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A seismically triggered landslide dam in Honshiyan, Yunnan, China: from emergency management to hydropower potential

Abstract At 16:30 (Beijing time) on August 3rd, 2014, an Ms 6.5 earthquake occurred in Ludian County in Yunnan Province, China. The Ludian earthquake triggered a collapse in Chapingzi, right bank of the Niulanjiang River, and a landslide in Hongshiyan at the left bank on the same location. These events occurred 1.5 km downstream of the Hongshiyan hydropower station. Debris deposits from the collapse and the landslide blocked the river channel and formed a landslide dam. In this study, the Hongshiyan landslide dam induced by the Ludian earthquake was chosen as the study case to discuss integrated landslide dam management and its potential hydropower uses. After emergency management measures are carried out, further analysis shows the outflow through the Hongshiyan landslide dam is manageable, which indicate safety issues are controllable. Two management schemes are discussed in this paper: one that uses the Hongshiyan landslide dam for power generation and one that removes the debris deposit. The result shows that using the strengthened landslide dam for power generation is feasible and economically sound. This research estimate a capital recovery period of approximately 3 to 4 years with an investment-return ration of 1:40, which is considered a significant economic benefit.

Keywords Ludian earthquake · Landslide · Landslide dam · Stable assessment · Hydroelectric power

Introduction

On August 3rd, 2014, an Ms 6.5 earthquake occurred in Ludian County of Yunnan Province, China. The epicenter with a focal depth of 12 km was located near Longtoushan town in Lundian County (27° 6′ 0″ N, 103° 17′ 60″ E). By August 8th, 2014, this earthquake resulted in 617 deaths, more than 3000 injured persons, and a significant number of houses destroyed. The Ludian earthquake triggered the Chapingzi collapse and Hongshiyan landslide from the right and left bank of the Niulanjiang River, respectively. Both events occurred downstream the Hongshiyan hydropower station. The ensuing accumulation body blocked the river channel and formed the Hongshiyan landslide dam. Landslide dams are expected to be generally loose and thus extremely prone to fail causing catastrophic downstream flood or debris flow soon after its formation.

Costa and Schuster (1988) analyzed 73 landslide dams and concluded that the longevity of more than 50 % of natural dams were less than 10 days. Casagli and Ermini (2002) analyzed 205 landslide dams and found that more than 55 % of then breached within 10 days after their formation. A landslide dam breach usually results in catastrophic downstream flash floods or debris flow causing loss of life, property, and infrastructure. For example, in 1786, an Ms 7.5 earthquake occurred in the Kangding-Luding area of Sichuan Province, inducing the formation of a large landslide dam in the Dadu River. This dam suddenly breached 10 days later and caused downstream floods resulting in more than 100,000 deaths (Dai et al. 2005). On April 9th, 2000, a large landslide occurred in Bomi County, Tibet, China. The accumulation body from this large landslide with a volume of 3×10^8 m³ blocked the Yigongzangbu River creating a landslide dam. On June 10th, 2000, this landslide had a partial breach leaving 30 dead and 100 missing (Shang et al. 2003).

Landslide dam failure is a complex geohazard that has received increasing attention in many countries (Korup 2002; Xu et al. 2009). Research on this subject has focused on rapid safety assessment of landslide dams (Costa and Schuster 1991; Canuti et al. 1998; Casagli and Ermini 1999, 2002; Ermini et al. 2006; Dong et al. 2009, 2011, 2014; Petley 2010; Peng and Zhang 2013). Analyses of geomorphometric parameters suggest that landslide dam height, volume, and upstream catchment area are key factors for safety assessment (Korup 2004). Casagli and Ermini (1999, 2002) used dam height, volume, and upstream catchment area as indices to assess the stability of landslide dams. Based on works of Casagli and Ermini (1999, 2002), Chen et al. (2014) and Dal Sasso et al. (2014) successfully assessed the stability of landslide dams in the Taiwan area and Noce River. Dong et al. (2009) utilized the peak flow (or upstream watershed area), dam height, width, and length as variables in the construction of a multivariate regression model that had an 88.4 % prediction rate (Dong et al. 2009).

With the progress of research on landslide dams, it was found that grain-size distribution of the dam material is a decisive factor influencing the overall strength of landslide dams. This factor is related to erosion processes that can lead to failures by overtopping or piping (Swanson et al. 1986; Costa and Schuster 1988; Casagli and Ermini 1999; Casagli et al. 2003). Several scholars have analyzed the effects of grain size distribution on the stability of landslide dams (King et al. 1989; Plaza et al. 1990; Mora et al. 1993; Xu et al. 2009). The results of these studies suggest that landslide dams mainly composed of coarse particles are more stable (Casagli et al. 2003; Wang et al. 2010). However, Wang et al. (2010) pointed out that if the dams are composed of both coarse and fine particles, then the self-stabilization process would require a long time period, and the risk of breaching would be high during this time. Cui et al. (2009) classified landslide dams into four risk levels (extremely high risk, high risk, medium risk, and low risk) by translating the material composition into assessment indices, and qualitatively analyzed the stability of 32 landslide dams with detailed data from the Wenchuan earthquake region.

