HEC 2006a, b). However, Wahl (2004) and Zhu et al. (2004) reported that there are considerable uncertainties in the predicted peak discharge. For example, for the possible dam break of the Tangjiashan barrier lake, the predicted peak discharge was 46,000 m^3/s, which was eight times larger than the actual measured discharge (Liu et al. 2009). A simplified dam breach model was recently developed by the authors' research group that is highlighted as follows (Chen et al. 2015).

By equating the discharge through the breach based on the theory of flow over a broad crested weir, and the loss of storage in the reservoir in a unit time, the governing equation for a dam break analytical model is

$$CB(H - z)^{3/2} = \frac{\Delta W}{\Delta H} \frac{\Delta H}{\Delta t} + q \tag{1}$$

where C is the discharge coefficient, B is the width of the weir, H is the elevation of water level, z is the elevation of breach bed, q is the inflow of the river, W is reservoir water storage, and t is time.

Both B and z vary throughout the dam break process due to the lateral enlargement and soil erosion of the breach. With respect to the soil erosion rate that relates z to the shear stress τ, Chen et al. (2015) recommended a hyperbolic model:

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \frac{k(\tau - \tau_c)}{a + b \cdot k(\tau - \tau_c)} \tag{2}$$

where k is a unit conversion factor that allows E to approach its asymptote E_{ult} within the working range of τ. As shown in Fig. 13, the hyperbolic curve has an asymptote represented by $E_{\mathrm{ult}} = 1/b$ as $\tau - \tau_c$ approaches infinity. This is the maximum possible soil erosion rate. The parameter $1/a$ represents the tangent of this curve at $\tau = \tau_c$.

Slope stability analysis using a wedge failure has been widely adopted to find the enlarged value of B in Eq. (1) (e.g., Fread 1984). It was found that the breach lateral enlargement process ought to be modeled using more rigorous analytical methods with circular slip surfaces, such as Bishop's simplified method (1955). The procedure for calculating the factor of safety F is repeated among various possible slip surfaces until a critical one associated with the minimum factor of safety F_m is found (Chen et al. 2015). This algorithm enables fast and robust calculations to be carried out using an Excel spreadsheet DB-IWHR 2014, which is available for download at the following website: http://www.geoeng.iwhr.com/geoeng/download.htm.

Since the Hongshiyan dam material is very similar to that of Tangjiashan, all the related parameters for the latter are adopted for the current study, which can be found in Chen et al. (2015).

A dam break flood travels downstream can be mathematically described by the unsteady, open channel flow based on Saint–Venant equations (Fread 1988; HEC 2006b; Moussa and Bocquillon 1996). Based on the analysis of the dam break at Tangjiashan barrier, it was shown that the breaching hydrograph remains practically unchanged in a narrow valley (Liu et al. 2009). Since the Hongshiyan landslide dam and the Niulan River are also situated within a narrow valley, the hydrograph that passes the two dams downstream is therefore expected to be the same as the breaching hydrograph.
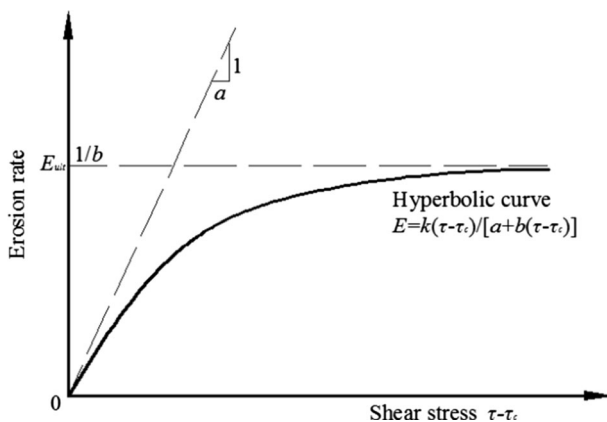

