CASE HISTORY

Formation and evolution of a successive landslide dam by the erosion of river: a case study of the Gendakan landslide dam on the Lancang River, China

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Abstract

A landslide dam located on the Lancang River in Southwest China was used as a case to study the landslide formation and evolution process induced by river erosion. The Lancang River has been blocked at least twice by landslides at the same location and formed a landslide dam with a length of over 162 m, a height of over 96.8 m, and a volume of over 2.7×10^6 m^3. The rapid and continuous downcutting of the Lancang River induced the steeply dipping layered rock mass to intensively topple, and multiple toppling fracture zones formed in the rock mass. The Gendakan landslide was formed at the base of a deep-seated toppling failure of the rock mass. The Yagong intensively toppled rock mass, which is located 800 m upstream of the Gendakan landslide, has topographical, geological, and stratigraphic conditions similar to those of the studied landslide. The Yagong rock mass has a probability of evolving into a large landslide and blocking the Lancang River during further river erosion. In addition, the residual deposits of the Gendakan landslide, which has a volume of 4.7×10^7 m^3 and is distributed at a relatively high elevation on the right bank of the Lancang River, have a probability of reactivating and blocking the river again due to further river erosion and rainstorms.

Keywords Landslide dam · Erosion of river · Toppling failure · Lancang River

Introduction

As a geological disaster, landslide damming is widely distributed in steep river valleys worldwide (Evans et al. 2011; Fan et al. 2018; Plan et al. 2018; Shyu et al. 2019; Wu et al. 2019). These dams could be classified into two types: partial and complete (Stefanelli et al. 2016; Kumar et al. 2019). The most dangerous condition is the latter, which usually results in the impounding of lakes and outburst floods. Many terrible events caused by outburst water from dammed lakes have been reported (Cenderelli 2000; Shang et al. 2003; Dai et al. 2005).

Many researchers have focused on landslide damming, including upstream submersion and downstream flood burst by the breaching of the landslide dam (Chen et al. 2008; Korup

and Montgomery 2008; Phartiyal et al. 2009; Zhang et al. 2011a, b, 2014; Peng et al. 2014; Zhao et al. 2015). Previous researchers have proposed many methods to evaluate the stability of landslide dams (Ermini and Casagli 2003; Dong et al. 2011; Stefanelli et al. 2016) and assess the hazard of landslide dam breaches (Clague and Evans 2000; Peng and Zhang 2012).

Earthquakes (Huang 2009; Zhang et al. 2011a, 2011b) and rainstorms (Costa and Schuster 1991) are two important triggering factors for landslide damming. It is well recognized that adverse tectonic conditions, the rapid and strong erosion of rivers, and the characteristics of rock masses are the key factors causing the formation and evolution of a landslide dam (Weidinger et al. 2002; Weidinger 2006; Huang 2009; Futalan et al. 2010; Youssef et al. 2012; Papadopoulou-Vrynioti et al. 2013; Zhang and McSaveney 2017). Landslide dams might be formed successively several times at the same location (Shang et al. 2003; Chen et al. 2006). Sometimes, a landslide dam can be maintained for a long time before being breached, and many lake sediments can be deposited along both banks of the river upstream (Liu et al. 2018; Wu et al. 2019; Shyu et al. 2019).

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An old landslide, named the Gendakan landslide, is located on the right bank of the Lancang River upstream, which was formed based on a deep-seated intensively toppled rock mass hundreds of years ago. The landslide dammed the Lancang River twice in history and left a residual dam on the present right bank of the river. The objective of this case study was to analyze the formation mechanism of the old landslide and the evolution of the landslide dam by the erosion of the Lancang River. We investigated the geological characteristics of the study area, the material composition and structure of the residual landslide deposit, and the features of the lake sediments in the impounded lake.

Study area

The study area is located upstream of the Lancang River, Yunnan Province, Southwest China. Its geographic coordinates are E 98° 47′–98° 36′ and N 28° 33′–29° 10′, and it is part of the longitudinal valley geomorphic unit in Western Yunnan. The Lancang River has a water level of 2065 m above sea level, and the slope of the valley is approximately 50–60° (Tu et al. 2019).

The study area is located at the junction of the Songpan-Ganzi fold belt and the Tanggula-Lanping-Simao fold belt and is in a monoclinal structural area. Faults are well developed mainly in the NNW-SN direction in the study area (Fig. 1). The principal compressive stress has a dominant direction of NW-NWW, and the direction of the principal tensile stress is NE-NEE, indicating that the stress field in the study area is dominated by regional horizontal tectonic stress (Sichuan Provincial Bureau of Geology 1979; Liu et al. 2016).

The strata in the study area are composed mainly of the Lower Permian Jidonglong Formation (P_1j) and the Middle Permian Shamu Formation (P_2sh) (Fig. 2). The Lower Permian Jidonglong Formation (P_1j) can be divided into six members from bottom to top according to the lithological association (Table 1). The Middle Permian Shamu Formation (P_2sh) is composed mainly of dark gray metasandstone with slate, which has a single layer thickness of 5–50 cm and a total thickness of over 1000 m.

The original attitude of the stratum is approximately N 30–45° W/NE < 70–80°. However, the dip angle varies to 15–65° in shallow and surficial rock masses on both banks of the Lancang River due to the strong toppling of the rock mass.

The Yanjin-Gushui fault, across the rear of the landslide, is the nearest regional fault, which has a strike of N 10–30° W. It is a thrust fault and has a fracture zone thickness of approximately 2–8 m.

The Lancang River flows in the direction of 130–140°, coinciding with the strike of the strata upstream and downstream of the landslide dam. However, it is convex to the left bank in the study area (Fig. 2). The river has a width of 60–80 m and an average annual discharge of 682 m^3/s.

Field investigation

The residual landslide deposits are distributed at elevations of 2060–2860 m (Tu et al. 2019). The landslide has a maximum width and length of 700 m and 850 m, respectively, and has a volume of 4.7×10^7 m^3 with a thickness of 30–110 m (Figs. 2 and 3). For the safety of residents, we and the builder of the Gushui power station were instructed by the local government to investigate and assess the hazard of the landslide. Several holes and horizontal adits were performed by the builder.

We surveyed the engineering-geological characteristics of the study area in detail, including the material composition and structure of the landslide deposits, the features of the slip zone, and the bedrock. We also investigated the features of landslide dam and sediments in impounded lake.

Investigation of the landslide

The landslide deposits are trumpet-shaped in plane and convex to the left bank. Its landform has a mean slope of approximately 30–40°. The front and rear have steeper slopes of 40–60°, while the middle part is gentler with a slope of 7–12°.

The adit Pd1004 lies in the middle of the landslide deposits with an elevation of 2284.98 m (Fig. 3) and a horizontal length of 176 m (Fig. 4). Figure 4 shows that the landslide deposit had a horizontal thickness of over 160 m and was composed mainly of gravelly soil, crushed stone soil, and fragment-blocks of rock. In the sections of 22–34 m, 48–83 m, and 100–119 m away from the entrance, the landslide deposits consisted mainly of gray-green basaltic fragments.

Two slip zones were exposed in adit Pd1004. One was located at 134–135 m away from the entrance of the adit with a thickness of 30–50 cm and an attitude of N 30–40° W/NE < 30–45°; another slip zone was located at 156–165 m away from the entrance with a thickness of 30–50 cm and an attitude of approximately N 30–40° W/NE < 50–60°. Both of the slip zones were composed mainly of yellow clay with gravels (Fig. 5c, d). Gravels in the slip zones were mostly subangular to subrounded and had a particle size of 2–20 mm with a percentage less than 10%.

The bedrock, exposed in adit Pd1004, was composed of metabasalt. The rock mass, underlain by the slip zone, was cataclastic and strongly mylonized (Fig. 6b).

