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The Hejiapingzi landslide in Weining County, Guizhou Province, Southwest China: a recent slow-moving landslide triggered by reservoir drawdown

Abstract The Hejiapingzi landslide is a slow-moving landslide along the shore of the reservoir created by the Xiangbiling hydro-power dam in Weining County, Guizhou Province, Southwest China. Movement caused cracks in the land surface and residential buildings of Heping village on 20 August 2017 and was triggered after an 8-day continuous drawdown of the reservoir water by 2.2 m. Field investigations and borehole and landslide surface monitoring were carried out to determine the landslide features and deformation characteristics. Based on analysis of the monitoring data, the behavior of the landslide was neither spatially nor temporally uniform. In general, it could not move quickly due to the gentle sliding surface. The possible reasons for landslide occurrence were the drawdown of the reservoir water, the increase in seepage force, and the loss of strength in a soft mudstone layer to form the landslide slip surface. Although mitigation measures, including engineering control or resident relocation to a safe place, have not yet been finally determined, some interim measures including covering landslide cracks, subsurface monitoring, decreasing the reservoir drawdown velocity, and setting velocity thresholds of landslide displacement for warnings are advised to reduce the landslide risk caused by planned reservoir drawdown in 2019.

Keywords Reservoir landslide · Southwest China · Triggering factor · Failure mechanism · Landslide mitigation

Introduction

The Hejiapingzi landslide is a large but slow-moving landslide adjacent to the reservoir of the Xiangbiling hydropower dam in Weining County, Guizhou Province, Southwest China (Fig. 1a, b). The Xiangbiling Hydropower Station is located on the middle-lower Niulan River and has a roller-compacted concrete double-curvature arch dam that spans the river. The dam contains 2.63 million m³ of concrete and has a maximum height of 141.5 m. It is a major project in the county and provides support to the local economy.

The first impoundment of the reservoir started in June 2017. The reservoir has a design normal water level of 1405 m, and reservoir levels have fluctuated from 1405 to 1370 m during the operational phase. Seven landslides along the reservoir shores were identified through field investigation and they were triggered by the reservoir. One of the most hazardous of these landslides is the Hejiapingzi landslide (Fig. 2). The Hejiapingzi landslide is on the left bank of Yulong River, a tributary of Niulan River that was flooded and became part of the reservoir. The landslide is about 4.7 km from the hydropower dam and was triggered by the drawdown of the reservoir.

The Hejiapingzi landslide has an estimated volume of 13×10^6 m³ and underlies most of a residential area—Heping

village. On 20 August 2017, local people reported cracks in the village land surface and residential buildings to workers at the Xiangbiling Hydroelectric Power Plant, but the exact time when the landslide occurred was not known. The residents did not flee the village because the landslide was extremely slow-moving. The 552 residents of Heping village were later asked to stay in temporary shelters in 2018, because the government worried that drawdown of the reservoir might cause further landslide movement.

In order to reduce the landslide risk, field investigations, borehole investigations, and surface monitoring have been carried out since October 2017. This paper presents the features of the Hejiapingzi landslide and its deformation characteristics, based on the investigation and monitoring data. A preliminary analysis of triggering factors and landslide mechanisms was carried out. Landslide mitigation measures are also discussed because investigations show the landslide is deeply seated and has a great volume.

Study area

Weining County is located in western Guizhou Province (Fig. 1a). It covers an area of about 6296 km² and has a population of 1.28 million (Bijie Municipal Bureau of Statistics 2017). The area is in a subtropical monsoon climate zone with four distinctive seasons. The average annual temperature varies from 10 to 12 °C, and temperature extremes range from −15.3 to 32.3 °C. Mean annual precipitation totals 950.9 mm, most of which falls in the summer, from May to September. It is located on the Yunnan-Guizhou Plateau, and its topography includes mountains, plateaus, and hills. The terrain decreases from the central area to the surrounding county borders (Fig. 1b). The average elevation of the county is 2200 m. On the basis of a landslide inventory at a regional scale, there are 153 landslides in the county, mainly slides and rock falls. The main triggers of landslides include excessive rainfall and human engineering activity, such as dam construction and mining. Data analysis indicates the Hejiapingzi landslide was caused by the drawdown of the Xiangbiling reservoir, changing the hydrological conditions of the landslide.

Landslide features

The Hejiapingzi landslide covers an area of 0.28 km² and has an estimated volume of 13×10^6 m³. The landslide is wide, with a maximum width of 650 m and a longitudinal length of 445 m, and a maximum thickness of 80 m. The right and left boundaries are defined by two large gullies (NO.1 Gully and NO.2 Gully), as shown in Fig. 3. The rear of the landslide is delineated by visible tension cracks. The landslide toe is below the surface of the reservoir along the Yulong River. Based on topography, the landslide can be divided into three sub-zones: a steep rear region (I), a flat platform region (II), and a toe region (III) (Fig. 4).

Recent Landslides

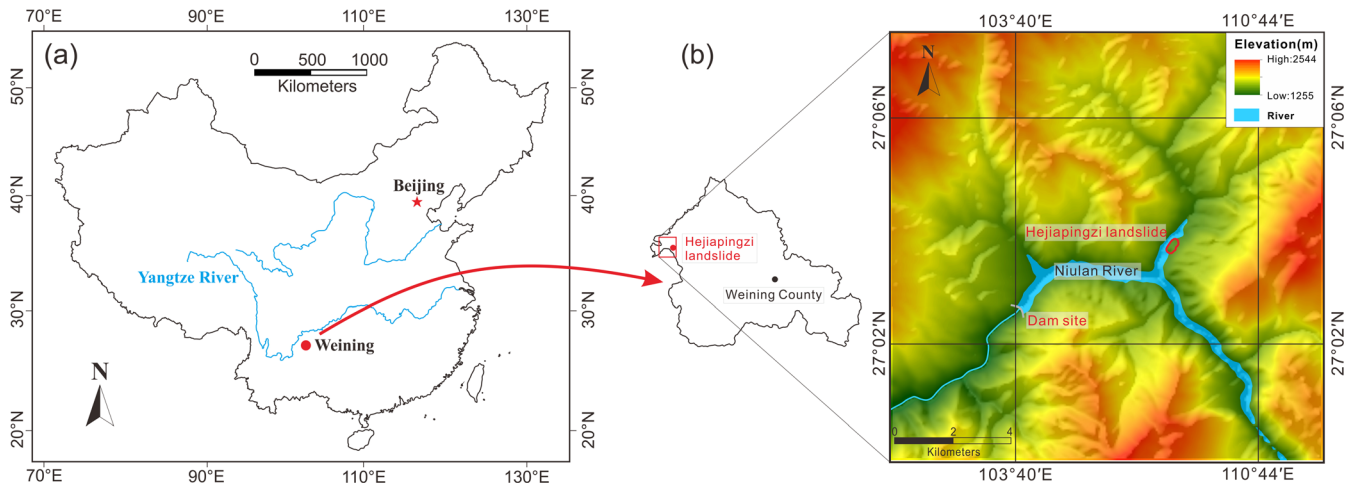


Fig. 1 (a) Location of Weining County, China. (b) Location of Hejiapingzi landslide in Weining County. The digital elevation model is derived from 1:10,000 cartography contour lines and is based on China's National Geodetic Coordinate System 1980

- (1) **Region I:** The rear region is a steep slope of 40 to 60° and it is characterized by gravel soil. The elevation of the rear boundary varies between 1508 and 1550 m.
- (2) **Region II:** A flat platform is located in the middle of the landslide and it has a length of 650 m roughly aligned with the Yulong River and a width of 180 to 220 m. The topography of the platform near Yulong River is a raised, with its highest elevation at 1452 m. The elevation of the platform near NO.1 Gully ranges from 1400 to 1420 m and the elevation near NO.2 Gully ranges from 1430 to 1440 m. The platform slopes in a north-east direction in general. The soil on the surface is characterized by clay with gravel. Most of the Heping village houses are concentrated here.
- (3) **Region III:** The landslide toe was approximately 14 to 17 m below the water level of 1370 m. There is a road along the landslide front which ranges in elevation from 1360 to 1411 m. The slope of the Yulong River bank below the road ranges from 50 to 70°. The slope above the road near the NO.1 Gully ranges from 10 to 25°, and near the NO.2 Gully ranges from 30 to 50°. Most of the surface is covered by gravel soil.

