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Original Article

A catastrophic natural disaster chain of typhoon–rainstorm–landslide–barrier lake–flooding in Zhejiang Province, China

CUI Yu-long[1] https://orcid.org/0000-0002-4848-7079; e-mail: ylcui@aust.edu.cn

HU Jun-hong[1] https://orcid.org/0000-0003-1925-1822; e-mail: 786416066@qq.com

XU Chong[2*] https://orcid.org/0000-0002-3956-4925; e-mail: chongxu@ninhm.ac.cn

ZHENG Jun[3] https://orcid.org/0000-0003-2131-6816; e-mail: zhengjun12@zju.edu.cn

WEI Jiang-bo[4] https://orcid.org/0000-0002-7437-1109; e-mail: 1138634379@qq.com

**Corresponding author*

1 School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan 232001, China

2 National Institute of Natural Hazards, Ministry of Emergency Management of China (former Institute of Crustal Dynamics, China Earthquake Administration), Beijing 100085, China

3 Department of Civil Engineering, Zhejiang University, Hangzhou 310058, China

4 College of Geology and Environment, Xi'an University of Science and Technology, Xi'an 710054, China

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Abstract: On August 10, 2019, due to the effect of a rainstorm caused by Super Typhoon Lekima, a landslide occurred in Shanzao Village, China. It blocked the Shanzao stream, forming a barrier lake, and then the barrier lake burst. This is a rare natural disaster chain of typhoon–rainstorm–landslide–barrier lake–flooding. This study was built on field surveys, satellite image interpretation, the digital elevation model (DEM), engineering geological analysis and empirical regression. The purpose was to reveal the characteristics and causes of the landslide, the features and formation process of the barrier lake and the dam break flooding discharge. The results show that the volume of the landslide deposit is approximately 2.4×10^5 m^3. The burst mode of the landslide dam is overtopping, which took only 22 minutes from the formation of the landslide dam to its overtopping. The dam-break peak flow was 1353 m^3/s, and the average velocity was 2.8-3.0 m/s. This study shows that the strongly weathered rock and soil slope has low strength and high permeability under the condition of heavy rainfall, which reminds us the high risk of landslides and the importance of accurate early warning of landslides under heavy rainfalls in densely populated areas of Southeast China, as well as the severity of the disaster chain of typhoon–rainstorm–landslide–barrier lake–flooding.

Keywords: Natural disaster chain; Landslide; Barrier lake; Dam break flood; Typhoon Lekima; Yongjia County

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1 Introduction

A natural disaster chain is a phenomenon in which one disaster occurs first, and then several other disasters are immediately or after a period of time caused by this first disaster. Natural disaster chains often occur in mountainous areas and have obvious triggering factors, including earthquakes, typhoons, heavy rainfalls or glacial movements. In a natural disaster chain event, a close relationship exists between these secondary disasters including floods, landslides, debris flows, rock avalanches, and dammed lakes (Liu and He 2018; Cui et al. 2021). In recent years, associated with major earthquakes and strong convective weather such as typhoons and heavy rainfalls, geological hazards such as landslides and debris flows have occurred frequently around the world (Martha et al. 2017; Xu et al. 2018; Cui et al. 2020). In mountainous areas, such events may form landslide dams, and block rivers, then produce subsequent hazards. Tacconi Stefanelli et al. (2016) put forward a Bmorphological Obstruction Index (MOI) to determine whether a landslide dam can be formed, and a Bhydromorphological Dam Stability Index (HDSI) to characterize the long-term stability of the dam. There are also some other geomorphological index approaches to assess the formation of landslide dams, but these empirical approaches are not completely reliable (Swanson et al. 1986; Ermini and Casagli 2003; Tacconi Stefanelli et al. 2016). Well-directed numerical simulation analysis for specific case is more accurate (Braun et al. 2018).

If a landslide dam is formed, then the produced barrier lake would not only submerge the upstream area but also cause floods downstream if the barrier dam breaks. This kind of the natural disaster chain composed of landslide dams, barrier lakes and floods often poses a great threat to life and property and even causes major losses. For example, the 2008 Ms 8.0 Wenchuan earthquake in China triggered massive landslides (Xu et al. 2014) and created many barrier lakes on rivers, causing severe hazards (Cui et al. 2009; Liu et al. 2009). On March 20, 2019, a landslide blocked a tributary of the Jinsha River in Yagu Village, Derong County, Sichuan Province (Xu et al. 2019). On October 10 and November 3, 2018, two landslide damming–barrier lake breaking–flooding events, occurred on the left bank of the Jinsha River in Baige Village, Jiangda County, Tibet (Deng et al. 2019; Zhang et al. 2019; Cui et al. 2020). Similar events also occurred on October 16, 2018, in the Sedongpu Basin at Gyala Peri Peak (Tong et al. 2018), on March 5, 2018 in Mabian County, Sichuan Province (Ma et al. 2018), on June 24, 2017 in Maoxian Sichuan (Intrieri et al. 2018; Ouyang et al. 2019), and on April 9, 2000 in Zhamu Creek, southeast Tibet (Shang et al. 2003).

Many such disaster chains have been documented throughout Chinese history. For example, in 1786, a landslide triggered by the M 7.7 earthquake in the Kangding-Luding region of Sichuan Province blocked the Dadu River, and then the landslide dam burst which resulted in flood killing 100,000 people downstream (Dai et al. 2005). In 1933, an M 7.5 earthquake occurred in Diexi Town, Sichuan Province, creating three continuous landslide dams on the Min River; afterwards, the lake water overflowed the last dam, and the resultant flood caused 2,500 deaths (Chai et al. 2000). In 1917, an M 6.7 earthquake occurred in the Beiguan River basin in Yunnan Province, in which a barrier lake created by an earthquake-triggered landslide drowned more than 1600 people (Chai et al. 1995).

