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Risk assessment and mitigation for the Hongshiyan landslide dam triggered by the 2014 Ludian earthquake in Yunnan, China

Abstract An Ms 6.5 earthquake shocked the Ludian County, Yunnan Province, China, on 3 August 2014 and triggered the Hongshiyan landslide dam. The dam, with a height of 83 m and a lake capacity of 260×10^6 m^3, threatened more than 10,000 people. A unique feature of this landslide dam was that it formed between a man-made dam and a hydropower plant. An existing drainage tunnel connecting the lake and the hydropower plant became a natural drainage conduit for the landslide dam, which played an important role in the mitigation of the landslide dam risks. This paper reports a quantitative risk assessment for the Hongshiyan landslide dam considering both engineering and non-engineering risk mitigation measures. The risk assessment is divided into three stages according to the implementation of two engineering measures: construction of a diversion channel and excavation of a branch drainage tunnel. The dam breaching hydrographs, flood zones, population at risk, and likely fatalities in each of the three stages are analysed. The optimum evacuation strategy in each stage is also studied based on the principle of minimum total consequence. It is found that the diversion channel decreases the dam breaching peak discharge and the associated risks significantly. The branch drainage tunnel prevent the landslide dam from overtopping failure in non-flooded period; however, the landslide dam may fail by overtopping in a future flood if the inflow rate is larger than the outflow rate through the drainage tunnels, resulting in serious losses of lives and properties. The dam breaching risks in all the three stages could be largely reduced by the optimal evacuation decision, which shows that timely evacuation is vital to save life and properties. The study provides a scientific basis for decision making in landslide dam risk management.

Keywords Landslide dam · Dam failure · Risk assessment · Risk mitigation · Erosion · Earthquake

Introduction

An Ms 6.5 earthquake shocked the Ludian County, Yunnan Province, China (27°6′N, 103°18′E) on 3 August 2014. The earthquake, with a focal depth of only 12 km, caused the collapse of 80,900 buildings, impacted 1.08 million people, and led to 617 deaths (Fig. 1) (Chang et al. 2015). Hundreds of landslides were triggered by the earthquake. Two landslides occurred on two sides of the Niulan River nearby the Hongshiyan Village (27.035N, 103.397E), which formed a large landslide dam with a height of 83 m (dam crest elevation = 1216 m), a width of 750 m, and a dam volume of 12×10^6 m^3, as shown in Table 1 and Fig. 2 (Liu 2014; Chang et al. 2015). Coincidentally, the landslide dam formed between a man-made dam and a hydropower plant. An existing drainage tunnel connecting the barrier lake and the hydropower plant naturally became a drainage conduit for the landslide dam.

Landslide dams pose risks to the people and properties both the upstream areas by inundation and the downstream areas by dam breaching floods (Costa and Schuster 1988; Dunning et al. 2006; Schuster 2006; Evans et al. 2011; Zhang et al. 2014; Liu and He 2015). Most landslide dams failed by overtopping in a short period after formation because of the lack of flood control measures such as diversion channels and discharge orifices (Costa and Schuster 1988; Peng and Zhang 2012a). Qualitative risk assessment of landslide dams has been reported by Korup (2002), Ermini and Casagli (2003), Cui et al. (2009), and others, which helps understand the potential risks. However quantitative risk assessment is urgently needed to support decision making in landslide-dam risk management.

Risk mitigation measures for landslide dams can be divided into two categories: engineering measures and non-engineering measures. Non-engineering measures (e.g. warning and evacuation) mitigate risks by reducing the elements at risk (i.e. transferring people and movable properties out of the flooded areas; Frieser 2004; Peng and Zhang 2013a, b). Engineering measures not only reduce the elements at risk by limiting flooded areas but also reduce the dam failure probability, flood severity, and the vulnerability of the elements at risk (Schuster and Evans 2011; Peng and Zhang 2014). Engineering measures include stabilizing the blockage, temporarily controlling water level using pumps or siphons, and constructing tunnels, conduits, or diversion channels through the dams to avoid dam breaching or reduce dam breaching floods. Normally, non-engineering measures are of low cost and very efficient to save people and movable properties, but cannot reduce the loss of unmovable properties like houses and crops. Engineering measures are able to reduce the dam failure probability, elements at risks and failure consequences, but are costly since the conditions at the landslide dam shortly after its formation are rather dangerous (Schuster 2006; Schuster and Evans 2011; Peng and Zhang 2014). For a particular landslide dam, the combined application of engineering measures and non-engineering measures is often more efficient in mitigating dam breaching risks.

This paper reports a case study of quantitative risk assessment and decision making in the mitigation of the risks of the Hongshiyan landslide dam considering both engineering and non-engineering measures. First, the characteristics of the Hongshiyan landslide dam are introduced. Then, risk assessment is conducted by considering the progression of the engineering measures. Finally, optimal warning and evacuation plans are obtained by minimizing the total dam breaching costs, which are the sum of evacuation costs, flood damage, and monetized loss of lives.

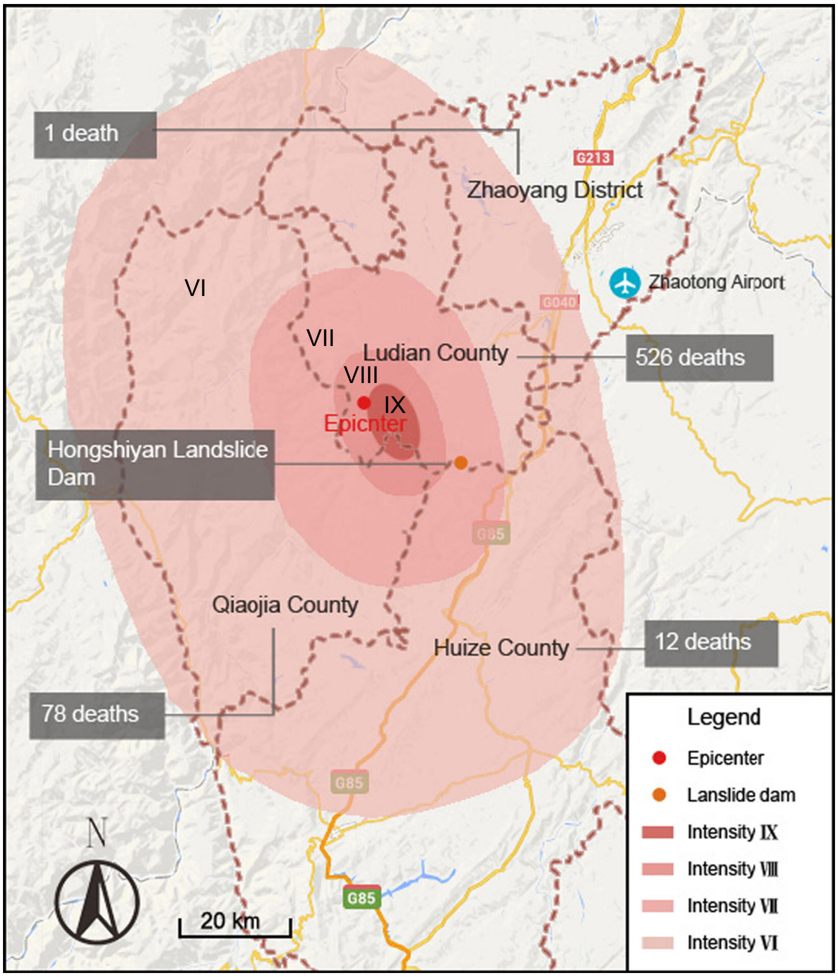


Fig. 1 The impact of the Ludian earthquake (based on Google Map; China Earthquake Administration 2014; Chang et al. 2015)

Characteristics of the Hongshiyan landslide dam

Landslides on both sides of the Niulan River

The valley along the Niulan River at the dam site is V-shaped, which was formed by the cutting of the Niulan River (Fig. 3). On the left bank, the slope angles are 35–50° and the slope heights near the riverbed are 200–220 m. On the right bank, the slope angles are up to 70° and the slope is 800 m high over the riverbed. The rocks consist of four layers from bottom up: dolomitite and limestone of lower Ordovician, sandstone with shale and mudstone of middle Ordovician, dolomitite and limestone with argillutite of middle Devonian, and massive limestone and dolomitite of lower Permian. The rock layering direction on the right and left banks is around NW230°/SW ∠30° (Chang et al. 2015).

The slope failure on the right bank was mainly caused by three reasons: fractures caused by lasting deformation in the mudstone and shale, weathering, and seismic loading from the earthquake (Chang et al. 2015). The upper portion of the slope is dolomitite, which is relatively tough and brittle, while the mudstone and shale below are relatively soft (Fig. 3). The large weight from the upper portion caused steady deformation in the soft rock, leading to fractures in the upper rocks. Weathering enhanced the fracture

Table 1 Geometric parameters of Hongshiyan Landslide Dam (Liu 2014; Chang et al. 2015)

Landslide dam parameters	Value	Diversion channel parameters	Value
Dam volume (m^3)	12×10^6	Depth (m)	8
Height (m)	83	Top width (m)	30
Width (m)	753	Bottom width (m)	5
Length (m)	286	Length (m)	740
Lake capacity (m^3)	260×10^6	Lake capacity after the construction of the channel (m^3)	206×10^6

development in the slope. Avalanches were finally triggered by the earthquake. The avalanche on the right bank had a length of 890 m, a high rear edge wall of 500 m, and a volume of 10×10^6 m^3.

There was an old landslide on the left bank before the earthquake. It was 1200 m wide at the base, 900 m from the top to the bottom in planar projection, 80 m in average thickness, and 79.2×10^6 m^3 in volume (Fig. 3). Triggered by the Ludian earthquake, the frontal part of the old landslide reactivated and slid into the river. The relatively small landslide from the right bank joined the avalanche and formed the Hongshiyan landslide dam.