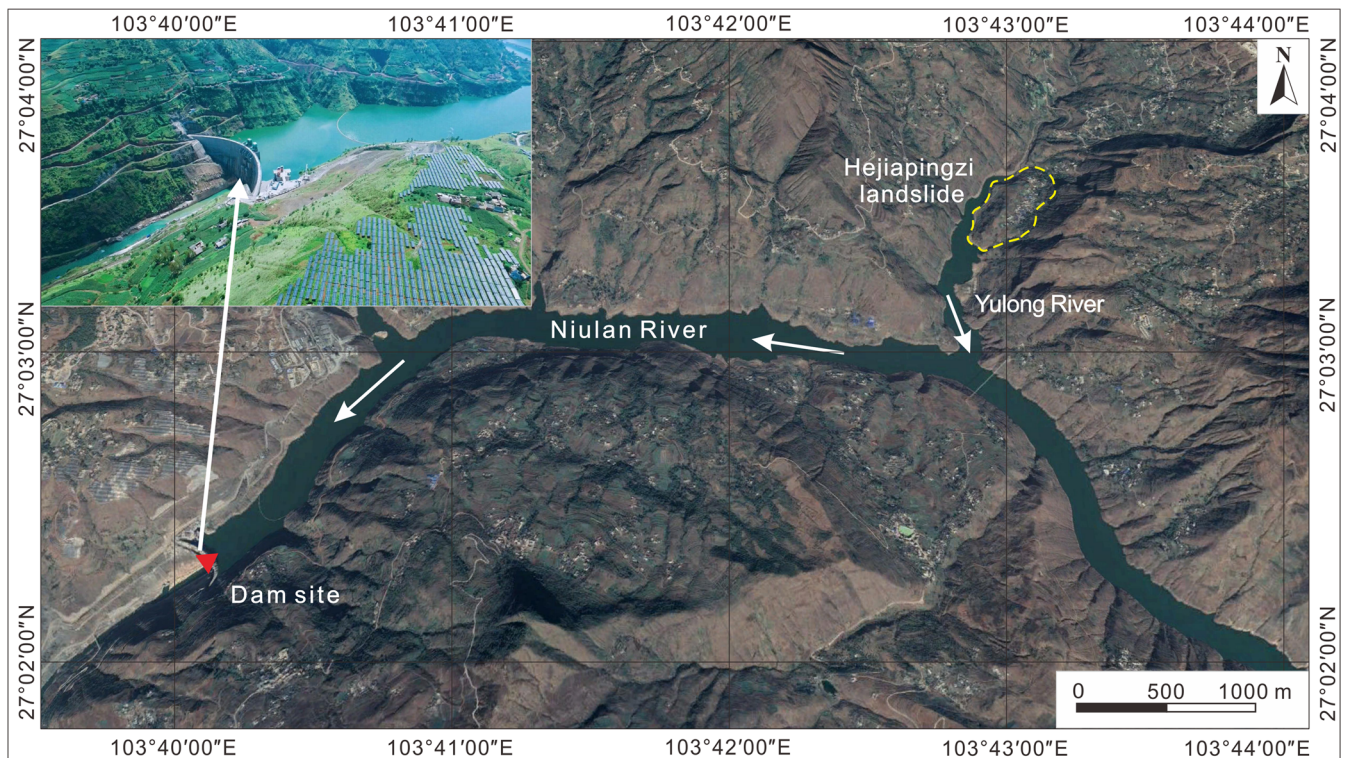


Fig. 2 Topographic features of the study area and location of the landslide site (from Google Earth, 2018)

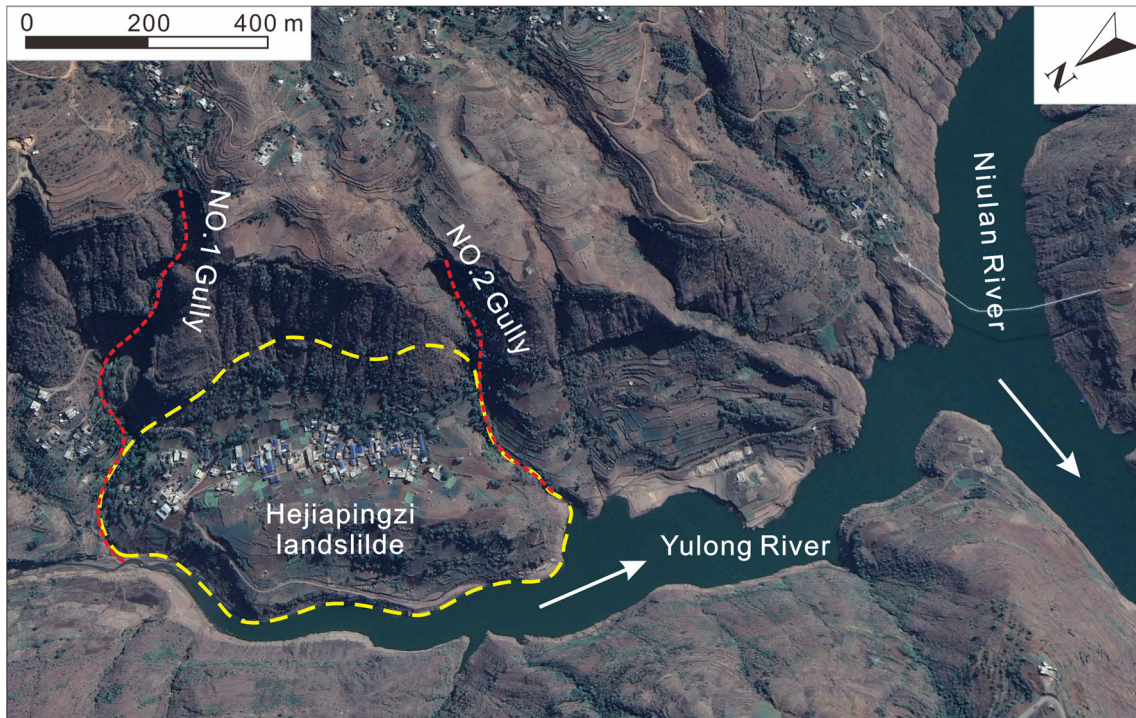


Fig. 3 Overall view of the landslide (from Google Earth, 2018)

The geological structure of the landslide has been obtained from borehole and field surveys. The borehole locations are shown in Fig. 5. From a geomorphological point of view, the landslide is of a translational and rotational type. The longitudinal profile shows a steeper upper slope and gentler lower slope increasing in thickness toward the toe. The bedrock is mainly basalt, which is overlain by a thinner layer of tuffaceous mudstone. The bedrock is overlain by

Quaternary deposits. The mobilized material was composed of Quaternary deposits over tuffaceous mudstone with a lower shear strength. Figures 6, 7, and 8 show the landslide structure and the distribution of landslide material. The groundwater level in the landslide body was observed during the drilling boreholes. The dashed blue line of groundwater level was estimated based on the measured data during the drilling investigation. From the top to the

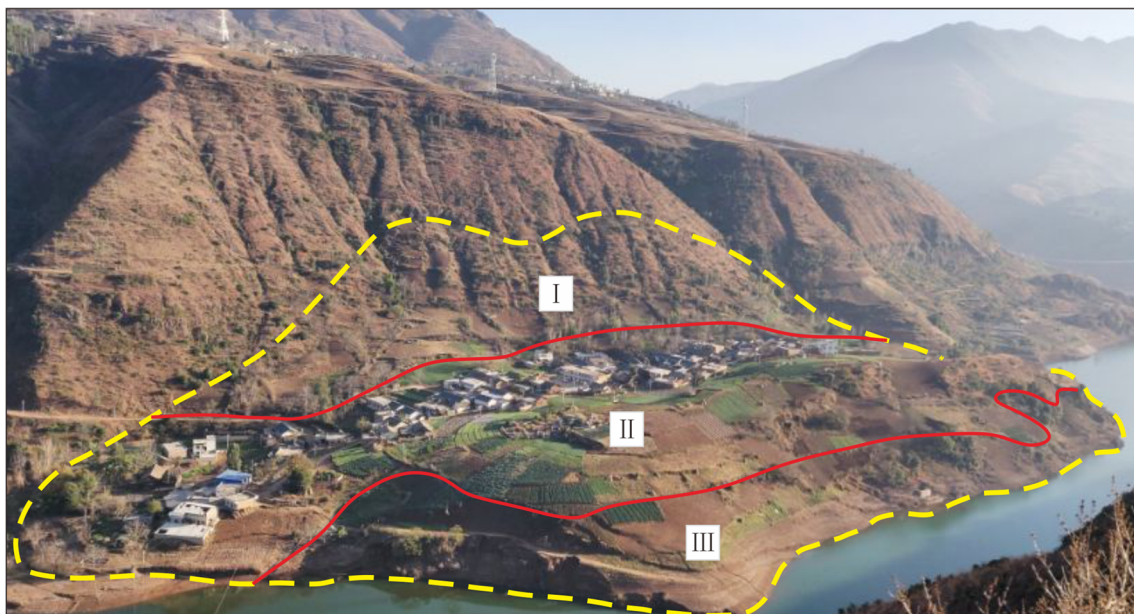


Fig. 4 Photo of the landslide, showing three sub-regions based on their varying terrain