Apart from China, many similar natural disaster chains have occurred all over the world. For example, on April 20, 2017, in the upstream Barun Valley of Nepal, a rock avalanche made a glacial lake break and immediately formed a flood (Byers et al. 2019). On July 27, 2011, the Matthieu landslide-dam in Dominica, West Indies suddenly broke, the complete draining of the dammed lake caused major flooding along the lower Layou River Valley. The economic loss in the downstream was about $18 million (James and De Graff 2012). On January 4, 2010, a landslide occurred in Northern Pakistan, which swept two villages and blocked the Hunza River, forming a barrier lake; then the dam broke and formed a flood in the downstream. Devastating effects had been made by this natural disaster chain (Butt et al. 2013). Investigation of the literature shows that these natural disaster chains all over the world usually contain some hazards such as earthquakes, typhoons, rainstorms, landslides, barrier lakes and lake-break floods. In addition, the natural disaster chains in China often occur in mountainous areas with intense tectonic activity and large topographic relief, especially in southwest China. However, such disaster chains appear to rather rare in those mountainous or hilly areas with weak tectonic activity, such as southeastern China, only a few cases have been reported (Ouyang et al. 2018; Wei et al. 2020).

In this paper, we presented an exceptional case, a natural disaster chain composed of typhoon, rainstorm, landslide, barrier lake, and lake-break flood, which occurred near the coast of southeastern China with weak tectonic activity. This event was caused by Super Typhoon Lekima (International No. 1909). According to statistics, Typhoon Lekima has affected 14.024 million people in China, and the direct economic loss reached 7745 million US$ (51,530 million RMB). The Typhoon Lekima killed 70 people, of which 48 deaths were in Zhejiang Province. Unusually, the main lethal factor of Typhoon Lekima was not the large-scale strong typhoon, subsequent heavy rainfalls and floods, instead it was a localized landslide–barrier lake–flooding disaster chain in Shanzao Village, Yongjia County, Zhejiang Province (hereafter called Shanzao landslide). This disaster chain event alone resulted in 32 deaths, accounting for 46% of the total death toll caused by Typhoon Lekima. The Shanzao landslide occurred at approximately 5:00 am on August 10 at E120°40′19″, N28°32′07″. The landslide deposits blocked the Shanzao stream; consequently, the torrential floods caused by typhoons and rainstorms were collected upstream from the dam and formed a barrier lake. The water level rose abruptly and submerged Shanzao Village upstream, causing approximately 30 deaths in the upstream. Then, the landslide dam broke, and the dam-break flood caused 2 casualties downstream. According to government reports (Xinhua News Agency 2019), the landslide did not directly kill anyone, while the formation of the barrier lake and dam-break flood caused 32 deaths in total.

Based on field investigations, satellite image interpretation, and engineering geological analysis using the digital elevation model (DEM), we characterized this rainstorm-induced landslide dam and the barrier lake and discuss the causes of the slope failure and subsequent disaster chain effects. Combined with hydrological calculations, the time from the formation of the landslide dam to the overtopping was estimated, and then the peak discharge and average velocity of the dam-break peak flow were calculated by the empirical equations.

2 Geological and Climatic Setting

2.1 Geological setting

Yongjia County lies on the north bank downstream on the Oujiang River in southern Zhejiang Province, with high terrain in the north and low terrain in the south. Overall, the mountains run slightly from the northwest to southeast, with an elevation of 1000 metres above sea level (m.a.s.l.) on average and peaking at 1270.8 m.a.s.l. The landslide area is characterized by low mountains and hills, crisscross gullies and abundant water systems (Fig. 1). The strata include the lower subsection of the first member of the Xishantou Formation of upper Jurassic (J_3x^{1-1}), bearing rhyolitic vitric tuff. The structure in the landslide area is complex, with a strike-slip fault ① on the south side of the landslide and two NE-trending faults ② and ③ on the northwest side, which are offset by the later-developed fault ① with an offset of approximately 130 m (Fig. 2). Multiple periods of tectonic activities resulted in numerous joints and fissures, which made the rock mass very fragmented. No major earthquake has been documented in the landslide area.

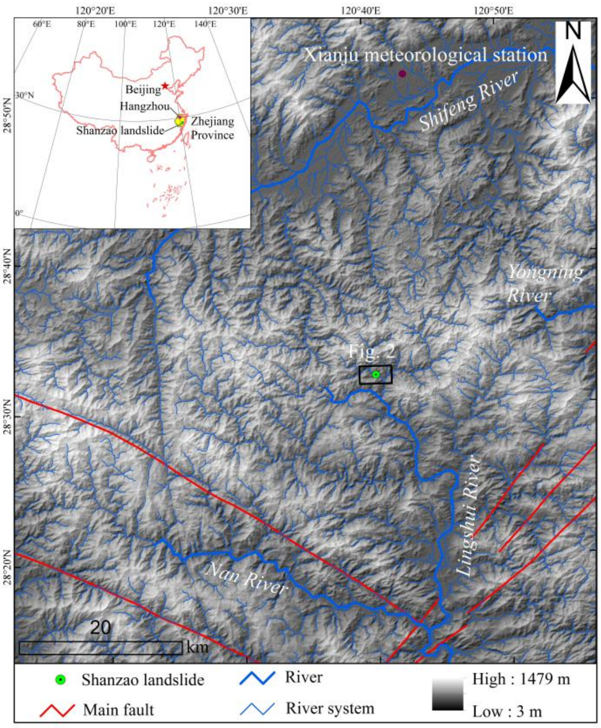

Fig. 1 Map showing the location of the Shanzao landslide and physiography of the study area. The base map is a 12.5 m-resolution DEM from ALOS satellites. The fault data are from the China Geological Survey with a scale of 1:500,000.