The adit Pd1003 lies in the middle-rear of the landslide with an elevation of 2445.86 m (Fig. 3) and a horizontal length of 121 m (Fig. 7a). The landslide deposit had a thickness of approximately 114 m in adit Pd1003 and was composed mainly of humus soil, gravelly soil, and fragment blocks of rock. Two slip zones were exposed in the section 111–116 m away
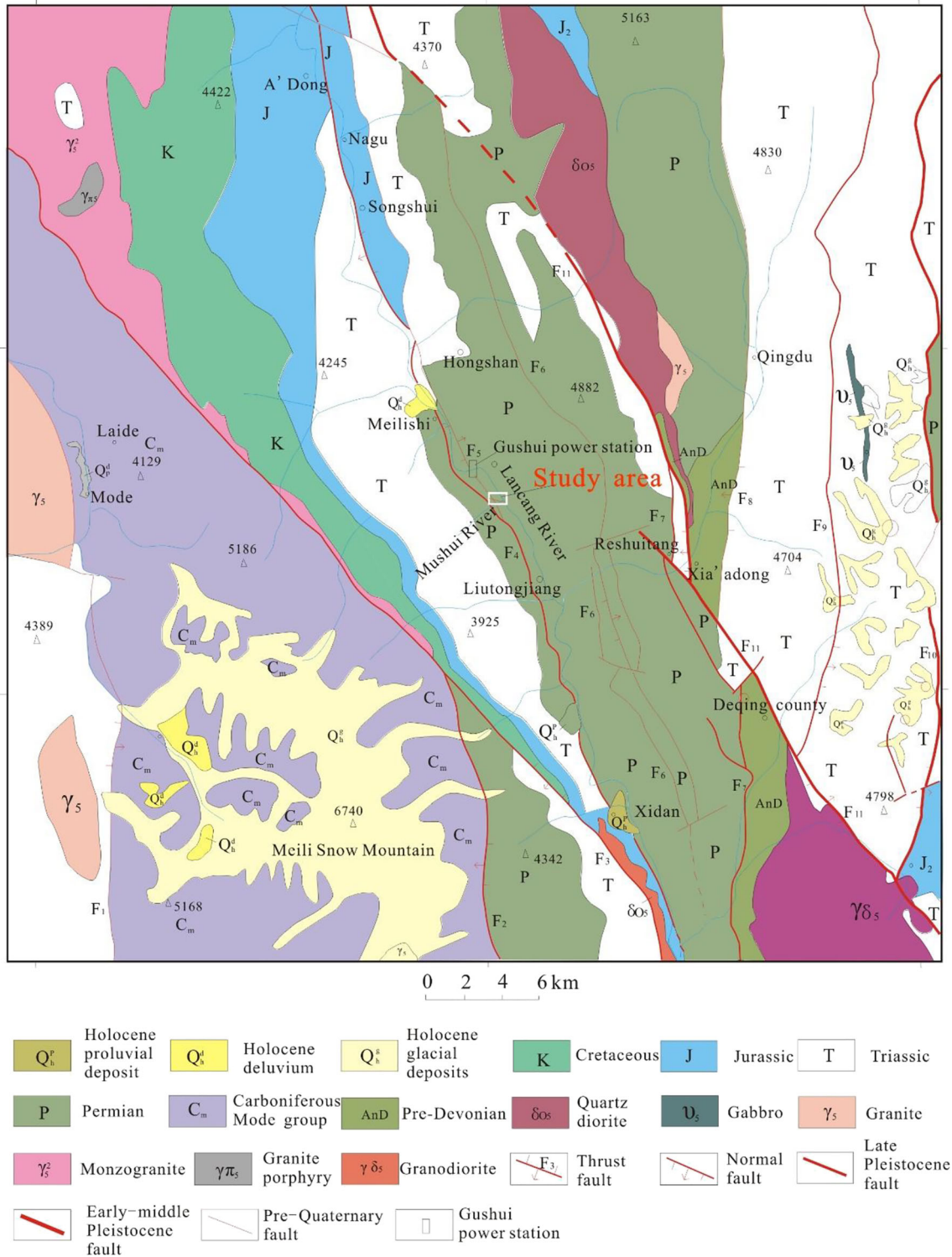
Fig. 1 Regional structure of the study area

from the entrance. The outer slip zone was composed mainly of black clay with gravels with a thickness of 2.5–3 m and an attitude of N 40° W/NE < 20–30°. The inner slip zone had a thickness of 0.3–0.6 m with an attitude of N 40° W/NE < 40–50° and consisted mainly of purplish-red clay with gravels.

The gravels in both slip zones were subangular to subrounded with a percentage less than 10% and had a grain size of approximately 2–10 mm. The bedrock in adit Pd1003 was cataclastic metabasalt and had a strong mylonitization zone with a thickness of 4–6 m underlain by the slip zone (Fig. 6a).
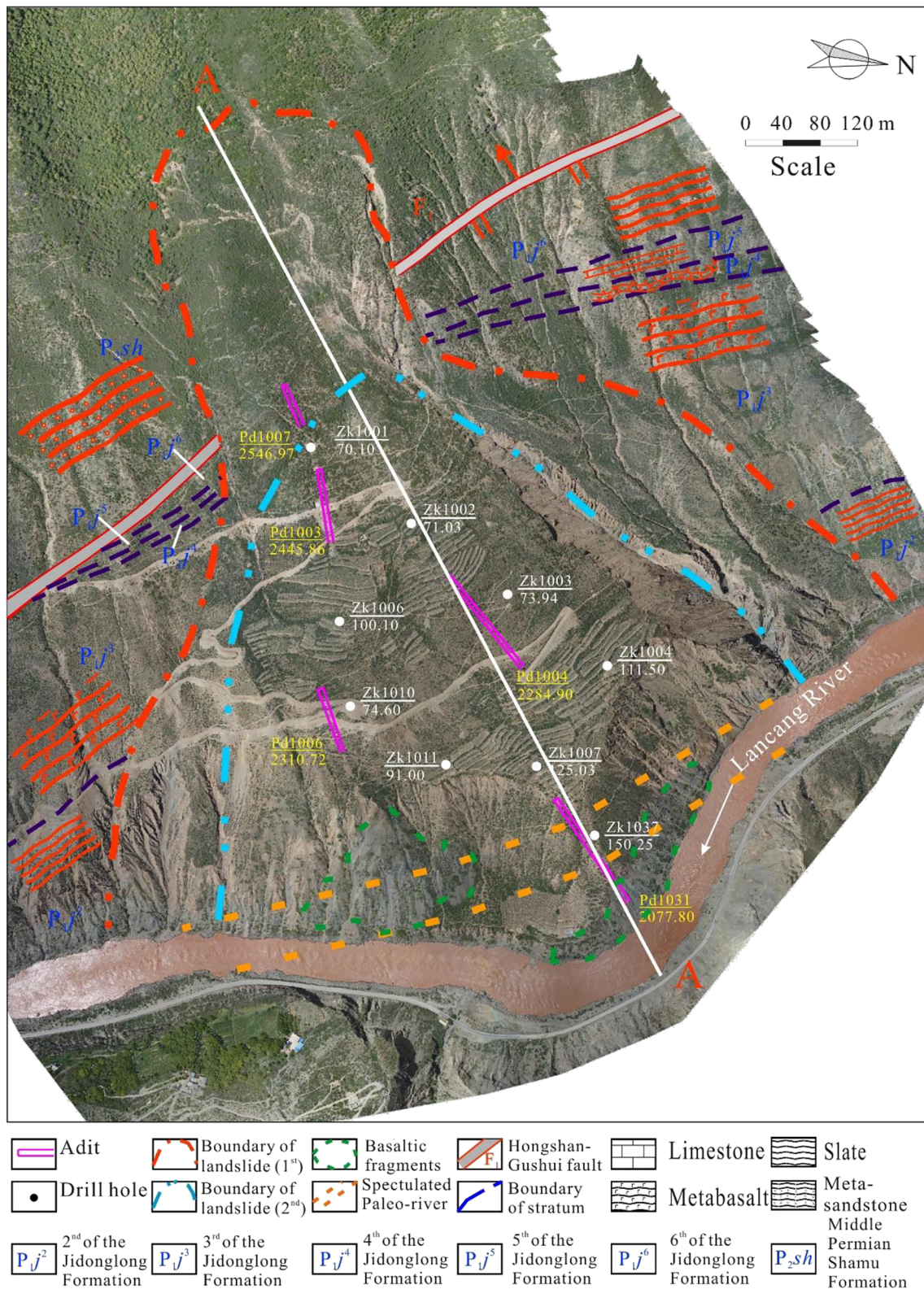
Fig. 2 Engineering-geological planar graph of the study area