Fig. 13 Hyperbolic model for soil erosion rate

4.2 Flood analysis at Hongshiyan barrier lake

It is proposed that flood regulation comes into operation when the water level reaches 1180 m. This is the water level elevation in which the natural flow equals the discharge capacity of the surge tank. The objective of this study is to determine whether the 5- and 20-year floods would cause the lake water level to rise above 1222 m which is the elevation of the dam crest, or above 1214 m which is the new elevation of the dam crest if the 8-m-deep channel is constructed. The process of flood regulation can be calculated by the Eqs. (3) and (4):
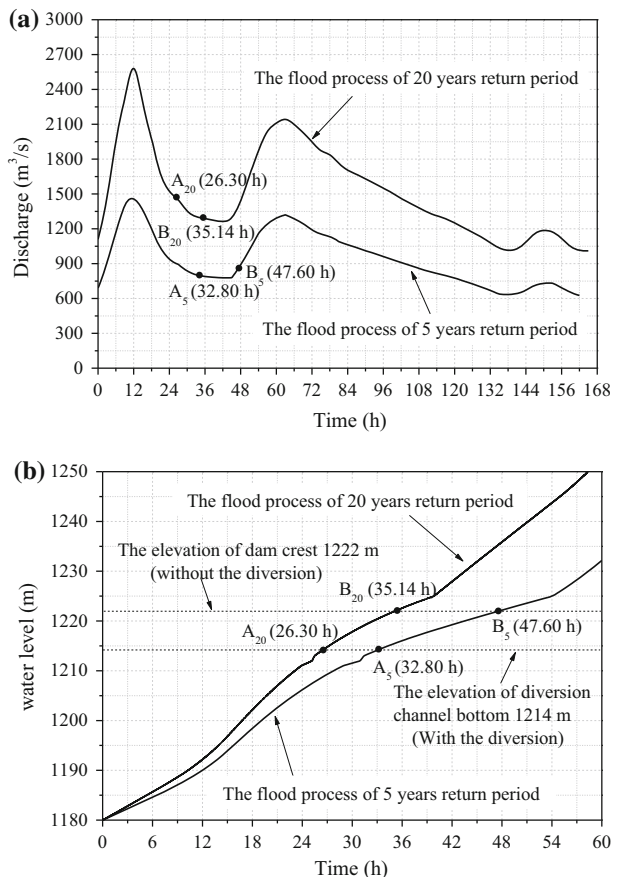
$$\frac{Q_1 + Q_2}{2}\Delta t - \frac{q_1 + q_2}{2}\Delta t = V_2 - V_1 \tag{3}$$

in which V is a function of Z

$$V = f(Z) \tag{4}$$

where Δt is time step; Q_1 and Q_2 are the initial and final inflows of calculated period, respectively; q_1 and q_2 are the initial and final outflows of calculated period, respectively;

Fig. 14 Flood hydrograph at Hongshiyan. **a** 5- and 20-year return period (7 days), **b** regulated flood process

V_1 and V_2 are the initial and final volume of calculated period, respectively; Z is the elevation of barrier lake. Integration is made with the given time step.

The inputs involved in Eq. (3) are as follows:

1. Q_1, Q_2 can be found in Fig. 14a for either the 5- or 20-year flood;
2. q_1, q_2 are the discharge capacities of the surge tank and bulkhead gate, respectively, associated with the lake water level elevation, as shown in Fig. 6, and
3. the relationship between the lake water level Z and the storage in the lake V is shown in Fig. 7.

The flood routing results show that (Fig. 14b):

1. for the 5-year design flood, the water level reaches 1214 m at 32.80 h (point A_5) and 1222 m at 47.60 h (point B_5), and
2. for the 20-year design flood, the water level reaches 1214 m at 26.30 h (point A_{20}) and 1222 m at 35.14 h (point B_{20}).

As shown in the flood routing results, for both design floods (5- and 20-year), the dam is overtopped. Hence, it is necessary to assess the impact of the dam break flood on the downstream structures and villages.