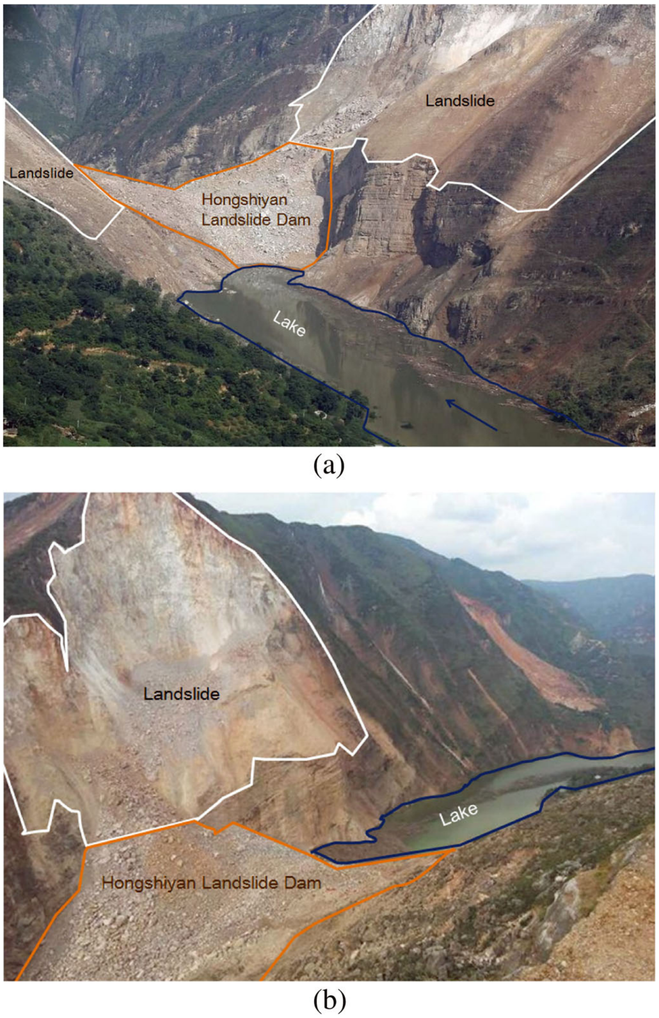


Fig. 2 The Hongshiyan landslide dam: a view from upstream; b view from downstream (based on Cai 2014)

The Hongshiyan landslide dam and lake

The Hongshiyan landslide dam consisted of materials from the avalanche on the right bank (70 %) and the avalanche on the left bank (30 %). The dam had a height of 83 m, a crest width of 17 m, a base width of 753 m, a length (perpendicular to the river) of 286 m, and a volume of 12×10^6 m^3 (Fig. 4). The upstream slope ratio was 1:2.5 and the downstream slope ratio was much gentler at a slope ratio of 1:5.5. The dam materials consist of giant stones (10 %) and boulders with size over 30 cm (30 %), in the range of 10–30 cm (40 %), and smaller than 10 cm (20 %) (Liu 2014).

The lake was estimated to have a catchment area of 11,800 km^2, a maximal length of the back water area of 25 km, and a lake capacity of 260×10^6 m^3 (Liu 2014; Chang et al. 2015). The relationship between the lake volume and the water level is shown in Fig. 5. As shown in Table 2, the average annual flow rate of the Niulan River is 128 m^3/s. The flow rate is relatively high in the rainy season from July to September. The average flow rate in August, 270 m^3/s, is the largest (Liu 2014). The maximal recorded flow rate in the past 50 years was 1890 m^3/s (in 1968) and the maximal recorded flow rate was 3620 m^3/s in 1886.

Potential flooding areas

The Hongshiyan landslide dam is 25 km downstream of the Jiangdi Town and 48 km upstream of the Xiaohe Town (Fig. 6). There is a hydropower station just upstream of this landslide dam. The Hongshiyan Hydropower Station is a diversion hydropower station. A tunnel 2920 m in length connects the impounded lake and

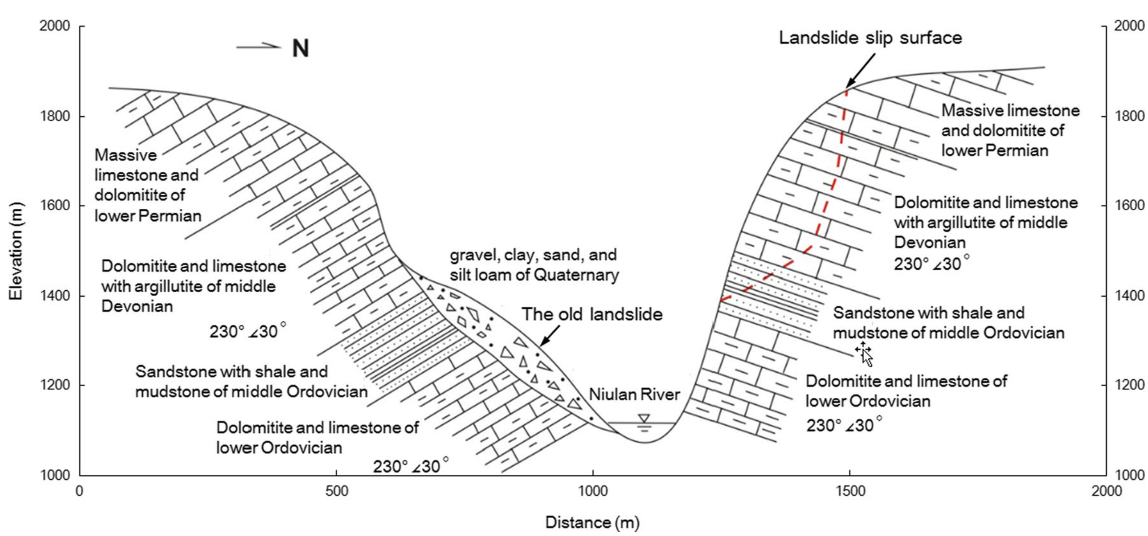


Fig. 3 The geological conditions of the original slopes on both sides of the Niulan River before the Ludian earthquake (based on Chang et al. 2015)

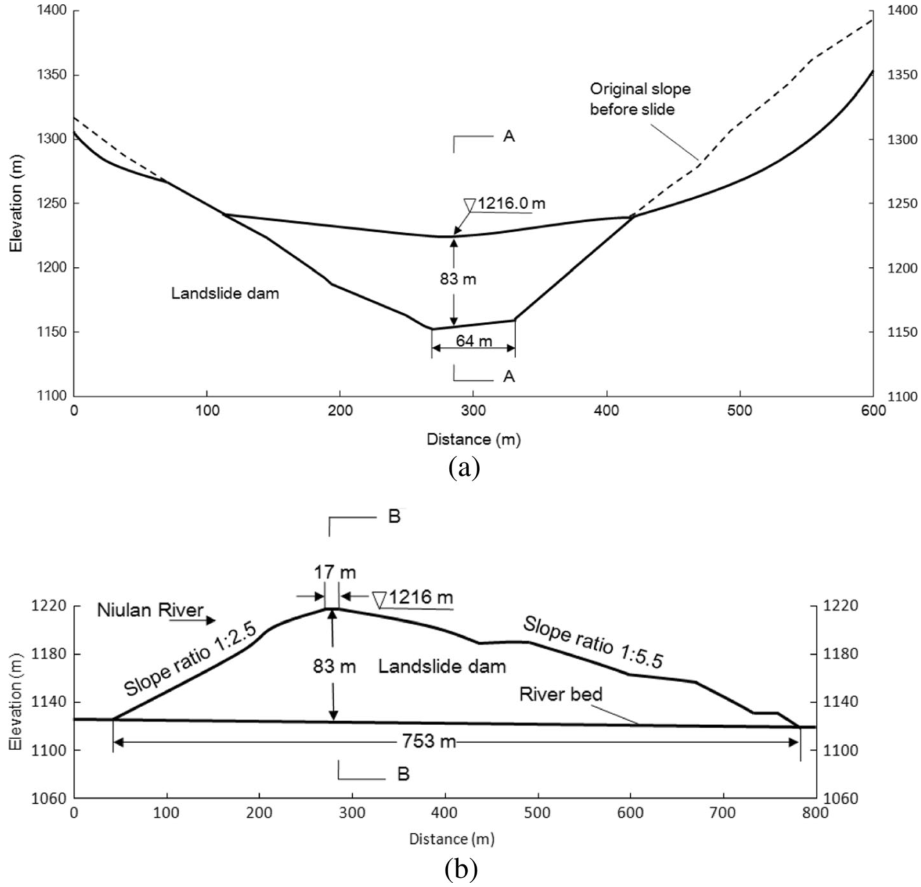


Fig. 4 Typical sections of Hongshiyan landslide dam: **a** cross section; **b** longitudinal profile (the A-A, B-B cross sections, refer to Fig. 8) (modified from Liu 2014)

the hydropower plant downstream with a water level drop of 41 m. The Hongshiyan landslide dam formed between the man-made Hongshiyan dam and the hydropower plant, at distances of 1600 and 600 m, respectively. The tunnel naturally became a drainage conduit for the landslide lake, which will be introduced later.

Most of the areas downstream of the Hongshiyan dam are deep valleys with few residents, except four locations: Dianzi Village, Liuhe Village, Xiaohe Town, and Tongyang Bridge, which are 21, 38, 48, and 84 km downstream of the dam, respectively. The populations in the four places are estimated as 458, 3682, 5179, and 4000, respectively (Table 3).