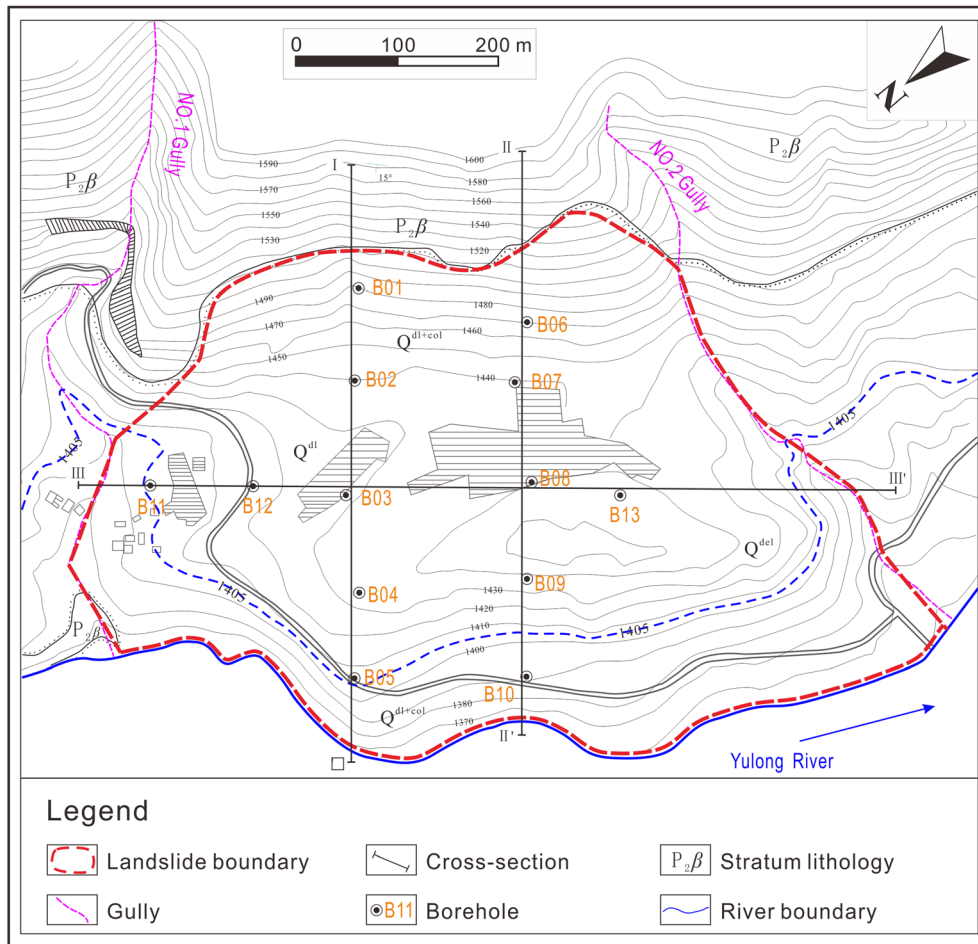


Fig. 5 Geomorphological map of the landslide, showing the locations of the cross sections and the boreholes. $P_2\beta$ is the Emeishan basalt of the Permian system, Q^{dl} is a Quaternary diluvial deposit, Q^{dl+col} is a Quaternary diluvial and colluvial deposit, Q^{col} is a Quaternary colluvial deposit, Q^{el} is a Quaternary eluvial deposit, and Q^{del} is the landslide deposit

bottom, the landslide profile includes the following: (1) yellow and brown clay with 10–30% gravel, consisting of basalt, 2–50 m thick; (2) yellow gravel soil with 20–30% clay, 0–30 m thick; (3) brown gravel soil with some boulders, 18–40 m thick in general; (4) fractured rock from an old rock slide, 30–50 m thick in general, but locally up to 80 m thick, occurring mainly near NO.2 Gully; (5) purple-red clay from weathered mudstone, located on the top of tuffaceous mudstone, 0–2 m thick. The sliding zone is in the weathered mudstone layer. It is shown in the dashed line due to the thinner thickness. The shear strength parameters of potential slide zone soil were measured by direct shear test. The cohesion and friction angle of saturated sample were 8.9–13.8 kPa and 5.4–7.6° respectively. The typical landslide structure, including clay, gravel soil, mudstone, and basalt, illustrated by Borehole B04, is shown in detail in Fig. 9, which also shows the core samples of gravel soil, purple-red clay, and mudstone.

There may be two kinds of landslide soils located in the contact zone between the Quaternary deposits and the bedrock: (1) gravel soil with clay—an unsaturated soil, which is located in the rear region with a steep slope of 40 to 60°; (2) purple-red clay located mainly in regions II and III—its slope of 2 to 8° is very gentle and would have been saturated after the reservoir impoundment.

Landslide deformation characteristics

Field investigation on 20 August 2017 revealed more than 20 ground cracks with slow growth along the length of the landslide surface and several local failures in the landslide front, as shown in Fig. 10. Four tension cracks occurred at the top of I region at approximate elevations of 1490 m and 1510 m. These cracks were about 12–208 m long and had a maximum width of 0.44 m. The majority of the landslide cracks were mainly distributed on the platform of the II region and their extension direction was parallel to the direction of the river valley. These cracks have a length of 21–140 m and a width of 0.02–0.1 m, and they caused damage to several houses. The mainly local failure near NO.1 Gully covers an area of $1.8 \times 10^4 \text{ m}^2$ and is toe-erosion collapse along the river bank. It occurred on about 20 August 2017, following the draw-down of the reservoir water level, and caused damage to the village road.

To understand the landslide deformation characteristics and their evolution with time, landslide monitoring has been carried out since 28 October 2017. Surface deformation at the landslide site was monitored using a total station and simple crack measurements. Figure 11 shows the locations of the monitoring points. A total of 10 crack monitoring points and 12 survey points using a

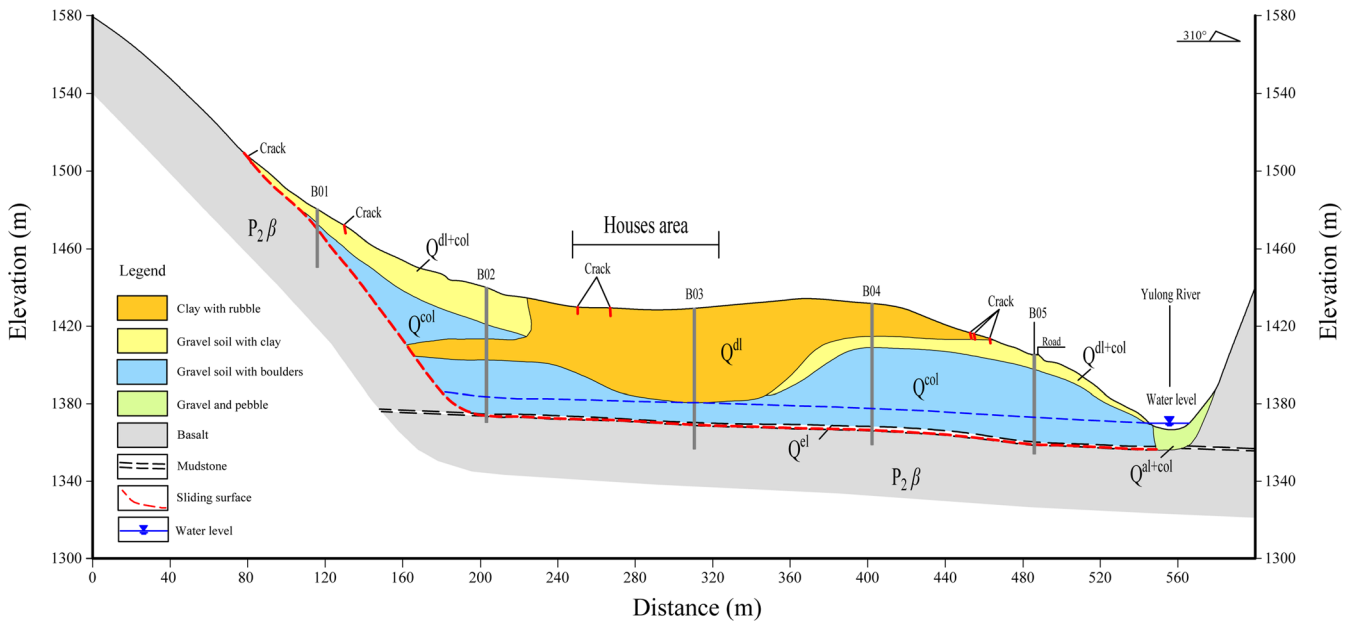


Fig. 6 Geological longitudinal section of the landslide (I–I') (see Fig. 5)

total station were progressively positioned for landslide monitoring. Simple crack monitoring points were installed to measure changes in the width of surface cracks since 28 October 2017. Monitoring points using a total station have been installed since 24 June 2018. The monitoring points were measured every 1 day or 4 days, depending on the landslide deformation situation.