2.2 Climatic

Yongjia County has a subtropical monsoon climate, which is warm and moist with abundant rain. The annual average temperature is 18.5°C, and the annual average precipitation is 1720 mm. The maximum monthly average precipitation is in August and reaches 279.4 mm. Heavy rainfall and developed vegetation lead to strong physical weathering in this area. According to the monitoring data from August 1-15, 2019 (Fig. 3) of the Xianju meteorological station 37 km from the Shanzao landslide, the rainfall during this period was concentrated on August 8-10, with an accumulative amount of 215.7 mm. The accumulated rainfall from August 8 to the first half day of August 10 before the landslide occurred was approximately 197.6 mm, of which the rainfall during the first half day of August 10 was as high as 130.1 mm. In addition, according to the government report, the rainfall in the landslide area reached 160 mm within 3 hours before the landslide occurred (Pengpai News 2019), which indicates the rainfall in the landslide area was indeed heavier than that in the Xianju meteorological station.

Typhoon Lekima landed on China from the coast of Wenling City, Zhejiang Province at 1:45 am on August 10, 2019. The maximum wind speed near the centre when the typhoon landed reaches 52 m/s. It triggered severe storms, rainfalls, and floods. This was the fifth super-strong typhoon landing in China since 1949.

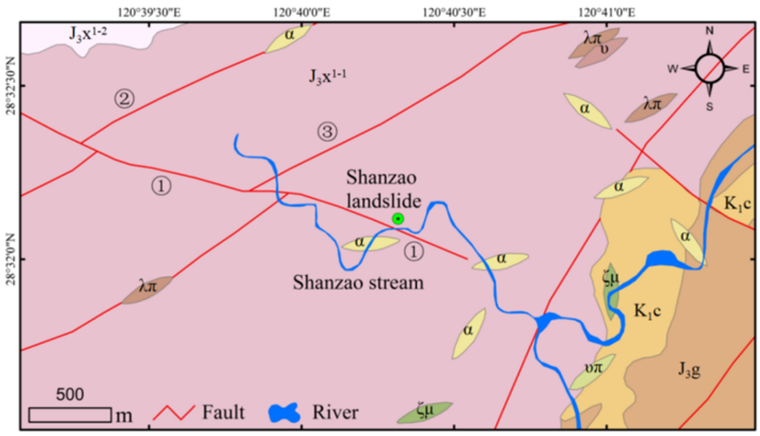

Fig. 2 Geological map of the study area. See the black box in Fig. 1 for its location. J_3x^{1-1} and J_3x^{1-2}: Xishantou Group of Jurassic; J_3g: Gaowu Group of Jurassic; K_1c: Chaochuan Group of Cretaceous; α, λπ, ζμ, υπ and υ: the igneous rock of Jurassic. The data are from the 1:50,000 geological map by the China Geological Survey.

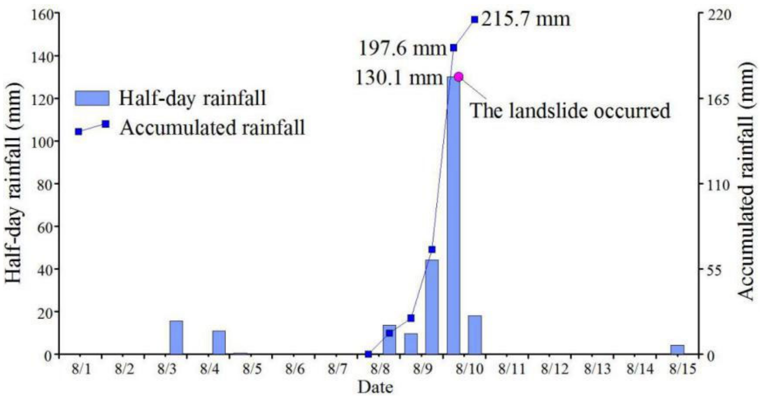

Fig. 3 Rainfall data from August 1-15 from the Xianju meteorological station. Each day has two values: the first value is of the first half-day, which is from 20:00 the day before to 8:00 the current day, and the second value is from 8:00 to 20:00 of this day.

3 Data and Methods

The data used in this study involve 1:50,000 and 1:500,000 geological maps from the China Geological Survey, 12.5 m-resolution DEM from ALOS satellites (earth observation satellites of Japan), rainfall data of August 1-15 from the Xianju meteorological station with half-day resolution, photos and unmanned aerial vehicle (UAV) photographs from government reports, plant images with 3 m-resolution, and Google Earth images with 0.6 m-resolution. Fig. 4 shows a flowchart of the methodology of this work, including the following main steps: (1) The surface elevation before the landslide was extracted from the DEM, the geological profiles before and after the landslide were drawn, and the basic characteristics of the landslide were analysed; (2) According to the internal factors, such as the topographic and geological setting of the landslide area, as well as the induced factors, such as human activities and rainfall, the causes of the landslide were discussed; (3) The water level of the barrier lake was determined, the scope of the barrier lake was delineated on the DEM based map, and the volume of the barrier lake was calculated; (4) According to the volume of the barrier lake and the surface water catchment, the time required for the overtopping of the barrier lake was calculated, and the dam-break peak flow and the average velocity were finally calculated based on empirical equations.

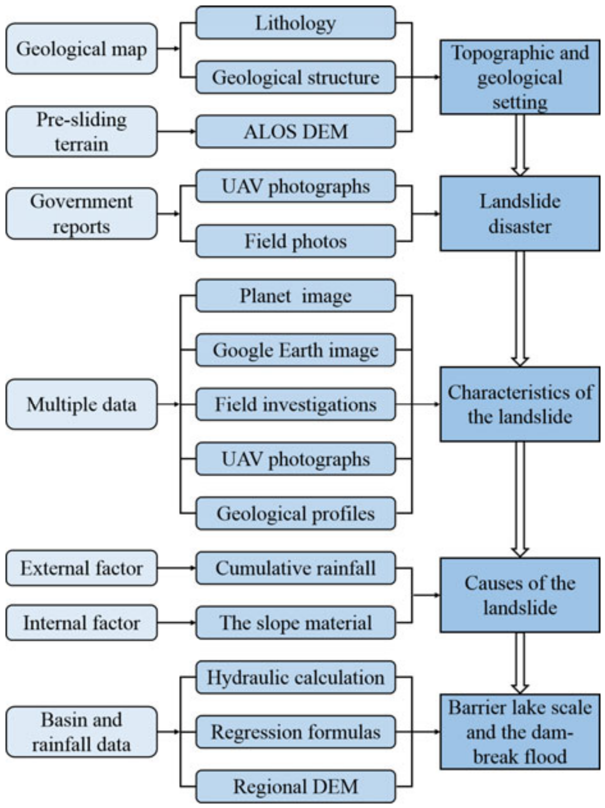

Fig. 4 Flowchart showing the methodology of this study.