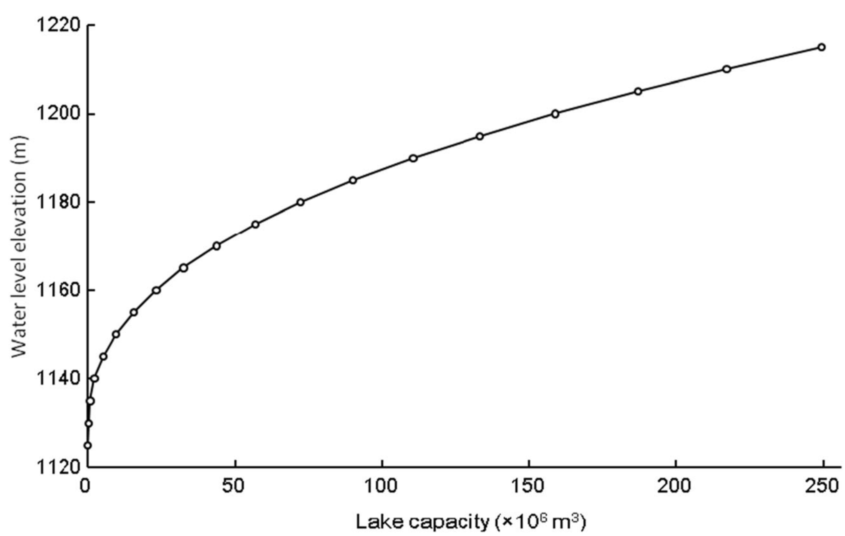


Fig. 5 Relationship between water level and lake volume based on Google Map (2014)

Table 2 Average flow rate at the Hongshiyan landslide dam site (Liu 2014)

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.
Average flow rate (m^3/s)	62.6	53.1	46	41.4	50.9	149	245
Proportion (%)	4	3	3	3	3	10	16
Month	Aug.	Sep.	Oct.	Nov.	Dec.	Total	Annual average
Average flow rate (m^3/s)	270	237	187	117	78	–	128
Proportion (%)	18	15	12	8	5	100	–

Contingent engineering risk mitigation measures

Two contingent engineering measures were taken to mitigate the dam breaching risks: constructing a diversion channel and excavating a drainage tunnel. Details of these measures are presented in Table 4.

Constructing a diversion channel through an earthquake-induced landslide dam is often a difficult task since the landslide dam is normally short in longevity and not easily accessible to people and construction machinery. The roads to the Hongshiyan landslide dam were destroyed by landslides triggered by the earthquake. Great efforts were made to transport 150 diggers, bulldozers, and trucks to the dam site using floating bridges and temporary roads under the influence of aftershocks (Liu 2014). A trapezoidal diversion channel was completed on 24 August, with a depth of 8 m, and top and bottom widths of 30 and 5 m, respectively (Fig. 7). The excavated material volume was 103×10^3 m^3. The weir elevation was lowered from 1216 to 1208 m and the corresponding lake capacity was reduced from 260×10^6 to 206×10^6 m^3, as shown in Table 1 (Liu 2014).

Despite the great efforts on excavating the diversion channel, overflow did not occur through the diversion channel. The maximal water level was only 1181 m, which was 27 m below the invert of the excavated diversion channel. The main reason was that a diversion tunnel was available, which connects the landslide lake to the downstream area (Fig. 8). The tunnel, with a length of 2920 m, was a water-intake tunnel for the Hongshiyan hydropower station. The tunnel consists of three parts: the main tunnel, a surge shaft, and some sub-tunnels. The main tunnel has a length of 2800 m and a diameter of 8.8 m, connecting the lake to the surge shaft. A tunnel with a diameter of 6 m connects the surge shaft to the sub-tunnels for four turbines in the hydropower plant (Liu 2014).

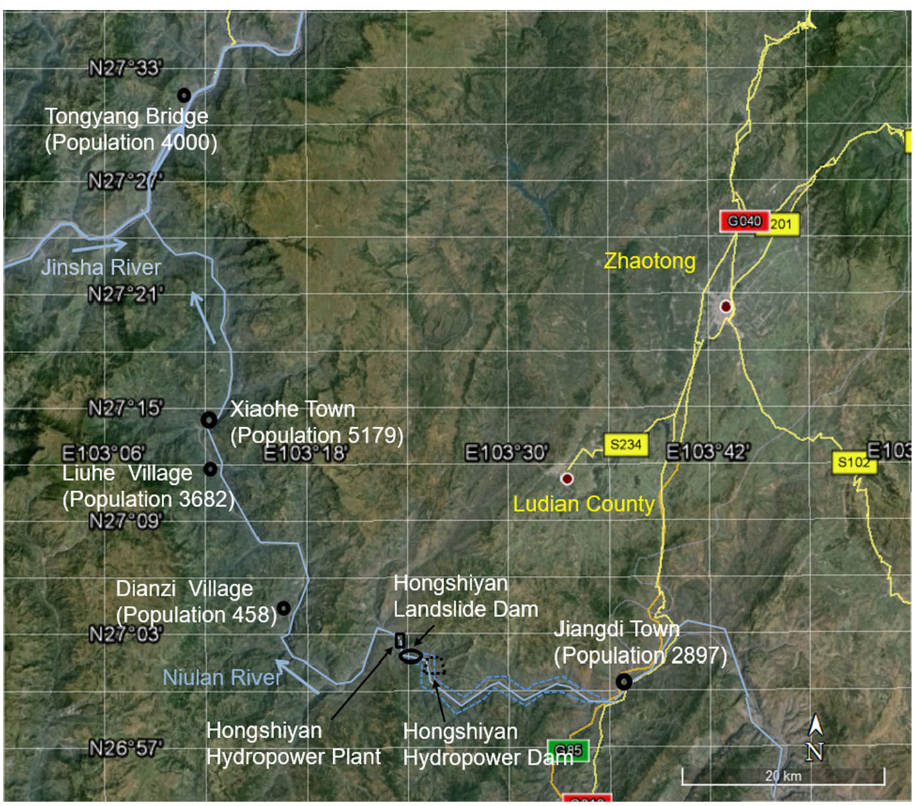


Fig. 6 Locations of Hongshiyan landslide dam and elements at risk (based on Google Map 2014)

Table 3 Villages and towns at risk downstream of the Hongshiyan landslide dam

Locations	Distance to dam site (km)	Elevation (m)	Number of residents
Dianzi Village	21	953–975	458
Liuhe Village	38	849–1000	3682
Xiaohe Town	48	788–848	5179
Tongyang Bridge	84	550–720	4000

The tunnels were fully opened for releasing the lake water after the formation of the landslide dam. However, the outflow rate was only 80 m^3/s, which was smaller than the average inflow rate of 197 m^3/s on 5 August. The landslide lake level kept rising. The gate of a maintenance tunnel that connected the main tunnel and the downstream area for routine checking and repairing (Fig. 8) was stuck because of the earthquake. The gate was opened by blasting on 10 August to release more water. The outflow rate increased from 80 to nearly 200 m^3/s. After this, the inflow and outflow rates nearly reached balance and the lake water level stopped rising.

Despite of the temporary control of the water level, the landslide dam was still unsafe as the inflow rate could increase significantly during a heavy storm. In that case, the water level could increase and the dam could fail by overtopping. Besides, the inundated areas upstream demanded lowering of the lake water level. A new drainage tunnel connecting the main tunnel and the downstream area near the power plant was planned to increase the outflow rate. The tunnel has a length of 280 m and a width of 7.5 m. The downstream entrance elevation was 1095.5 m, which was 41 m below the inlet of the tunnel in the landslide lake. The tunnel construction started on 14 August and the tunnel was broken through by water gushing on 3 October. The landslide lake was emptied in 28 h with the peak outflow rate being 840 m^3/s. Figure 9 shows the landslide lake before and after drainage. The inundated Hongshiyan hydropower dam appeared after drainage.

Dam breaching risk assessment and evacuation decision making

The timeline and stages of risk assessment and management

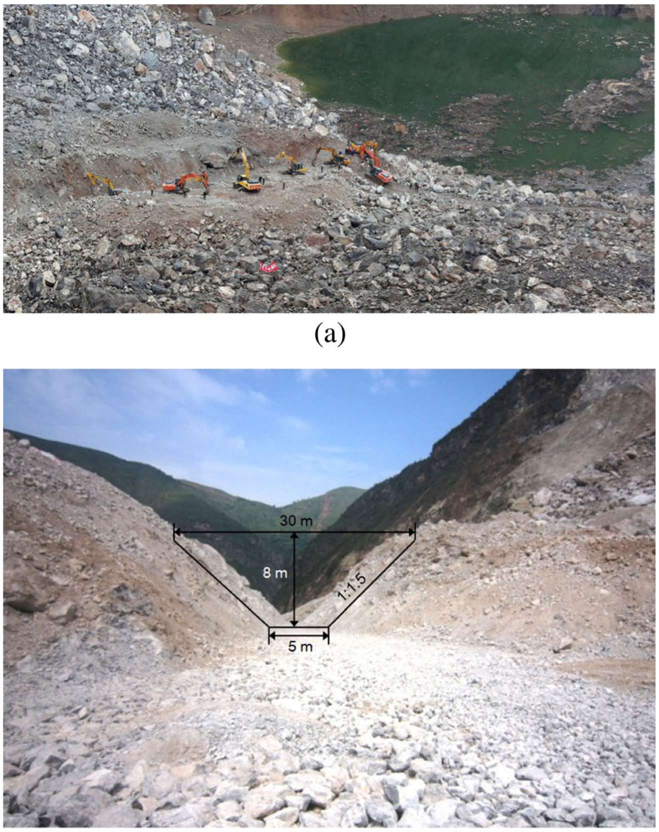
Figure 10 summarizes the milestones along the timeline of the Hongshiyan landslide dam event. Three stages can be distinguished for risk assessment and evacuation decision making in Table 5:

1. Stage 1 started on 3 August 2014, when the landslide dam formed. No engineering measure was taken in this stage. The dam crest elevation was 1216 m and the lake capacity was estimated to be 260×10^6 m^3. The inflow rate was set as

Table 4 Risk mitigation measures along time line (Liu 2014; Chang et al. 2015)