Landslide dams with poor stability pose high breaching risks. Emergency management measures should be executed based on rapid stability assessment (Wang et al. 2010) as soon as possible. Thus, the management of landslide dams can be generally divided
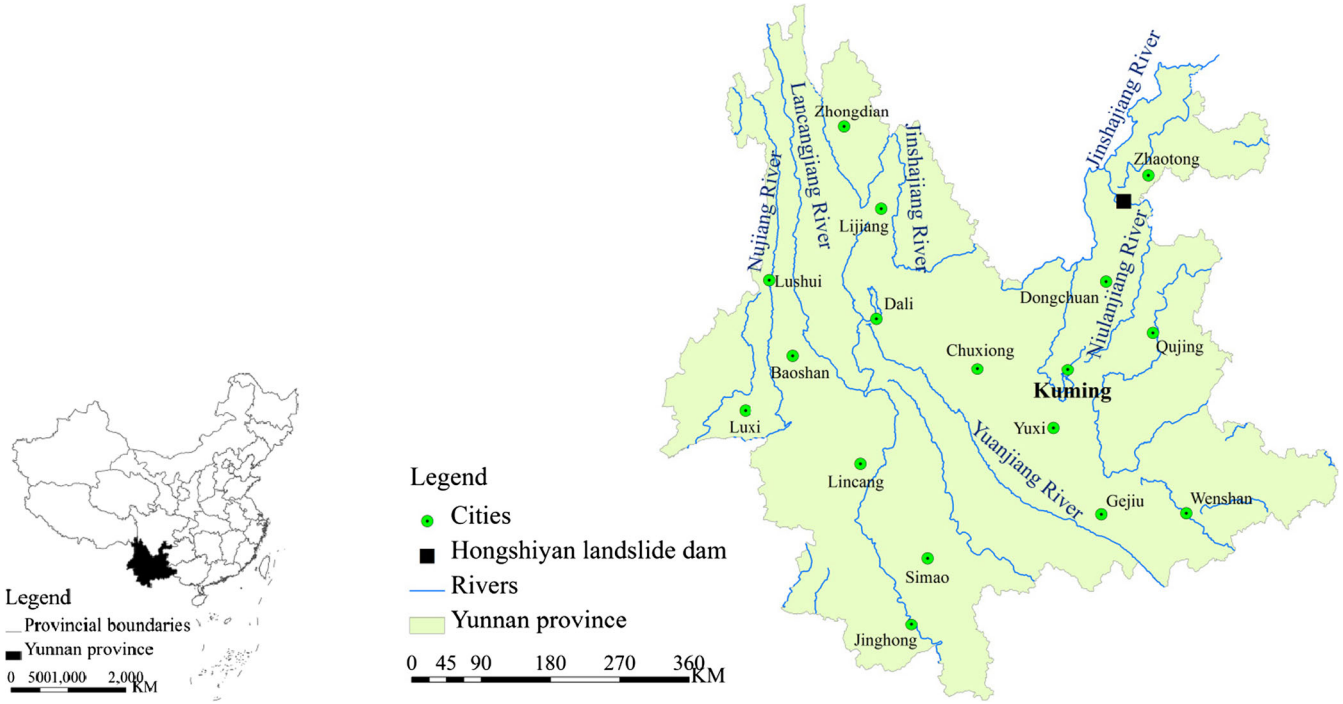
Fig. 1 Location of the Niulanjiang River and the Hongshiyan landslide dam in Yunnan Province

into two periods: emergency management that prevents the potential hazard situations immediately after the formation of the landslide dam and integrated management after emergency measures are in place.

The first period focus on how to prevent, or at least decrease, the breaching probability of a high-risk landslide dam and on making the dam manageable. Engineering measures such as excavating spillways or emergent spillway tunnels are mandatory in
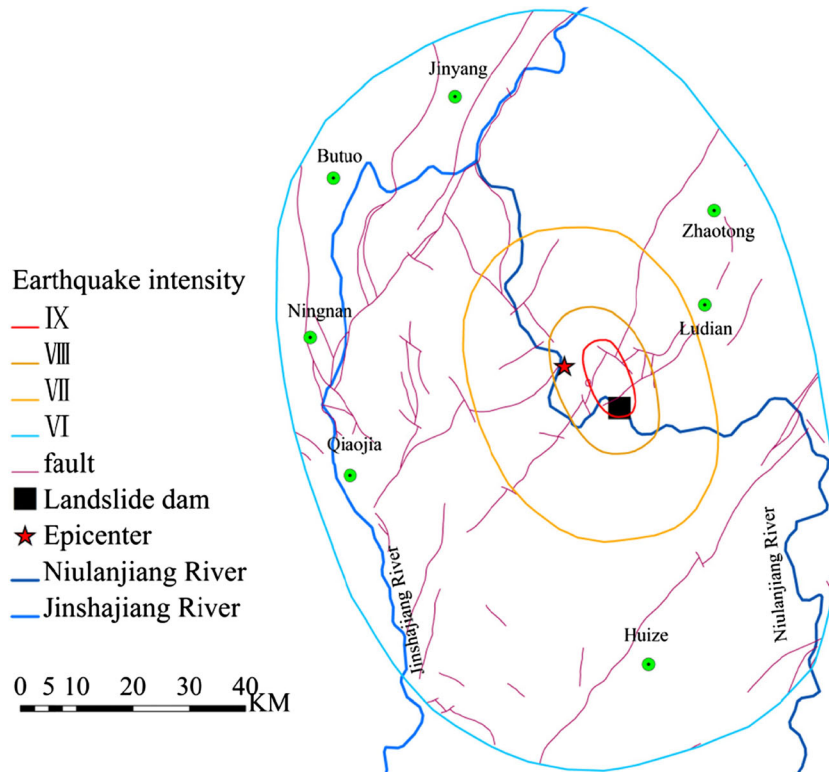

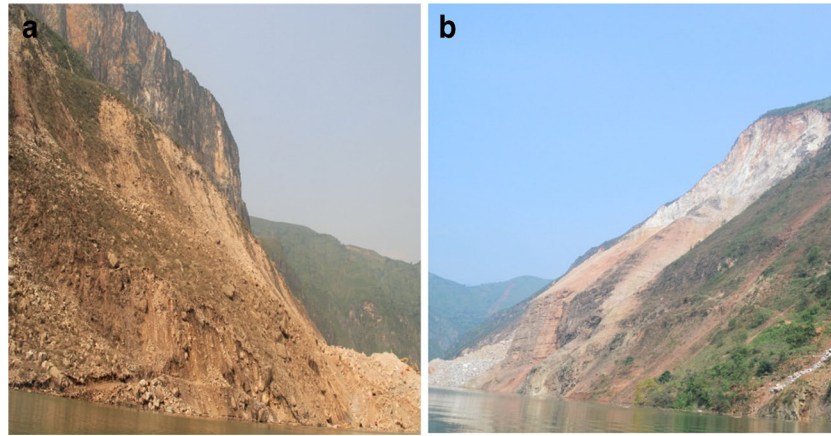**Fig. 2** Location of the epicenter and distribution of faults in Ludian earthquake region