Figures 12 and 13 show the evolution over time of cumulative changes in crack width based on the simple crack measurements. Total station monitoring points To2, To8, and T12 could not be observed, because trees hid the monitoring points from view, so there is no observed data for these three points. Cumulative

displacements of To3 and To6 beyond the landslide boundary were respectively 5.1 mm and 3.3 mm. Figure 14 shows the cumulative displacement versus time data for other total station points. Based on the observed results, the main features are as follow:

1. The deformation varied spatially. The maximum crack width change of J11 was 44.15 cm. The maximum crack deformation observed created a long continuous crack of the boundary at the rear of the landslide—it was 208 m long. The change in crack width was larger than the changes at other monitoring points of 2.26 to 10.17 cm in the platform. This indicated that the deformation in the rear region was greater than that in the

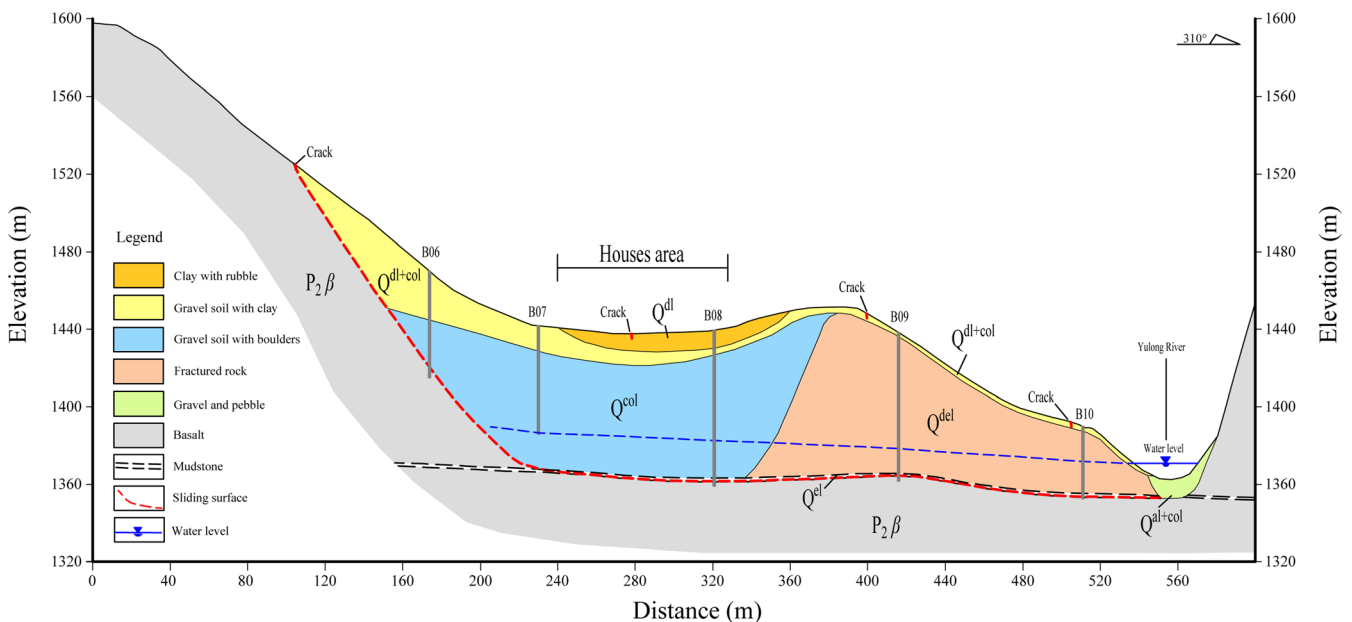


Fig. 7 Geological longitudinal section of the landslide (II–II') (see Fig. 5)

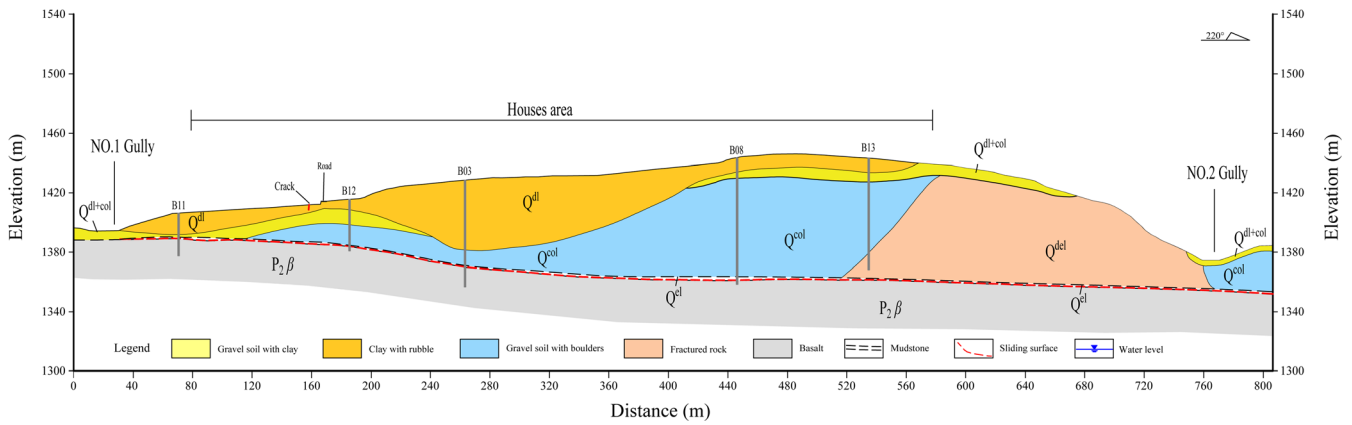


Fig. 8 Geological longitudinal section of the landslide (III-III') (see Fig. 5)

flat platform. In addition, the cumulative displacements of To1 and To4 were respectively 335.7 mm and 332.3 mm. The cumulative displacement of other total stations was smaller than 205.1 mm. This shows that the landslide toe near NO.1 Gully moved quickly by comparison.

2. The deformation fluctuated with time and reservoir level changes. The monitoring data shows that the landslide was stable from December 2017 to July 2018. The rate of crack width change registered 0-0.08 mm/day in this period, but increased to 6.1-16.2 mm/day from mid-August to mid-

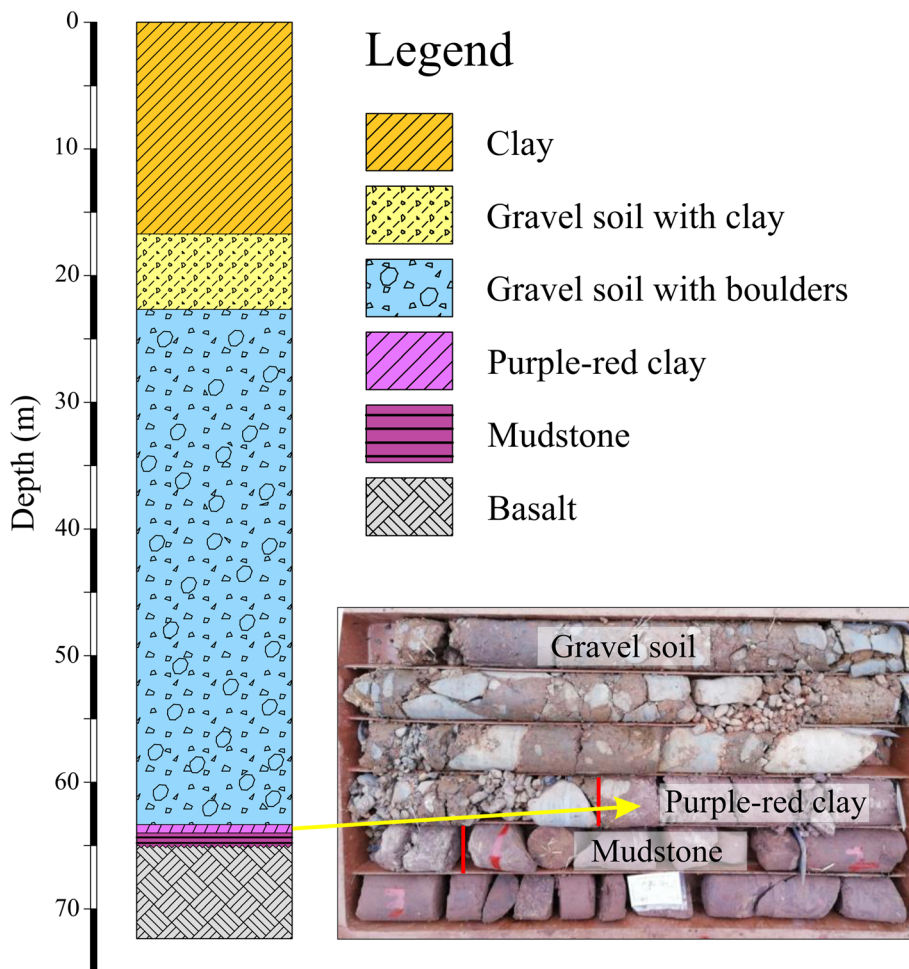


Fig. 9 Borehole log of B04 and a photo of the core samples showing the potential sliding soil