The adit Pd1007 is located at the rear of the landslide and has an elevation of 2546.97 m with a horizontal length of 73.5 m (Fig. 7b). The landslide deposit had a thickness of 63.5 m exposed in the adit Pd1007 and consisted mainly of humus soil and crushed stone soil. Only one slip zone was exposed in the section 60–63.5 m away from the entrance. The

Table 1 Lithological association of the Lower Permian Jidonglong Formation (P_1j)

Member	Composition	Thickness of single layer	Total thickness	Remarks
P_1j^1	Grayish-green metabasalt		500 m	It has blastoporphyritic texture and massive structure. Foliation formed by tectonic compression is well developed in this member
P_1j^2	Dark gray slate	2–5 cm	600–800 m	
P_1j^3	Grayish-green metabasalt		200–400 m	It has blastoporphyritic texture and massive structure. Foliation formed by tectonic compression is well developed in this member
P_1j^4	Red metasandstone	5–100 cm	50–100 m	
P_1j^5	Gray limestone interbedded with metasandstone	5–20 cm	50–75 m	
P_1j^6	Gray slate	2–5 cm	100–150 m	

slip zone was composed mainly of yellow clay with gravels and had an attitude of N 25–30° W/NE < 25–35° (Fig. 5f). The bedrock in adit Pd1007 is limestone. It toppled strongly with an attitude of N 45–50° W/NE < 3–8° (Fig. 8).

Two slip zones were exposed in adit Pd1031 (Fig. 5a, b), which is located at the front of the landslide with an elevation of 2077.8 m. The outer slip zone was located in the section 28–45 m away from the entrance of adit with an attitude of N 30–40° W/NE < 3–5° and consisted mainly of yellow clay with some small gravels. The inner slip zone was located 145 m away from the entrance of the adit and was composed mainly of yellow and black clay soil. Gravels in the two slip zones were subangular to subrounded and had a diameter of 2–20 mm with a weight percentage less than 5%.

In addition, two slip zones were exposed in drill hole ZK1037 (Figs. 2 and 3) with depths of 71–75.5 m and 89.2–91.4 m. They had characteristics similar to those of the slip zones exposed in adit Pd1031.

According to the field investigation on the residual landslide deposits, two slip zones were developed in the landslide during the formation and evolution process of the landslide (Fig. 3). They were composed mainly of clay with some subangular or subrounded gravels; their thickness varied in a wide range of 0.5–5 m. This indicated that the landslide at least twice experienced the intensive process of sliding during its formation and evolution process.

The paleo-landslide dam

The drill hole ZK1037, which is located in the front of the landslide with an elevation of 2160.38 m (Figs. 2 and 3), exposed an interesting phenomenon. A sandy pebble layer was exposed at a depth of 96.8–112.5 m of the drill hole (Fig. 9). According to the buried depth of the pebble layer, we could speculate that it had an elevation of 2063.58–

2047.88 m, corresponding to the elevation of the present fluvial deposits of the Lancang River bed. The pebbles had a diameter of 1–8 cm with a relatively high roundness and weight percentage over 70% in this layer. The pebble layer should belong to the fluvial deposits of the Lancang River. We speculate that the landslide blocked the Lancang River and diverted the river course to the present location. The paleo-river course should be as shown in Fig. 2.

The pebble layer had a buried depth of 96.8–112.5 m, which indicated that the landslide dam had an initial height of over 96.8 m. Figures 2 and 3 show that the distance between the paleo-river course and the present river course was 162 m. Then, we estimated that the initial landslide dam had a length of over 162 m, height of over 96.8 m, and volume of over 2.7×10^6 m^3.

A special phenomenon was found in the front part of the landslide (Fig. 10a), where a fluvial sandy gravel layer was buried by gravelly soil and overlain by another gravelly soil. The fluvial sandy gravel had a thickness of 1–2 m, and the gravel in this layer was subangular with a diameter of approximately 2–50 cm. It had a height of 12 m above the present river level. The same phenomenon was observed in the section 0–28 m away from the entrance of adit Pd1031 (Fig. 10b), where the fluvial sandy gravel layer was overlain by gravelly soil and underlain by crushed stone soil and had a thickness of 30–50 cm.

According to the depositional characteristics of the fluvial sandy gravel, it should belong to the sediments of the spillway after the landslide was breached. The underlain soils (gravelly soil and crushed stone soil) should belong to the deposits of the original landslide. The overlying gravelly soil should belong to the second landslide deposits. Thus, we speculate that the Lancang River had been blocked at least twice at this location.
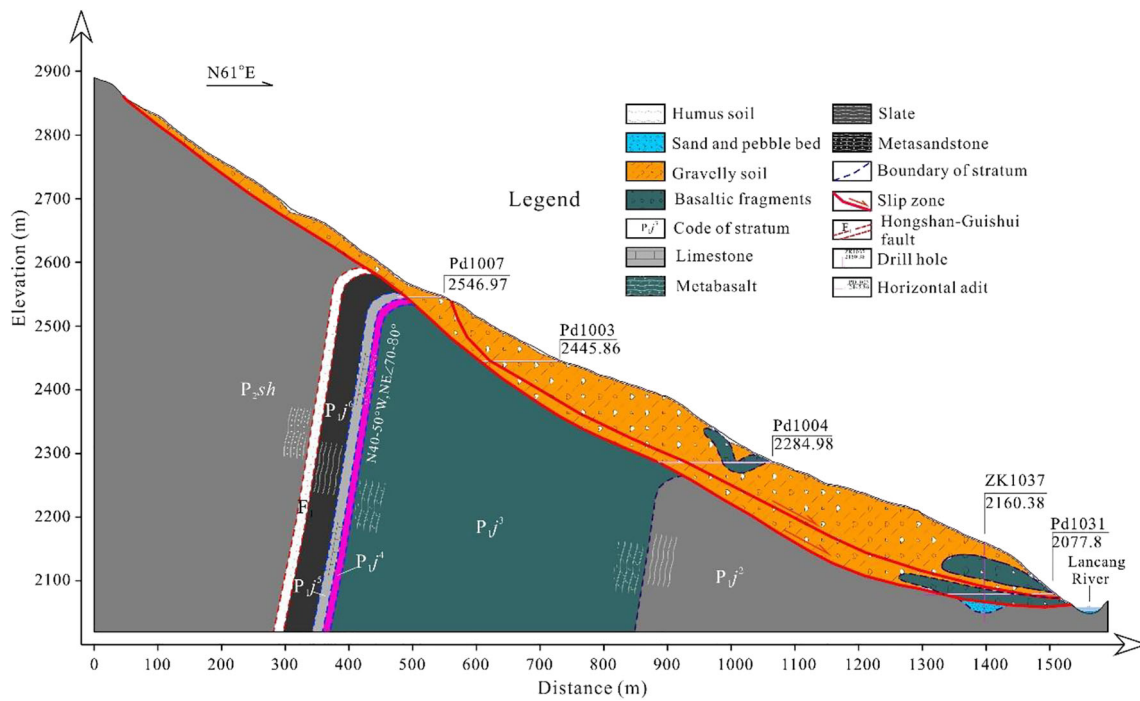
Fig. 3 Engineering-geological A-A profile of the Gendakan landslide

Sediments in the dammed lake

Figure 11a shows some clayey silt sediments distributed on both banks approximately 1–5 km upstream from the landslide. The clayey silt layer had a thickness of 15–20 m and was 40–50 m above the present river level (Fig. 11c). The layer had a fairly horizontal layered structure with a single layer thickness of 1–5 mm (Fig. 11b). The clayey silt soil was composed mainly of silt with a particle size of 10–100 μm (Fig. 12). The yellow clayey silt sediments were overlain by a fluvial pebble bed. Pebbles in the fluvial pebble bed were subrounded with a grain size of 2–50 cm and weight percentage over 80% (Fig. 11b).

According to the material composition and characteristics of the structure of the clayey silt, it should belong to sediments deposited in a relatively still water condition. Thus, we speculate that it was deposited in the dammed lake after the Lancang River was blocked by the landslide. The fluvial pebble bed overlying the clayey silt layer was deposited after the breach of the landslide dam. The thickness and height above the river level of the clayey silt layer indicated that the initial depth of the dammed lake was over 50 m.

