Catastrophic Mechanism and Stability Analysis of Jiangdingya Landslide in Zhouqu County, Gansu Province, China

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ORIGINAL PAPER

Catastrophic Mechanism and Stability Analysis of Jiangdingya Landslide in Zhouqu County, Gansu Province, China

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Abstract

On July 12, 2018, a large-scale landslide occurred in the Jiangdingya area, Nanyu Town, Gansu Province, China. According to remote sensing interpretation and field investigation, the landslide volume is about 480×10^4 - $550\times10^4 m^3$, which caused the Bailongjiang River to be blocked and the water level to rise, forming a dammed lake, flooding Nanyu Town. The landslide is characterized by chain disasters, which poses a serious threat to the ecological security of the upper reaches of the Yangtze River. In this paper, the catastrophic mechanism of Jiangdingya landslide is analyzed, and the stability of the slope is studied. According to the disaster characteristics, comprehensive safety control measures are put forward. The study shows that the occurrence of landslides is closely related to geological structure, environmental evolution, precipitation infiltration, earthquake damage and human activities, among which geological structure is the decisive factor and earthquake and rainstorm are the inducing factors. Under the action of river erosion and precipitation infiltration, it is easy to trigger the revival of new large-scale landslides. Therefore, it is necessary to take risk management measures for landslides, strengthen the risk identification of landslide disasters, and avoid the recurrence of serious geological disasters. The research results of this paper are of great significance to the prevention and control of chain disasters and the comprehensive treatment of slopes.

Key words Landslide · Catastrophic mechanism · Stability analysis

1 Introduction

China is one of the countries with serious landslide disasters in the world. Due to the special landform and geological environment conditions, landslide disasters occurred every year in history. There are nearly one million geological disaster points in China, among which there are more than 34,000 serious geological disaster points. Nearly 1,000 people die every year due to geological disasters, and the direct economic loss is 20 billion yuan. The annual cost of landslide remediation of the state is as high as 50 million yuan (Huang 2012; Zhou et al. 2016). In 1999, the Deng Long Street landslide in Wushan County, China, with a volume of 500,000 cubic meters, made 3,600 people homeless. In 2010, 99 people died in a landslide in Guanling, Guizhou Province, China (Wang et al. 2004). In 2014, the ancient OSO landslide in Washington State, USA, was resurrected with a volume of 760 × 104 m^3. The landslide caused 43 deaths and buried the highway SR530 (Iverson et al. 2015; Guo et al. 2015; Guo et al. 2020).

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The study of the development characteristics and formation mechanism of landslides has gradually become one of the core problems and hot issues in landslide disaster research. Landslides are mostly caused by some natural factors such as rainfall, earthquakes, river erosion, etc., or some human engineering activities such as digging mountains to build the land, cutting slopes and building dams (Wang et al. 2008; Yin et al. 2010; Gorum et al. 2011; Xu et al. 2015; Deng et al. 2017; Fan, et al. 2018). The Zhouqu County of Gansu Province is located in the south of the West Qinling tectonic belt, with high mountains and deep valleys, well-developed geological structure and strong neotectonic movement, which is a seismic prone area (Huang and Li 2011; Jiang et al. 2016; Liu et al. 2015). The rock mass in this area is broken, the structure is loose, the slope is large, the geological environment is fragile, and the soil erosion is serious (Meng et al. 2013; Zhang et al. 2015). It is one of the areas with high incidence of landslides, collapses and mudslides in China. There is a high frequency of resurrection of landslides in this area, such as Xieliupo landslide, Nanyu landslide, Suoertou landslide and so on (Scheidegger and AI 1987; Yang et al. 2014; Jiang et al. 2016). At present, some landslides continue to deform and cause new disasters (Fig. 1).

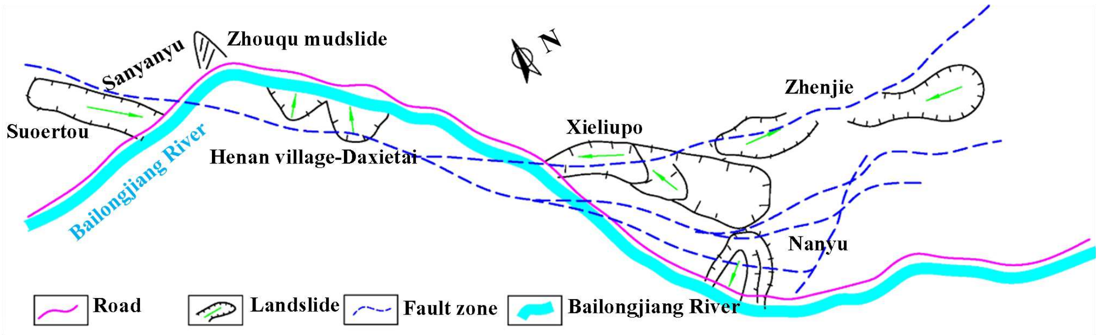


Fig. 1 Landslide group in Bailongjiang River Basin

At about 17:00 on June 13, 1991, the Jiangdingya landslide of Nanyu Landslide Group in Nanyu Town, Zhouqu County, Gansu Province, China, experienced a large-scale sliding (Chen 1991; Ren 1993; Wang et al. 1994; Mu 2011). The lower part of the landslide body was firstly sheared and destroyed, then slowly declined and instantly blocked the Bailongjiang River. Then, the upper part of the landslide mass was pulled to slide rapidly. The huge thrust of landslide soil and the jacking action of the steep wall on the other side of the Bailongjiang River made the sliding tongue of the sliding body climb along the steep wall, and finally form an earth dam with a height of 20m and a width of 50m. As a result, the Bailongjiang River is cut off for up to 8 hours, the backwater in the upper reaches of Bailongjiang River is about 2.8km, and the accumulated water is 754.9×104 m^3. Half of the Nanyu Town is submerged and the loss is serious (Huang et al.2013). In the following years, the Jiangdingya landslide was basically stable. At about 8: 00 on July 12, 2018, the Jiangdingya ancient landslide was reactivated (Fig. 2). The reactivated Jiangdingya landslide (H_1 landslide) belongs to the local part of Jiangdingya ancient landslide (H landslide) The earthwork volume of landslide reached 480×104 - 550×104 m^3, which caused the Bailongjiang River to be blocked and the water level to rise.

Fig. 2 The resurrected Jiangdingya landslide (H_1 landslide) in 2018

The Jiangdingya landslide has the characteristics of chain disaster, which not only threatens the safety of Nanyu Town, but also interrupts the safe operation of roads and hydropower stations. The blocking of large-scale rivers will endanger the safety of the Zhouqu County in the upper reaches and Longnan City in the lower reaches. It will also pose a serious threat to the ecological security of the upper reaches of the Yangtze River with immeasurable losses. In this paper, the catastrophic mechanism of Jiangdingya landslide is analyzed, and the stability of the slope is studied. According to the characteristics of disasters, the comprehensive safety control scheme is put forward. The research results of this paper are of great significance to the prevention and control of chain disasters and the comprehensive treatment of slopes.