Fig. 15 Landslide dam break discharge. **a** With the diversion channel, **b** without the diversion channel
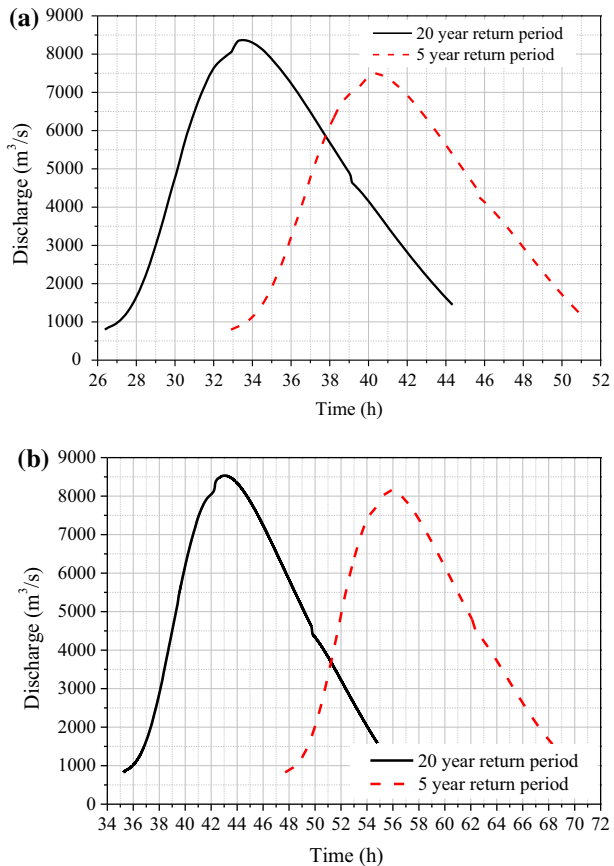
4.3 Dam break flood at Hongshiyan

The dam break analysis at the Hongshiyan barrier lake follows the procedure described in Sect. 4.1. The discharge hydrographs for the 5- and 20-year design floods are shown in Fig. 15. Table 5 contains a summary of the dam break analysis results.

The analysis results show that for the 20-year flood, construction of the diversion channel can reduce the total released water from 3.54×10^8 to 3.15×10^8 m^3. As will be shown in Sect. 4.5, this reduction in released water prevents the downstream Huangjiaoshu rockfill dam from being overtopped.

4.4 Flood analyses at Tianhuaban dam

The flood routing analyses through Tianhuaban dam were carried out by balancing the incoming dam break flood (Fig. 15) with the outflow through the discharge facilities according to the relationship as shown in Fig. 9. As explained in Sect. 4.1, the dam break flood at Hongshiyan can be used as the inflow to Tianhuaban. The calculation commenced at the initial water level 1040 m. Figures 16 and 17 show flood hydrographs at Tianhuaban for 5- and 20-year design floods, respectively. Table 6 contains a summary of the floods at Tianhuaban.

It is apparent that for all cases, the highest water levels exceed 1076.8 m which is the elevation of the dam crest. For the 20-year design flood, the depths of the overtopping flow at the dam crest are 4.55 and 4.16 m for with and without the diversion channel, respectively. On the other hand, it is generally known that a concrete arch dam can sustain overtopping for a period of time without being damaged. For example, the famous Vajont arch dam, one of the tallest dams in the world with the height of 261.6 m, survived with only small damages when a gigantic water wave overtopped it by as much as higher than 200 m (Kilburn and Petley 2003; Genevois and Ghirotti 2005; Alonso et al. 2010).

4.5 Flood analyses at Huangjiaoshu dam

Similar to the flood analyses through Tianhuaban dam, the flood analyses were carried out using the incoming floods from Figs. 16 and 17 with the hydraulic relationships in Figs. 10 and 11. The initial water level at Huangjiaoshu reservoir is controlled at 720 m. Figures 18

Table 5 Summary of dam break analysis results at Hongshiyan

Return period (year)	Emergency disposal scheme	Dam crest (m)	Overtopping time (h)	Peak discharge (m^3/s)	Peak discharge time (h)	Released water (10^6 m^3)
5	Without the diversion channel	1222	47.60	8163	55.71	351.93
	With the diversion channel	1214	32.80	7342	40.53	283.03
20	Without the diversion channel	1222	35.14	8534	43.02	353.63
	With the diversion channel	1214	26.30	8368	33.47	314.93

"Overtopping time" and "peak discharge time" are measured from the moment that the pool water level arrives at 1180 m when the inflow is greater than the outflow for the surge tank and starts rising