4 Results

4.1 Landslide characteristics

Based on the Planet image and the field investigations after the landslide, we delineated the boundaries of the source and deposit areas of the landslide, respectively. The source area of the landslide is 158 m long, with a maximum width of 115-120 m and a projected area 11130 m^2. The azimuth of the slip direction is about 160°, which is perpendicular to the flow direction of the Shanzao stream. The maximum length and width of the landslide deposit area are 216 m and 140-145 m, respectively, with a projected area 15778 m^2. According to an estimated average thickness of 15 m, the volume of the landslide deposit is estimated to be 2.4×10^5 m^3 (Fig. 5a). It can be seen from the pre-sliding image that the upper part of the landslide source area is cultivated land, covered with completely weathered soil, and the lower part contains shrubbery, indicating that there is coverage of strong weathered rock at this location (Fig. 5b).

Overall, the landslide body is "tongue shaped". The front part of the landslide deposit travelled to the right bank of the Shanzao stream, and the back part accumulated on the slope. The upper part of the deposit is a stacking platform, below which the slope is relatively steep. Below the slope was the landslide dam that has been washed. In front of it, obvious landslide deposits are observed (Fig. 5c). Scarps (back wall and side wall) of the landslide can be seen above and on both sides of the stacking platform.

Both Zhuji-Yongjia expressway and Shanzao Road pass through the landslide. Due to the construction of the expressway, the right side of the landslide was excavated and four piers were built. The possible influence of the Shanzao Road was from the excavation of the slope toe during the initial construction, with a nearly 3-m-high subvertical slope formed inside the road (Fig. 5d). After the Shanzao landslide deposit was cleared, no deformation was observed on the road and the near vertical slope after excavation, thus the shear outlet of the landslide is located above the top of the cut slope. From the field investigations, it was found the boundary between strong weathered rock layer and weakly weathered rock layer on the right side of the landslide was behind the two piers beside Shanzao road, about 6 m higher than the road. In addition, on the axis of the landslide, about 5 m higher than the Shanzao Road, an obvious step was generated, which is also the boundary between the strong weathered rock and the weakly weathered rock. According to this, it can be inferred that the front sliding surface of the landslide is distributed along the boundary between the strong weathering rock layer and the weak weathering rock layer, and the shear outlet of the landslide is located about 5 m above the Shanzao Road. The exposed back wall of the landslide is composed of strong weathered rocks (Fig. 5d), indicating that the sliding surface at the rear of the landslide is distributed along the interior of the strong weathered rock layer.

The main pre-sliding geological profile of the slope was drawn according to the pre-sliding surface elevation extracted from the DEM (Fig. 6a). It shows the elevation of the trailing edge is 286 m.a.s.l., the elevation of the leading edge of the sliding surface, i.e. the shear outlet, is 215 m.a.s.l., the height difference between the leading edge and trailing edge is 71 m, and the maximum thickness of the source area is approximately 27 m. On-site measurement indicates