2 General situation of physical geography and regional geology

2.1 Geological overview of landslide area

1.1.1 Geographical location and topography

The Jiangdingya ancient landslide is located in Nanyu Town, Zhouqu County, Gannan Tibetan Autonomous Prefecture, Gansu Province, China (Chen 1991; Ren 1993) (Fig. 3). The geographic coordinate of the landslide is 104°25'7"~104°25'47" E and 33°43'03"~ 33°43'43" N. Zhouqu County is located in the eastern edge of Qinghai-Tibet Plateau, where the west wing of West Qinling meets Minshan Mountains. The elevation of the top of the mountain is 2052m, the elevation of the foot of the slope is 1241m, the relative height difference is 811m, and the topography fluctuates greatly. The Boiling River passes from the northwest to the southeast from the front edge of the slope (Fig. 2). Due to the combined action of structural erosion and water erosion, the landform of this area can be divided into two types: the eroded structural alpine landform and the eroded accumulation valley terrace landform.

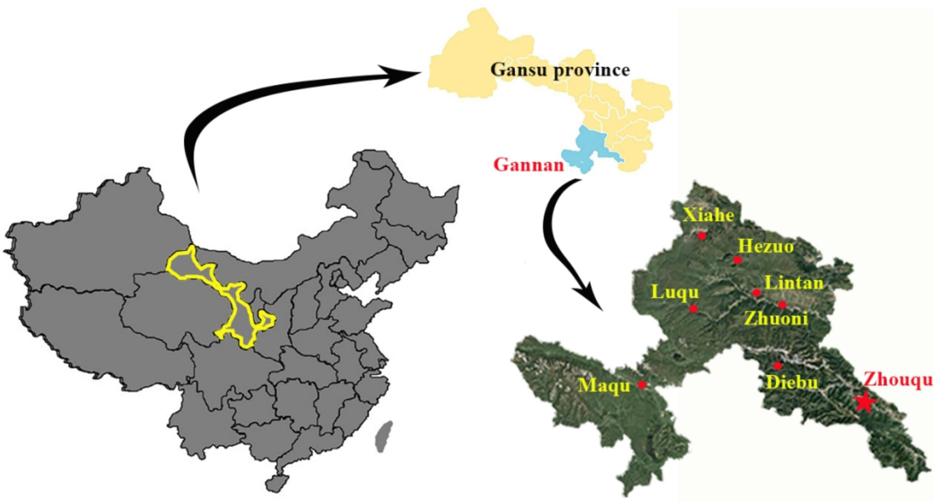


Fig. 3 Geographical location of landslide

The left bank of Bailongjiang River is an eroded structural alpine landform with a slope of about 20°-45°. Due to the long-term spalling and accumulation of residual slope sediments, a gentle slope platform is formed in the middle of the slope. The lower slope of the slope body is relatively gentle, about 20-25° and the upper slope is steep, about 30-45°. The topography of the slope is strongly cut, forming a number of small "V" shaped gullies, which are mostly long strips. The Jiangdingya ancient landslide is located in the upper part of the slope body with a gradient of about 20°. The topography of the slope surface fluctuates greatly. The rear part of the sliding body is depression, and tensile cracks and shear cracks are developed in the middle, lower part and front edge, forming drumlins locally (Fig. 4. (a)). The leading edge has been obviously transformed by human engineering activities, and a scarp with a slope of 45° is formed by manual excavation (Fig. 4. (b)).

(a) Drumlin (b) Scarp

Fig. 4 The eroded structural alpine landform

The front edge of the slope body is eroded accumulation valley terrace landform. The widest part is located on the west front edge of the Jiangdingya ancient landslide, which is the second terrace of the valley. It is distributed in the gentle slope form from northeast to southwest, with an average slope of about 3° and about 8-10 m higher than Bailongjiang River (Fig. 5. (a)). The narrowest part is located at the front edge of the landslide mass. Affected by the accumulation of landslide mass, the width of the river is only 35-40 m, the river is turbulent and the bank wall is upright (Fig. 5. (b)).

(a) The front edge of the second terrace of the valley (b) The river is turbulent and the bank wall is upright

Fig. 5 The eroded accumulation valley terrace landform

2.1.2 Stratigraphic structure

The exposed strata of the Jiangdingya landslide (Fig. 6) from bottom to top are: Bailongjiang River group of Middle-Upper Silurian system ($S_{2+3}bl_1$), Gudaoling formation of Xihan Water group of Middle Devonian system (D_2^2g), Upper Carboniferous System (C_{2+3}), Holocene old landslide deposits (Q_4^{del}), and Holocene proluvial (Q_4^{al+pl}).

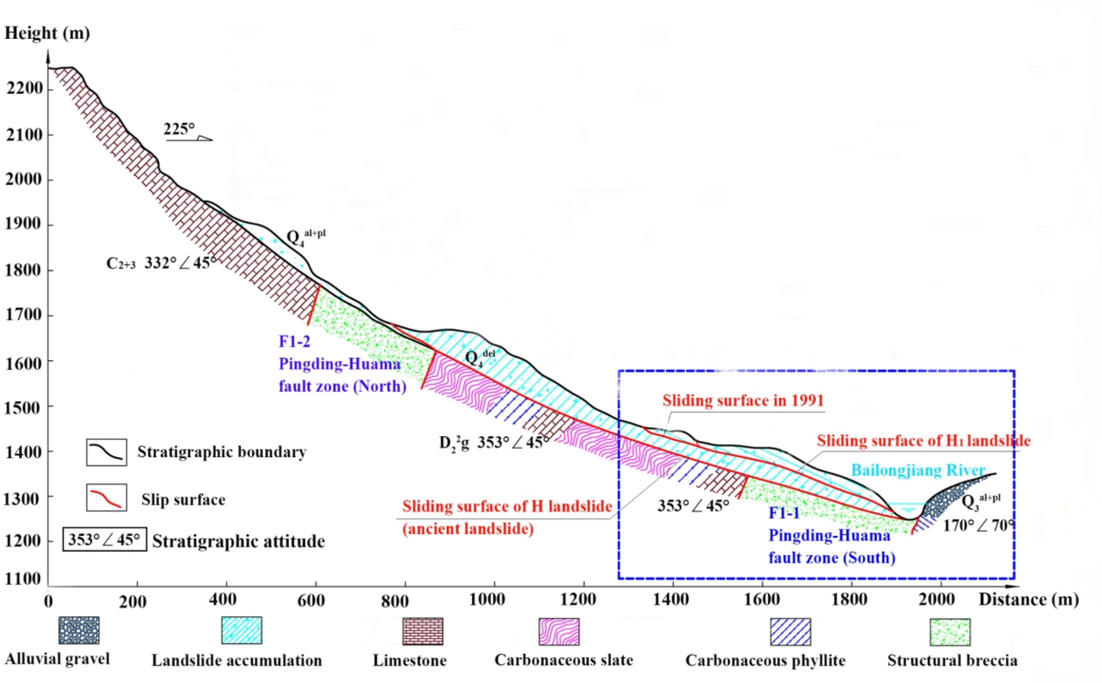


Fig. 6 Stratigraphic structure section (section1-1')

2.1.3 Hydrogeological conditions

The Jiangdingya landslide develops along the fault zone, and the slope surface is the loose and broken gravelly soil, which determines that the recharge of groundwater is mainly atmospheric rainfall and the water in karst fissures at the top of the mountain. The aquifer of the water in karst fissures is mainly composed of Carboniferous limestone, and the groundwater occurs in the weathered fracture of limestone, which is phreatic water. There is pore water in loose rock in landslide accumulation. According to the post-disaster investigation, there is no water in the middle part of the landslide, but there is water in the back and middle front part, which indicates that there has not been a unified aquifer after the landslide. Because the gray-black gravel clay in the landslide belongs to the relative water-resisting layer, there is stagnant water in the upper part of the slope. There is a "water gathering effect" on the upper part of the sliding surface, and the groundwater mainly occurs in the layer of gravelly soil. The existence of groundwater in the sliding body reduces the cohesion and internal friction angle of the slope, and increases the instability of the sliding body.