Point	Time	Water level (m)	Elevation of overflow (m)	Risk mitigation measures	Remarks
A	3 Aug.	1136.5	1216	Investigation	The Hongshiyan landslide dam formed during the Ms 6.5 Ludian earthquake on 3 Aug. 2014.
B	4 Aug.	1148.4	1216	Regulating upstream inflow	The inflow rate into the Hongshiyan lake was reduced by the Deze dam 188 km upstream.
C	7 Aug.	1176.4	1216	Starting to excavate a diversion channel through the dam	A trapezoidal diversion channel with a depth of 8 m, a top width of 30 m, and a bottom width of 5 m was designed. The overflow water elevation was reduced from 1216 to 1208 m. The corresponding lake capacity was reduced from 260 to 206×10^6 m^3.
D	10 Aug.	1182	–	Blasting the gate of the maintenance tunnel	The outflow rate from an existing drainage tunnel increased from 80 m^3/s to nearly 200 m^3/s. The lake water level stopped rising.
E	12 Aug.	1181.2	–	Evacuating the population at risk	A total of 13,044 people from 12 towns had been evacuated.
F	14 Aug.	1178.1	–	Starting to excavate a new drainage tunnel	A new drainage tunnel was designed to connect to the main tunnel to increase the outflow rate. The new tunnel would have a length of 280 m, a width and a height of 7.5 m, and an entrance elevation of 1095.5 m.
G	24 Aug.	1177[a]	1208	The diversion channel was completed.	The diversion channel was completed with an overflow elevation of 1208 m. The excavation volume was 1.03×10^5 m^3.
H	3 Oct.	1172[a]	1208	Water gushing	Water gushing occurred in the new drainage tunnel when the last 13 m of the tunnel was being constructed. The peak outflow rate was 840 m^3/s.
I	5 Oct.	1136.5	1208	The landslide lake was drained.	After 28 h, the landslide lake was drained with a residual water level of 1136.5 m and a residual lake capacity of 0.65×10^6 m^3.

[a] The water levels are estimated



(a)

(b)

Fig. 7 The diversion channel: **a** during construction (Sun 2014); **b** the completed diversion channel (based on KECL 2014)

270 m^3/s since it was the average flow rate of the Niulan River on August. This stage is considered in assessing the risks of the original landslide dam without any control measures.

2. Stage 2 started on 23 August 2014, when a diversion channel had been constructed. The channel was trapezoidal with a depth of 8 m, a bottom width of 5 m, and a top width of 30 m. The dam crest elevation was lowered to 1208 m, with a reduced lake capacity of 206×10^6 m^3. The inflow rate was set as 270 m^3/s as well. This stage is considered in assessing the risks of the landslide dam after the diversion channel has been constructed.
3. Stage 3 started on 3 October 2014, when a new drainage tunnel had been excavated to connect the major tunnel. The maximal outflow rate increased from 80 to 1507 m^3/s. No overtopping failure would occur in the non-flooding period. However, the maximal recorded historic inflow rate is as large as 3520 m^3/s, which is much larger than the outflow capability, namely 1507 m^3/s. The inflow rate was set as 3520 m^3/s. Stage 3 is considered in assessing the risks under the maximal recorded inflow with the presence of both the diversion channel and the drainage tunnel.

In the following sections, the dam breaching parameters are estimated with a statistical model by Peng and Zhang (2012a). A flood routing analysis is conducted with HEC-RAS (HEC 2008) to obtain the hydraulic parameters (e.g. water depth, flow velocity, rise rate, and flow rate). After that, the risks of dam failure are evaluated using a human risk analysis model HURAM. Finally, optimal evacuation decisions are made with a dynamic decision making model (DYDEM) for each of the three stages.

Estimating dam breaching parameters

Several physical methods are available for simulating the breaching parameters of landslide dams (e.g. Fread 1988; Chang and Zhang 2010). However, these physical models require information on the geologic conditions, which are often not available upon the formation of a new landslide dam. The Hongshiyan landslide dam falls into one of the cases. Peng and Zhang (2012a) presented a set of empirical equations (Table 6) for estimating the breaching parameters of landslide dams based on a landslide dam database. The input variables include dam height, lake capacity, dam width, dam volume, and dam erodibility. The breaching parameters include breach size (i.e. depth, top and bottom widths), breaching time, and peak outflow rate. The equations in Table 6 are applied to estimate the breaching parameters of the Hongshiyan landslide dam.

Table 7 shows the predicted breaching parameters assuming that the dam materials are of medium erodibility according to the description of the dam materials (Peng and Zhang 2012a). In stage 1, the final breach has a depth of 38.5 m, a bottom width of 74 m, and a top width of 145 m, and the breaching time is 7.6 h. The peak outflow rate, which is obtained with HEC-RAS 4.1 by inputting the breach size, the breaching time, and a lake level-volume curve, is 12,565 m^3/s. The peak outflow rate of dam breaching in stage 2 is reduced to 9661 m^3/s. The main reason is that the water level was lowered by 8 m through the construction of the channel and the corresponding lake volume is decreased by 54×10^6 m^3. In stage 3, the breach size and the peak outflow rate (22,068 m^3/s) become very large and the breaching time becomes shorter due to the large inflow; hence, the flood severity is much larger than those in the first two stages.

Simulating flood routing process

Flood routing along the downstream river was simulated with HEC-RAS 4.1, which is a one-dimensional river hydraulics analysis program developed by the US Army Corps of Engineers. The main physical laws for the program are the conservation of energy for steady flows and the conservation of mass and momentum for unsteady flows (HEC 2008).

The dam model in HEC-RAS is shown in Fig. 11. The diversion channel is set as a spillway and the drainage tunnel is set as a rectangular conduit with a height of 8.2 m and a width of 8.2 m. The inputted final breach size and breach time refers to Table 7; the topographic parameters are based on Google Map with the horizontal precise about 30 m and relatively vertical precise about 20 m (Google Map 2014), and the Manning coefficient refers to Manual of HEC-RAS (HEC 2008). The outflow rate can be adjusted by opening a gate with a certain height. In stages 1 and 2, the opening height is set as 0.6 m and the outflow rate is 80 m^3/s at the lake elevation of 1208 m. In stage 3, the gate is fully opened and the outflow rate is 1560 m^3/s at the water elevation of 1208 m. The inflow rates are assumed to be 270 m^3/s (the average on August) in stages 1 and 2 and 3520 m^3/s (the maximal record in history) in stage 3. The final breach size is shown in Table 7.

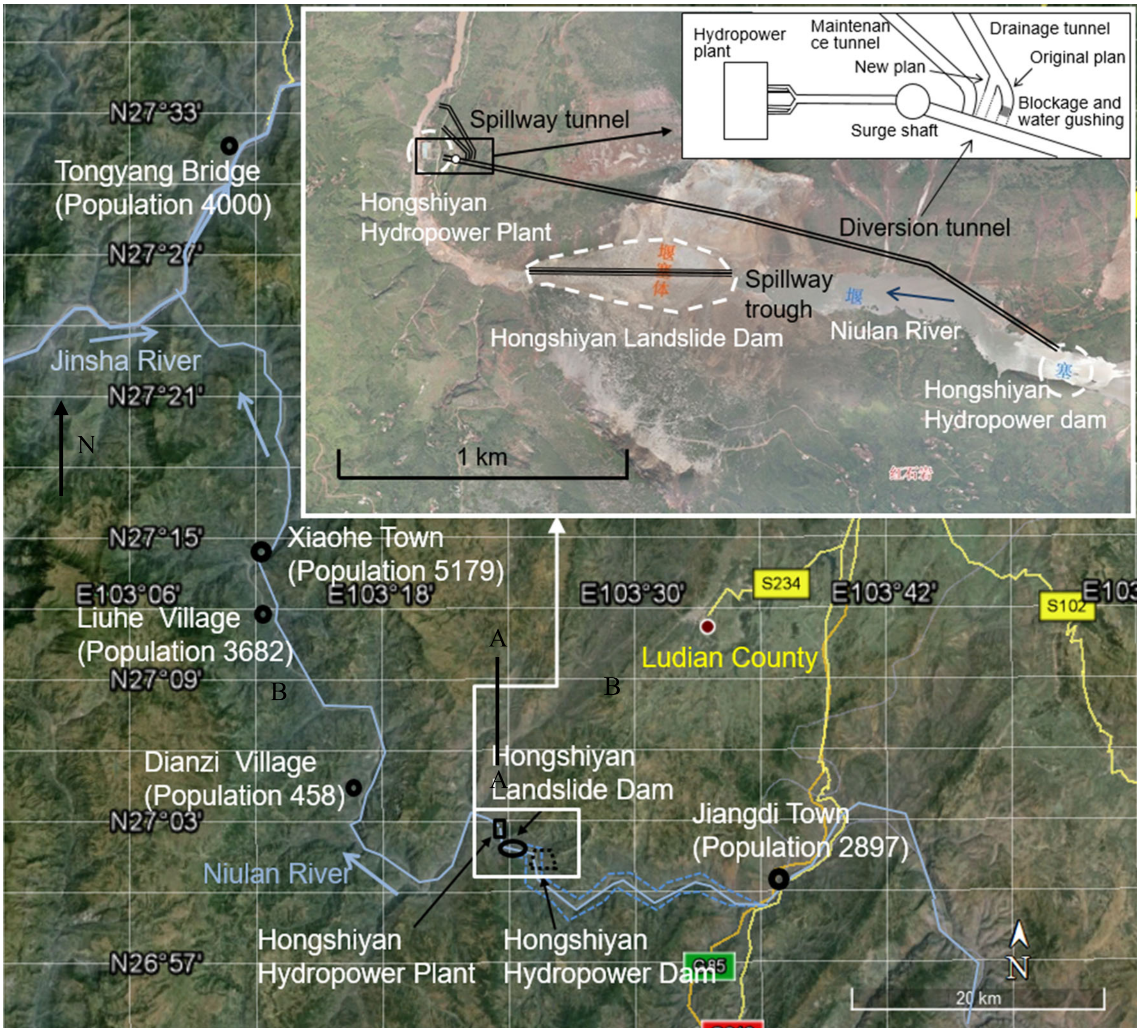


Fig. 8 Engineering mitigation measures: spillway and tunnel (based on Liu 2014)