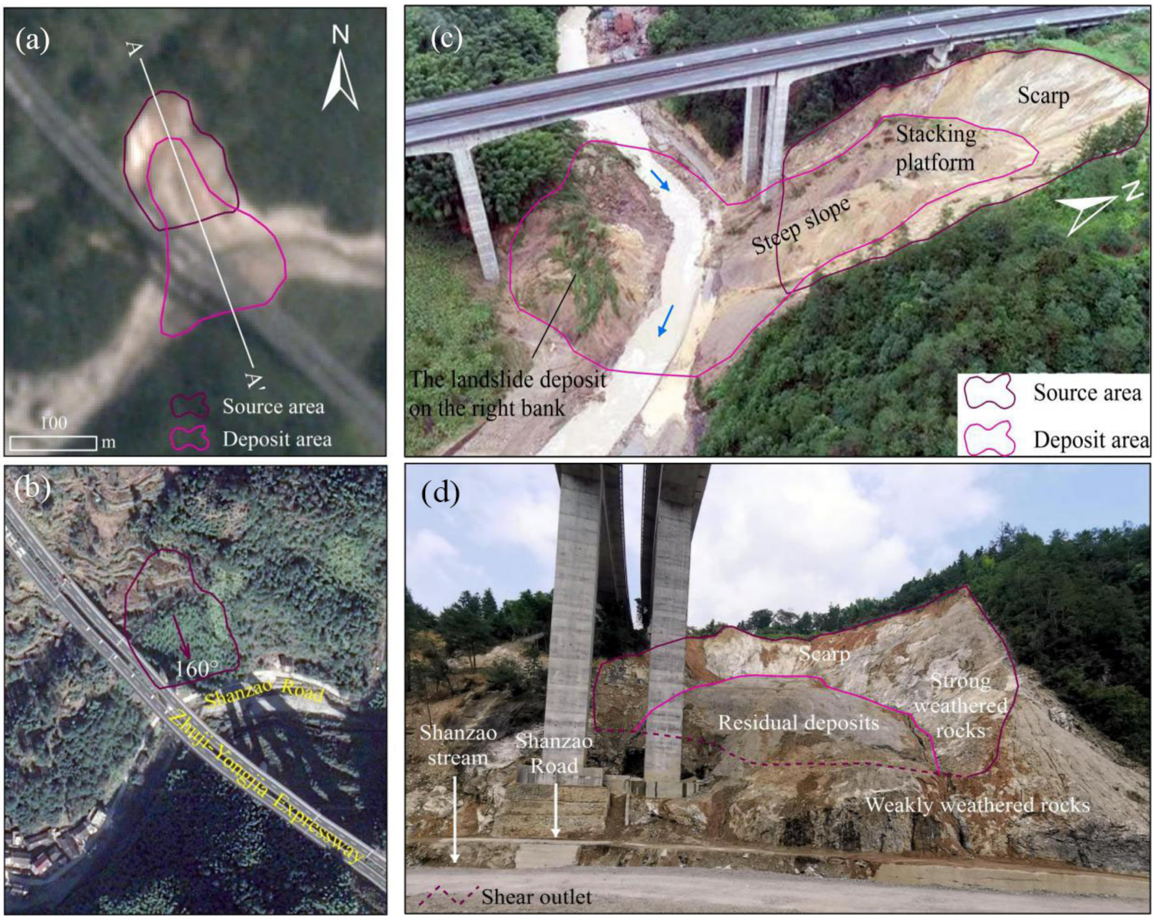

Fig. 5 Characteristics of the landslide. (a) The post-sliding planet image with 3 m resolution on August 18, 2019 and (b) Pre-sliding Google Earth image with 0.6 m resolution on December 19, 2017. (c) Overhead view of the Shanzao landslide (modified from a picture from www.news.cn) and (d) A panoramic view of the landslide source.

that the highest water level of the barrier lake is 205 m.a.s.l. Combined with the visually inspected surface shape of the landslide deposit, the geological profile after the landslide but before the dam broke was drawn (Fig. 6b). According to the analysis of the highest water level of the barrier lake in the following text, the lowest elevation of the dam is 205 m.a.s.l. Then, the maximum thickness of the dam is approximately 11 m, and the elevation of the front edge of the landslide deposit is approximately 205 m.a.s.l. (Fig. 6b).

The top of the landslide back wall is completely weathered soil, and the lower part is strongly weathered bedrock with a visible boundary. This back wall consists of two sliding surfaces, which face at 220° on the left and 135° on the right (looking from the back to the front), respectively, and both intersect to form a wedge (Fig. 7a). The two black right triangles in Fig. 7a represent two surfaces perpendicular to the two sliding surfaces, respectively which are two sets of joints of the rock mass, indicating a wedge-shaped sliding manner. The slide surfaces are flat and smooth, bearing obvious scratches (Fig. 7b).

The landslide deposit on the right bank of the stream is composed of crushed stone and soil (Fig. 8a), in which the proportion of crushed stone and block stone is over 80%. The crushed stone is approximately 3-20 cm thick, accounting for more than 50% of the total content. The maximum diameter of the block stone is 50-70 cm, accounting for less than 30% and is mainly distributed in the upstream area. This observation also indicates that the landslide source was dominated by strong weathered bedrock with broken structures.

On the right side (looking from the back to the front) of the landslide source is at a highway with four piers around the site (Fig. 8b). After the landslide, no displacement was observed on the piers and pavements of the expressway, indicating no damage on them from the landslide. Field investigations show