2.1.4 Geological structure

The Nanyu landslide group is located in the west wing of the front arc of the "mountain-shaped" structural system in Wudu City, China. Which is greatly influenced by the famous latitudinal structural system in China. The Heiyu – Zhouqu - Huama fault zone that runs through the north side of Zhouqu County, it is a group of regionally-strike compression fault zones, which strictly control the strike of the Bailongjiang River, and is accompanied by many faults in EW, NNE and NE directions, forming a fault fracture zone with a width of about 4.0km. The Nanyu landslide group is cut by three fault zones, which are the NWW-oriented fault between Lower Carboniferous in Upper Paleozoic and Gudaoling Formation in Xihan Water Group in Middle Devonian, a NWW-oriented fault between Gudaoling Formation in Devonian and Bailongjiang River Group in Middle and Upper Silurian in Lower Paleozoic, and another NE-oriented fault that cuts off the above two faults. The Jiangdingya ancient landslide is located in the subsidence block between the above three faults, and its stability is extremely poor (Fig. 1).

The Jiangdingya landslide has strong tectonic activity, which forming a roughly parallel NW trending fault zone. As shown in Fig. 7, the Pingding-Huama fault zone constitutes of NW and SE fault zone. There are many secondary branch faults along the south side of the main fault. The Pingding-Huama fault zone is composed of the North Branch fault zone and South branch fault zone, which are distributed in parallel. After the rock mass in the middle of the South and North Branch faults is compressed, the rock mass is broken and many small folds and secondary faults are developed.

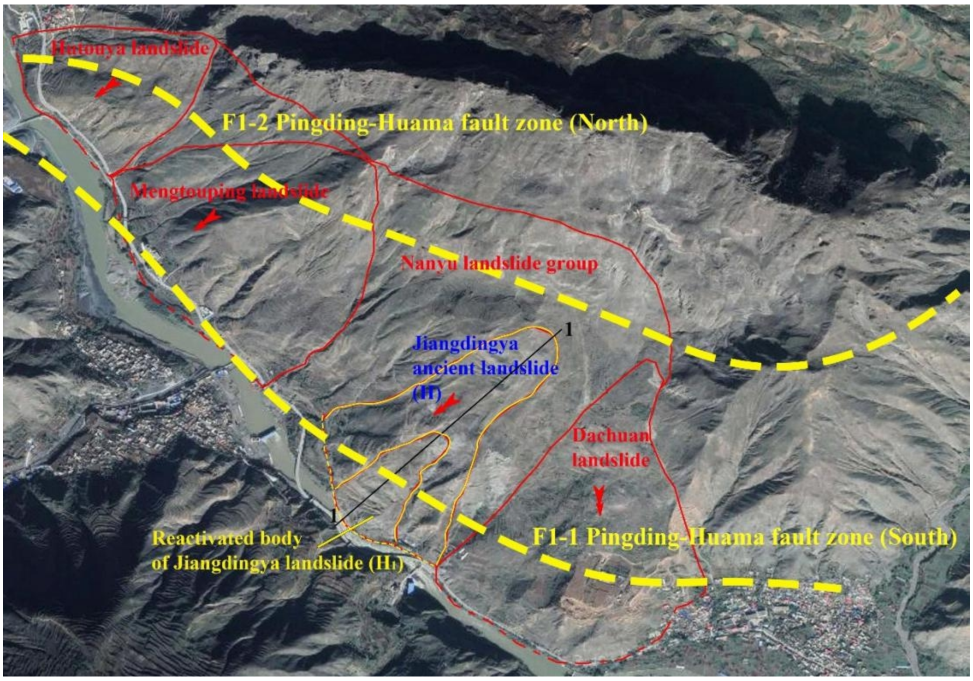
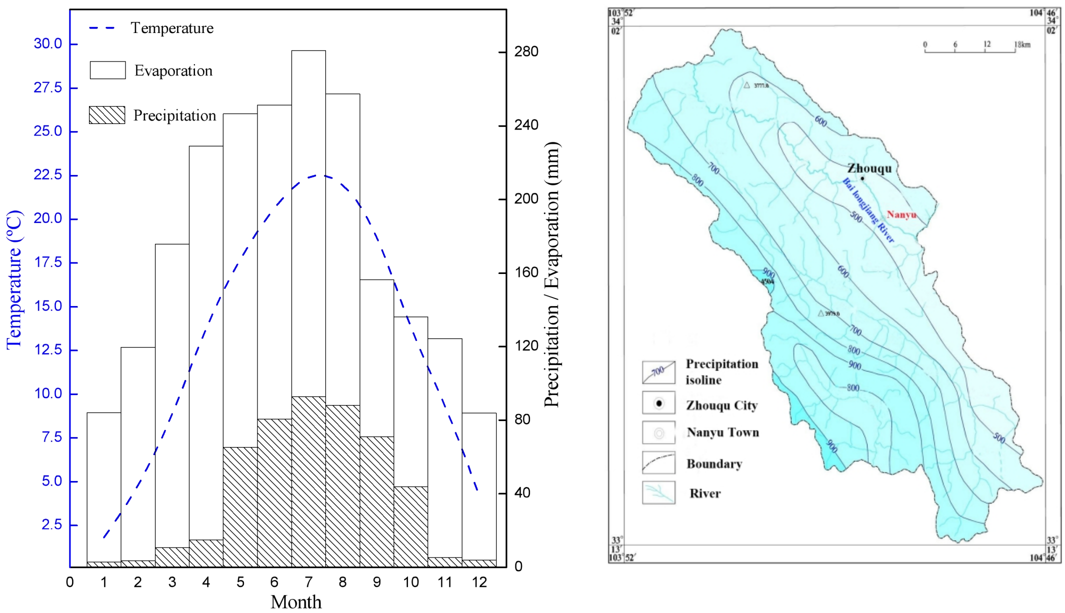


Fig. 7 Remote sensing image of Nanyu landslide group

2.1.5 Climatic characteristics

The Bailongjiang River Basin belongs to the transitional zone from north subtropical zone to the north temperate zone. Influenced by atmospheric circulation and topography, it is characterized by obvious vertical climate zoning and distinct dry and wet seasons. During the year, the climate is controlled by the monsoon. With the increase of altitude, the climate of mountain and valley changes obviously vertically. The precipitation is small and uneven, with large evaporation, dry in winter and spring, rainy in summer and autumn, and the precipitation is mainly concentrated in May to September (Fig. 8. (a)). The temperature change in the region is small, and the temperature difference between day and night is small. The annual average temperature is 12.9°C. The highest temperature is in July, the average temperature is 23.0°C, the lowest is in January and the average temperature is 1.7°C. According to the statistics of Zhouqu County Meteorological Station collected in 2017, the average rainfall is 400-800mm, the maximum daily rainfall is 96.7mm, and the maximum rainfall in one hour is 77.3mm. With the increase of altitude, precipitation also increases (Fig. 8. (b)).