Fig. 3 Two landslides induced by the Ludian earthquake form the landslide-dammed lake (**a**)Hongshiyan landslide on left bank; (**b**)Chapingzi collapse on the right bank (view from upstream)

this period. For example, the emergency measure of excavating a spillway was applied on the Tangjiashan landslide dam in Beichuan County of Sichuan Province in 2008. The total volume of water contained in the dammed lake decreased to 86×10^6 from 2×10^8 m³ after the emergency measure was taken, which notably decreased the breaching probability of the Tangjiashan landslide dam. After the first step is complete, the landslide dam can be considered to be in a safe and manageable status. Under certain conditions, the safe and manageable landslide dams have potential hydropower energy owing to huge storage capacity of their dammed lake.

The second period focuses on assessing possible economic benefits derived from transforming landslide dams into impounding dams via engineering measures. For example, a landslide occurred in Quarto Sul Savio creating a landslide dam on the Savio River in 1812. Eighteen persons died in this event from drowning upstream in the dammed lake. However, the dam was finally transformed into an impounding dam for hydropower in 1923 (Casagli and Ermini 2000). Additionally, the Waikarernoan landslide dam in New Zealand which has a height of 400 m was also successfully used for hydropower; its installed capacity reached 12.4×10^4 kW (Read and Beetham 1991).

In this research, the Hongshiyan landslide dam induced by the Ludian earthquake is taken as a case study. The authors focus on the management strategy of this dam from soon after its formation following emergency management rules. A team of scientists from the Institute of Mountain Hazards and Environment of the Chinese Academy of Science and from Moscow State University arrived at the area 17 days after the event. During the field campaign from 19 August to 23 August of 2014, the geomorphometric parameters of the Hongshiyan landslide dam and its related dammed lake were measured. Soil samples from representative locations of the landslide and collapse were collected and tested in the laboratory. Based on these measured data, the stability of the Hongshiyan landslide dam was assessed using quick quantitative and qualitative methods. This assessment led to the proposal of emergency engineering measures to prevent breaching. Given the socio-economical conditions of the area and after the safety of the Hongshiyan landslide was deemed manageable, the economic and other benefits of using it for hydropower generation or recovering the near Hongshiyan hydropower station were assessed.

Study area

The Niulanjiang River in northeastern Yunnan Province is the first tributary of the Jinsha River (Fig. 1). It acts as a demarcation line for Ludian and Huize Counties. The Hongshiyan landslide dam (Fig. 2) is located in the river section between the Village of Hongshiyan from the town of Huodehong in Ludian County, and the Village of Jiangbian from the town of Zhichang in Huize County (103° 23′ 56.58″ E, 27° 2′ 2.74″ N).

The catchment area of the Niulanjiang River is 13 320 km² with a typical annual rainfall of 700–1500 mm. There is a nearby hydrologic station in the river, the Dashadian hydrologic station which is located 25 km upstream of the Hongshiyan landslide dam. According to its hydrological data during the years 1966–1982, the
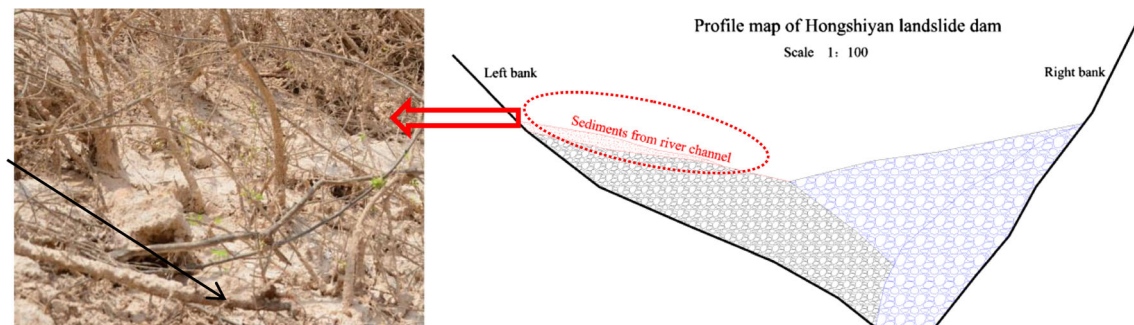

Fig. 4 Conjectural profile map of the Hongshiyan landslide dam based on field observations
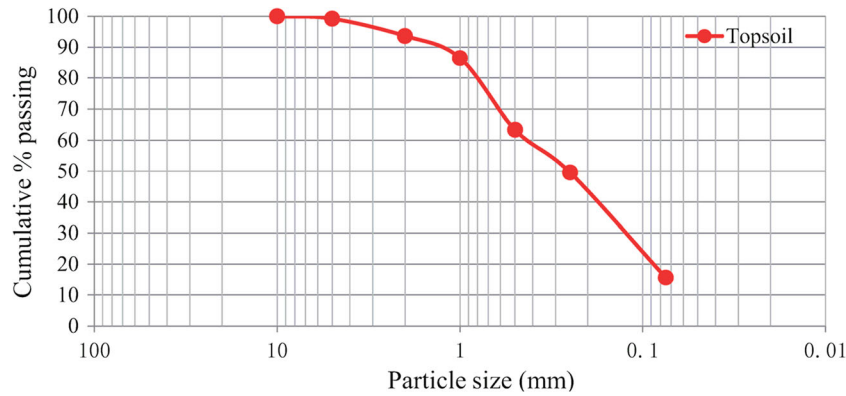
Fig. 5 Cumulative grain size distribution of the topsoil

11,800 km² catchment area of the Hongshiyan landslide dam had a yearly average precipitation of 912.8 mm with a maximum yearly value of 1100 mm within this river section. The average precipitation in May is 796.3 mm accounting for 87 % of the annual precipitation. The rainfall intensity in June is the highest with the maximum value of 72.5 mm in 24 h (Ma et al. 1995). Such distribution of rainfall can lead to higher peak values of floods upstream of the Hongshiyan landslide dam. For example, the peak discharge in this river section measured by the Dashadian hydrologic station reached 1890 m³/s, which may represent a threat to the stability of the Hongshiyan landslide dam. Landforms in the middle and lower reaches of the Niulanjiang River are characterized by high mountains and deep valleys (the average height difference between mountain ridges and valleys bottom is approximately 2000 m) making this river section suitable for hydropower generation. The theoretical potential waterpower resource in the main stream of the Niulanjiang River is approximately 1670 MW. There are eight hydropower stations in this river section, one of which (Hongshiyan station) is located upstream of the Hongshiyan landslide dam.