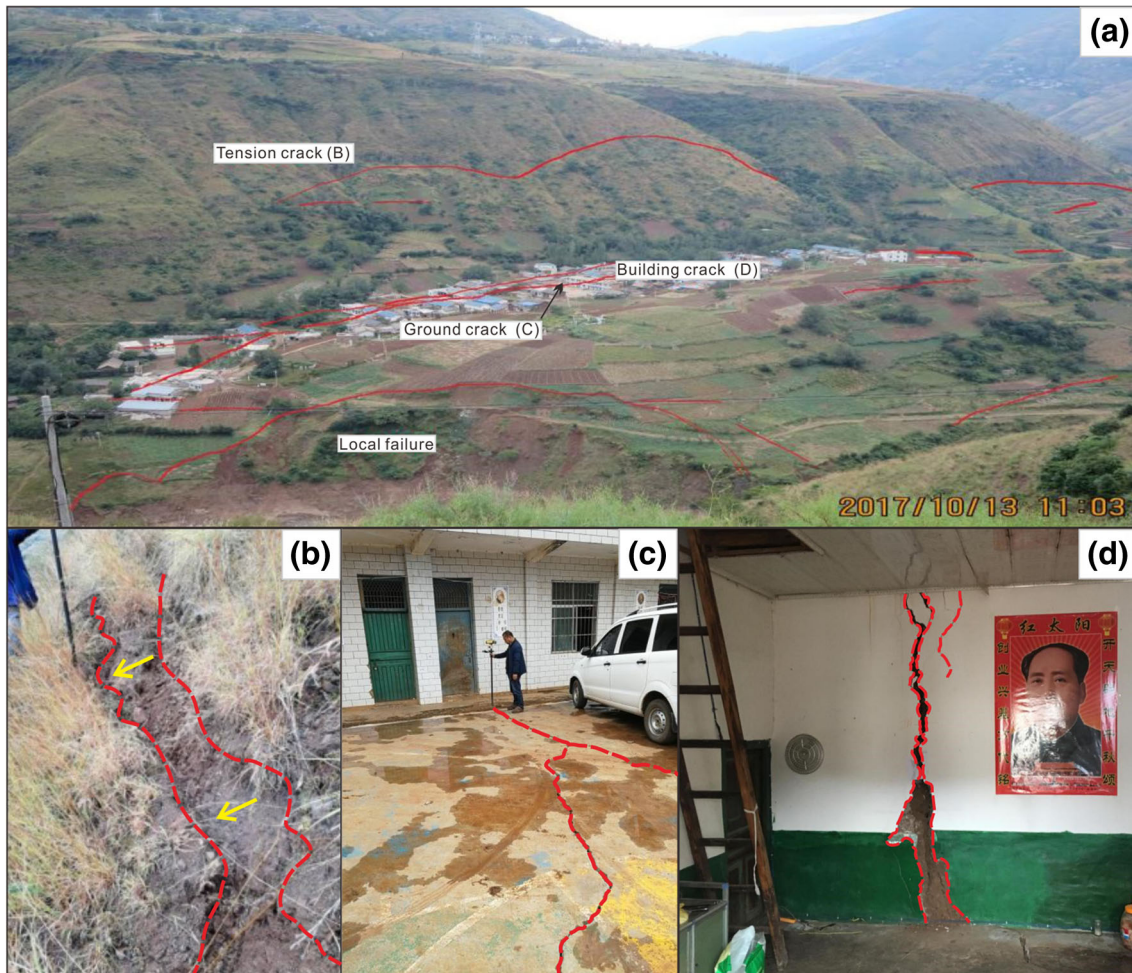


Fig. 10 Characteristics of landslide cracks: (A) distribution of landslide cracks; (B) tension crack in the rear region; (C) damage to a paved area in the platform region; (D) damage to a house interior in the platform region

November of 2018. The same phenomena occurred in the monitoring results for the total station. The landslide decreased or became stable when the reservoir water level was raised from June to mid-August 2018. During the drawdown period from mid-October to mid-November 2018, however, the displacement occurred at a rate of 12.3–21.8 mm/day and the landslide became very active. The displacement curve shows power law acceleration phases during the drawdown period. The temporal variability is shown by the increase in the slope of the displacement curves corresponding to this period.>

Triggering factors and failure mechanisms

Field investigation and monitoring data analysis was carried out after the landslide occurrence to determine the landslide mechanism and the causes. At the village of He Hejiapingzi, the water supply was derived from springs on the rear region where emerges from several fissures in the rock. There was no drainage system or surface water within the settlement area. Therefore, the domestic use of water did not influence the landslide stability. The likely cause of the landslide was a combination of the drawdown of the reservoir water level, the

increase in seepage force, and the existence of a soft mudstone layer in the basement rock that formed the sliding surface.

Rainfall

The nearest rain gauge to the landslide is at the dam site and rainfall data from that station was used. Figure 15 shows the daily rainfall from May 2017 to November 2018 and the cumulative change in crack width from October 2017 to November 2018. Although the cumulative 2-day rainfall totaled 46 mm from 14 August to 15 August 2017, there was no rainfall from 16 August to 20 August 2017. There was thus a period of about 5 days without rainfall prior to the landslide occurrence. From 29 July to 5 August 2018, it rained every day and the cumulative 8-day rainfall totaled 111 mm. However, the crack width at the J3 monitoring point increased by just 0.2 mm during this period. Based on the field investigation and the analysis of monitoring data, there was no obvious evidence that the landslide was triggered by rainfall.

Reservoir water level

In order to explore the influence of reservoir water level on landslide displacement, the relationship between landslide

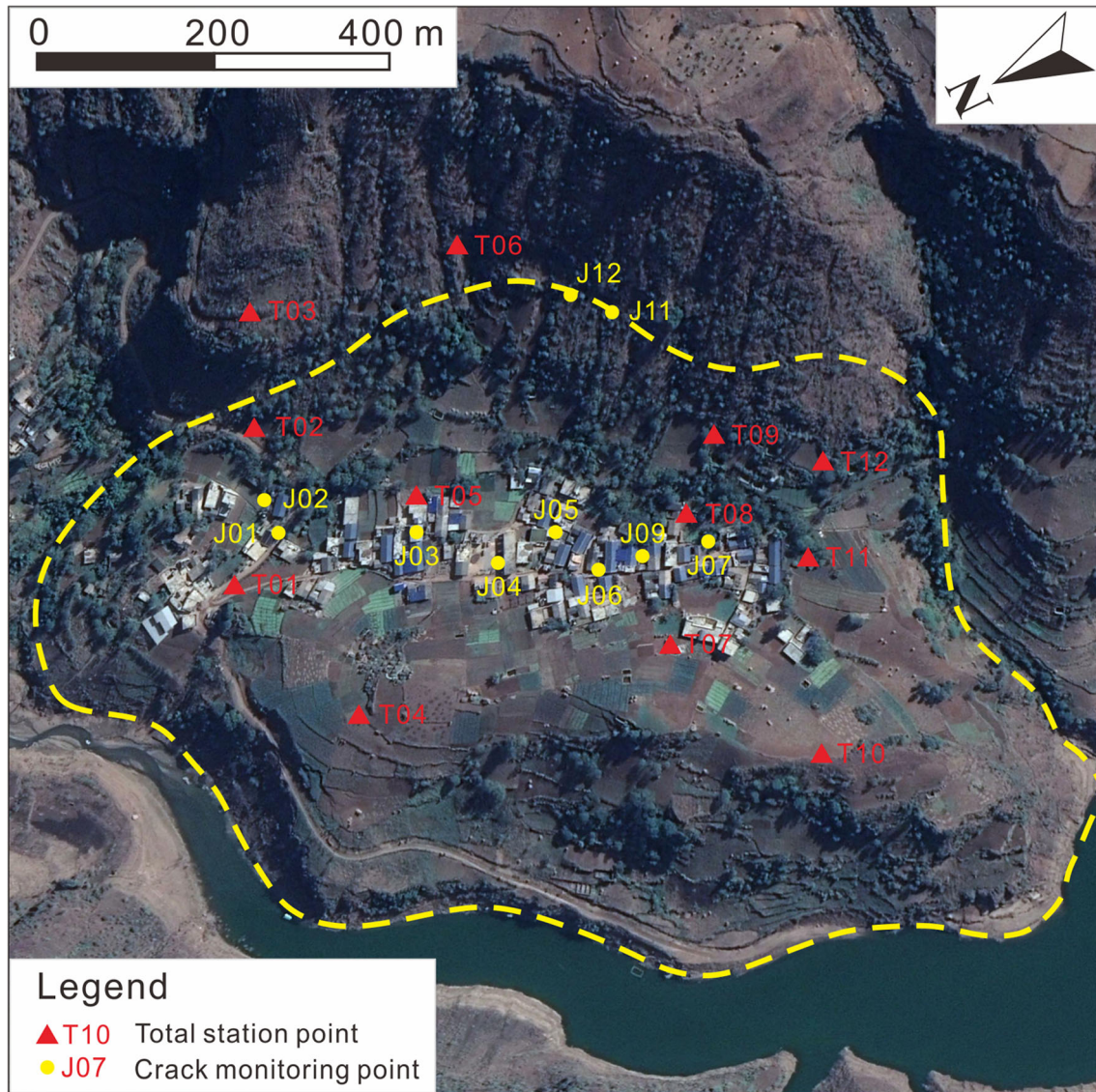


Fig. 11 Map of monitoring points installed in the landslide

displacement and variations in the reservoir water level is shown in Figs. 12, 13, and 14. These graphs show that the landslide was evidently affected by the drawdown of the water level from 10 October to 8 November 2018, but not by the earlier sharp rise in water level from 14 June to 18 August 2018. For example, the water level rose rapidly from 1370.0 to 1386.7 m in June 2018, but the change in crack width was virtually negligible. Another period of rise of the reservoir water from 23 July to 18 August 2018 also produced a negligible change in landslide deformation. One reason was that the rise of the reservoir water increased normal stress on the landslide front located below the reservoir and consequently increased the resistance force against sliding (Li et al. 2010).