(a) Meteorological element **(b) Multi-year rainfall isogram**

Fig. 8 Climate characteristic of the Bailongjiang River Basin

2.1.6 Human engineering activity

Human activities in the Jiangdingya landslide area are mainly manifested in two aspects: cutting slope to build roads and gentle slope cultivation. According to the investigation, due to the construction of national highway G345, the foot of the front edge of the Jiangdingya ancient landslide was artificially cutting and turned into a steep scarp with a height of about 9-16m, which increased the free surface at the leading edge of the ancient landslide body and reduced the stability of the leading edge slope of the landslide body (Fig. 9. (a)).

With the increasing population, the planting area of steep slope and gentle slope in Jiangdingya area is expanding, which destroys the original vegetation, makes the surface bare, reduces the water-holding capacity of soil, and forms a softening layer at the interface between soil layer and bedrock. In addition, the slope at the back and front of Jiangdingya ancient landslide is mostly cultivated artificially. Perennial irrigation increases the water content of the slope, and a large amount of water enters the landslide along the gravelly soil, which increases the water content of the soil and reduces the shear strength, resulting in a gradual decrease in the stability of the slope (Fig. 9. (b)).

(a) Scarp formed by road construction **(b) Slope cultivation**

Fig. 9 Human activity in Jiangdingya landslide area

2.2 Evolution history of landslide

The Jiangdingya landslide (H_1 landslide) is the reactivated body in the middle of the Jiangdingya ancient landslide (H landslide) of Nanyu landslide group, and it has been in sliding state. In the year of 1986, 1988, 1990 and 1991, there were four large-scale sliding events on the Jiangdingya slope, and the river was blocked in the last three times, which caused extremely serious losses. (Chen 1991; Wang et al. 1994) Among them: on September 11, 1990, The Jiangdingya ancient landslide slipped. Millions of cubic meters of landslide pushed the road at the foot of the mountain to the middle of Bailongjiang River. The soil in Bailongjiang River was as high as 5 ~15 m, and the river was partially blocked, and the water level of the river rose and flooded farmland. On June 13, 1991, about 5.3 million cubic meters of soil slipped down from the landslide, blocking the Bailongjiang River for 8 hours, and the upstream backwater was about 2.8 km, which forced Nanyu township to select a site for the reconstruction and suffered serious loss. The resurrection landslide (H_1 landslide) in 2018 has a maximum length of about 462 m, an average width of about 210 m, an average thickness of about 26.5 m, and a total volume of 338.1×104 m^3. It is a large-scale landslide.

3 Development characteristics of landslide

3.1 General situation of landslide

The Jiangdingya ancient landslide is a part of Nanyu landslide group. As shown in Fig. 7, from Hutouya to Dachuan Town, there are four large-scale landslides in the upper part of the 3.7km long slope, they are Hutouya landslide, Mentouping landslide, Jiangdingya landslide and Dachuan landslide in turn. As mentioned above, the Nanyu landslide group belongs to the fault zone landslide group controlled by the Pingding-Huama fault zone. Since historical records, the Nanyu landslide group has experienced multiple landslide disasters, causing serious damage. The Jiangdingya landslide (H_1) resurrected this time is a partial resurrection of the Jiangdingya ancient landslide. The landslide mainly slides along the groove formed by the landslide in 1991, and its scale is smaller than that of the landslide in 1991. The main sliding part of the landslide in 1991 was in the shape of a "long strip". After the sliding body fell, it blocked the Bailongjiang River, causing the river to form an earth dam with a width of about 50 m and a height of about 20 m. According to the sliding characteristics of each part of the sliding body, it is divided into four blocks (Fig. 10).

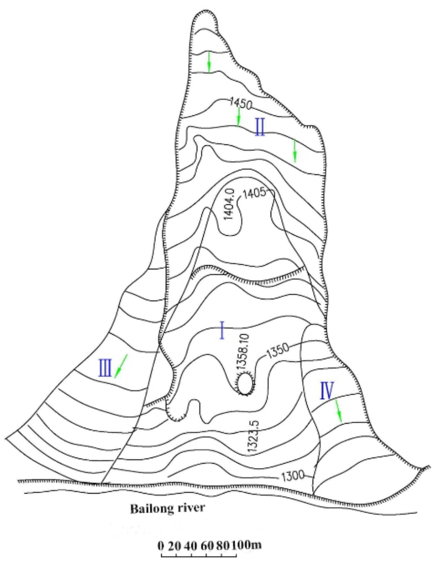


Fig. 10 Jiangdingya landslide in 1991

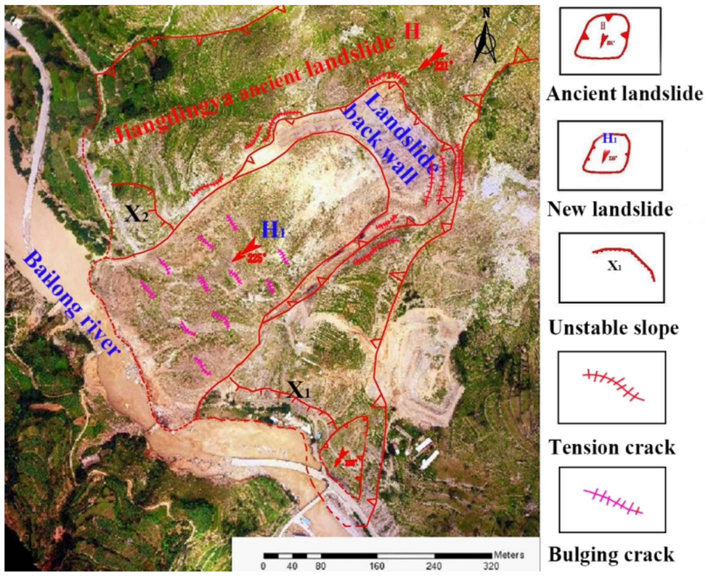


Fig.11 Remote sensing image of Jiangdingya landslide landform

3.2 Development characteristics of jiangdingya landslide

3.2.1 Morphological characteristics

The basic characteristics of the Jiangdingya landslide are shown in Table 1. The reactivation body (H_1 landslide) of the Jiangdingya ancient landslide is a large-scale sliding accumulation landslide. The rear and middle parts of H_1 landslide are relatively gentle, about 13° to 15°, the lower part and front edge are relatively steep, about 20° to 25°. The landslide blocked the Bailongjiang River and destroyed the highway, resulting in the formation of a barrier lake in the upper reaches of Bailongjiang River. In order to dredge the river channel and restore road traffic, the temporary access road was excavated at the lower part of the landslide mass, and the part blocking the river channel at the front edge of the landslide mass was cleaned up, resulting in the formation of scarps in the middle and lower parts of the landslide. After the slide, the lower part of the ancient landslide is pushed and pressed, resulting in the formation of drumlins in the middle of the landslide.