The tectonics in the region along the Niulanjiang River is characterized by compound folds in the S-N and N-E directions, which are located in the southern section of the Yaoshan tectonic belt near the Xiaojiang fault zone. It is composed of a series of large-scale and high-development faults (Fig. 2).

The stratum types in the Niulanjiang catchment are well exposed. Rocks from the Proterozoic to Quaternary are widely distributed in this region. The middle and lower reaches of the

Niulanjiang River are composed of Emeishan flood basalts generated in the Permian Period. The Neocathaysian structural system distributed in eastern and central section of this catchment is a series of compressional torsion fractures and folds in the S-N direction. Influenced by the fractures and folds, two banks of the Niulanjiang River have become thickly covered by the accumulation horizon with loose structure, low shear strength, and anti-weathering ability. Consequently, landslides or collapses in this area are extremely vulnerable to triggering factors such as earthquakes or rainfall (Hu et al. 2007).

The terrain of the eastern and western regions within the Ludian section of the Niulanjiang River is higher than that of the central region. The landforms within this river section are characterized by high mountains and deep valleys caused by the strong effect of erosion and undercutting process of the Niulanjiang River. The cross-section of the river valley is mainly "V"-shaped with few river shoals.

Methods

Emergency field investigation

Events triggered by the Ludian earthquake
The debris deposit from the Hongshiyan landslide and Chapingzi collapse was mainly composed of limestone (Fig. 3). However, there was a clear border in the accumulation body due to differing influence of weathering degree on the two banks (Fig. 8a). The surface of the Hongshiyan landslide was covered by a dry layer of fine sediment with a maximum height of 109 m on the left bank (Fig. 4). The grain composition distribution of the fine sediment (shown in Fig. 5) indicated that the particles with a diameter less than 1 mm accounted for more than 85 % of the sample. This fine sediment is generated through a long separation process that might have originated in the sediment of the original Hongshiyan reservoir.

Based on these above phenomenon and tested results, some details about the formation of this landslide and collapse can be described as follows: The Ludian earthquake first triggered the Hongshiyan landslide on the left bank. The rockslide from the Chapingzi collapse on the right bank then ran down into the river channel with high kinetic energy. Under the action of the rock impacts, the sediment from the river channel was lifted to the left bank with a maximum height of up to 109 m above the river

Fig. 6 Panoramic view of the Hongshiyan landslide dam. This photo was taken upstream of the landslide dam

Table 1 Geomorphometric parameters of the Hongshiyan landslide dam

Dam volume/m³	Dam height/m	Dam width/m	Dam length/m
1200×10⁴	92	753	283

channel. Impacted by the lifted sediment, some plants on the accumulation body of Hongshiyan landslide overturned in the reverse slope direction (Fig. 4).

The Hongshiyan landslide dam

According to the patterns of river channel obstruction, landslide dams can be classified into six types (Costa and Schuster 1988). Type 1 landslide dams are those that do not block the valley from side to side, type 2 landslide dams block the valley entirely and may reach the opposite slope, type 3 landslide dams fill the valley and move considerably up and down the valley, type 4 landslide dams form by failure of materials from both sides of a valley, type 5 landslide dams are caused by multiple lobes of a given landslide, and type 6 landslide dams form when the failure surfaces extend under the stream bed which is raised when the landslide moves. A landslide dam could be classified as type 2, type 3, and type 5 or other types at the same time (Xu et al. 2009). The Hongshiyan landslide dam is a type 3 and type 4 in this classification.

The debris deposit from the Hongshiyan landslide and Chapingzi collapse blocked the river channel with a V shape and formed the Hongshiyan landslide dam (Fig. 6).

The geomorphometric parameters of the Hongshiyan landslide dam were measured using a laser range finder (with a precision of 0.1 m) and are shown in Table 1. In Table 1, the dam width is parallel to the Niulanjiang River flow, and the dam length is the length of the dam axis across the river.

Two samples of the debris deposit were collected from typical locations of the landslide and collapse, which were screening passed through sieves in the laboratory for analysis. The grain composition distribution of the samples from the left and right bank is shown in Fig. 7. Particles with a diameter of less than 1 mm accounted for 24.3 and 18.1 % of samples, respectively. This indicates abundant fine particles in the accumulation body of the landslide and collapse.

Due to field conditions, particles with a diameter larger than 60 mm were not sampled. However, as shown in field pictures (Fig. 8a), coarse particles accounted for a large proportion of the debris deposit. The authors visually estimated that the boulder percentage (partilce size greater than 256 mm) is supposed to be more than 50 %. Additionally, it was reported in media accounts that the main structure of Hongshiyan landslide dam is composed by big rocks (http://news.qq.com/a/20140808/012107.htm). This report had further supported our visual estimation on the boulder percentage.