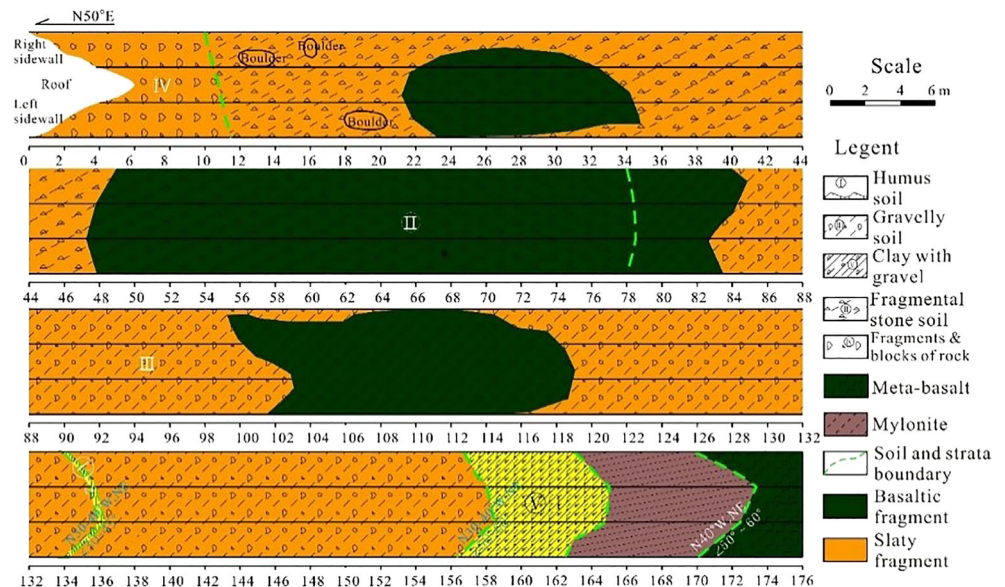Fig. 4 Material composition of the landslides in adit Pd1004

Fig. 5 Characteristics of the original slip zone. **a** Slip zone 2 in adit Pd1031; **b** slip zone 1 in adit Pd1031; **c** slip zone 2 in adit Pd1004; **d** slip zone 1 in adit Pd1004; **e** slip zones in adit Pd1003; **f** slip zone in adit Pd1007
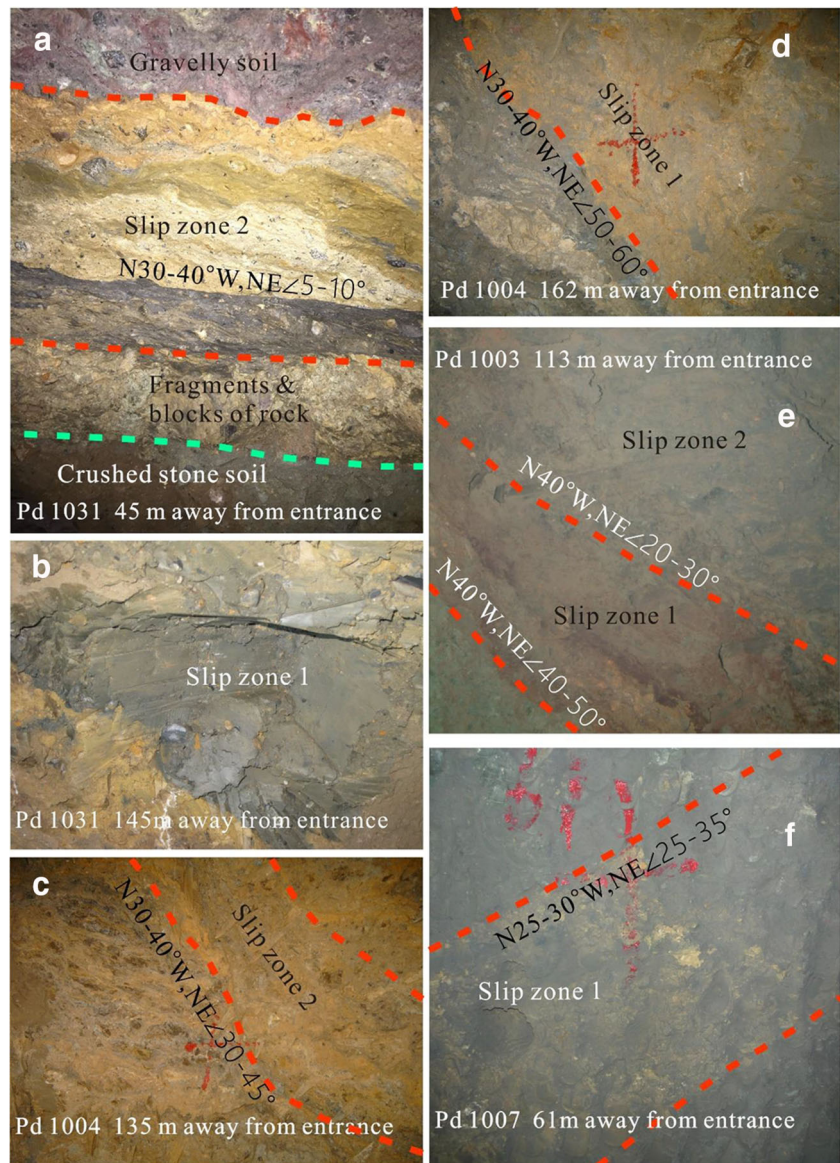