Table 1: Basic characteristics of landslide

Landslide		H landslide	H_1 landslide
Type		Accumulation landslide	Accumulation landslide
Scale	Length (m)	1041	462

	Width (m)	350	210
	Average thickness (m)	55	26.5
	Earthwork (×10^4 m^3)	1493	338.1
Main sliding direction		SW221º	SW225º
Elevation of leading edge/m		1241	1241
Elevation of trailing edge/m		1593	1355
Shape of sliding surface		Broken line	Broken line
Characteristics of slip zone		Carbonaceous slate detritus	Black gravelly clay
Characteristics of sliding bed		The upper part is limestone weathered layer, and the middle and lower parts are gravel soil	Gravel soil

After H1 landslide slides, steep walls are formed at the back and both sides of the landslide mass, and the side and back walls are distributed in the shape of “circle chair”. There are obvious black scratches on the back wall of the landslide (Fig. 12. (a)), and a large number of tensile cracks are developed on the slope surface (Fig. 12. (b)). On the upper part of the top of the slope on the right side of the landslide, there are many tension cracks (Fig. 12. (c)), and a staggered platform with a height of about 1.0 m is formed locally (Fig. 12. (d)). The left side wall of the landslide is basically upright in some parts (Fig. 12. (e)). According to the field measurement, the angle between the side wall scratch and the horizontal is 18° (Fig. 12. (f)), and the sliding surface is relatively gentle.

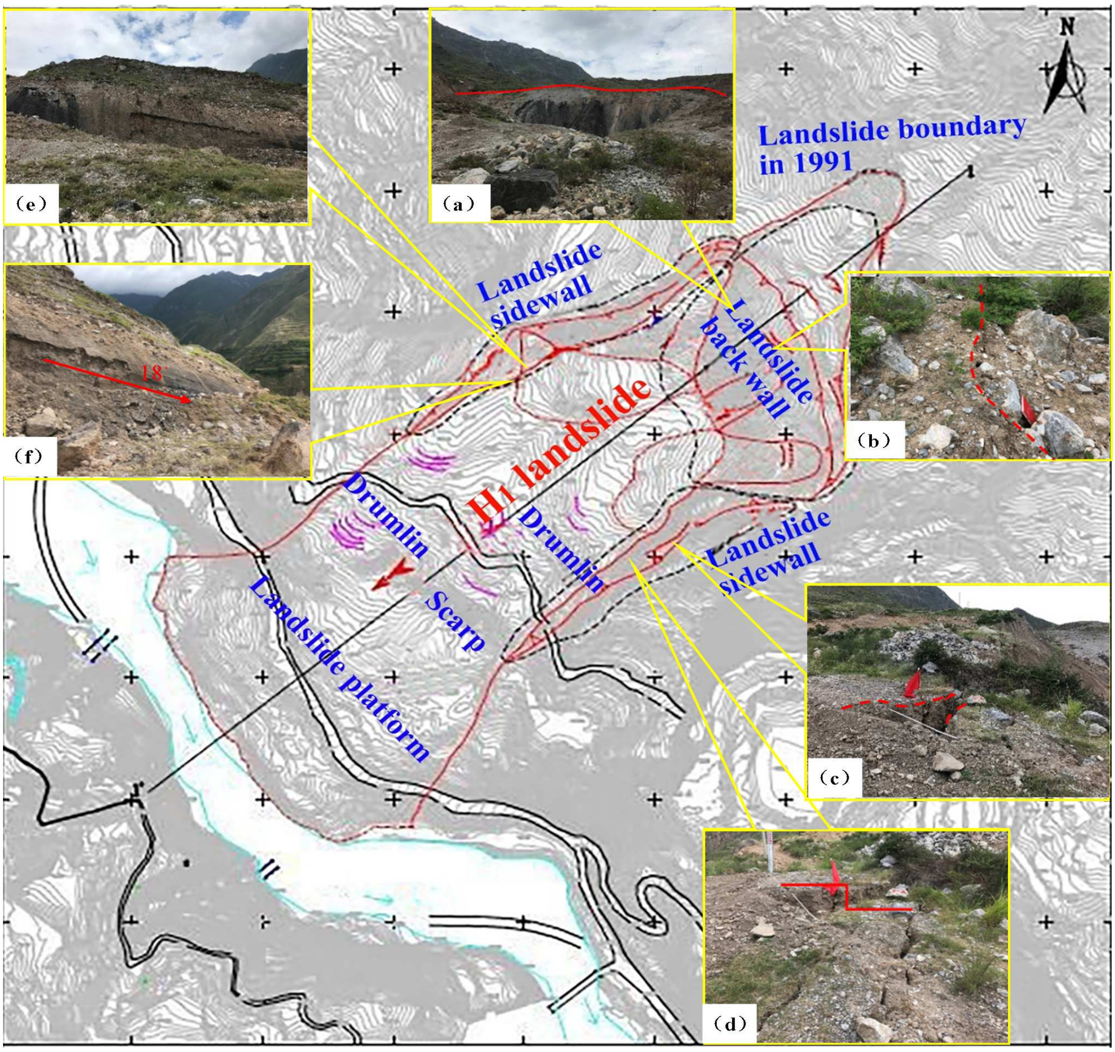


Fig. 12 Morphological characteristics of the Jiangdingya landslide

3.2.2 Structural characteristics

The sliding boundary of H_1 landslide is obvious. The slope of the sliding surface is 14°, 12°, and 9° from the rear to the front edge. The shape of the sliding surface is "broken line", which is relatively flat. The front part of the landslide is affected by factors such as displacement and extrusion, and the main characteristics of landslide are as follows:

(a) Structural and mechanical characteristics of landslide body

The H_1 landslide belongs to accumulation landslide. In the longitudinal direction, the thickness of the landslide is thicker in the middle and upper part, followed by the rear part, and the middle and the front part is thinner. The sliding body in the middle and rear part of the landslide is mainly composed of two layers of soil (Fig. 13), the upper part is gravel soil, it is yellowish brown, the composition is mainly limestone gravels and block stones, and some parts contain large stones with a grain size of 1~2m. The lower part is mainly composed of gray black carbonaceous slate debris with high water content and low strength. The front edge of the sliding mass is gravel soil, and the soil contains large-sized block stones. The statistics of physical and mechanical index test results of the landslide body are shown in Table 2.

(a) Soil layer distribution of landslide body **(b) Gravel soil**

Fig.13 Structural and mechanical characteristics of landslide body

Table 2: Physical properties of landslide body

Type		Maximum	Minimum	Average
Water content (W)	%	19.7	6.5	13.1
Natural density (ρ)	g/cm^3	2.10	1.89	1.99
Dry density (ρ_d)	g/cm^3	1.83	1.64	1.74
Specific gravity (G_s)	-	2.73	2.71	2.72
Void ratio (e_0)	-	0.657	0.502	0.58
Saturation (S_r)	%	99.4	56.5	77.9
Liquid limit (W_L)	%	38.2	29.2	33.7
Plastic limit (W_P)	%	22.0	17.6	19.8
Plasticity index (I_P)	%	15.3	10.5	12.9
Internal friction angle (Φ)	°	24.59	18.2	21.8
Cohesion (C)	kPa	12.4	10.2	11.3

(b) Structural and mechanical characteristics of sliding zone soil

The sliding zone soil at the back of landslide is mainly gray-black gravelly clay, and the soil is soft plastic with a small amount of fine-grained breccia. The water content is high and the soil is saturated. The scratches on the surface of sliding zone soil are obvious (Fig. 14). The statistics of physical and mechanical index test results of the sliding zone soil are shown in Table 3.