Hongshiyan landslide-dammed lake

After the Niulanjiang River channel was blocked by Hongshiyan landslide dam, the water level upstream rapidly increased creating the Hongshiyan landslide-dammed lake. On August 21st, 2014, the impounded depth of the Hongshiyan landslide-dammed lake was measured using a motorboat-mounted Lowrance 525 CF two-ray echo sounder which produces geo-referenced echograms. The device contains a GPS receiver with external antenna and a two-ray echo sounder working in the 50–200-kHz frequency band. It is capable of measuring water depths from 0.5 to 300 m with an estimated error of less than 0.2 up to 2 m of water depth and of 1 % if water is deeper. This device was successfully used for bathymetric surveys in Tian Shan, St. Elias Mts., and the Russian Caucasus (Petrakov et al. 2012). To compile the bathymetric map using calculations of lake volume and average depth, we employed ESRI ArcGIS 10.1 software. As is shown in Figs. 9 and 10, the maximum backwater distance from the landslide dam was approximately 15 km. The elevation of the dam crest was approximately 1216 m, with the water table at 1178 m. The Hongshiyan landslide dam was 1.5 km downstream from the Hongshiyan concrete dam. The measured volume of the water in Hongshiyan landslide-dammed lake was 62.5×10⁶ m³, and the maximum storage capacity of this landslide dam was estimated at more than 1.2×10⁸ m³.

Rapid stability assessment

Outburst floods or debris flows frequently occur soon after the formation of a natural dammed lake; thus, a rapid assessment of landslide-dam stability is essential (Schuster and Costa 1986). The stability of Hongshiyan landslide dam was rapidly assessed through quantitative assessment methods (Casagli and Ermini 1999, 2002; Dong et al. 2009). These methods can provide first-hand information
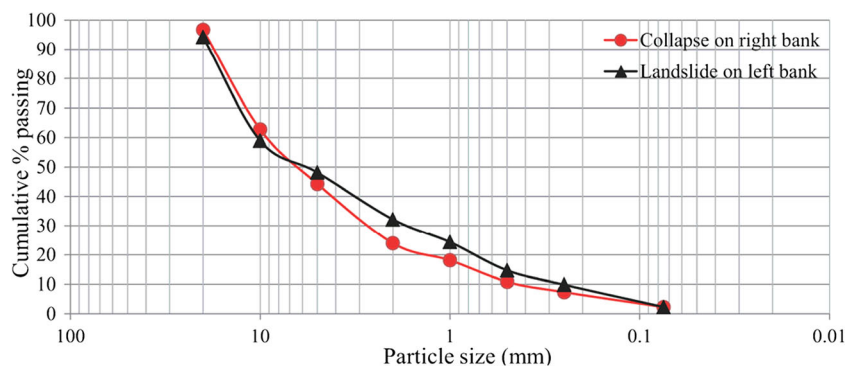
Fig. 7 Cumulative grain size distributions of the samples obtained from left and right banks
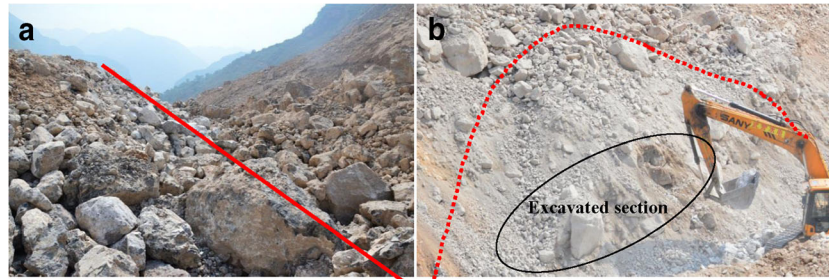
Fig. 8 Pictures of the coarse particles in the debris deposit and the excavated section of the collapse on the right bank. **a** Photograph of the upstream direction. **b** The area within *black oval* is a typical matrix-support structure

to guide the emergency management works. The measured geomorphic variables of the Hongshiyan landslide dam and its related dammed lake are listed in Table 2. The first-order estimation results of the rapid assessment methods are shown in Table 3.

The assessment formulae listed in Table 3 identifies catchment area A_b as the crucial factor influencing the assessment results, due to its large value (exceeding 10,000×10^6 m²) as well as its weighting coefficient. To some degree, the catchment area can reflect the value of peak flow (P) that discharges into the dammed lake as it correlates well with peak flow (McCuen 1998; Dong et al. 2009). Thus, a large catchment area represents a high peak flow value within the catchment. When the peak flow is larger, the risk of landslide dam breach is higher. The stability assessment of the Hongshiyan landslide dam in Table 3 shows that the dam was in a potentially unstable state.

Qualitative stability analysis based on grain structure was also performed. Schuster (1993, 1995) pointed out that landslide dams formed by coarse particle boulders or cohesive clays are less likely to breach than dams composed of permeable soil or unconsolidated barriers. Casagli et al. (2003) analyzed the influence of grain composition on the stability of 58 landslide dams and summarized two structure types of landslide dams: matrix-supported structure (unstable type) with coarse particles scattered amongst fine particles so that there is no contact between coarse particles in the profile and grain-supported structure (stable type) composed of coarse particles in contact with each other and fine particles filling the gaps.

An excavated section of the Chapingzi collapse on the right bank is shown in Fig. 8b. As is shown in this picture, the debris deposit and grain components in this section are best characterized by the matrix-supported type. The results of laboratory tests and field observation indicate that the structure of the Hongshiyan landslide dam was formed by both coarse and fine particles.

According to the research of Wang et al. (2010), the self-stabilization process of a landslide dam with this structure will take a long time, and the breaching risk is high during this process (Wang et al. 2010). Cui et al. (2009) proposed another rapid risk assessment method of landslide dam breaching (shown in Table 4). They classify the breaching risk into four grades including extremely high risk, high risk, medium risk, and low risk.

Based on the parameters of the Hongshiyan landslide dam and the field observations, the breaching risk of this landslide dam is located between the levels of "high risk" and "low risk" (Table 4). Both the quantitative and qualitative rapid assessment methods indicate that the Hongshiyan landslide dam should be considered unstable.