Fig. 9 The landslide lake before and after drainage (based on QQ News 2014)

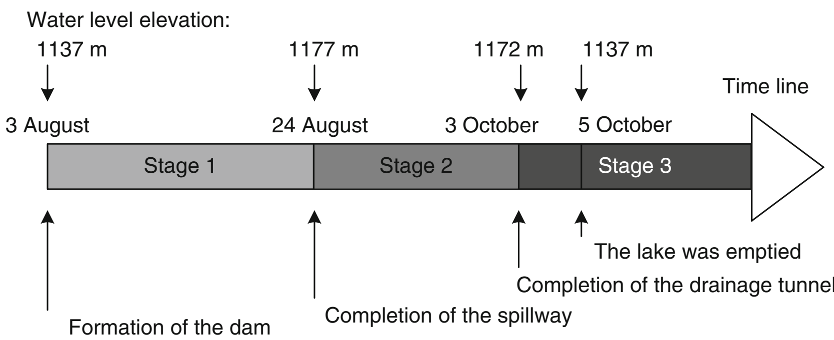


Fig. 10 Timeline of the Hongshiyan landslide dam event

Table 5 Available information on the three stages of risk assessment and decision making for the Hongshiyan landslide dam

Stage	Start date	Diversion channel	Drainage tunnel	Dam crest elevation (m)	Lake capacity ($\times 10^6$ m^3)	Inflow rate (m^3/s)
1	3 Aug. 2014	No	The old one	1216	260	270[a]
2	24 Aug. 2014	Yes	The old one	1208	206	270[a]
3	3 Oct. 2014	Yes	A new one	1208	206	3520[b]

[a] The average inflow rate in August

[b] The largest inflow rate recorded in 1886

Table 6 Empirical equations for estimating the breaching parameters of landslide dams (Peng and Zhang 2012a)

Para.	Equation	Erodibility coefficient α		R^2
Q_p	$\frac{Q_p}{g^{1/2}H_d^{5/2}} = \left(\frac{H_d}{H_r}\right)^{-1.417}\left(\frac{H_d}{W_d}\right)^{-0.265}\left(\frac{V_d^{1/3}}{H_d}\right)^{-0.471}\left(\frac{V_l^{1/3}}{H_d}\right)^{1.569}e^a$	High	1.276	0.946
		Med.	−0.336	
		Low	−1.532	
H_b	$\frac{H_b}{H_r} = \left(\frac{H_d}{H_r}\right)^{0.882}\left(\frac{H_d}{W_d}\right)^{-0.041}\left(\frac{V_d^{1/3}}{H_d}\right)^{-0.099}\left(\frac{V_l^{1/3}}{H_d}\right)^{0.139}e^a$	High	−0.316	0.871
		Med.	−0.520	
		Low	–[a]	
W_t	$\frac{W_t}{H_r} = \left(\frac{H_d}{H_r}\right)^{0.752}\left(\frac{H_d}{W_d}\right)^{0.315}\left(\frac{V_d^{1/3}}{H_d}\right)^{-0.243}\left(\frac{V_l^{1/3}}{H_d}\right)^{0.682}e^a$	High	1.683	0.855
		Med.	1.201	
		Low	–[a]	
W_b	$\frac{W_b}{H_d} = 0.004\left(\frac{H_d}{H_r}\right) + 0.050\left(\frac{H_d}{W_d}\right) - 0.044\left(\frac{V_d^{1/3}}{H_d}\right) + 0.088\left(\frac{V_l^{1/3}}{H_d}\right) + a$	High	0.775	0.822
		Med.	0.532	
		Low	–[a]	
T_b	$\frac{T_b}{T_r} = \left(\frac{H_d}{H_r}\right)^{0.262}\left(\frac{H_d}{W_d}\right)^{-0.024}\left(\frac{V_d^{1/3}}{H_d}\right)^{-0.103}\left(\frac{V_l^{1/3}}{H_d}\right)^{0.705}e^a$	High	−0.635	0.624
		Med.	−0.518	
		Low	–[a]	

H_r = 1 m, e = 2.7183, T_r = 1 h

Q_p peak outflow rate, H_b breach depth, W_t breach top width, W_b breach bottom width, W_d dam width, T_b breach time, g gravity acceleration, H_d dam height, V_d dam volume, V_l lake capacity

[a] No records are available for the low erodibility coefficient cases

Table 7 Breaching parameters of the Hongshiyan landslide dam

Stage	Inflow rate (m^3/s)	Final breach size (m)			Breaching time (h)	Peak outflow rate (m^3/s)
		Depth	Bottom width	Top width		
1	270	38.5	74	145	7.6	12,565
2	270	38.1	70	136	7.1	9661
3	3520	49.1	102	194	5.4	22,068

Figure 12 shows the outflow rates at the dam site, Xiaohe Town, and Tongyang Bridge in the three stages. The hydraulic parameters are shown in Table 8. At the dam site, the peak outflow rate of 12,565 m^3/s occurs at 33 h in stage 1; the peak outflow rate is brought forward in stage 2 with a smaller value of 9661 m^3/s. This is because the construction of the diversion tunnel lowered the elevation of the dam crest, leading to a shorter time to fill the lake. The smaller peak outflow rate is caused by the smaller lake capacity due to the presence of the diversion tunnel. In stage 3, the peak outflow rate is much larger (22,069 m^3/s) and the dam breaching occurs much earlier than those in stages 1 and 2. The reason is that the inflow rate in stage 3 is much larger (3520 m^3/s), leading to a shorter time to fill the lake and faster erosion during the breaching process. The peak outflow rates at Tongyang Bridge are much larger than those at other locations because Tongyang Bridge is located at the bank of Jinsha River instead of Niulan River. The average flow rate in Jinsha Rvier is 10,046 m^3/s in August (Song et al. 2012).

Table 8 presents the hydraulic parameters of the flooded areas in the three stages. In stage 1, the maximal water depth in the residential areas in Dianzi Village is 11.5 m, and the corresponding average flow velocity is 3.01 m/s. The inundated area is shown in Fig. 13a. The evacuation distance to non-flooded areas is estimated to be 0–100 m. In this case, 78.2 % of the residential areas are inundated with a population at risk of 358. The situations in Liuhe Village and Xiaohe Town are better despite of maximal water depths of 7.3 and 3.1 m, respectively. Both places are located on steep slopes over the Niulan River. Only 5 and 3 houses may be inundated in Liuhe Village and Xiaohe Town, with the estimated population of 25 and 15, respectively. The inundated areas in Liuhe Village and Xiaohe Town are shown in Fig. 13b, c. Niulan River joins the Jinsha River 75 km downstream of the Hongshiyan landslide dam. Tongyang Bridge is located 10 km downstream of the junction of the two rivers. The residential areas are above the maximal flood level and no population is at risk, as shown in Fig. 13d.

In stage 2, the flood is obviously reduced due to the construction of the diversion channel, as shown in Fig. 13. The maximal water levels are 10.2, 5.2, and 0.9 m in Dianzi Village, Liuhe Village, and Xiaohe Town, respectively. The population at risks is 308 in Dianzi Village, 20 in Liuhe Village, and 5 in Xiaohe Village. Tongyang Bridge is not flooded, as shown in Table 10.

In stage 3, the maximal recorded inflow leads to a more serious dam breaching flood at the locations downstream the Hongshiyan dam, as shown in Fig. 13. The maximal water levels in the three upstream locations are as high as 15.2, 12.9, and 8.8 m, respectively,

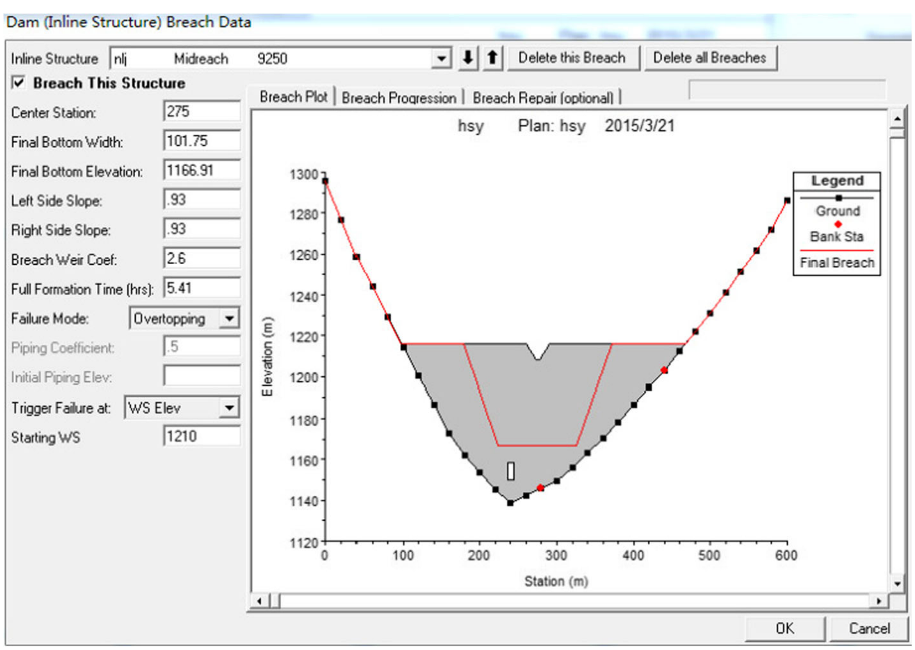


Fig. 11 Modelling of the breaching of the Hongshiyan landslide dam with a diversion channel and a drainage tunnel