Fig.14 Scratch marks of sliding zone soil

Fig.15 Sliding bed soil

Table 3 Physical properties of sliding zone soil

Type		Maximum	Minimum	Average
Water content (W)	%	17.2	6.5	11.85
Natural density (ρ)	g/cm^3	2.1	1.93	2.02
Dry density (ρ_d)	g/cm^3	1.70	1.56	1.63
Specific gravity(G_s)	-	2.73	2.72	2.73
Void ratio (e_0)	-	0.536	0.501	0.518
Saturation (S_r)	%	90.3	35.3	62.8
Liquid limit (W_L)	%	34.2	31.2	32.7
Plastic limit (W_P)	%	22.0	19.9	20.1
Plasticity index (I_P)	%	13.9	12.6	13.2
Internal friction angle (ϕ)	°	7.0	5.8	6.4
Cohesion (C)	kPa	21.2	16.3	16.4

(c) Structural and mechanical characteristics of sliding bed

The lithology of the sliding bed is the accumulation of the ancient landslide, which is yellow-brown with a thickness of about 20~50cm, and is mainly composed of limestone gravels, block stones and carbonaceous slate fragments (Fig. 15). The statistics of physical and mechanical index test results of the sliding bed are shown in Table 4.

Table 4 Physical properties of sliding bed soil

Type		Maximum	Minimum	Average
Water content (W)	%	13.5	6.4	9.9
Natural density (ρ)	g/cm^3	2.21	1.88	2.05
Dry density (ρ_d)	g/cm^3	1.90	1.60	1.75
Specific gravity (G_s)	-	2.72	2.72	2.72
Void ratio (e_0)	-	0.696	0.657	0.677
Saturation (S_r)	%	67.3	66.5	66.9
Liquid limit (W_L)	%	31.7	31.2	31.5
Plastic limit (W_P)	%	19.8	19.5	19.7
Plasticity index (I_P)	%	12.6	11.4	12.0
Internal friction angle (ϕ)	°	24.2	21.6	22.9
Cohesion (C)	kPa	25.8	16.8	21.3

4 Catastrophic mechanism of landslide

4.1 Formation conditions of the landslide

(1) Topographical conditions

Topography is one of the decisive factors affecting the development of landslides. The suitable slope and certain height difference are the basic topographical conditions for landslides. The slope of the Jiangdingya ancient landslide is relatively steep. The height difference between the front slope toe and the back wall of H_1 landslide is 177 m, with a slope of 13° to 25°. The topography with steep trailing edge and open front provides good conditions for the formation of landslide. The soil has a tendency to move to the bottom under the action of gravity due to its large potential energy. Under the action of this trend force, the soil on the upper part of the slope has certain downward dynamic conditions.

(2) Characteristics of the rock and soil

Rock and soil are the material basis for the development of landslides (Zhang et al. 2011). The H_1 landslide developed in the Jiangdingya ancient landslide and is a secondary landslide. According to the geological survey results, the upper geological layer of H_1 landslide is mainly gravel soil, the lower layer is carbonaceous slate debris, and the sliding bed is mainly composed of carbonaceous slate. The upper gravelly soil is mainly composed of block stone and gravel with loose structure and sparse vegetation, which is conducive to the infiltration and circulation of surface water. Under the influence of the fault structure and sliding disturbance, the lower carbonaceous slate debris is extremely broken, it is easy to soften and argillaceous when encountering water, and its engineering properties are extremely poor, so it belongs to the easy-to-slide stratum. The sliding bed is mainly carbonaceous slate, which is affected by Pingding-Huama fault, and the whole stratum is broken, with messy occurrence and developed joints. The lithology of the above strata determines the occurrence and development of the landslide.

(3) Geological structure and earthquake

The distribution and development scale of geological disasters, especially landslides, are obviously controlled by structures. The landslide area is located in one of the areas with the strongest neotectonic movement, with steep mountains and developed river valley terraces. During the long-term rising process, the crust has experienced many tectonic movements, with high mountains and developed rivers. The Jiangdingya landslide is controlled by a large regional fault (Pingding-Huama fault), which is characterized by compression fracture, large scale and long extension, and the width of fracture zone is about 1.0km. The fault passes through the Jiangdingya slope, which divides the strata and controls the mountain trend, making the mountain show fault block development and strong damage, forming a typical structural damage zone. Which provides good conditions for the development of geological disasters.

In addition, the landslide is located in the Zhouqu-Wudu earthquake subzone, which is an earthquake-prone zone. In recent years, frequent seismic actions (such as “5.12” Wenchuan earthquake and “8.7” Jiuzhaigou earthquake) have loosened the rock and soil structure of the slope and reduced the shear strength index, and provided a weak surface for the formation of the later landslide, which is one of the factors inducing and aggravating the landslide.

(4) Water

①Precipitation

According to the data from the Zhouqu County Meteorological Station, the annual average rainfall in the Jiangdingya landslide area is 400-800 mm, and the rainfall is unevenly distributed in time and space. In terms of time, precipitation is mainly concentrated in May to September during the year. Among them, the precipitation from June to September accounts for 61.7% of the annual precipitation, and the rainfall time is relatively concentrated, with short-term rainstorm (Fig. 8.a). Due to the loose structure of the landslide, there are many cracks on the surface of the slope, which provides a transmission channel for precipitation infiltration. Under the action of heavy rainfall or long-term rainfall, rainwater rapidly infiltrates into the slope cracks, destroys the soil structure, reduces the shear strength of rock and soil, and increases the slope load, which is not conducive to the slope stability (White and

Singham 2012; Zhang et al.2014). The instantaneous rapid rainfall has the greatest impact on landslide. The rainfall infiltration not only changes the shear strength of soil structure surface, but also forms seepage through landslide mass in a short time, which increases the hydrodynamic pressure of slope. The rainfall erodes the slope and destroys the soil structure, which makes the landslide slide along the joint fissure surface and the sliding surface of the old landslide, thus causing landslide and other geological disasters.

②Water erosion

The front edge of the landslide continuously squeezed the Bailongjiang River, but due to the water erosion, the river channel has not been blocked. Under the influence of heavy rainfall or long-term rainfall, the water level of Bailongjiang River rises, which increases the buoyancy and the saturation weight of the slope at the front edge of the landslide, and reduces the anti-sliding stability of the slope. Due to the large flow and high velocity of the river, the front edge of the landslide is scoured and eroded strongly. As a result, the front edge of the slope collapses, which causes the upper slope to lose its support and produce sliding deformation, and pulls the rear soil to slide.

(5) Human factors

Due to the construction of the G345 National Road, the toe of the front slope of the Jiangdingya ancient landslide was artificially squared into a steep scarp with a height of about 9-16m, which led to the increase of the free surface at the leading edge of the slide body and reduced the stability of the ancient landslide. In addition, the Jiangdingya ancient landslide is relatively gentle, and the back and front edge of the slope are mostly reclaimed into cultivated land. Irrigation of cultivated land increases the water content of the slope, and a large number of water bodies enter the landslide, which increases the water content of the soil and reduces the shear strength, and causes the slope stability to gradually decrease.

4.2 Analysis of deformation mode and catastrophe mechanism of landslides

According to the remote sensing image of landslide, the sliding distance at the back of landslide is 89.57m, that in the middle is 87.31-97.25m, and that in the front is 29.79-90.47m (Fig. 16). The sliding distance decreases in turn, which indicates that when the middle-rear block slides down, it is blocked by the front block, the sliding speed slows down. The results show that the sliding mass belongs to the deep deformation of push type landslide.