Discussions

Emergency management measures

The potentially unstable Hongshiyan landslide dam may be susceptible to a breach at any time given some variation in the external hydrologic environment (Wassmer et al. 2004). Accordingly, emergency engineering measures should be adopted to decrease the breaching risk. The simplest and most commonly used engineering measure for stabilizing landslide dams is to build a spillway across the landslide dam (Costa and Schuster 1988). However, the proper excavation position should be carefully determined to achieve maximum effectiveness. As the water level of the dammed lake rises up to the entrance of the spillway, big rocks that have armoring potential within the spillway will stack with each other and form a stop-pool structure under the natural scouring action. This process can improve the stability of landslide dam (Wang et al. 2004).

Since the debris deposit of the Hongshiyan landslide dam from the Chapingzi collapse is mainly composed of big rocks (Fig. 8a). If
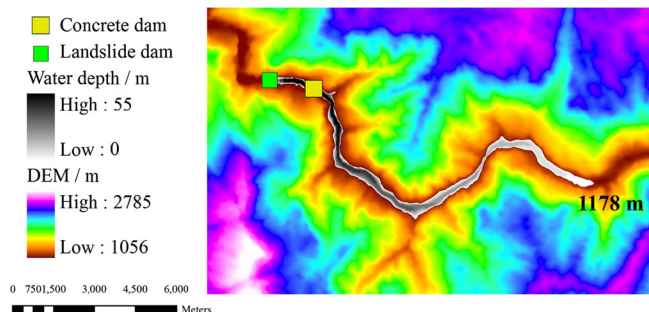

Fig. 9 Measured depth data of Hongshiyan landslide-dammed lake

Cross profile

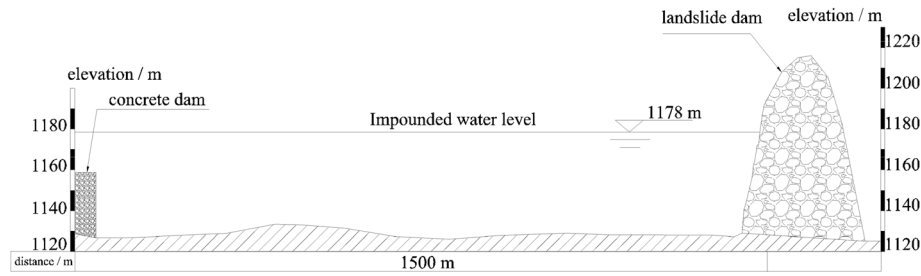Plotting scale: horizontal 1:500, vertical 1:100

Fig. 10 Profiles of Hongshiyan landslide and artificial concrete dam that show the location relationship of the two dams

the excavation position is chosen on that side of the dam, it will have the potential to form a stop-pool structure. The project to excavate a spillway near the right bank started on August 10th, 2014. This spillway with a top width of 30 m, a bottom width of 5 m, and a depth of 8 m was finished on August 21st, 2014.

The spillway had a positive effect in preventing breaching induced by overtopping (Schenider et al. 2013). However, spillways excavated across landslide dams are not always successful in preventing dam failure (Costa and Schuster 1988). In order to further reduce the breaching potential of the landslide dam by overtopping, the engineering measures (e.g., the construction of spillway channels) should focus on controlling the water level of the dammed lake. The scenario in the Hongshiyan landslide-dammed lake is unusual because there is a diversion tunnel built for Hongshiyan hydropower station. That tunnel became flooded by the impounded water before October 4th 2014. Its upper entrance is located 1.5 km upstream from the Hongshiyan landslide dam with the discharging end located downstream of the dam (Fig. 11). This unique situation provides a convenient opportunity to repurpose the tunnel as an emergency spillway channel. The excavation of the emergency spillway channel was advised by the authors in discussions with local authorities. This way, the water contained in the Hongshiyan landslide-dammed lake was drained into the river channel of the Niulanjiang River.

The built emergency spillway channel was finished with a diversion capacity of 840 m³/s. It was located as suggested on the right bank of the Niulanjiang River, connecting with the diversion channel of the Hongshiyan hydropower station (http://society.yunnan.cn/html/2014-08/26/content_3341859.htm). This channel with a length of 280 m was built between August 14th and October 4th, 2014. The draining of the Hongshiyan landslide-dammed lake was completed in the evening of October 4th, 2014 (Fig. 12). This way, the water level of the impound lake and thus the safety of the Hongshiyan landslide dam was effectively controlled.

Integrated management

Water impounded in the Hongshiyan landslide-dammed lake was discharged through an emergency spillway tunnel which increases the Hongshiyan landslide dam safety. In this situation, there is sufficient time to consider a strategy for the next stage of management of Hongshiyan landslide dam. Following international standard procedures, this landslide dam should be first considered with regard to its hydropower capacity. However, the discussion of using the Hongshiyan landslide dam for hydropower becomes complex due to the existence of an artificial concrete dam at only 1.5 km upstream the Niulanjiang River (Fig. 10). Consequently, the ultimate decision regarding the Hongshiyan landslide dam depends on the economic benefits of using the Hongshiyan landslide dam over the cost of restarting the existing Hongshiyan hydrologic power station.

Economic analysis of Hongshiyan landslide dam for potential hydroelectric generation

The Hongshiyan hydropower station, 1.5 km upstream from Hongshiyan landslide dam, was inundated by the dammed lake from August 3rd to October 3rd, 2014. It was exposed as well as the 32-m-high concrete dam after the emergency spillway tunnel was in operation (Fig. 11). The maximum installed capacity of this station was 80 MW with an expected annual energy production of 380×10³ MW□h. The diversion tunnel of the Hongshiyan hydropower station is located on the right bank of the Niulanjiang River with a diversion capacity 174 m³/s (Liu et al. 2005). The total reservoir capacity of the concrete dam is 0.693×10⁶ m³. Public data shows a cumulative deficit exceeding 100 million CN¥ during the years of 2008–2011. The power generation in 2010 was higher than 2009; however, the deficit of 2010 was 30 % higher than in year 2009. This problem was related to design defects deriving from not taking in account the high sediment concentration of the Niulanjiang River. Abundant sediments were transported by the diversion tunnel downstream to the power house, and they were deposited near the power house increasing the elevation of the

Table 2 Geomorphic variables of the Hongsiyan landslide dam and its associated barrier lake