Conversely, greater deformation occurred when the reservoir water level fell rapidly. The drawdown of the reservoir from a water level of 1380.8 m began on 12 August 2017. The landslide occurred on 20 August 2017 after 8 days of continuous

drawdown of the reservoir, with a drawdown of 2.2 m. The same phenomenon also happened in 2018. For example, the maximum displacement reached 252 mm during the period from 10 October to 8 November 2018, following a 24-m drawdown of the reservoir. Therefore, the landslide deformation was affected by the drawdown. From the landslide displacement evidence, it can be deduced that the landslide was triggered by the drawdown of the reservoir.

Failure mechanisms

The landslide occurred after the drawdown of reservoir water. The maximum drawdown velocity of the reservoir reached 2.4 m/day. The seepage process depended on the property of the landslide body. The diluvial deposit consisted of clay soil which had a liquid limit of 41.7–42.6% and plastic limit 22.9–23.7%. The coarse particle percentage of clay soil varied from 10 to 30 based on its grain size distribution. When the reservoir

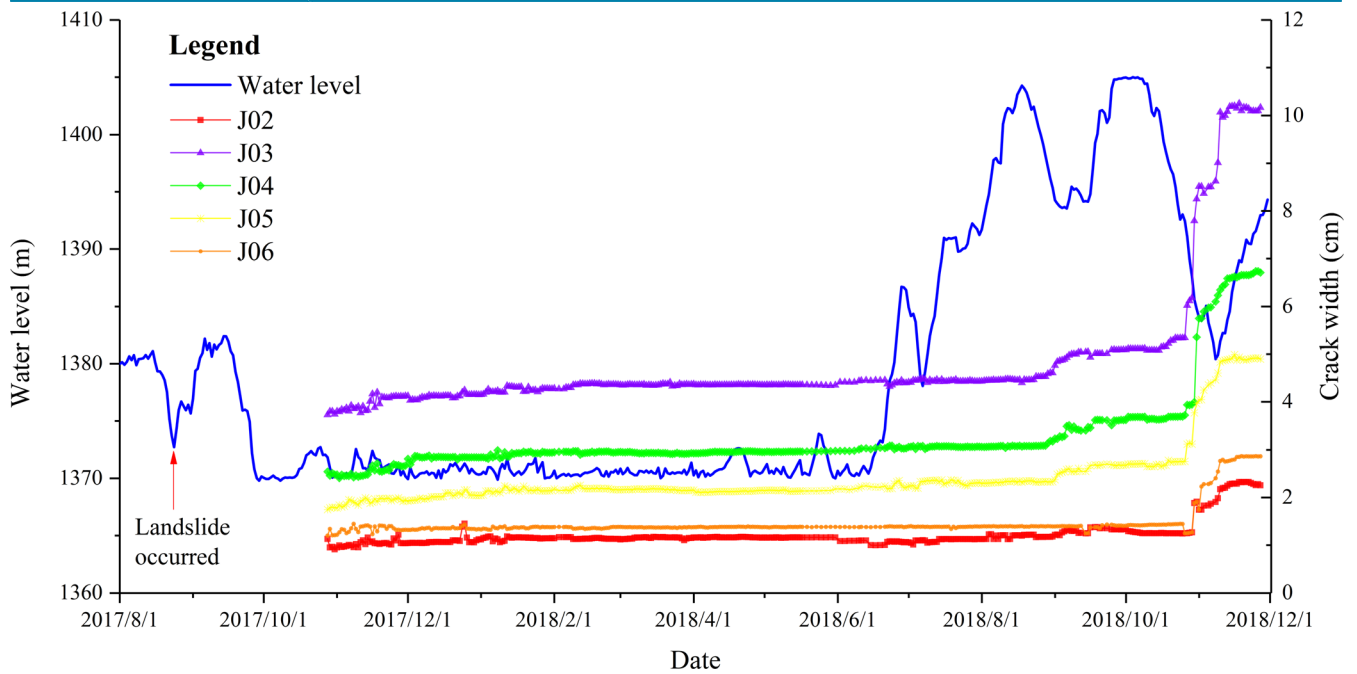


Fig. 12 Cumulative change in crack width at the crack monitoring points

level rapidly declined, however, groundwater within the landslide slowly dissipated and the groundwater levels remained high due to the poor permeability of Quaternary diluvial deposit. Therefore, this may increase the pore water pressure in the landslide body and the seepage force would become larger due to the excess water drained downslope, which resulted in the landslide movement (Yang and Wang 2014; Chen et al. 2018). It

may be a main reason that the landslide occurred after the reservoir drawdown. Another possible reason was that reservoir water seeped into the sliding mass due to the big rise and may have affected the structure of the mudstone, resulting in a loss of strength. Therefore, the landslide mechanism was influenced by both the drawdown of the reservoir and strength loss in the mudstone.