Fig. 16 Flood hydrographs at Tianhuaban for 5-year design flood. **a** Without diversion channel, **b** with diversion channel
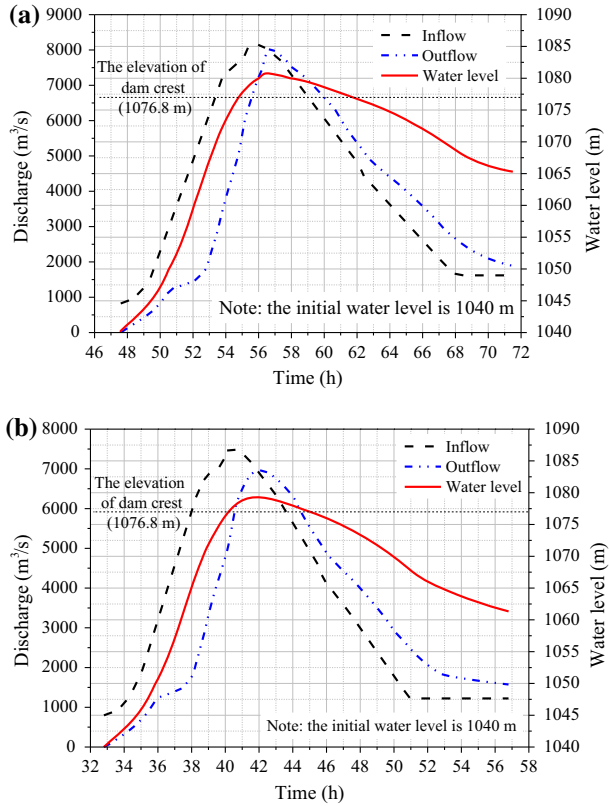
and 19 show the flood hydrographs at Huangjiaoshu for 5- and 20-year design floods. Table 7 contains a summary of the floods at Huangjiaoshu.

In order to ensure that Huangjiaoshu dam is safe, the maximum water level in the lake cannot exceed the elevation of the dam crest which is 775 m. Otherwise, the rockfill dam will break, resulting in another disaster. According to the results in Table 7, the only two cases in which the maximum water level elevation is lower than 775 m are the emergency work with the diversion channel. As such, the diversion channel is recommended as the emergency work.

While dam break flood analysis is not a precise science (Gee 2009), the results in Table 7, together with other results that are not presented in this paper, do provide a sound reason to adopt the alternative of having a diversion channel in order to minimize the catastrophic risk.

4.6 Diversion channel

As shown in Sect. 4.5, the construction of the diversion channel is a good solution to prevent possible catastrophes that may be triggered by the breaking of the Hongshiyan landslide dam. Historically, there are a number of landslide-dammed lakes that have used spillways or diversion channels to drain the water in the lakes, such as the Madison River Quake Lake in August 1959 in Montana, America (USACE 1960), the

Fig. 17 Flood hydrographs at Tianhuaban for 20-year design flood. **a** Without diversion channel, **b** with diversion channel
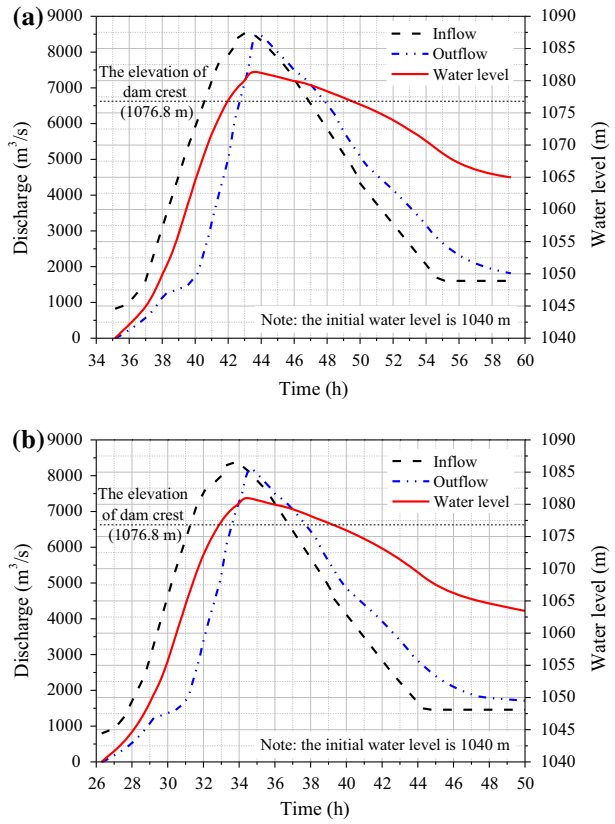