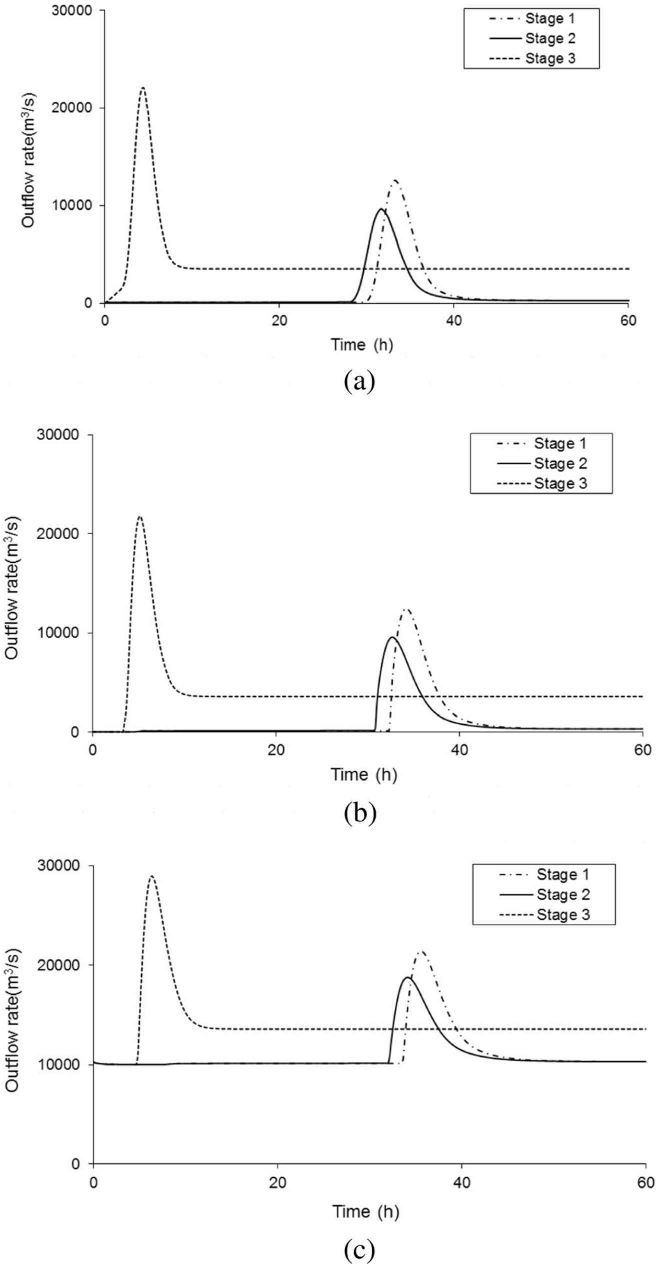


Fig. 12 The calculated flow rates at three locations: **a** the dam site; **b** Xiaohe Town; and **c** Tongyang Bridge

leading to larger populations at risk: 438 in Dianzi Village, 50 in Liuhe Village, and 165 in Xiaohe Town, as shown in Table 10. Thanks to the long distance and the high elevation of Tongyang Bridge and the large convey capability of Jinsha River, the highest water level dose not reach the residential area.

Assessing risks of dam failure

Peng and Zhang (2012a, b) presented a human risk analysis model (HURAM) using Bayesian networks. A Bayesian network combines the knowledge of graph theory and statistics theory. It consists of nodes and arcs/links with their (conditional) probabilities, which solves uncertain problems by logic reasoning (Jensen 2001). The Bayesian network in HURAM consists of 15 nodes and 23 arcs. Each node is characterized by several discrete states as shown in Table 9. The Bayesian network was quantified with statistical data, existing physical models, empirical models, and judgment (Peng and Zhang 2012b). The quantified network includes the prior probabilities of the basic nodes (the nodes without parents) and prior conditional probabilities of the other nodes given their parents.

HURAM works by updating the prior probabilities with evidence from a specific case using Bayes' theory and keeping the structure of the Bayesian network unchanged. For detailed introduction of the HURAM and its application, refer to Peng and Zhang (2012b, c). In this study, the site-specific evidence refers to the values of the eight basic nodes in the Bayesian network (Fig. 14). The buildings in the flooded areas are assumed as three-story brick structures; the breaching time is shown in Table 7; the evacuation distance, water depth, and flow velocity are given in Table 8; the distance to dam site is shown Table 3; and the time of a day remains uniformly distributed.

The calculated risks in the three stages are shown in Table 10, which are obtained by inputting the values in the eight uppermost basic parameters in Fig. 14. The probabilities of evacuation, loss of lives, and other parameters are calculated via the Bayesian networks. In stage 1, the population at risk (PAR) in Dianzi Village is 358, among which 88.6 % (317 people) have been successfully evacuated and 7.54 % (27 people) may lose their lives. The relatively high fatality rate is caused by the high flood severity in this village, with the maximal water depth of 11.5 m and a flow velocity of 3.0 m/s. Almost all the PAR in Liuhe Village and Xiaohe Town can be evacuated due to the long flood routing time. In this case, people are very likely to be naturally warned by the flood and evacuated timely. There is no predicted flood in Tongyang Bridge district. The total evacuation rate and fatality ratio in this stage are 89.5 and 6.78 %, respectively.

In stage 2, thanks to the construction of the diversion channel, the PAR and fatality ratio are smaller due to the relatively smaller flood. Fatalities occur only in Dianzi Village, with a fatality ratio of 3.9 %. No PAR is predicted in the Tongyang Bridge district. The total evacuation rate and fatality ratio in this stage are 89.8 and 3.60 %, respectively.

In stage 3 with the high inflow rate, larger PAR and higher fatality ratio values are predicted. In Dianzi Village, 40 out of 438 PAR may lose their lives with a fatality ratio of 9.13 %. Loss of life may also occur in Liuhe Village and Xiaohe Town, with expected fatalities of 2 and 5, respectively. Fortunately, the Tongyang Bridge district will not be flooded though the highest water level is very close to the residential elevation. In this stage, the total evacuation rate and fatality ratio are 90.4 and 7.20 %, respectively.

It is found that the breaching flood in all the three stages may cause fatalities. Hence, warning and evacuation are urgently demanded. A late evacuation decision may lead to loss of lives and properties, but a very early evacuation will incur unnecessary expenses. In the next section, optimal evacuation strategy is studied to achieve minimal consequences.

Optimal evacuation decision making

Peng and Zhang (2013a, b) provided a dynamic decision making model (DYDEM) for dam break evacuation analysis. The optimal

Table 8 Hydraulic parameters of the flooded areas in three stages

Location	Hydraulic parameters	Stage 1	Stage 2	Stage 3
Dam site	Peak outflow rate (m^3/s)	12,565	9661	22,068
Dianzi Village	Peak outflow rate (m^3/s)	12,576	9633	22,069
	Maximal water depth (m)	11.5	10.2	15.2
	Average flow velocity (m/s)	3.01	2.58	3.97
	Evacuation distance (m)	0–100	0–100	0–100
Liuhe Village	Peak outflow rate (m^3/s)	12,504	9585	21,873
	Maximal water depth (m)	7.3	5.2	12.9
	Average flow velocity (m/s)	1.80	1.55	2.24
	Evacuation distance (m)	0–100	0–100	0–172
Xiaohe Town	Peak outflow rate (m^3/s)	12,486	9572	21,820
	Maximal water depth (m)	3.1	0.9	8.8
	Average flow velocity (m/s)	1.62	1.43	2.05
	Evacuation distance (m)	0–100	0–100	0–117
Tongyang Bridge	Peak outflow rate (m^3/s)	21,428	18,773	29,021
	Maximal water depth (m)	–	–	–
	Average flow velocity (m/s)	–	–	–
	Evacuation distance (m)	–	–	–

decision is made to achieve the minimal total loss. The total loss (T) consists of three parts: evacuation cost (C), flood damage (D), and loss of lives (L), which can be expressed as functions of warning time (w_t).

$$T(w_t) = C(w_t) + D(w_t) + L(w_t) \tag{1}$$

The warning time denotes the period from the issuing of warning to the arrival of the flood, which is the available time for evacuation. Normally, $C(w_t)$ increases and $D(w_t)$ and $L(w_t)$ decrease with w_t. Thus, $T(w_t)$ would decrease first and then increase with w_t. Therefore, the minimal $T(w_t)$ can be achieved if a proper w_t is chosen.

The evacuation cost consists of the initial costs and Gross Domestic Product (GDP) interruption:

$$C = C_i + C_{\mathrm{GDP}} \tag{2}$$

The initial costs are the expenses for evacuating and arranging the people at risk and necessary services (e.g. security and medical care):

$$C_i = cP_{\mathrm{eva}}\mathrm{PAR}(w_t + 3) \tag{3}$$

where P_{eva} is the ratio of the evacuated population, and c is the expense per person per day (e.g. RMB 60 or US$ 9.5 per person per day is assumed in this case). The 3-day time is taken as the minimal period of time between the predicted moment of flooding and the return of the residents (Frieser 2004). The GDP interruption is the loss due to interruption of production, working and business, which can be calculated as

$$C_{\mathrm{GDP}} = \frac{\mathrm{GDP}_P}{365}(\mathrm{PAR})(W_t + 4) \tag{4}$$

where G_{GDP} is the average GDP per person in the flood area. It is expected that economic sectors need time to restore their business (Frieser 2004). Therefore, a duration of 4 days is added to the warning time.