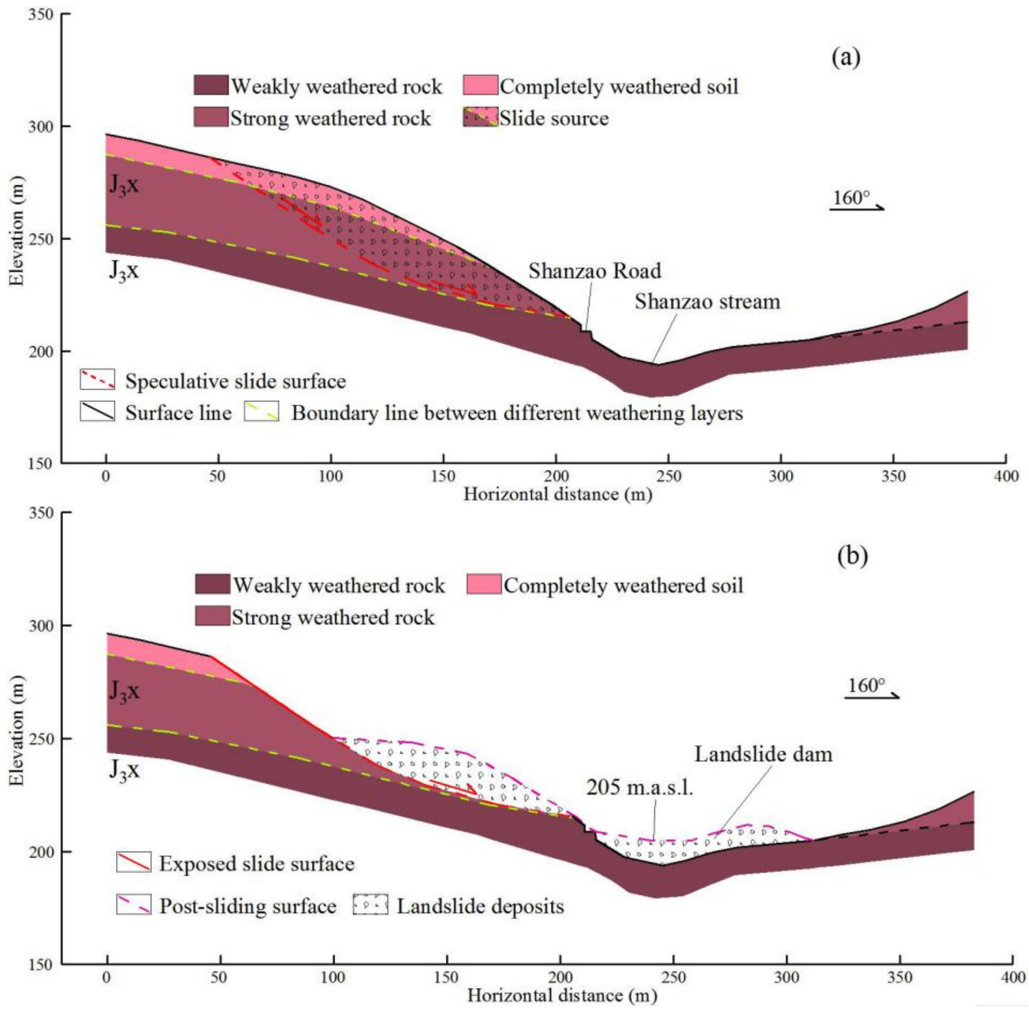

Fig. 6 Geological profile A-A'. (a) Pre-sliding profile. (b) Post-sliding profile. See Fig. 5a for their locations.

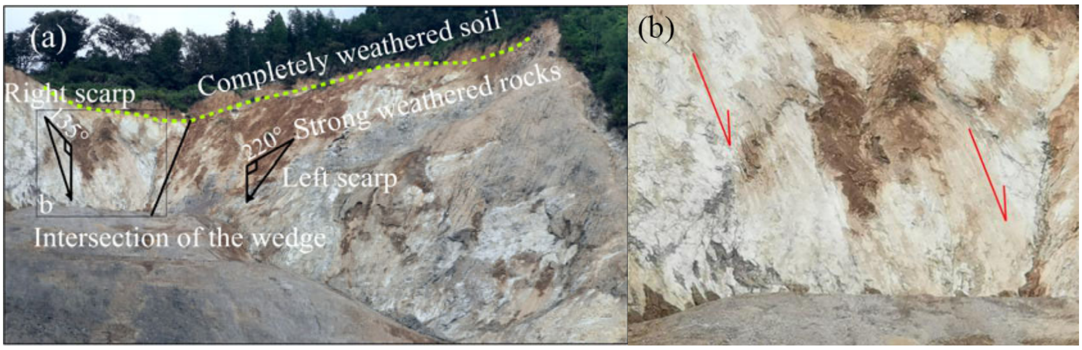

Fig. 7 Characteristics of the landslide scarp. (a) Overview of the scarp. (b) Smooth sides on the sliding surface, see (a) for its location.

that the landslide has different influences on these piers. No influence is observed on Pier 4 because it is located outside the landslide. Obvious mud marks were found on Piers 1 and 2, demonstrating the impact by the landslide deposit. Considering that these piles are very thick, the dashed heights are small, the landslide does not have a high speed, and the composition of the landslide deposit is saturated block-gravel soil, it is concluded that the landslide has little impact on these two piers. The Pier 3 is located on the side wall of the landslide. After the landslide, the pile foundation of the pier was exposed, forming a steeper slope at this location. If the foundation of the pier slides, it will cause serious damage to the pier,

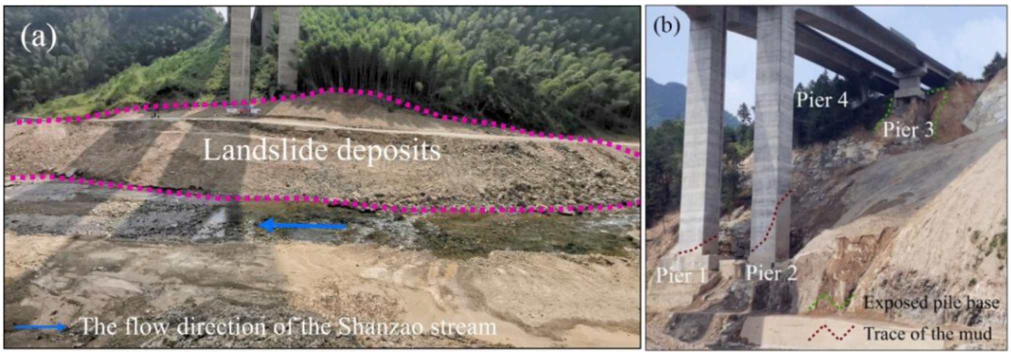

Fig. 8 (a) Present landslide deposit on the right bank of the stream and (b) The piers of the expressway beside the Shanzao landslide.

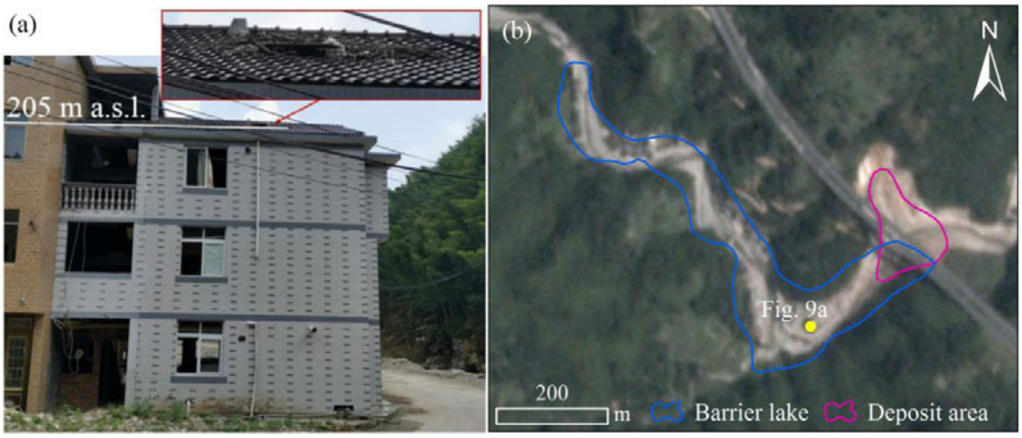

Fig. 9 (a) The floating weeds and debris on the roof of a three-story building and (b) The barrier lake caused by the Shanzao landslide. The base map is from a plant image with a 3 m resolution.

pile foundation, and the expressway.