H_d (m)	W_d (m)	L_d (m)	V_d (m³)	A_b (m²)	P (m³/s)
92	283	753	1200×10⁴	1087×10⁷	1890

H_d dam height, W_d dam width, L_d dam length, V_d dam volume, A_b catchment area, P peak flow

Table 3 Stability assessment of the Hongshiyan landslide dam using different quantitative prediction models (Casagli and Ermini 1999, 2002; Dong et al. 2009)

Prediction models	Prediction formula	Stability condition	Assessment results
Index-based graphic model	$DBI = \log(A_b * H_d * V_d^{-1})$	$DBI < 2.75$	$DBI = 4.92$, unstable
PHWL model	$D_s = -2.94\log\ (P) - 4.58\log\ (H_d) + 4.17\log\ (W_d) + 2.39\log\ (L_d) - 2.52$	$D_s > 0$	$D_s = -4.69$, unstable
AHWL model	$D_s = -2.62\log\ (A_b) - 4.67\log\ (H_d) + 4.57\log\ (W_d) + 2.67\log\ (L_d) + 8.26$	$D_s > 0$	$D_s = -6.7$, unstable

riverbed downstream. The elevation of downstream riverbed above the level of the power house required continuous removal of sediments to guarantee proper operation. This increased the operational costs of power generation.

The Hongshiyan hydropower station is a diversion-type power generation plant. Detailed data on the elevations of the intake and outlet of the diversion channel were not available for this research. Accordingly, it was not possible to exactly identify the water column height at the generator. However, this value can be estimated by the hydro-turbine output formula:

$$P = \eta 9.81QH \qquad (1)$$

where P is the hydro-turbine output, η is the coefficient of the hydro-turbine (90–95 %), Q is the power generation, and H is the water column at the generator. Based on the parameters of power generation at the Hongshiyan hydrologic station ($Q_{max} = 174$, $P_{max} = 800,00$ kW) and Eq. 1, the water column at the power generator is in the range of 49–52 m.

The total reservoir capacity of Hongshiyan landslide is at least 1.2×10^8 m³, which is approximately 120 times the reservoir capacity of the Hongshiyan hydropower station. If the Hongshiyan landslide dam is used for impoundment, the regulation capacity for the runoff of the Niulanjiang River will be much higher than the capacity of the Hongshiyan hydropower dam. In addition, the volume of impounded water within the Hongshiyan landslide-dammed lake available for power generation will be much larger than the Hongshiyan hydropower station, and this difference would be even greater during dry seasons.

The economic benefits produced by the Hongshiyan landslide-dammed lake if used for power generation can be preliminarily estimated as follows: The corresponding capacities of the normal storage water level and the low water level are assumed to be 50×10^6 and 30×10^6 m³, respectively. After the impounded water reaches its normal storage level, the volume of impounded water available for power generation will be approximately 20×10^6 m³. If the parameters of the new power generation system for the Hongshiyan landslide dam are same as those of the Hongshiyan hydropower station, the annual power generation of the landslide dam would be 8600 million kW·h larger. Based on Eq. 1 and the price of hydropower at 0.07 CN¥/kW·h market prices for Yunnan Province, the gross economic benefit of a new power generation system in the Hongshiyan landslide-dammed lake is about 605 million CN¥ more than the current hydropower station each year.

It must be noted that the Hongshiyan hydropower station is currently in a loss. In order to restart its operations it should undergo extensive repair and preparation works. This would require the removal of the Hongshiyan landslide dam, since the maximum value of peak flow in the Niulanjiang River can reach 1890 m³/s, which is larger than the diversion capacity in place (the emergency spillway tunnel and the diversion tunnel of Hongshiyan hydropower station, totaling 1014 m³/s). Without this measure, the water exceeding the diversion capacity of the tunnels will be blocked by the Hongshiyan landslide dam. This newly impounded water may eventually inundate Hongshiyan hydropower station again, which will disrupt power generation. Furthermore, the volume of the Hongshiyan landslide is 1200×10^4 m³, which will be extremely costly to remove.

The above analysis shows that using the Hongshiyan landslide dam for power generation appears to yield significant economic benefits. However, been the Hongshiyan landslide dam potentially unstable, engineering measures should be taken in order to improve the anti-leakage and strength of this dam. The cost of building a new hydro-junction revolving around the Hongshiyan landslide dam should be concentrated on a new power generation system and a reinforcement project. As a reference, the construction project for the Hongshiyan hydropower station took roughly

Table 4 Risk degree classification of landslide dams (Cui et al. 2009)

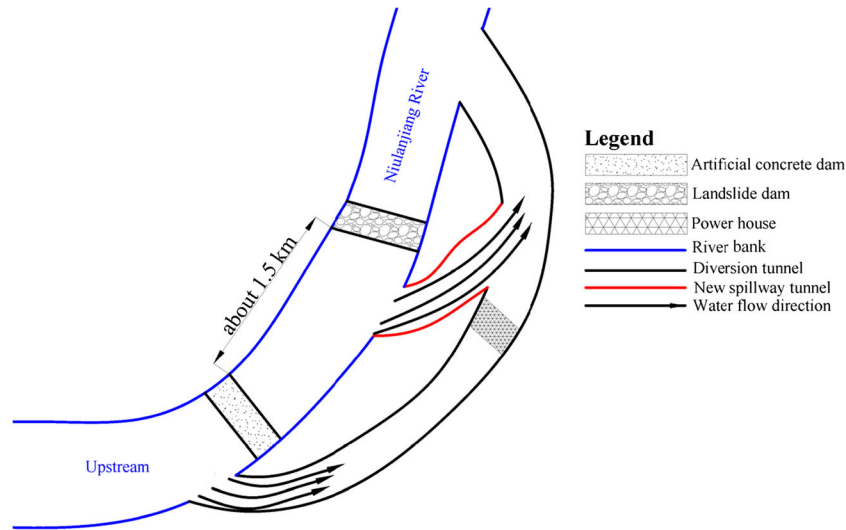| Risk category	Classification indices		
	Dam height/m	Reservoir capacity/10^4 m³	Material composition of dam
Extremely high risk	>100	>10^4	Soil texture dominated
High risk	50–100	10^3–10^4	Soil texture with some big rocks
Medium risk	25–50	10^2–10^3	Big rocks texture with some soil
Low risk	<25	<10^2	Big rocks texture dominated

Fig. 11 Schematic diagram of the suggested spillway tunnel. This picture also shows the location relationship of the artificial concrete dam, landslide dam, diversion tunnel, and the new spillway tunnel

2 years from December 20th, 2003, to December 31st, 2005, with a total cost of approximately 400 million CN¥.