Table 6 Summary of floods passing Tianhuaban dam

Return period (year)	Emergency disposal scheme	Initial water level (m)	Maximum water level (m)	Overtopping time (h)	Inflow peak (m^3/s)	Inflow peak time (h)
5	Without the diversion channel	1040	1080.77	54.80	8163.89	55.79
	With the diversion channel	1040	1079.27	40.15	7502.14	40.30
20	Without the diversion channel	1040	1081.35	41.95	8532.60	43.15
	With the diversion channel	1040	1080.96	32.88	8367.93	33.60

Fig. 18 Flood hydrographs at Huangjiaoshu for 5-year design flood. **a** Without diversion channel, **b** with diversion channel
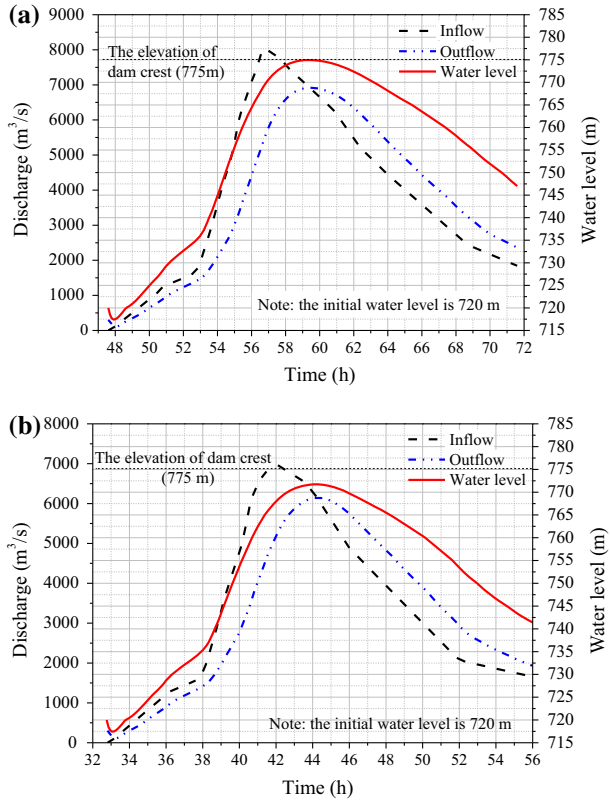
Mayunmarca rockslide dam occurred in April 1974 in Peru (Kojean and Hutchinson 1978), the Jiboa River landslide dam occurred in February 2001 in El Salvador (Bommer et al. 2002; Jibson et al. 2004), the Karli and Tung landslide dam in October 2005 in Pakistan (Schneider 2009), the Hunza rockslide-dammed lake in July 2010 in Kashmir (Kargel et al. 2010). In June 2008, an emergency channel (8 m wide and 13 m deep) was constructed at Tangjiashan landslide dam. This channel reduced the volume and the head of the released water during the dam breach, thereby created a controlled flood and prevented catastrophic consequences to 1.2 million residents downstream (Liu et al. 2010).

Based on the risk assessment of Hongshiyan landslide dam and the past emergency works at other sites, the diversion channel was decided to be built for the safety of the residents and structures in the downstream area, including Huangjiaoshu rockfill dam. After comparing the discharge and size of the channels and the construction time in other schemes, it was decided on a trapezoidal diversion channel with a side slope of 1:1.5 on both sides. The channel is 8 m deep with a base width of 5 m. The invert elevation of the channel inlet is 1214 m. The construction work started on August 8, 2014, and completed on August 12, 2014. Figure 20 shows the design ichnography of the diversion channel. Figure 21 shows the progress of the construction and the completed diversion channel.