Fig. 6 Mylonitization of the bedrock underlain by the slip zone. **a** Adit Pd1003; **b** Adit Pd1004
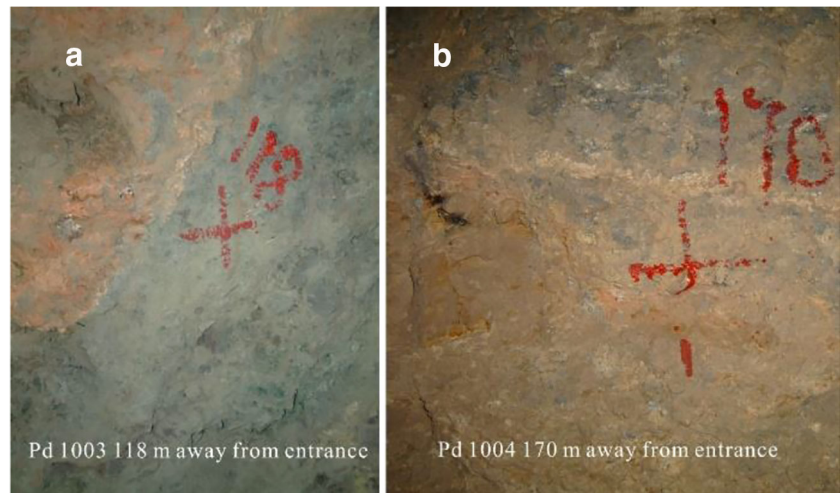
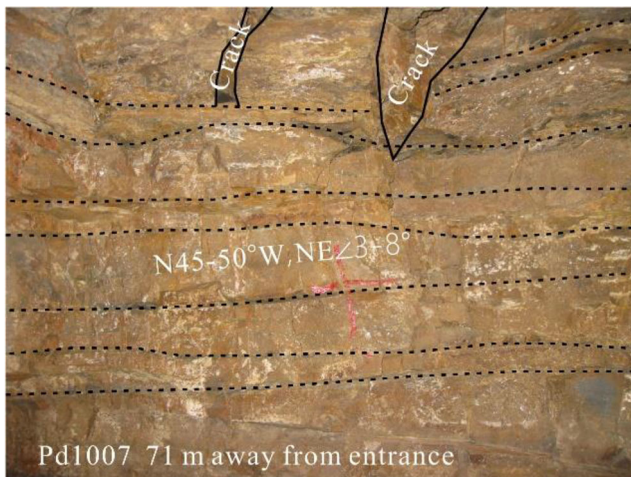Fig. 7 Material composition of the landslide in adits Pd1003 and Pd1007. a Adit Pd1003. b Adit Pd1007
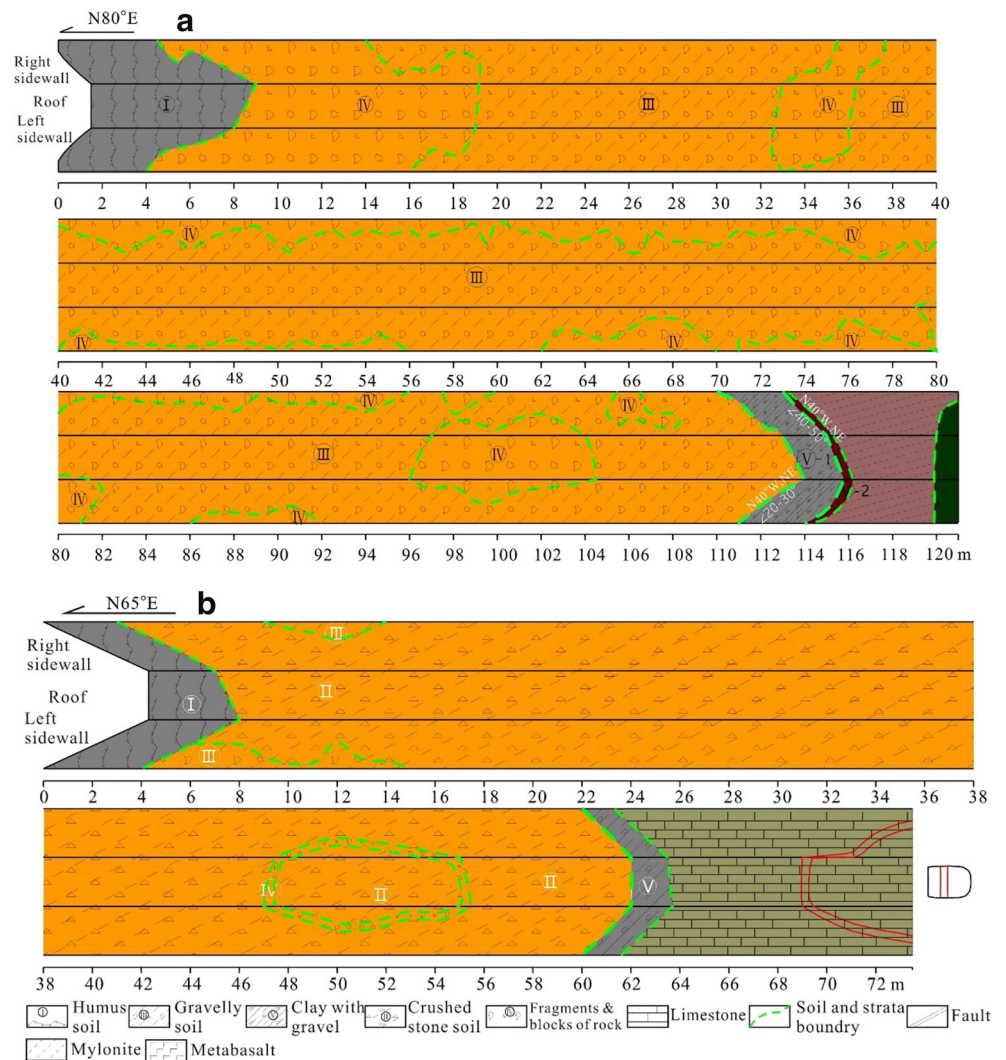

Fig. 8 Strong toppling of the bedrock in adit Pd1007

Moving distance of the landslide

Figures 2 and 3 show that the grayish green metabasalt is distributed mainly at elevations of 2250–2500 m in the studied area. According to the investigations in horizontal adits Pd1004, Pd1003, and Pd1007 (Figs. 4 and 7), many basalt fragments were exposed in adit Pd1004 in the landslide deposit, and few basalt fragments were found in adits Pd1003 and Pd1007 in the landslide deposits. The bedrock exposed in adits Pd1004 and Pd1003 was metabasalt. This indicated that the basalt originally distributed over 2445.86 m had moved to the middle and front part of the landslide along with the slipping of the landslide.

Many grayish-green metabasalt fragments were exposed in the front of the landslide (Fig. 13a, b), where many purplish-red sandy slate fragments were also found (Fig. 13c). According to the distribution of strata in the study area, the grayish-green metabasalt fragments should originate from the third member of the Lower Permian Jidonglong Formation,

Fig. 9 Characteristics of the paleo-river deposits
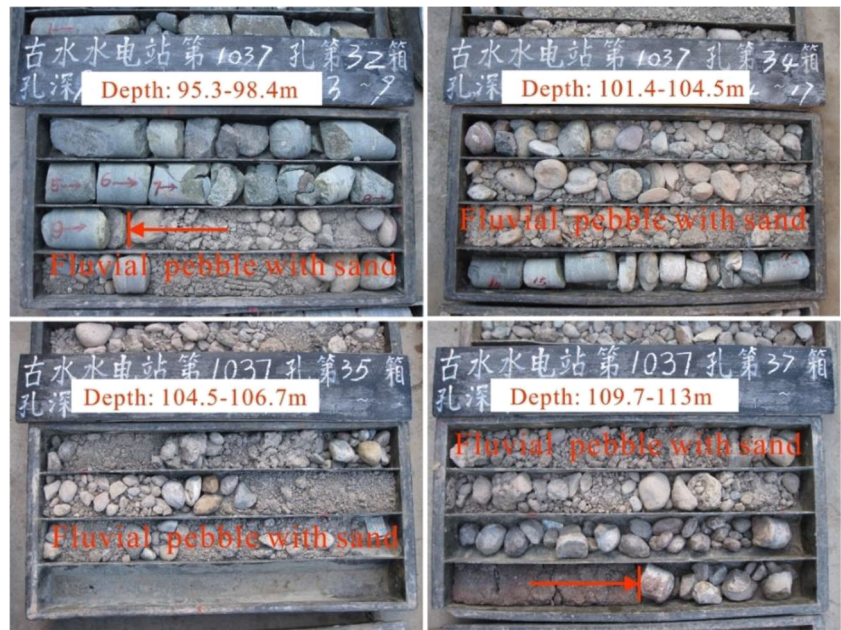
P_1j^3, and the purplish-red sandy slate fragments originated from the fourth member of the Lower Permian Jidonglong Formation, P_1j^4. The strata of P_1j^3 and P_1j^4 should be distributed at elevations of 2250–2500 m and 2500–2550 m,

Fig. 10 Characteristics of the landslide dam sediments. **a** In the front of the landslide; **b** in adit Pd1031

respectively. Thus, we could estimate that the maximum horizontal and vertical moving distances of the landslide were over 1100 m and 450 m, respectively (Figs. 2 and 3).

Formation time of the paleo-landslide dam

The field investigation indicated that the toe of the surface of the landslide rupture was close to the present river level (Figs. 2 and 3) and lower than the elevation of the 1st terrace of the Lancang River. We speculate that the landslide was formed in the Holocene.

The nearest village was built in the early twentieth century. The nearest county, Deqin County, was built in the 1950s. According to the local residents and government archives, the landslide has been there before they lived there. However, an old story was spread from generation to generation among local residents. It said that the Lancang River was ever dammed in the Middle of the Qin Dynasty (1720s–1800s), a large dammed lake was formed upstream, and the flood of the dam breach destroyed several villages downstream. Based on this information, we speculate that the landslide dam was formed 100–500 years ago.

Formation and evolution of the landslide dam

The original attitude of the rock layer is approximately N 30–40° W/NE < 70–80° in the study area (Fig. 14a, b). However, the dip angle of the rock layer ranged from 3 to 25° due to the strong toppling deformation in the shallow and surficial rock masses (Fig. 14c, d).