The flood damage (D) is limited to the moveable properties in this study, since unmovable properties cannot be saved by evacuation. The moveable properties are generally proportional to the number of people who have neither evacuated nor sheltered in safe zones:

$$D = (1{-}P_{\mathrm{eva}})(1{-}P_{\mathrm{safe}})(\mathrm{PAR})\alpha I_p \tag{5}$$

where P_{safe} is the ratio of the people taking sheltering in safe zones; α is the proportion of properties that can be transferred (0.1 is assumed); I_p is the property of each person, which is taken as the cumulative net income (i.e. income minus spending) per person:

$$I_p = (I{-}S)n \tag{6}$$

where I and S are the average income and spending per person, which are RMB 4604 and 3899, respectively, in villages and RMB18724 and 10649, respectively, in towns and cities in Zhaotong City in 2013 (ZMBS 2014); n is the average working period per person (e.g. 20 years).

Jonkman (2007) reviewed approaches of evaluating the human life. A method with macro-economic considerations is chosen in this study. In this method, the value of a human life (V_L) is given as the product of GDP per person (GDP_p) and the average longevity (L):

$$V_L = (\mathrm{GDP}_p)L \tag{7}$$

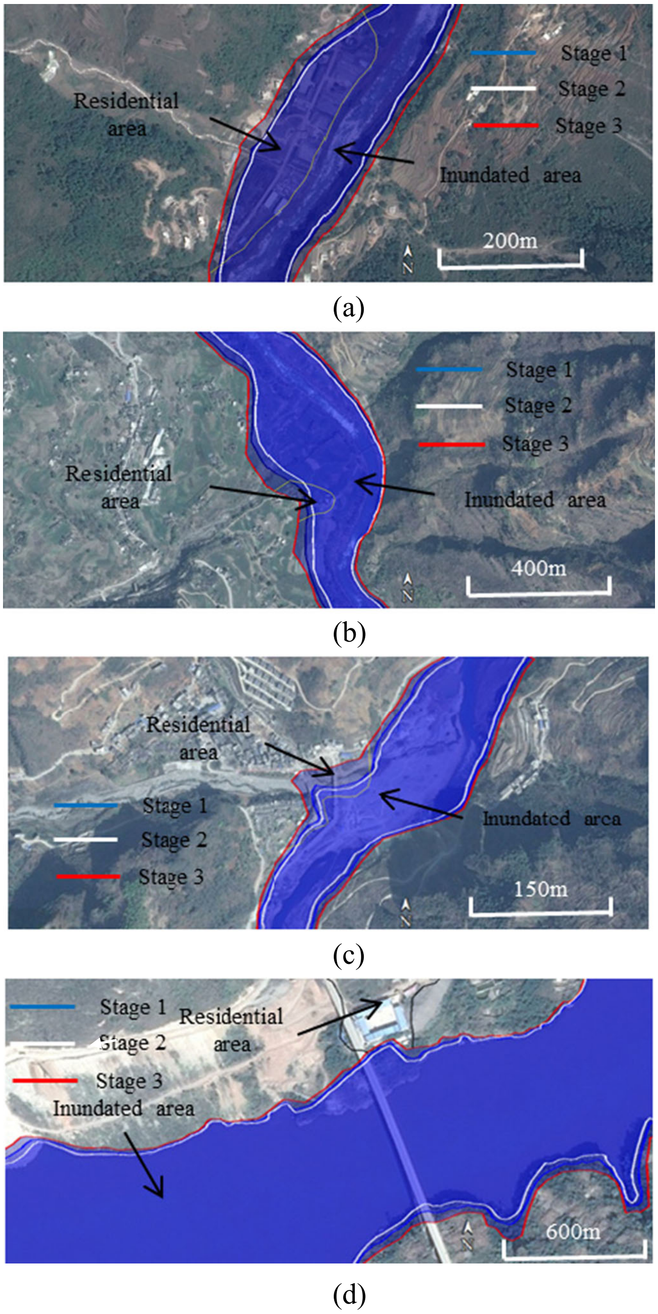


Fig. 13 The estimated flooding areas in three stages: **a** Dianzi Village; **b** Liuhe Village; **c** Xiaohe Town; and **d** Tongyang Bridge

For example, GDP_p and L in Zhaotong City, Yunnan Province, China, are RMB 122,58 and 75 years in 2013 (ZMBS 2014). Thus, the value of one person in 2013 in Zhaotong City is RMB 0.92 million. The monetized loss of life (M_L) is then calculated as

$$M_L = V_L(\mathrm{LOL}) \tag{8}$$

where LOL is the loss of life predicted with HURAM as a function of warning time. As P_{eva}, P_{safe}, and LOL can be predicted as functions of warning time with HURAM, the three categories of flood consequences are expressed as functions of warning time.

Table 9 Parameters with discrete states in the Bayesian network of HURAM model

Node	States No.	States
Evacuation distance	4	0–100; 100–500; 500–2000; and >2000 m
Time of a day	3	8:00–17:00; 17:00–22:00; and 22:00–08:00
Distance to dam site	4	0–4.8; 4.8–12; 12–36; and >36 km
Building story number	4	1; 2; 3; and >3 stories
Dam breaching duration	4	0–1; 1–3; 3–9; and >9 h
Water depth	7	0–1.5; 1.5–3; 3–4.5; 4.5–6; 6–7.5; 7.5–9; and >9 m
Water flow velocity	5	0–1; 1–2; 2–4; 4–6; and >6 m/s
Building type	3	Unanchored wood framed; anchored wood framed; and masonry, concrete and brick
Warning time	5	0–0.25; 0.25–1; 1–3; 3–6; and >6 h
Flood rise time	4	0–0.25; 0.25–1; 1–3; and >3 h
Building damage	3	Slight damage; partial damage; and major damage
Evacuation	2	Evacuated; and not-evacuated
Sheltering in building	4	Unsheltered; the second story; the third story; higher than three stories
Flood severity	4	Safe; low flood severity; medium flood severity; and high flood severity
Loss of life	2	Alive; died

Figures 15 and 16 show the three types of flood consequences as well as the total losses in different stages and locations. In Dianzi Village, the optimal time for evacuation is 22 h before dam breaching in all three stages. The minimal total loss is RMB 145,000, 126,000, and 181,000 for stages 1, 2, and 3, respectively. The monetized loss of lives and flood damage decrease and the evacuation cost increases with warning time. When the warning time is little, the total loss is dominated by the monetized loss of lives. The flood damage, which is limited to the loss of movable properties in this study, is relatively small compared to the monetized loss of lives. The evacuation cost gradually increases with the warning time. It dominates the total loss when the evacuation is made with more than 14 h before the dam breaching. The minimal total loss in stage 2 is smaller than that in stage 1 as the population at risk and the flood severity in stage 2 are reduced by the diversion channel. The minimal total loss in stage 3 is larger than those in stages 1 and 2 due to the higher breaching flood caused by the large inflow. The total losses in Dianzi Village without warning and evacuation are extremely high, RMB 24,880,000, 11,079,000, and 36,850,000 in stages 1, 2, and 3, respectively, as shown

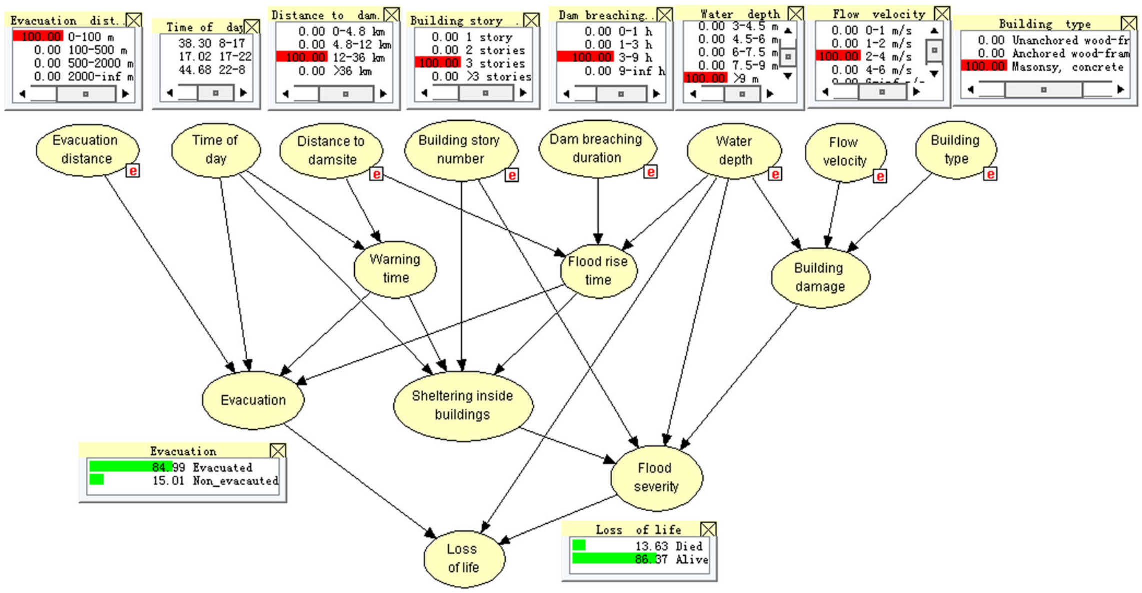


Fig. 14 The HURAM Bayesian network for estimating loss of life

in Table 11. The total losses in those cases are dominated by the loss of lives. The simulations show that timely evacuation is vital to save life and properties when dam breaching cannot be avoided.

There is no life loss in Liuhe Village and Xiaohe Town in stages 1 and 2 and no evacuation is needed. The two locations are far from the dam site, leading to longer available time for evacuation. In stage 3, the optimal times for evacuating the population at risk in Liuhe Village and Xiaohe Town are 21 and 20 h before dam breaching, with the minimal total loss of RMB 20,200 and RMB 66,100, respectively. The small number of people at risk explains the relatively small losses at these two locations. The total losses in these two locations without warning and evacuation are RMB 1,842,000 and RMB 4,607,000, respectively, which are much larger than the minimal values. Since the populations at risk in all three locations are not very large, earlier evacuation would not incur much expense. In other words, the government may evacuate the people earlier than the optimal time for safety.