Fig. 19 Flood hydrographs at
Huangjiaoshu for 20-year design
flood. **a** Without diversion
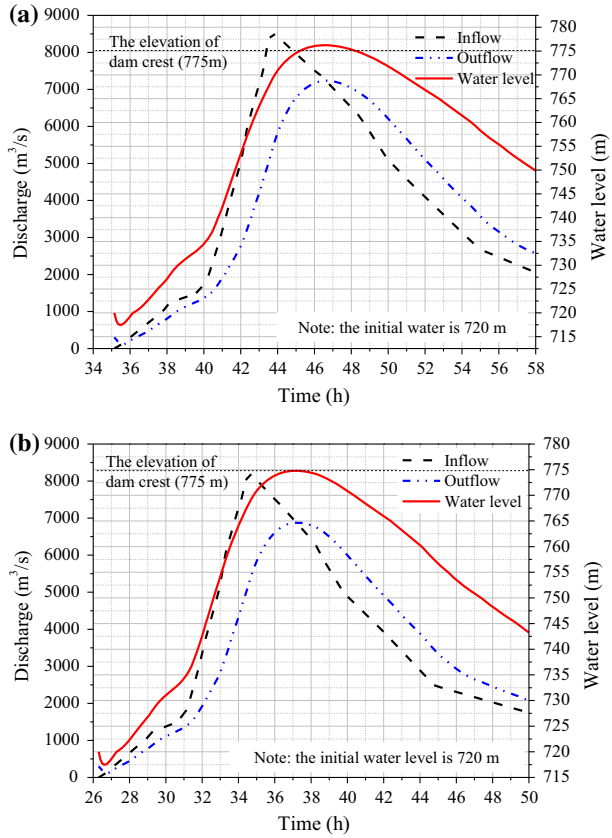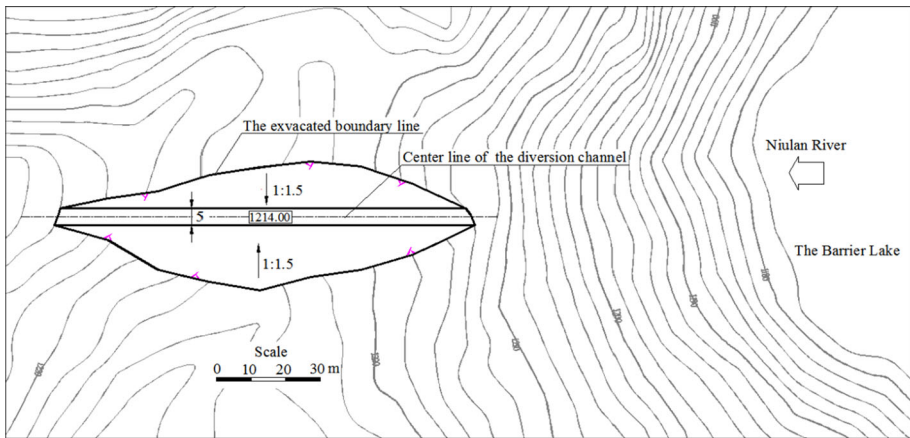channel, **b** with diversion channel

Table 7 Summary of floods passing Huangjiaoshu dam

Return period(year)	Emergency work	Initial water level (m)	Maximum water level (m)	Overtopping time (h)	Inflow peak (m³/s)	Inflow peak time (h)
5	Without the diversion channel	720	775.72	59.06	8037	56.80
	With the diversion channel	720	**771.58**	–	6849	42.30
20	Without the diversion channel	720	776.24	45.22	8502	43.74
	With the diversion channel	720	**774.78**	–	8187	34.70

Bold values indicate Huangjiaoshu Dam is safe

(From Kunming Engineering Corporation Limited)

Fig. 20 Design ichnography of the diversion channel

4.7 Draining lake water through deep tunnel

In order to drain the water in the Hongshiyan barrier lake, a new spillway tunnel was built. This tunnel is located on the right side of Niulan River and is connected to the old diversion tunnel. This tunnel is also useful for rebuilding the power station. The invert elevation of the tunnel inlet is at 1095.5 m and the length of the tunnel is approximately 278 m. The cross section of the tunnel is rectangular with the size 7.5 m × 7.5 m. The discharge capacity of the tunnel is 840 m³/s when the water level in the lake is at 1176 m. Figure 22 shows the operations in the tunnel and the portal of the tunnel. On October 2, 2014, the spillway tunnel was completed and the water in the lake was successfully drained during the October 6, 2014, flood. Figure 23 shows the reappearance of the previously submerged Hongshiyan power station. In comparison, the submerged water line can be seen clearly.