Figure 8 shows that the rock layer of bedrock of the landslide has an attitude of N 45–50° W/NE < 3–8°, and the dip
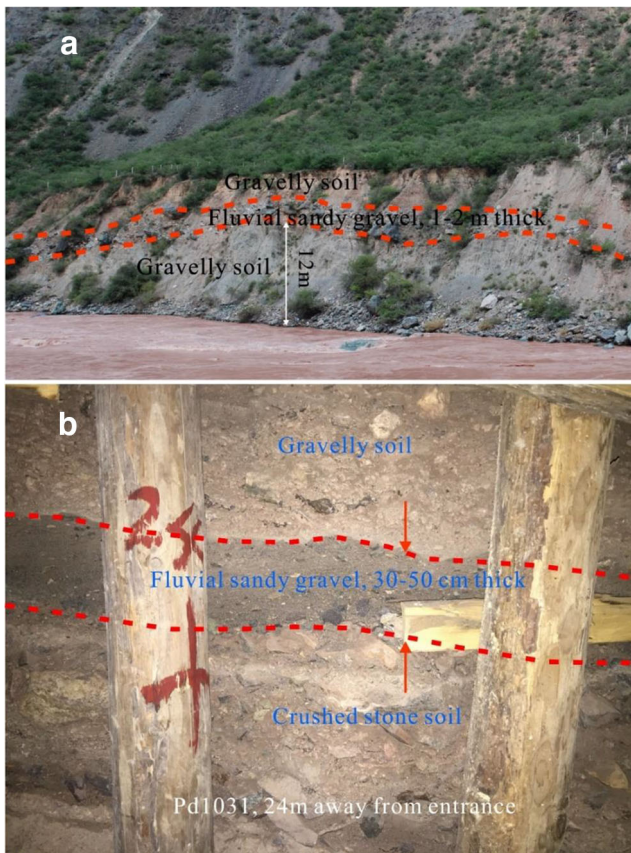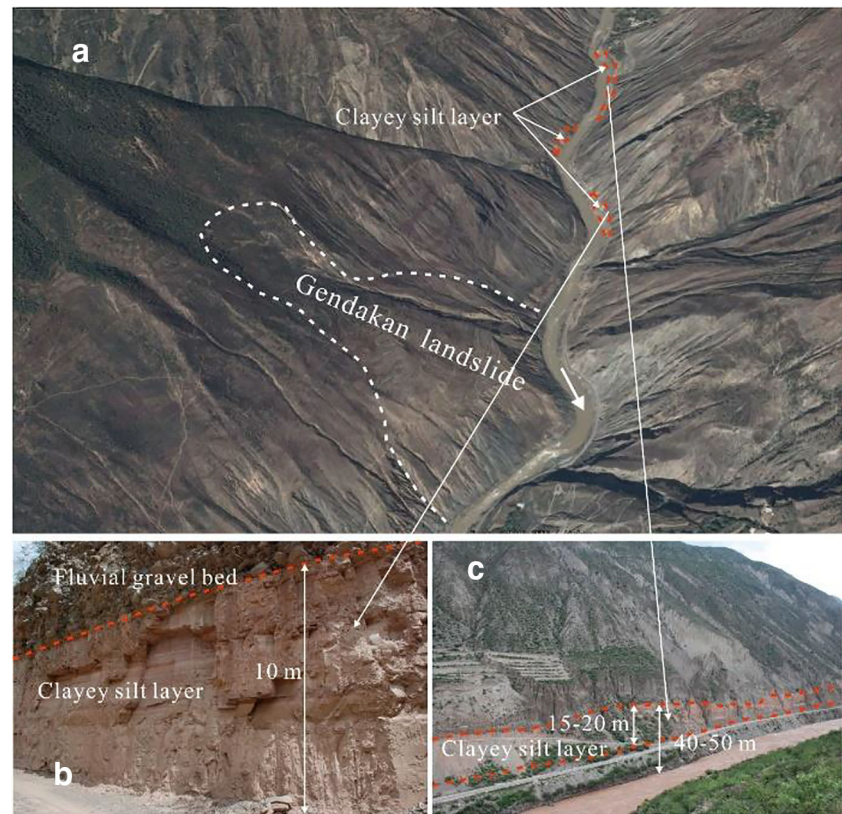
Fig. 11 Clayey silt sediments in the dammed lake. **a** Clayey silt sediments on both banks 1–5 km upstream from the landslide; **b** clayey silt sediments on the left bank 1 km upstream from the landslide; **c** clayey silt sediments on the left bank 3 km upstream from the landslide

angle is far from the initial dip angle of the rock layer. This indicated that the Gendakan landslide was formed based on the strongly toppled rock mass. Another landslide, called the Zengang landslide and located 1.5 km upstream of the Gendakan landslide, was also formed based on the strongly toppled rock mass (Fig. 15). Between the two landslides, a large toppled rock mass, named Yagong toppled rock mass, was developed with a volume exceeding fifty million cubic meters and a maximum depth of over 200 m (Fig. 15).

We investigated the Yagong toppled rock mass. The toppling fracture zones were well developed in the rock mass due to

toppling failure (Fig. 16). These toppling fracture zones consisted mainly of fragments and broken rock mass blocks with lengths of several meters to tens of meters and widths of 10 to 200 cm. Sometimes, the rock mass on both sides of the toppling fracture zone was even sheared and dislocated along the fracture zone with an offset of approximately 5–50 cm (Fig. 16b).

Figure 17 shows the variation in the attitude of the toppling fracture zone, which could be divided into two groups: one had a dip direction of 210–280°, and the other had a dip direction of 40–80°. The latter group, dipping toward the outside of the slope, developed better than the former (Fig. 17a).

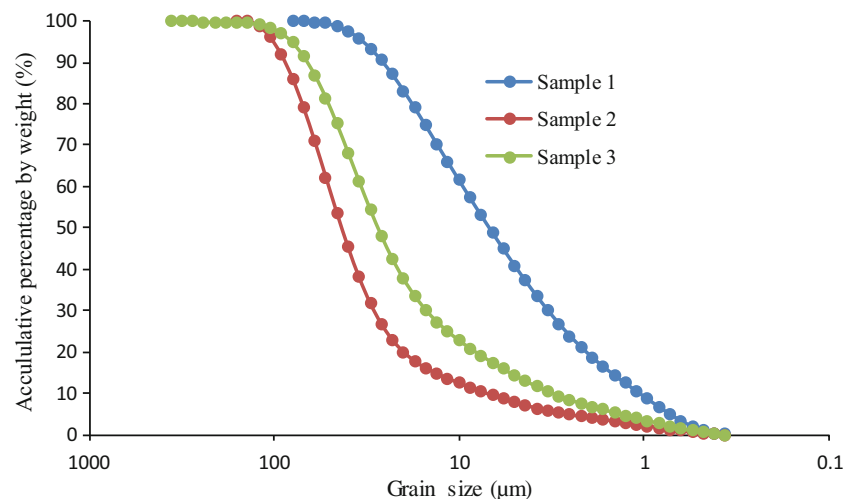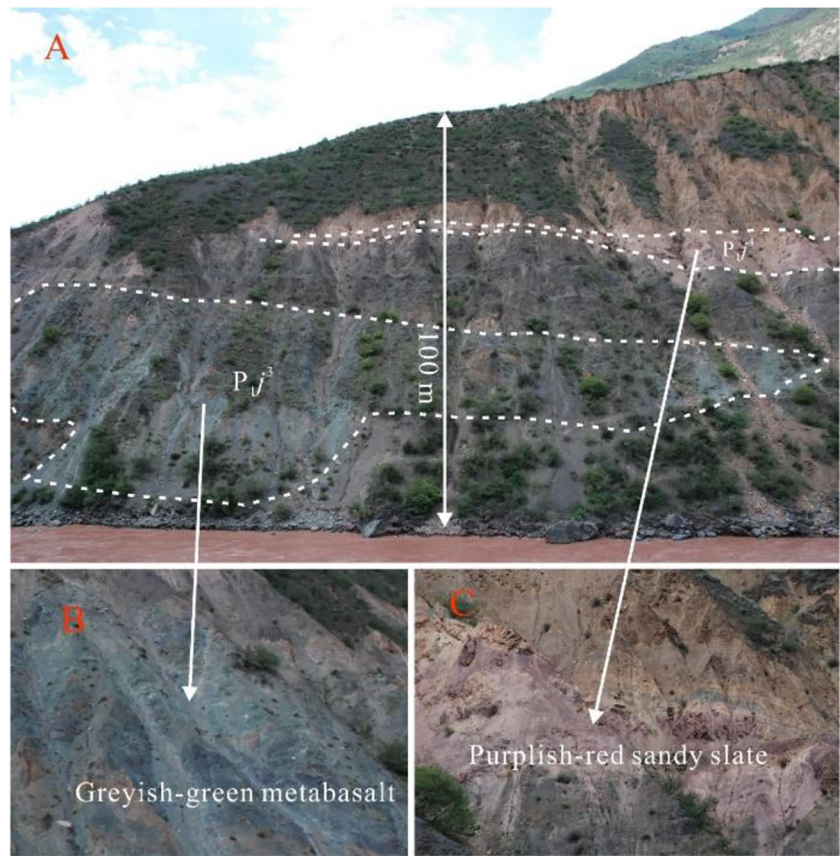**Fig. 12** Grain size distribution of clayey silt soil in the dammed lake