4.2 Barrier lake

Fig. 9a shows floating weeds and debris remained on the top of a three-story building. As verified by the residents, the top of the building was the location of the highest water level of the barrier lake created by the Shanzao landslide. Measurement and correction allowed us to estimate its elevation as 205 m.a.s.l. The 5 m interval contours of the lake are generated by the DEM. According to the 205 m contour and the position of the landslide, the scope of the barrier lake is delineated (Fig. 9b). Based on the ArcGIS, the lake area is measured to be 7.39 × 10^4 m^2, and the storage capacity is calculated to be 58.8 × 10^4 m^3.

The DEM was used to generate the barrier lake catchment and water system in the basin, and then with ArcGIS, Eq. (1) was used to calculate the surface water catchment discharge in the basin (Li and Meng 2015):

$$Q=\psi\times q\times F \tag{1}$$

where Q is the surface water catchment discharge (m^3/min), ψ is the runoff coefficient, q is the average rainfall intensity (m/min), and F is the catchment area (m^2). In the Specifications of the Drainage Design for Highways of China, ψ in steep mountains is estimated to be 0.75~0.9 (CCCC road and Bridge Technology Co., Ltd. 2012). As the catchment area experienced continuous heavy rainfall many times before the landslide, the surface was basically saturated, and ψ was then taken as 0.9. For the rainfall of 160 mm in 3 hours, the average rainfall intensity q was taken as 0.89 mm/min. The catchment area F was measured to be 3359 × 10^4 m^2 on the ArcGIS platform. Substituting these parameters into Eq. (1), the surface water catchment discharge Q was calculated to be 2.69 × 10^4 m^3/min.

First, it was assumed that the burst mode of the dam was overtopping, and then the time from the impoundment to overtopping was calculated by

$$t = V/Q \tag{2}$$

where t is the time from the impoundment to overtopping of the barrier lake (min), and V is the volume of the barrier lake (m^3). According to the previous calculation, the volume V was 58.8×10^4 m^3, and the surface water catchment discharge Q was 2.69×10^4 m^3/min. Substituting them into Eq. (2) yields that the barrier lake took 22 minutes from the impoundment to overtopping. The storage capacity of the barrier lake at different water levels was measured using ArcGIS according to the DEM. Based on the surface water catchment discharge and Eq. (2), the water levels in the barrier lake at 5 minutes, 10 minutes and 15 minutes were calculated to be 195.7 m, 199.4 m and 201.9 m, respectively. As shown in Fig. 10, the water level rose rapidly after the formation of the landslide dam, and the barrier lake expanded rapidly upstream.

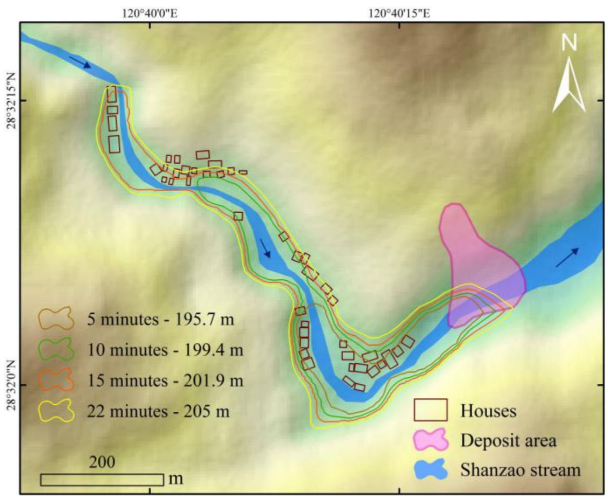

Fig. 10 The rising process of the water level in the barrier lake. The base map is the DEM from the ALOS satellites.

As shown in Fig. 10, the water rose up to 199.4 m in 10 minutes, and this elevation was approximately at the ground of the residential area of Shanzao Village. In addition, according to villagers' memories, it took approximately 10 minutes for the water appearing on the ground to rise to the roof, and then the water level began to fall. Thus, the barrier lake took approximately 20 minutes to form from the beginning of water storage to overtopping. It implies that the 22 minutes calculated by Eq. (2) are reliable, and the failure mode of the landslide dam was indeed overtopping. The area of the Shanzao stream basin is large, and the rainfall was very heavy with a long duration when slope failure occurred. After the landslide dam formed, the water level in the barrier lake rose rapidly, and the residents had no time to escape. This was the reason for a large number of deaths upstream from the dam.

4.3 Dam-break flood

We used the following three empirical regression formulas to calculate the dam-break peak flow (Cenderelli 2000). These regression equations were obtained from real dam-break floods of landslide dams all over the world, suitable for calculations for dam-break floods of landslide dams.

$$Q_P = 24 \times d^{1.73} \tag{3}$$

$$Q_P = 3.4 \times V^{0.46} \tag{4}$$

$$Q_P = 1.9 \times (Vd)^{0.4} \tag{5}$$

where Q_P is the peak discharge, (m^3/s), d is the falling depth of the water level at the landslide dam, (m), and V is the volume of the barrier lake, (m^3).

The falling depth d of the water level at the dam was taken as 11 m. The peak discharge Q_P calculated by Eqs. (3), (4) and (5) were 1520 m^3/s, 1532 m^3/s and 1007 m^3/s, respectively. For these three equations, it was difficult to determine which one was more suitable for this landslide dam. In addition, they were all regression equations, so the average value was the most reliable and closest to the real value. Here, the average value of 1353 m^3/s was assumed to be the dam-break peak flow. Then, the average velocity of the dam-break flow was obtained by dividing the peak discharge by the cross-sectional area of the breach. Due to the lack of an accurate topographic data, the cross-sectional area of the breach was taken as a floating value based on the profile in Fig. 6b, which was between 450-480 m^2. Finally, the average velocity of the dam-break flow was calculated to be 2.8-3.0 m/s. This was a large peak discharge of dam-break floods, which may partly explain why 2 people were killed by this hazard downstream.