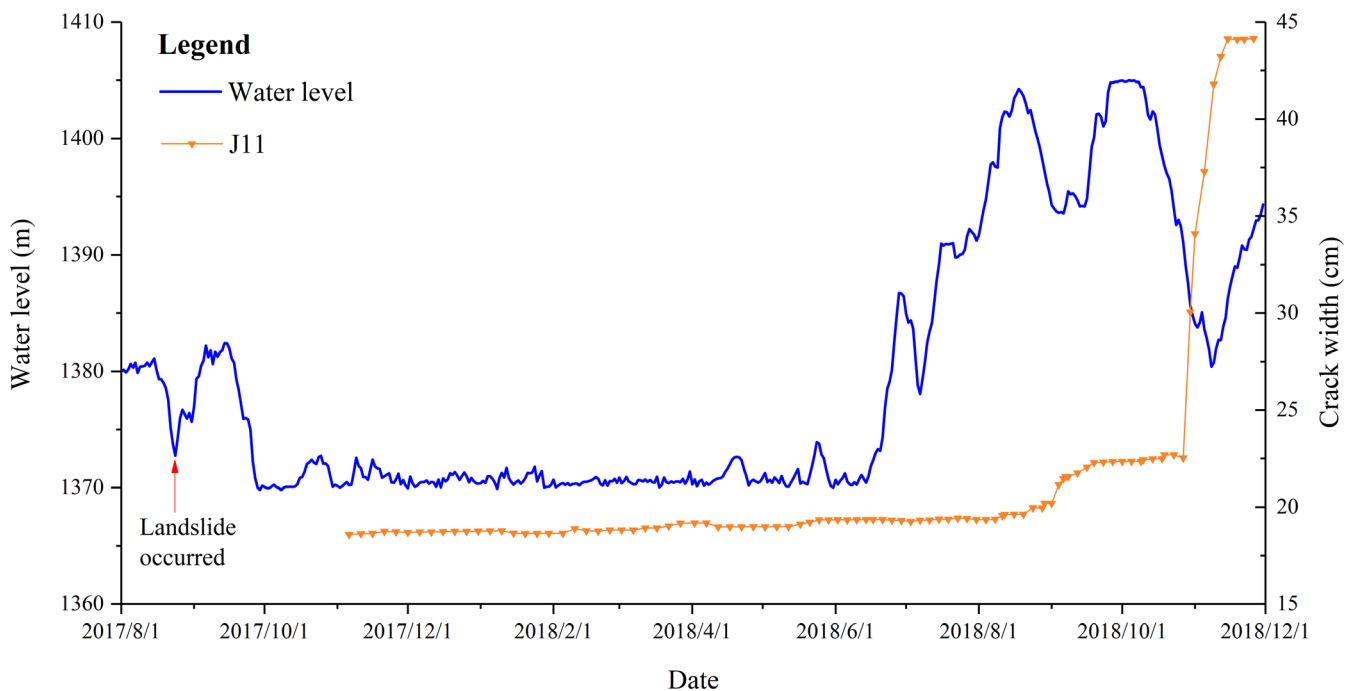


Fig. 13 Cumulative change in crack width at the J11 monitoring point

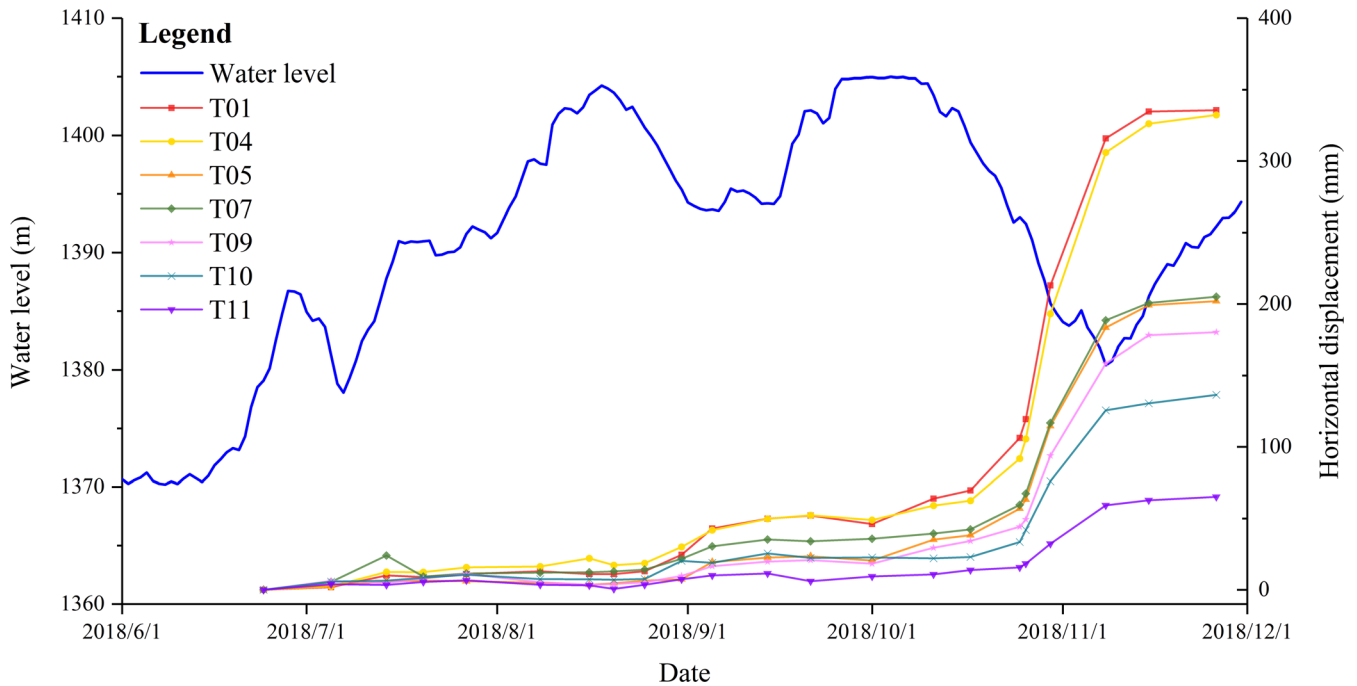


Fig. 14 Cumulative displacement measured by total station

Proposed landslide mitigation measures

The hydroelectric power plant and local government were aware of the serious nature of the landslide. Some measures, including field investigation, borehole investigation, landslide monitoring, and building temporary shelters, were taken after the landslide

occurred. When the landslide was found, the hydroelectric power plant immediately reported the landslide to the local government and hired a survey and design company to carry out a professional investigation and stability assessment. In the meantime, ground monitoring of the landslide was conducted using a total station

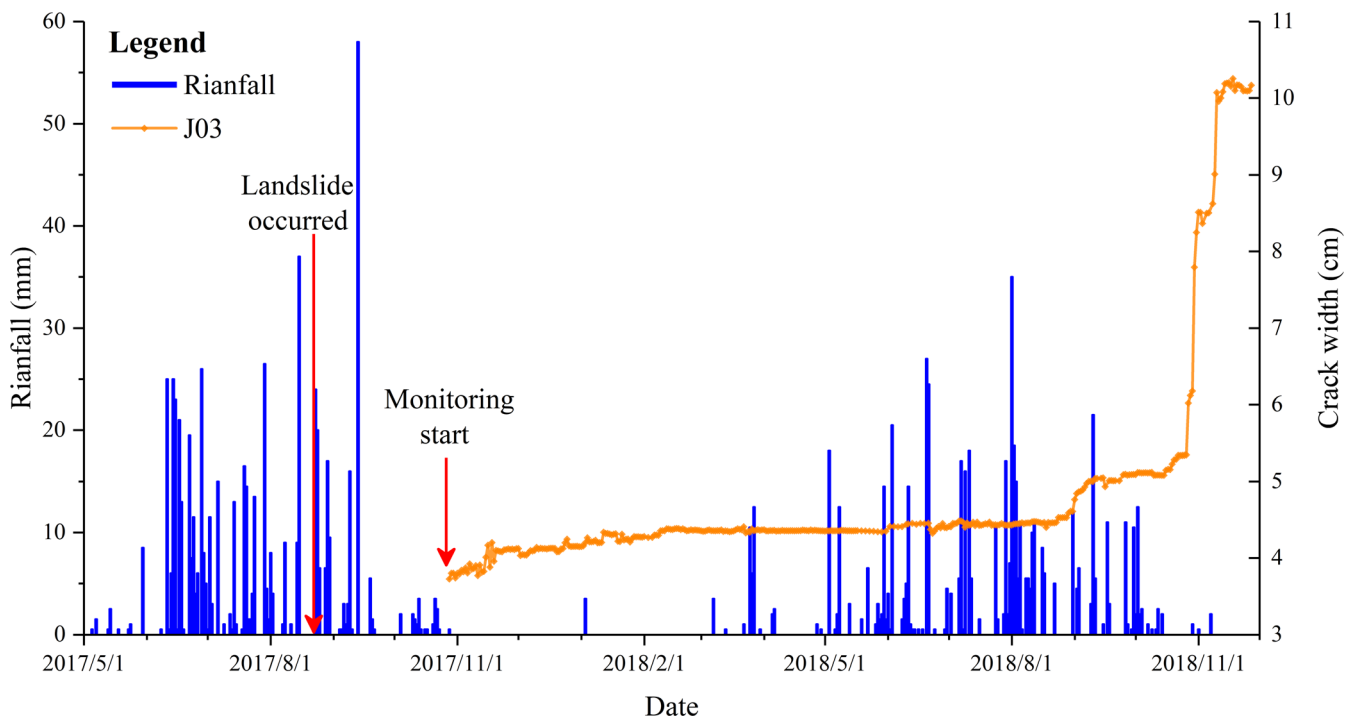


Fig. 15 The relationship between daily rainfall and cumulative change in crack width

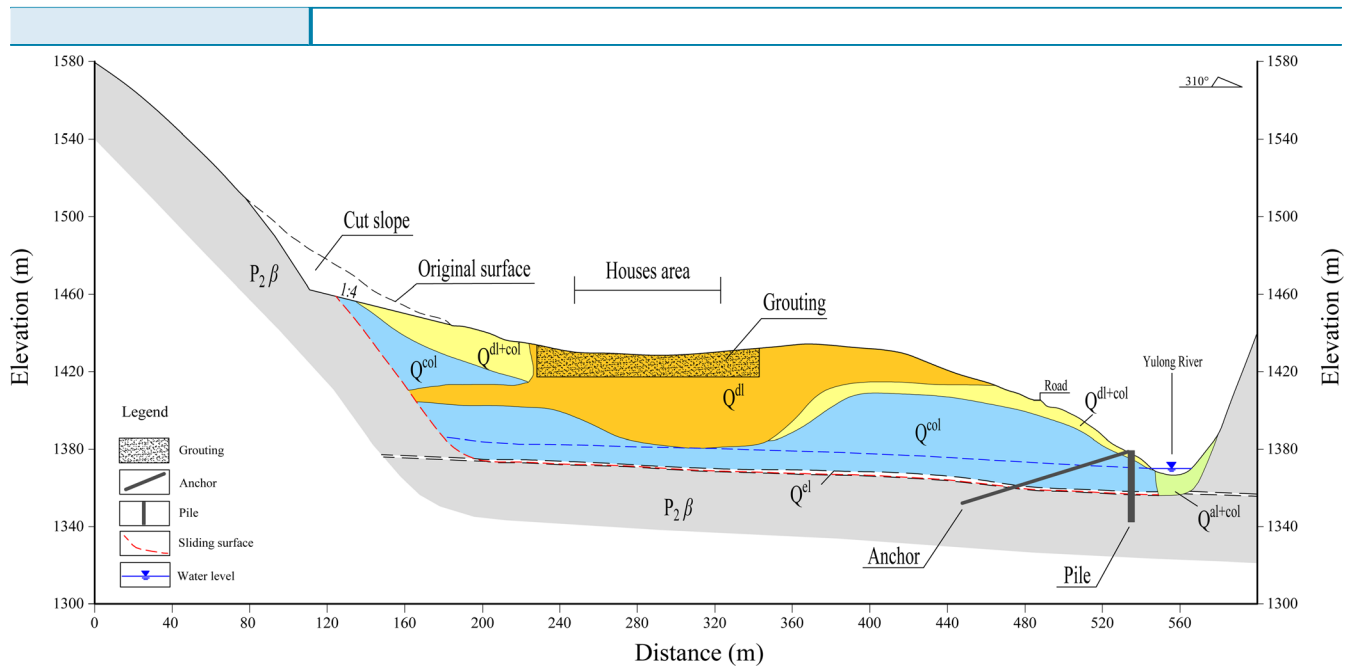


Fig. 16 Suggested engineering control measures to prevent landsliding

and simple crack measurements. In order to reduce the landslide risk, two different landslide mitigation measures have been proposed by experts: engineering control measures and relocation of the residents to a safe place.