According to the analysis of slip time, the landslide began to slide at 8:00 on July 12, 2018 and stopped at 9:00 on July 13, 2018, the sliding time lasted for 25 hours. The average sliding distance of the landslide mass is 65.76m, and the moving distance per hour is 2.63m/t, which indicates that the landslide is mainly characterized by push-type with slow deformation.

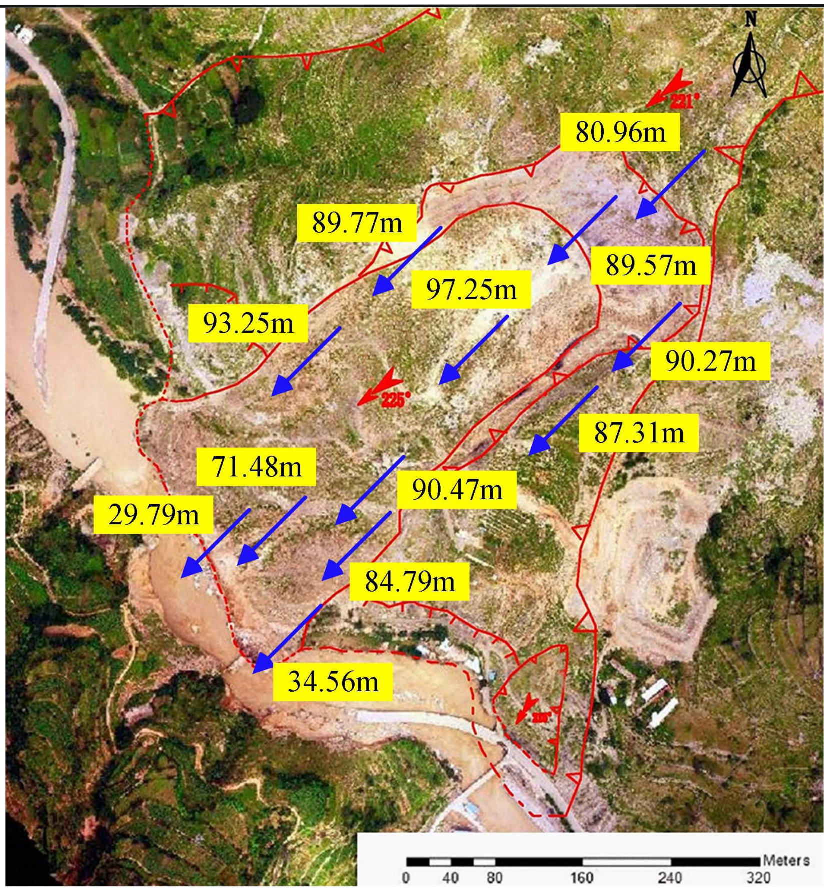


Fig. 16 Sliding distance of the landslide

According to the formation conditions of the landslide in Section 3.1, the mechanism of landslide is summarized as follows (Fig. 17): the Jiangdingya landslide was formed under the coupling action of endogenic and exogenic dynamic forces (Wang 2002; Li et al. 2008). The geological structure of Bailongjiang River basin is complex, weathering and groundwater activities have an obvious softening effect on landslide soil, which makes the Jiangdingya ancient landslide always in the creep deformation state. Tectonic activities, rock properties and terrain conditions are the internal factors of landslide. The appropriate terrain slope provides necessary potential energy and material accumulation for the development and formation of landslide. The tectonic stress of a certain mode and intensity is the external dynamic factor of landslide, and the earthquake is an important factor to induce landslide and collapse. Heavy rain is the main inducing factor in the revival of the Jiangdingya landslide. Atmospheric precipitation and river erosion increase the water content of slope, weaken the mechanical properties of rock and soil, and reduce the stability of slopes. The intervention of human engineering activities has changed the existing environment of landslide, affected the stability of the landslide, and finally aggravated the sliding instability of landslide.

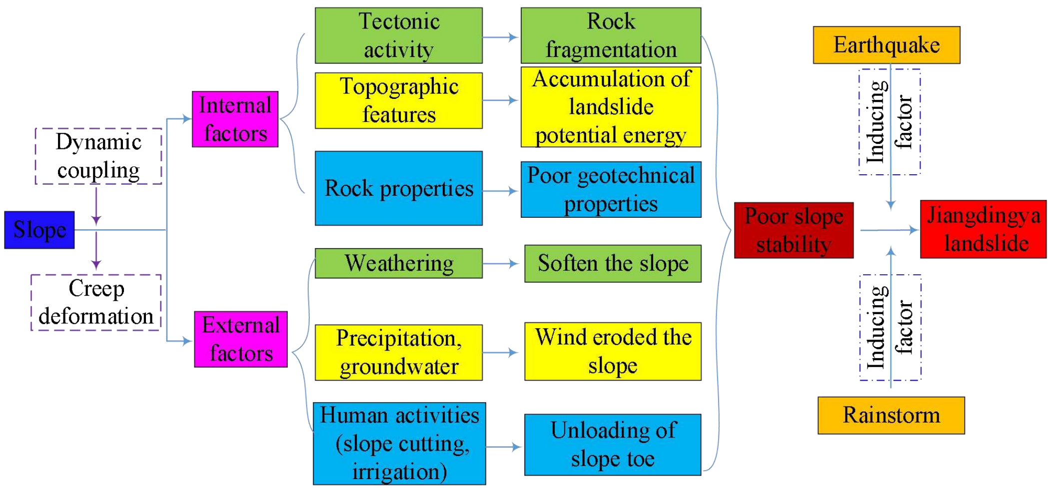


Fig.17 Catastrophe mechanism of landslide

5 Stability analysis and safety treatment of landslide

The landslide is simulated and analyzed by MIDAS GTS, the soil adopts Mohr Coulomb constitutive model, and the supporting structure adopts linear elastic constitutive model. The simulation is divided into two stages. In the first stage, the stability of the section 1-1' of the slope is calculated, and only the boundary conditions and self-weight load are activated. The calculation working conditions are as follows: working condition I: self-weight action. Working condition II: self-weight action + rainstorm action. Working condition III: self-weight action + earthquake action. The rainstorm standard is the rainstorm intensity with a return period of 50 years. The fortification intensity of Zhouqu County is VIII degree, and the peak ground motion acceleration is 0.2g.

Considering the complexity and harmfulness of the landslide, comprehensive treatment is carried out by adopting anchor cable lattice engineering, anti-slide pile engineering, interception and drainage engineering and slope crack treatment engineering. In the second stage, the simulation activates the lattice anchor cable element, anti-slide pile element. The anti-slide pile and anchor cable are set as embedded beam elements, and the lattice structure is set as beam elements. On the basis of statistical geotechnical test data, according to the physical and mechanical properties of sliding body and the soil of the sliding zone, the calculation parameter is shown in Table 5. The supporting structure parameters are shown in Table 6.