5 Discussion

5.1 Causes of the landslide

The landslide area is a low mountain and hill landform, and the slope before the landslide was 25-30°, on which the exposure face was prone to failure

Fig. 11 Photos showing the lithology and structure. (a) Strong weathered tuff. (b) Fragmented rock masses.

and sliding. The slope material is strong weathered tuff with a relatively low strength (Fig. 11), containing many joints and cracks that could provide good infiltration conditions for rainfall and surface water, likely further reducing the stability of the slope (Fig. 11). Thus, this slope is highly susceptible to sliding.

The meteorological conditions are presumably the main external factors that initiated the occurrence of the Shanzao landslide. According to the rainfall data from the Xianju meteorological station, this area had experienced continuous rain for 44 hours before the landslide occurred (Fig. 3). In addition, the rainfall in the landslide area reached 160 mm within 3 hours before the landsliding. A large amount of rain and surface water penetrated into the slope, which reduced the strength of the rock mass, increased the weight of the rock, and lowered the stability of the slope. Moreover, if the rainwater infiltrating into the slope body percolated to the outside of the slope, it would produce a large seepage force on the slope. If the groundwater inside the slope could not be discharged in time, it would generate a large hydrostatic pressure in the slope body. These effects would greatly reduce the slope stability.

The landslide area has experienced intensive human engineering activities, including road construction, residential land construction, farmland reclamation, etc. These human activities may change the stability of some natural slopes. In addition, data suggests that this area is also a landslide-prone area. A landslide distribution map in this area (Wu et al. 2014) shows that some of the landslides in this area occurred along the roads, indicating the possible impact of human engineering activities on the landslides. There are three human activities that are likely to be related to the landslide, namely the construction of Zhuji-Yongjia Expressway, the construction of Shanzao Road, and the reclamation of farmland on the slope. The piers of Zhuji-Yongjia Expressway are located on the side of the landslide. The excavation of these piers is still had a certain distance from the axis of the landslide (Figs. 5d and 8b), so the excavation had an extremely limited effect on the stability of the slope. Moreover, this expressway was fully connected on January 7, 2010 and the piers were built in 2007, i.e., 13 years ago. During the times, the expressway has been operating normally, with no signs of deformation. Even after the landslide, the highway and bridge piers did not undergo any displacement or damage. Meanwhile, the entire highway is connected with the bridge piers as a whole, and the bridge piers stand on the slope, which will increase the stability of the slope. Regarding the impact of the Shanzao Road, the construction of the road has cut off the slope toe and formed a 3-m-high cliff at the lower part of the slope (Figs. 5d and 6a). However, according to the previous analysis, the shear outlet of the landslide is located about 5 m above the road. Therefore, the impact of road excavation on the landslide is little. In addition, the construction of the road was made several decades ago. During the long period, the slope was not deformed. Therefore, the construction of the Shanzao road is not necessarily related to the occurrence of the landslide. On the other hand, the impact of farmland reclamation on slopes on landslides is a very complex issue. Because of the lack of relevant scientific research on the slope before the occurrence of the landslide, the impact of cultivated land on the landslide remains unclear. Therefore, the available data show that there is no direct connection between human engineering activities and the landslide. In this area, heavy rainfall often triggers small landslides (Wu et al. 2014). Although some landslides may be associated with human activities, most of the landslides seem not connected with human engineer activities as evidenced by data available.

5.2 Reason for the severe disaster

The landslide deposit blocked the Shanzao stream, forming a barrier lake, and then the water level dropped after the burst of the barrier lake. The landslide itself did not bury houses and cause casualties, but the upstream area of the Shanzao stream was only 130 m away from the landslide dam in a residential area, implying a large risk. In fact, the barrier lake submerged Shanzao Village, causing 52 houses to collapse, killing about 30 people. The most seriously affected area was located in a residential area approximately 200 m upstream from the barrier dam, where the water level rose approximately 10 m.

In recent years, another similar disaster chain has occurred near this region. It was in 2016, affected by a typhoon and rainstorms, in Su Village, Suichang County, Zhejiang Province, 20 houses were flooded, killing 28 people (Ning et al. 2017). In addition, in 2005, affected by Typhoon Talim, 14 landslides and 6 debris flows occurred in Wencheng County, Zhejiang Province, killing 17 people (Chen 2011). Compared with the alpine canyon areas in western China, the mountainous and hilly areas along the coast of southeast China are more economically developed, densely populated and have more human engineering activities, with more disturbances to natural slopes. With frequent typhoons and rainstorms, these areas are highly prone to landslides. After landslides occur, their deposits may block rivers and form landslide dams. The torrential flood caused by typhoons and rainstorms will cause the water level upstream from the landslide dams to rise rapidly and form barrier lakes. Moreover, the topographic relief in these areas is usually small. Most of the residents live along the rivers, and the barrier lakes can quickly submerge their houses. This kind of disaster chains is much more harmful than a single landslide or flood event. Therefore, it is particularly important to carry out the assessment of landslides in rainstorm conditions in mountainous and hilly areas along the coast of southeast China.

6 Conclusions

This paper presented a typical typhoon – rainstorm – landslide – barrier lake – flooding natural disaster chain in Yongjia County, Zhejiang Province, China that occurred in 2019. The landslide was induced by typhoon rainstorm and the internal factors include strong weathered rock and soil mass with low strength and local steep terrain. This case tells us that even if a not big landslide occurred in this area, once a natural disaster chain is formed, it will cause serious disaster. Therefore, it is necessary to strengthen the study of the mechanism of such landslides, which is of important for prediction and prevention of this kind of disaster chain. It is suggested that future research should focus on the more timely and accurate monitoring and warning methods for rainstorms, landslides, dammed lakes, flood, and associated disaster chains in low mountains and hilly areas of the southeastern China.

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