Prices and salaries have been increased by two to three times in China during the intervening 10 years lapse from Hongshiyan hydropower construction. If the new power generation system is similar to the Hongshiyan hydropower station, the cost of a new hydro-junction for Hongshiyan landslide dam could cost between 800 million and 1.2 billion CN¥. Additionally, the engineering measures to secure the dam could cost from 200 million to 300 million CN¥. Thus, the total cost of this project could range from 1 billion to 1.5 billion CN¥. The new system used for power generation should produce at least 605 million CN¥ a year. Within this prediction and considering the influence of dry years, the capital recovery period will be approximately 3 to 4 years. The investment-return ratio of transforming the Hongshiyan landslide dam into an impounding dam is roughly 1:40 (if the service life of the stabilized dam is 100 years).

Fig. 12 Water impounded in the dammed lake has been released by the new constructed channel. As shown in this picture taken on October 10th, the submerged artificial concrete dam has been exposed

Suggested long-term engineering measures

According to the above analysis, transforming the Hongshiyan landslide dam into a new hydropower junction has an excellent economic return. However, complementary engineering measures should be taken in order to permanently stabilize the Hongshiyan landslide dam before the flood season of 2015. These measures should take into account the location of the Hongshiyan landslide dam in an active seismic zone. The stabilization project should focus on minimizing the risk of earthquake-induced piping and landslide-triggered overtopping.

The landslide dam is formed by rapid accumulation of materials from the landslide and collapse, which is prone to leaking. Engineering measures designed to eliminate leakage are necessary for the Hongshiyan landslide dam. The body of this landslide dam is characterized by abundant large rocks and large pores. Experiments conducted on material components, leakage characteristics, and grouting demonstrated that the structure of the dam is favorable in terms of grouting, and grouting engineering measures can deal with potential leakage issues (Zhao 2008). For example, an engineering sealant measure was applied on the Xiaonanhai landslide dam with excellent sealant effectiveness according to leakage observation in later periods (Zhao 2008). This engineering sealant measure can be applied to Hongshiyan landslide dam, with the impervious curtain classified into different seal standards to account for differences in elevations of the Hongshiyan landslide dam.

Another issue to be addressed is the stability of the Hongshiyan landslide dam. In order to transform this natural dam into an impounding dam, engineering measures are necessary to strengthen its stability. The width (direction across the river) and thickness (parallel to the Niulanjiang River flow) of the downstream face of the Hongshiyan landslide dam should be enlarged from the slope toe. Additionally, stone ballast can be used to cover the tail of the downstream face. The previous measures, complemented with some bio-stabilization (e.g., grass), should prevent slope erosion and encourage stability. Additionally, excavation and support measures should be applied on the slopes of the two banks. In

the excavation process, any geological defects (e.g., faults, fractures, and weak intercalation) should be removed, and the supporting measures should be applied in each excavation layer to protect the working face from erosion induced by rainfall. Curtain grouting can also be applied on the slopes of the two banks if necessary, which can improve the sealant performance of the slopes and prevent piping.

The Hongshiyan landslide dam can be transformed into an impounding dam similar to an embankment dam. The suggested hydro-junction that revolves around the Hongshiyan landslide dam can only be implemented by using the diversion mode for power generation. The emergency spillway tunnel connected to the diversion tunnel of the Hongshiyan hydropower station can be used for flood regulation and sediment scour. A new spillway outlet for the power generation system should be built on the right bank. The design of the new power generation scheme should take full consideration of the sediment deposition issue downstream of the powerhouse.

Conclusions

The Hongshiyan landslide dam was identified immediately after its formation as potentially unstable via quantitative and qualitative methods based on field measurements. According to an emergency management strategy, urgent measures such as the excavation of a spill way across the dam and an emergency spillway tunnel were timely deployed in order to reduce breaching risks. Two options for post-emergency management of the Hongshiyan landslide dam where contrasted: power generation or removing the accumulation body. Some conclusions are drawn as follows:

1. The emergency field investigation and rapid stability assessment indicated that the Hongshiyan landslide dam was unstable. But the economic benefit of using this dam for power generation is significant. This is due to the storage capacity of the Hongshiyan landslide-dammed lake which is 170 times the capacity the Hongshiyan hydropower station. Furthermore, the investment-return ratio of the engineering measures needed to transform the Hongshiyan landslide dam into an impounding dam is roughly 1:40, which indicates excellent economic return.
2. Due to the larger capacity of the landslide dam reservoir, the regulation capacity of the runoff in the Niulanjiang River will increase, which will make this landslide dam and its related lake a hydroelectric project with seasonal regulation capacity. The Niulanjiang catchment is characterized as a typical dry-hot valley with a clear boundary between wet and dry seasons. Depending on its regulation capacity, the suggested hydro-junction should effectively control the peak flow during the flood seasons, which can protect the large-scale hydropower stations (Xiangjiaba and Xiluodu hydro-junction), located downstream on the Jiansha River. During the dry seasons, this hydro-junction can provide the water to the counties of Qiaojia, Ludian, and Zhaoyang (also depending on its seasonal regulation capacity). Besides these functions, the reinforced Hongshiyan landslide dam and dammed lake can also be used for developing the local tourist industry.
3. Landslide dams being used for power generation are uncommon. The preliminary scheme processing of the Hongshiyan landslide dam can provide a reference framework to explore long-term landslide dam management.

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