Fig. 13 Deposits in the front part of the landslide. **a** Material composition in the front of the landslide; **b** grayish-green metabasalt fragments exposed in the front of the landslide; **c** purplish-red sandy slate fragments exposed in the front of the landslide

The dip angle of the rock layer varied mainly in the range of 50–85° (Fig. 17b). Most of the toppling fracture zones were developed in the rock mass with a horizontal depth of 0–100 m, and the maximum depth exceeded 160 m.

According to the field investigation, the indicated landslide was formed and evolved based on the deep-seated toppling failure of the rock mass in the study area. The depositional features of the landslide dam and the sedimentary characteristics of the sediments in the dammed lake indicated that the Lancang River had been blocked twice by the landslide. We speculate that the formation and evolution of the landslide dam could be divided into five stages (Fig. 18).

Fig. 14 Attitude of the rock layer in the study area. **a** Right bank 500 m downstream of the landslide; **b** left bank 800 m upstream of the landslide; **c** toe of the landslide; **d** right bank 800 m upstream of the landslide
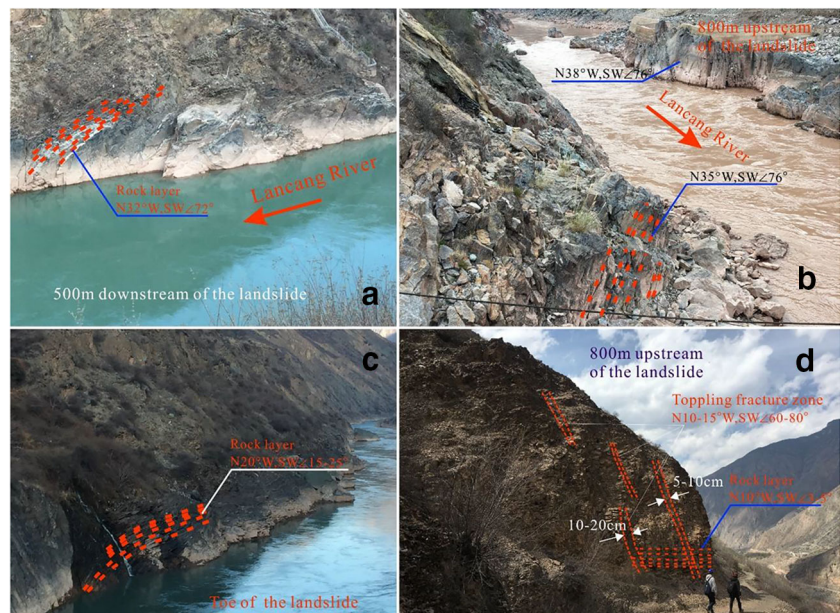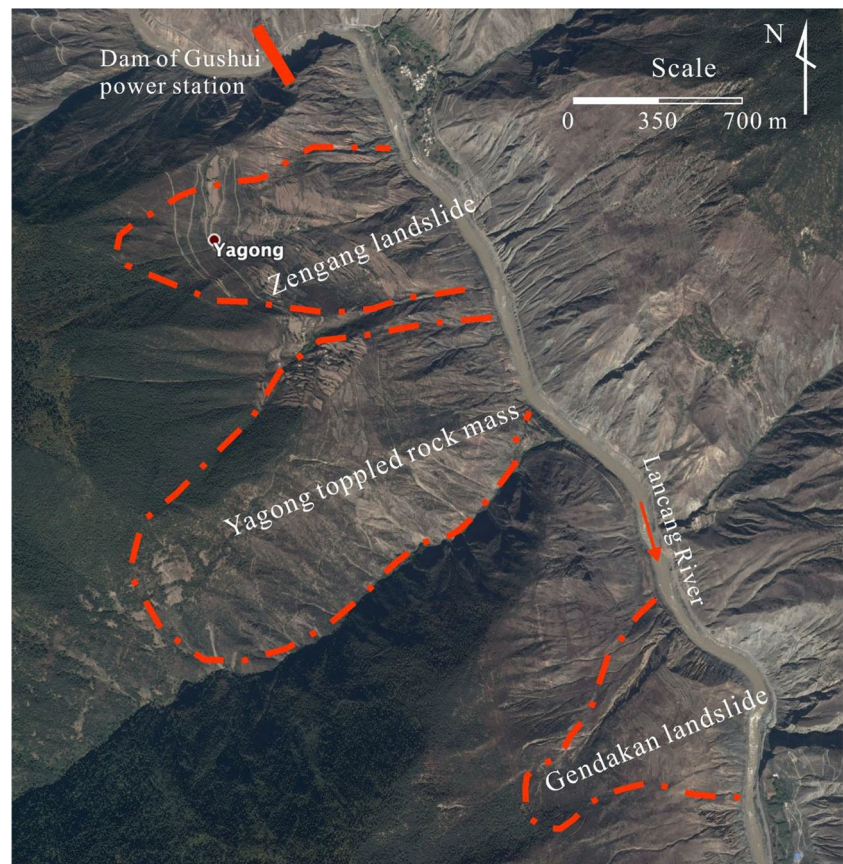
Fig. 15 Location of landslides and toppled rock mass

(1) During the rapid downcutting process of the Lancang River, the steeply dipping layered rock in the right bank toppled intensively and deeply and formed some toppling fractural zones/faces in the rock mass. When those toppling fracture zones/faces were connected and formed a slip zone, the Gendakan landslide occurred (Fig. 18a).

(2) The large landslide with a volume of over 4.7×10^7 m^3 rushed down to the valley. It blocked the Lancang River and formed a landslide dam with a length of over 100 m, a height of over 96.8 m, and a volume of over 2.7×10^6 m^3. The impact force was so large that it caused the rock mass and soil over 100 m in length on the left bank to be involved in the landslide deposits (Fig. 18b). The strong shear force in the slip zone caused the underlying rock mass to be cataclastic and intensively mylonized (Fig. 6). Then, a dammed lake with a depth of over 50 m was formed upstream. The Lancang River might

have been blocked for a long time before breaching the dam. Therefore, a clayey silt layer with a depth of 15–20 m was deposited in the dammed lake (Fig. 11).

(3) A spillway formed on the left side of the dam as the water level of the lake rose continually. Both banks of the spillway were increasingly downcut more steeply by the erosion of the spilled water. Then, a new slip zone formed in the landslide deposits (Fig. 18c).

(4) A new landslide occurred at the same location, and the spillway was blocked by the new landslide (Fig. 18d). The fluvial gravel deposited in the spillway was buried by the new landslide deposits (Fig. 10).

(5) A new spillway was formed on the left side of the landslide dam as the water level rose continually (Fig. 18e). Then, the Lancang River course was formed convex to the left bank by the erosion of spilled water, as shown in Fig. 2.