4.8 Rebuilding Hongshiyan hydropower station

With the draining of the water in Hongshiyan barrier lake by the newly built spillway tunnel, the risk of dam break has been eliminated. However, the total water storage of the landslide dam is approximately 10^7 m³ with the backwater extending up to 24 km upstream. While the water in the lake poses a great threat to the residents living downstream, the cost of dismantling the landslide dam is huge. The demolition work is also extremely difficult as the rubbles of the dam body are large and there is no suitable location to stack them within the range of 30 km. It has been finally decided that the landslide debris should be upgraded to a permanent dam accommodating a power station with installed capacity of 200 MW. Figure 24 shows the design plan of the hydropower station. The projected is being constructed.

(From Yunnan Daily)

(From Kunming Engineering Corporation Limited)

Fig. 21 Excavation of diversion channel

5 Concluding remarks

This paper documents various concerns involved in the decision makings for minimizing the hazards caused by a possible dam break flood induced by Hongshiyan barrier lake in a flood season. Highlights are as follows:

1. According to the code "Standard for classification of risk grade of landslide lake (SL 450-2009)," the barrier lake is classified as "grade I extremely high risk," for which a 20-year flood should be used for designing emergency works to prevent overtopping of the downstream Huangjiaoshu rockfill dam due to breaking of the landslide dam.

(By Zhu Lei)

(By Sun Xiaoyun)

Fig. 22 New spillway tunnel on right bank

2. The flood analysis indicates that the landslide dam would break in spite of the existing drainage tunnel provided by the submerged power station.
3. An 8-m-deep diversion channel was constructed by the rescue soldiers worked in a difficult environment with the after-quake and falling rocks. The dam break and flood routing analysis indicates that this civil work can reduce the total amount of the released reservoir storage by 3.87×10^7 m^3 and the peak dam break discharge to 8368 m^3/s in a 20-year flood, ensuring that the Huangjiaoshu rockfill dam would not be overtopped.
4. A large amount of dam break analytical work for different alternatives has been performed during the study. This was made possible due to our recent upgrading for

(By Wang Zhen)

(By Zhang Guangyu of XINHUA News Agency)

Fig. 23 Comparison of Hongshiyan hydropower station before and after submerged

dam break modeling and on the back analysis on a well-monitored case of the Tangjiashan barrier lake (Chen et al. 2015) and the computer program DB-IWHR 2014 that is coded in Microsoft Excel 2010, allowing fast, transparent and robust calculations for dam break flood predictions.

Response to the disasters caused by a barrier lake often involves considerations of many possible risks. Hence, it is important to have a key technology for performing the dam break flood analysis. The rescue actions described in this paper may be useful to other similar cases.
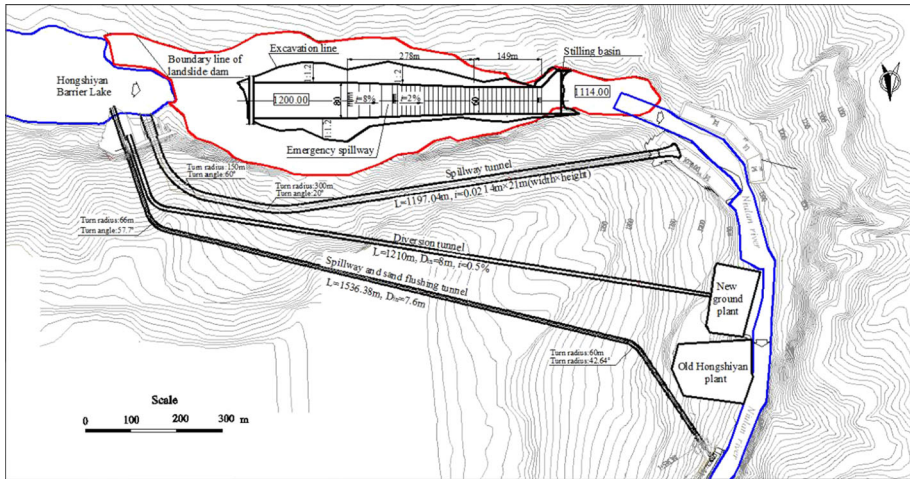
Fig. 24 Design plan of rebuilding Hongshiyan hydropower station

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