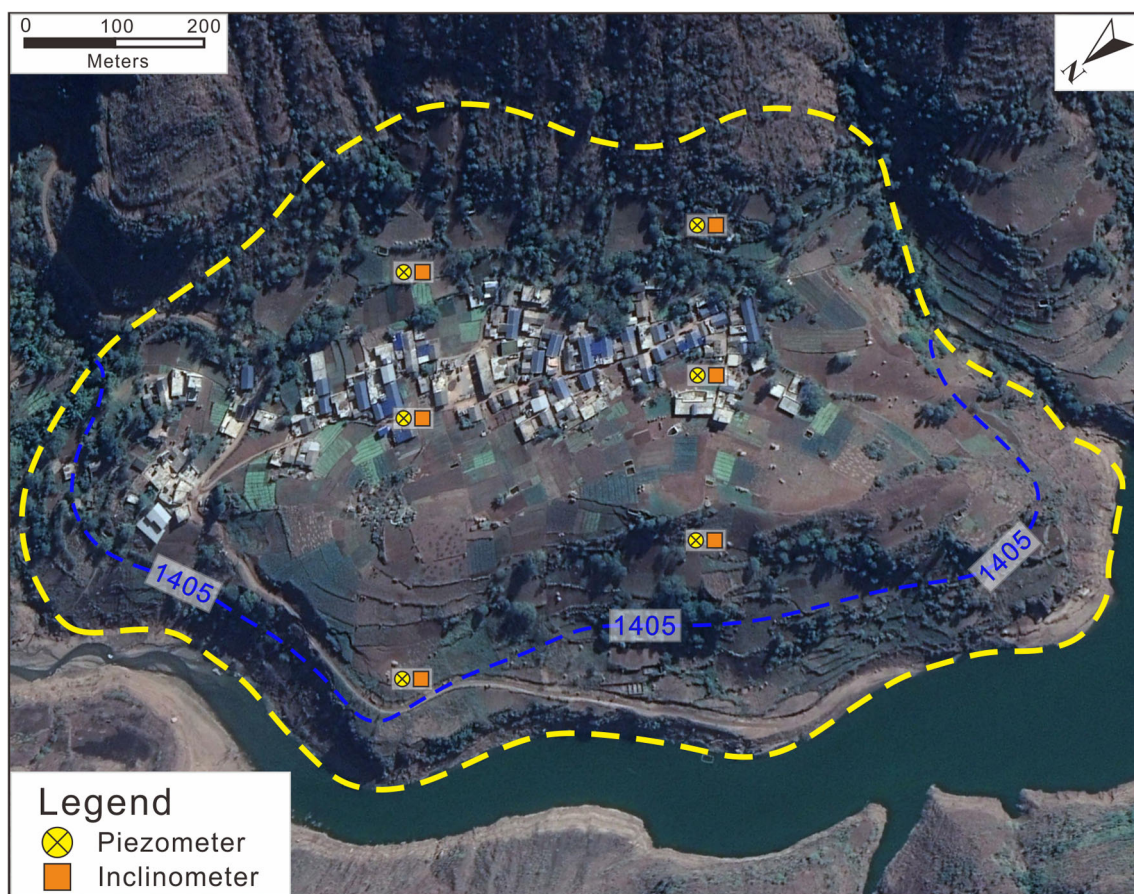


Fig. 17 Proposed monitoring locations of piezometers and inclinometers

Engineering control measures

Based on the landslide characteristics, different control measures could be carried out in different regions of the landslide, as shown in Fig. 16.

3. In the rear region (I), the deposits could slide in the future because of the very steep slope of 40 to 60°. The landslide thickness in this region is relatively thin by comparison. It has been proposed that the slope would be cut back to reduce the slope angle. The ratio of the slope after cutting would be 1:4 (see Fig. 16). Although it may increase the possibility of the area above the rear becoming unstable, an additional measure of building a netting fence along the rear region after cutting back the slope was proposed in order to avoid and reduce the impact of possible falling boulders or materials from the top.
4. In the flat platform region (II), piles cannot be placed because the thickness of the landslide body is too great to reach bedrock. In order to control house damage caused by landslide deformation, the measure was suggested that grouting the ground in the house distribution region. A depth of grouting from the ground level of approximately 20 m was suggested to reduce the differential settlement of houses caused by the landslide.
5. In the toe region (III), piles with anchors were designed to place along the Yulong River, because the landslide body in this area is thinner by comparison. The piles would have a length of about 38 m and a diameter of 2.2 m. The anchor has a length of about 90 m, with a down angle of 17°. The anchor cables would be anchored into bedrock, as shown in Fig. 16.>

Relocation of residents to a safer place

The 552 people of 131 households living on the flat platform were threatened by the landslide. It was suggested that the residents relocate their homes to another location where they would be safe and there is no ongoing risk.

However, there is great controversy over which mitigation measures should be taken in the future.

1. If the relocation measure were to be adopted, it would be very difficult to locate a nearby flat place that could hold 552 residents. Some residents do not want to move out and prefer to remain at Heping village because most of their houses are still functional. It is very probable that the residents would continue to farm in the land threatened by the landslide, because it is unlikely that the landslide would slide in general in the near future. In addition, the cost of relocation is very high. There is thus much pressure on the local government and a lot of difficulty in implementing the relocation plan.
2. If the engineering control measures are to be implemented, there is some uncertainty in the construction techniques and the design plans. It is possible that the landslide may deform in the future, even if the engineering measures were implemented. In addition, the construction would be very difficult, because the landslide body is very thick and it was close to the reservoir shore along the Yulong River. Technical risk thus exists in adopting the engineering control measures.>

Some advice for the future

Because the final landslide mitigation measure was not determined in 2018, the local government was afraid that the landslide

would move during the drawdown of the reservoir in 2018. Therefore, the residents were required to stay in the temporary shelters during that period. Although the final landslide mitigation measures have not been determined yet and require further research, some suggestions to reduce the landslide risk can be made.

1. Plastic sheets should be used to cover the landslide cracks. This would prevent surface water from seeping into the cracks and limit the increase of pore water pressure in the landslide.
2. Subsurface monitoring of the landslide should be adopted in the future. This should include monitoring of groundwater levels and measurement of underground displacement using inclinometers. The main aims are to identify the relationship between the groundwater level and reservoir water level and determine the possible sliding hazard zone. The locations of these measures installed proportionally in the landslide are proposed, as shown in Fig. 17.

The locations of the piezometers were placed at the original locations of the drilling boreholes (Bo2, Bo3, Bo5, Bo6, Bo8, and Bo9). The inclinometers were installed at vicinity of the piezometers.

3. The landslide deformation was influenced by the drawdown of the reservoir. Decreasing the drawdown velocity of the reservoir may be helpful in mitigating the landslide deformation. Its effect needs to be further confirmed by the analysis of new monitoring data.
4. During the periods when the reservoir is being drawn down, there should be an increase in the frequency of landslide surface monitoring, and velocity thresholds of landslide displacement should be set for warning the residents (Intrieri et al. 2012).>

Conclusions

The Hejiapingzi landslide in Weining County occurred on 20 August 2017 after drawdown of the Xiangbiling reservoir water level. Landslide features, deformation characteristics, triggering factors, and failure mechanism were studied based on field investigation and analysis of the monitoring data. The following conclusions could be drawn:

1. The Hejiapingzi landslide occurred along a weaker layer consisting of mudstone. The landslide could not move rapidly, because the sliding surface was very gentle, with a slope that ranged from 2 to 8°.
2. The deformation characteristics of the landslide are neither spatially nor temporally uniform. The landslide rear and landslide toe near NO.1 Gully moved quickly by comparison. The landslide became active when the reservoir water level declined.
3. The drawdown of the reservoir was the main triggering factor for the landslide. Other possible factors in the landslide occurrence were the increase in seepage force and the existence of a weathered thin mudstone with small cohesion and low internal friction angle, which formed the landslide slip surface.
4. Although which landslide mitigation measure will be selected—engineering control measures or resident relocation to a safer location—has not yet been finalized, some interim

measures are suggested. These include covering cracks with plastic sheets, subsurface monitoring, decreasing the drawdown velocity of the reservoir, and setting velocity thresholds of landslide displacement for warning residents to reduce the landslide risk.>

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