Fig. 16 Toppling fracture zone in the rock mass. **a** Rock mass with an elevation of 2160 m; **b** rock mass with an elevation of 2806 m
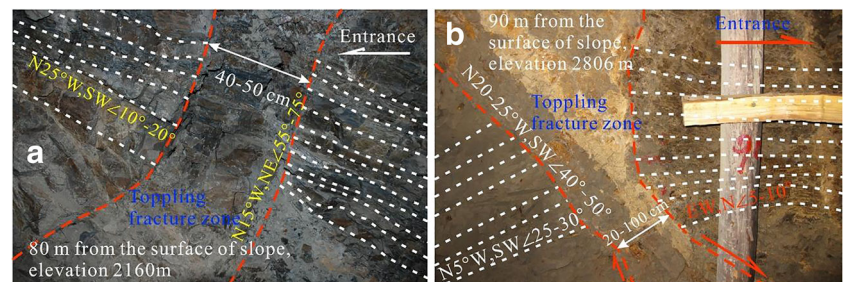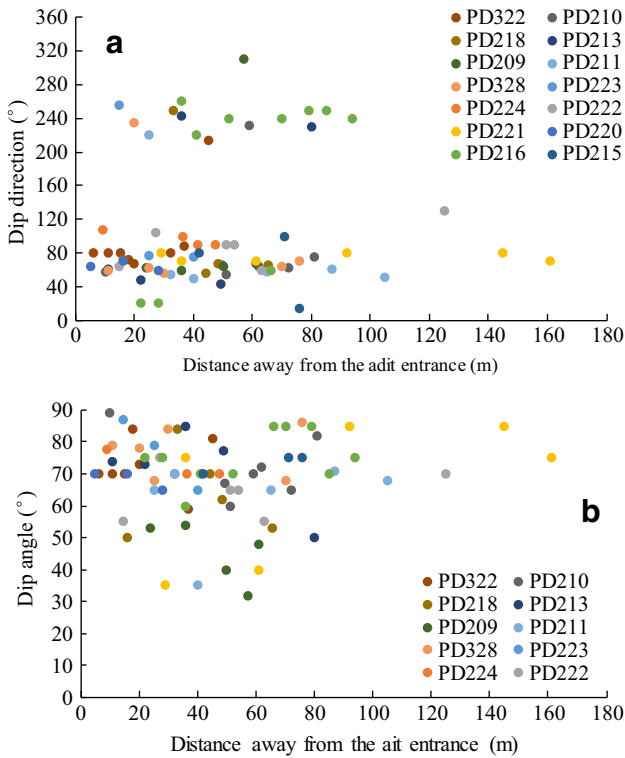
Fig. 17 Attitude of the toppling fracture zone in the rock mass. **a** Dip direction; **b** dip angle

Discussion of the results

Our investigation suggested that the landslide was initiated from the deep-seated toppling failure of the rock mass on the right bank of the Lancang River. There is another landslide, named the Zengang landslide, upstream of this landslide, which was also formed based on the intensively toppled rock mass. The rock mass on the right bank of the Lancang River in the study area toppled intensively and formed a large toppled rock mass between these two landslides, which was named the Yagong toppled rock mass.

As a common instability phenomenon, toppling failure has been studied by numerous researchers (Bukovansky et al. 1976; Goodman and Bray 1976; Wyllie 1980; Ishida et al. 1987; Li et al. 2015; Smith 2015). Previous investigation results inferred that the maximum thickness of toppling failure was less than 100 m (Zhang et al. 1994; Deng et al. 2000; Zhang et al. 2015; Gu and Huang 2016; Liu et al. 2016). In the study area, the toppled rock mass has a depth exceeding 200 m, and the maximum horizontal extent of the landslide formed based on the toppled rock mass is larger than 150 m. The mechanism of the deep-seated toppling failure of the rock mass and its evolution into landslides must be further investigated.

The toppling failure is the result of the rock mass under gravity during the erosion of the Lancang River. Hence, the formation of the Gendakan landslide should have experienced a long geological period. During this period, the rapid and continuous downcutting of the Lancang River should play a key factor in the formation of deep-seated toppling failure of rock masses and landslides.

According to Wang's (Wang et al. 1999, 2000a, b) study results, the Lancang River has downcut over 600 m with an average rate of 1–3 mm/a since the Quaternary period. We speculate on the mechanism of deep-seated toppling failure, formation of the landslide and the evolution of the landslide dam as follows: The rapid and continuous downcutting of the river induced the steeply dipping layered rock mass of the slope to topple intensively and form some toppling fracture zones/faces in the rock mass. When the toppling fracture zones/faces were connected by some triggering factors, a slip zone was formed, and the landslide occurred. Then, the landslide blocked the Lancang River, forming a large dammed lake upstream, and the clayey silt sediments with a thickness of 15–20 m were deposited in the lake. The breach of the landslide dam might occur over a relatively long time, which caused the fluvial gravel layer deposited in the spillway. The

Fig. 18 Formation and evolution of the landslide dam. **a** Toppling failure of rock mass; **b** the first blocking of river by the landslide; **c** the first breach of the landslide dam; **d** the second blocking of river by the landslide; **e** the second breach of the landslide dam
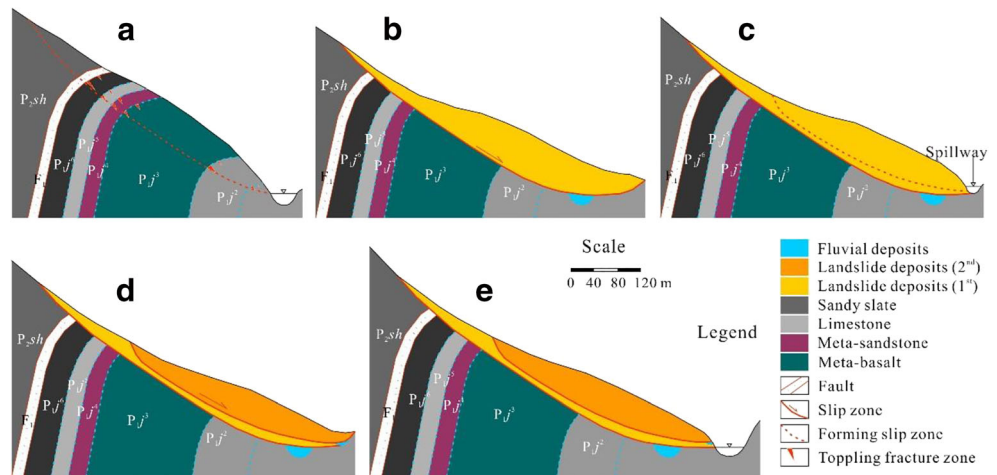
strong and continuous erosion of the spilled water caused the front side of the landslide deposits to become increasingly steeper. Then, the residual landslide deposits failed and blocked the river again.

The Yagong toppled rock mass, which was located 800 m upstream of the Gendakan landslide, has similar topographical, geological, and stratigraphic conditions to those of this landslide (Fig. 15). The rock mass toppled intensively with a depth exceeding 200 m and formed many toppling fracture zones in the rock mass (Fig. 17). It has a probability of evolving into a large landslide and blocking the Lancang River during further river erosion. That should be studied further in the future.

The residual deposits of the Gendakan landslide still have a large volume of 4.7×10^7 m^3 and are distributed at a relatively high elevation in the river valley. The landslide has a probability of reactivating and blocking the Lancang River again due to further river erosion and rainstorms in the future. That needs to be studied further.

Conclusions

An old landslide dam, which was located in Yunnan Province, Southwest China, was used as a case to study the landslide formation and evolution by the erosion of the Lancang River. In particular, we investigated the engineering-geological characteristics of the landslide, features of the landslide dam, and depositional characteristics of sediments in the dammed lake.

The rapid and continuous downcutting of the Lancang River induced the steeply dipping layered rock mass to topple intensively and form multiple toppling fracture zones in the rock mass. The Gendakan landslide formed and blocked the Lancang River when the toppling fracture zones were connected to form a slip zone in the rock mass. The Lancang River was blocked twice in history by the landslide causing the Paleo-river course offset over 150 m to the left bank, and forming a landslide dam with a length of over 162 m, a height of over 96.8 m, and a volume of over 2.7×10^6 m^3. A clayey silt layer with a thickness of 15–20 m was deposited in the dammed lake.

The Yagong intensively toppled rock mass, which was located 800 m upstream of the Gendakan landslide, has topographical, geological, and stratigraphic conditions similar to those of the studied landslide. It has a probability of evolving into a large landslide and blocking the Lancang River during the further river erosion. The residual landslide deposits still have a large volume and are distributed at a relatively high elevation in the river valley. The landslide has a probability of reactivating and blocking the Lancang River again due to further river erosion and rainstorms in the future.

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