Table 10 Assessment of the risks of dam breaching in three stages

Stage	Location	Population	Population at risk	Evacuation rate	Evacuated population	Exposed population	Fatality ratio	Deaths
1	Dianzi Village	458	358	0.8855	317	41	0.0754	27
	Liuhe Village	3682	25	0.9600	24	1	0	0
	Xiaohe Town	5179	15	1.0000	15	0	0	0
	Tongyang Bridge	4000	0	0	0	0	0	0
	Sum	13,319	398	0.8945	356	42	0.0678	27
2	Dianzi Village	458	308	0.8929	275	33	0.0390	12
	Liuhe Village	3682	20	0.9500	19	1	0	0
	Xiaohe Town	5179	5	1.0000	5	0	0	0
	Tongyang Bridge	4000	0	0	0	0	0	0
	Sum	13,319	333	0.8979	299	34	0.0360	12
3	Dianzi Village	458	438	0.8761	384	54	0.0913	40
	Liuhe Village	3682	50	0.9600	48	2	0.0400	2
	Xiaohe Town	5179	165	0.9576	158	7	0.0303	5
	Tongyang Bridge	4000	0	0	0	0	0	0
	Sum	13,319	653	0.9035	590	63	0.0720	47

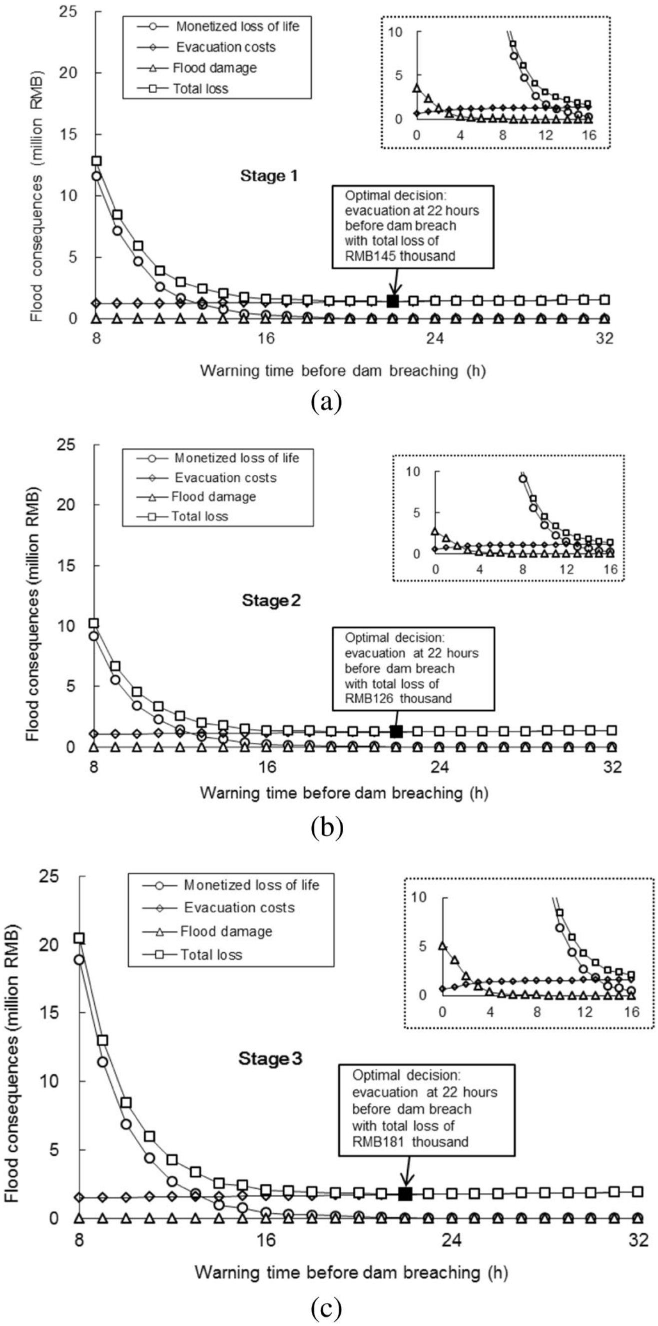


Fig. 15 Optimal decision making for Dianzi Village: **a** stage 1; **b** stage 2; **c** stage 3

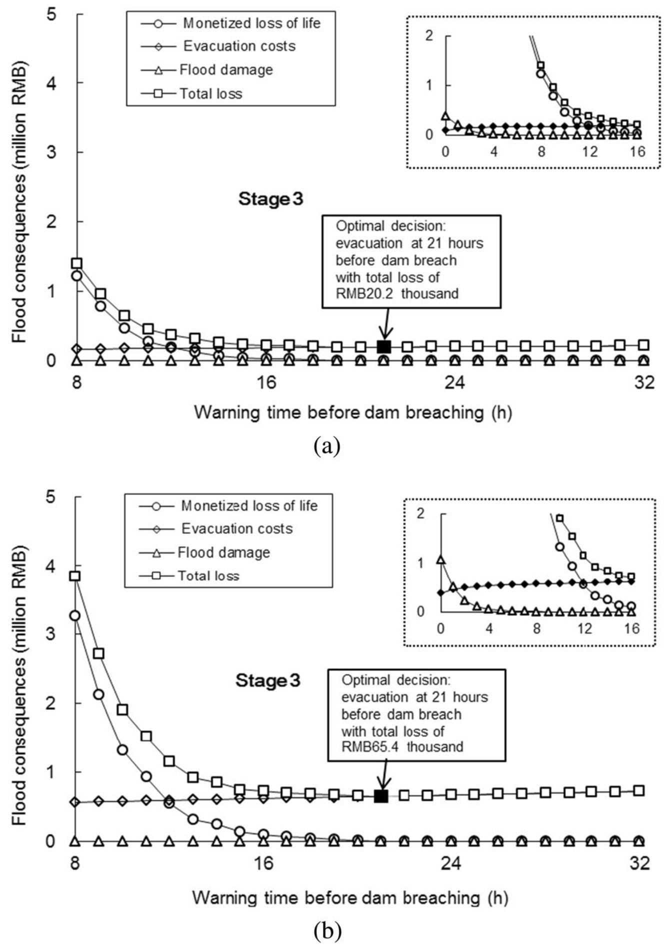


Fig. 16 Optimal decision making for Liuhe Village and Xiaohe Town in stage 3: **a** Liuhe Village; **b** Xiaohe Town (no warning and evacuation are needed in stages 1 and 2)

All the three stages were studied by considering the existing drainage tunnel. Without the drainage tunnel, the dam breaching risk would be largely different. Firstly, the dam would be overtopped and breached by the lasting rising water instead of keeping stable until now. Secondly, the peak outflow rate, if it is was overtopped, would be higher, since larger water flow would erode the dam crest. With the drainage tunnel, part of the flow passed through the tunnel and decreased the overtopping outflow rate. Finally, the dam breaching risk would also be much higher since higher water depth and flow rate would be produced in the downstream areas.

Conclusions

This paper introduces the characteristics of risk assessment and mitigation for the recent Hongshiyan Landslide Dam that formed on 3 August 2014 in Yunnan, China. The following conclusions can be drawn:

(1) The Hongshiyan landslide dam formed by two landslides at both sides of the Niulan River triggered by the Ms 6.5 Ludian earthquake. An existing drainage tunnel connecting the lake and a downstream hydropower plant became a drainage conduit for the landslide dam, which played a vital role in the mitigation of the landslide dam risks.

(2) The risk assessment and mitigation for the Hongshiyan landslide dam were divided into three stages according to the implementation of two engineering measures: construction of a diversion channel and excavation of a drainage tunnel. The peak outflow rate of dam breaching flood is reduced from 12,565 to 9633 m^3/s by constructing the diversion channel. Dam failure may not occur in non-flood seasons after completing the branch drainage tunnel as the drainage capability is high. However, the maximal historic flood would

Table 11 The optimal evacuation decision and flood consequences

Parameters	Dianzi Village			Liuhe Village	Xiaohe Town
Stage	1	2	3	3	3
PAR	358	308	438	50	165
Optimal time (hours before dam breaching)	22	22	22	21	20
Evacuation cost (thousand RMB)	143.2	123.2	175.3	20.0	64.7
Flood damage (thousand RMB)	0.003	0.005	0.010	0	0.003
Monetized loss of life (thousand RMB)	1.9	2.4	5.3	0.2	1.4
Minimal total loss (thousand RMB)	145	126	181	20.2	66.1
Total loss without evacuation (thousand RMB)	24,880	11,079	36,850	1842	4607

cause the landslide dam to breach with a peak outflow rate of 22,069 m^3/s.

(3) According to the results of risk assessment, 27, 12, and 47 people could lose their lives in stages 1, 2, and 3, respectively, if no warning and evacuation were made. Dianzi Village is the most vulnerable as the fatality ratios are estimated as 7.54, 3.90, and 9.13 % in stages 1, 2 and 3, respectively. The elevation of the village is relatively low and the distance to the dam site is relatively small. In Dianzi Village, the optimal time for evacuation is 22 h in all three stages.

(4) There will be no life loss in Liuhe Village and Xiaohe Town in stages 1 and 2 and hence no evacuation is needed. In stage 3, the optimal times for evacuating the population at risk in Liuhe Village and Xiaohe Town are 21 and 20 h before dam breaching. The dam breaching risks could be largely reduced by the optimal evacuation decision, which shows that timely evacuation is vital to save life and properties.

(5) The results of risk assessment show that the landslide dam may fail in stage 3 if the inflow rate is larger than the outflow rate through the drainage tunnels, resulting in large losses of lives and properties. Therefore, the landslide dam needs to be reinforced and contingent plans for warning and evacuating the population at risk need to be in place.

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