Table 5 Physical and mechanical parameters of rock and soil

Soil	Elastic modulus /MPa	Poisson's ratio	Unit weight /kN • m^{-3}	Cohesion /kPa	Internal friction angle /°
Sliding zone soil	12	0.35	20.5	9	18
Landslide body	18	0.32	21	12	22
Fault rupture zone	35	0.32	21	8	26
Gray slate	100	0.26	26	18	36

Table 6 Mechanical parameters of supporting structure

Structure	Element type	Elastic modulus (MPa)	Poisson's ratio	Unit weight (kN/m^3)
Lattice beam	1D beam	31500	0.3	23.5
Anchor	1D embedded beam	200000	0.3	78.5
Lattice column	1D beam	200000	0.3	78.5
Anti-slide pile	1D beam	31500	0.3	23.5

5.1 Stability analysis of landslide

The stability calculation results are shown in Table 7. It can be seen that the landslide is in a stable state under natural conditions, and the stability of the slope will be reduced to a certain extent under the influence of earthquake or heavy rainfall. Under the action of continuous precipitation, the gravity of the upper soil mass of the landslide increases, and the groundwater in the landslide body can not be discharged in time, thus forming a large hydrodynamic pressure in the landslide soil, increasing the sliding force and reducing the stability. Therefore, comprehensive treatment measures should be taken to reinforce the landslide.

Table 7 Summary of theoretical calculation results of landslide stability

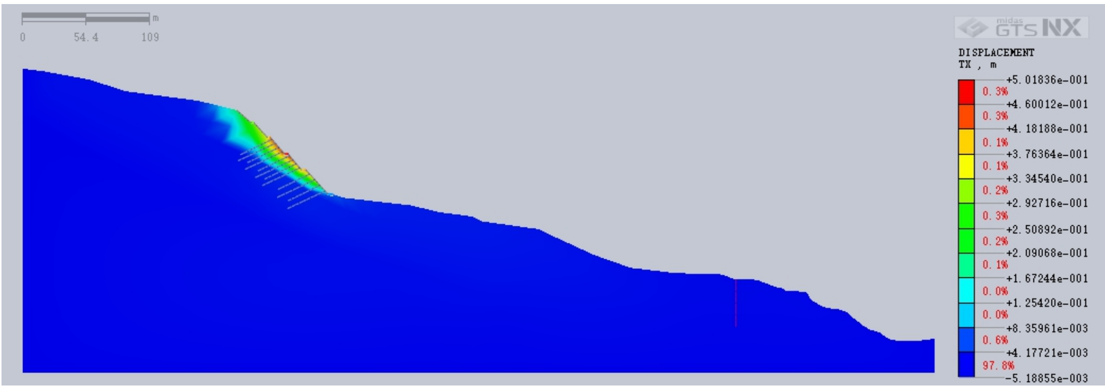
Calculation condition	Stability coefficient	stable state
working condition i: self-weight action.	1.195	stable

working condition ii: self-weight action + rainstorm action	0.979	unstable
working condition iii: self-weight action + earthquake action.	1.014	unstable

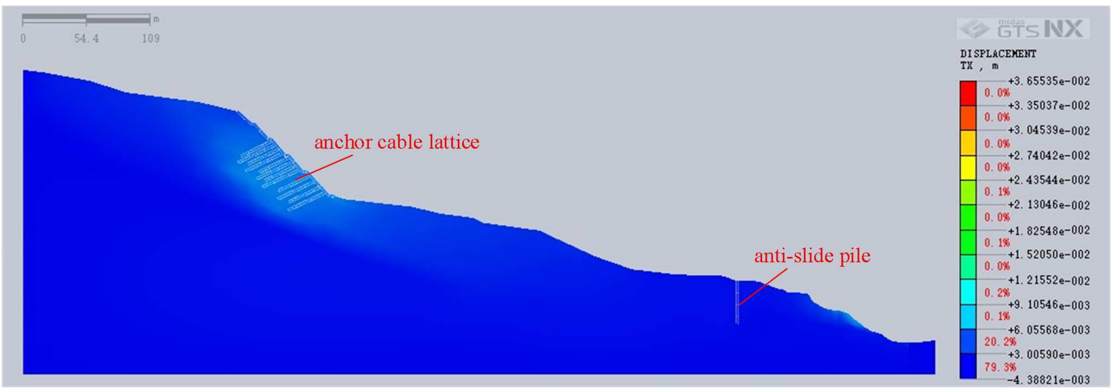
5.2 Safety treatment of landslide

The slope deformation before and after treatment is shown in Fig. 18. According to the horizontal displacement nephogram before landslide treatment (Fig. 18. (a)), the upper slope is the unstable part of the landslide mass, and the horizontal displacement of the upper slope suddenly increases to 20cm~50cm. The lower slope can basically keep stable under the natural state without external disturbance. The simulation results of horizontal displacement after landslide treatment are shown in Fig. 18. (b). It can be clearly seen from the figure that the deformation of the upper slope is effectively constrained after the anchor cable lattice is set, which indicates that the anchoring engineering effectively strengthens the unstable rock and soil mass and limits its deformation.

In addition, the reinforced concrete lattice beam plays an auxiliary role in retaining soil and dispersing the anchoring force. The anti-slide pile set in the lower slope provides greater shear bearing capacity to the originally weak sliding surface by passing through the pile body of the sliding surface. Because the displacement of the original lower slope is small, the effect of the anti-slide pile in the horizontal displacement result in the second stage is not obvious, but it can be used as a safety reserve.



(a) before the safety treatment



(b) after the safety treatment

Fig. 18 Displacement nephogram of slope

6 Conclusion

In this paper, the catastrophic mechanism and stability analysis of Jiangdingya landslide are studied, according to the characteristics of disasters, the comprehensive safety control scheme is put forward, the following conclusions are obtained:

(1). The Jiangdingya landslide is formed under the coupling effect of endogenic and exogenic dynamic forces. The deformation of the front edge of the landslide is mainly traction collapse. The upper part of the landslide is affected by groundwater infiltration and sliding force, and the main deformation is creep deformation. In general, the thrust from the upper part of the landslide is greater than the traction force in the front part of the landslide, the Jiangdingya landslide belongs to sliding-traction landslide.

(2) The Jiangdingya landslide is affected by the fault zone, with broken rock mass and special topography accumulating landslide potential energy, which provides conditions for landslide sliding. The geological environment in Jiangdingya area determines the diversity, susceptibility and regional variability of geological disasters.

(3) The occurrence of the Jiangdingya landslide is closely related to the superposition of geological structure, environmental evolution, precipitation infiltration, earthquake damage and human activities. Among them, the geological structure is the decisive factor, and earthquake and rainstorm are the inducing factors.

(4) The Jiangdingya slope is in a creep state under the coupling effect of endogenic and exogenic dynamic forces. Precipitation infiltration and agricultural irrigation increase the water content of slope and weaken the shear strength of slope continuously. The water erosion has continuously weakened the stability of the slope, which easily leads to the revival of new large-scale landslide.

(5) In view of Jiangdingya landslide, risk management measures should be taken to identify the landslide disaster risk, strengthen mass prevention and treatment, strengthen landslide early warning, and avoid the recurrence of major geological disasters.

(6) Under the influence of earthquake or heavy rainfall, the stability of slope will be reduced to a certain extent. The comprehensive treatment of anchor cable lattice structure engineering, anti-slide pile engineering, interception and drainage engineering and slope crack treatment engineering has a positive effect on landslide disaster prevention and ecological restoration.

Data Availability Statement All testing data appear in the submitted article figures, and curve diagrams.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest. Some or all data, models, or codes generated or used during the study are available from the corresponding author by request.

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Figures

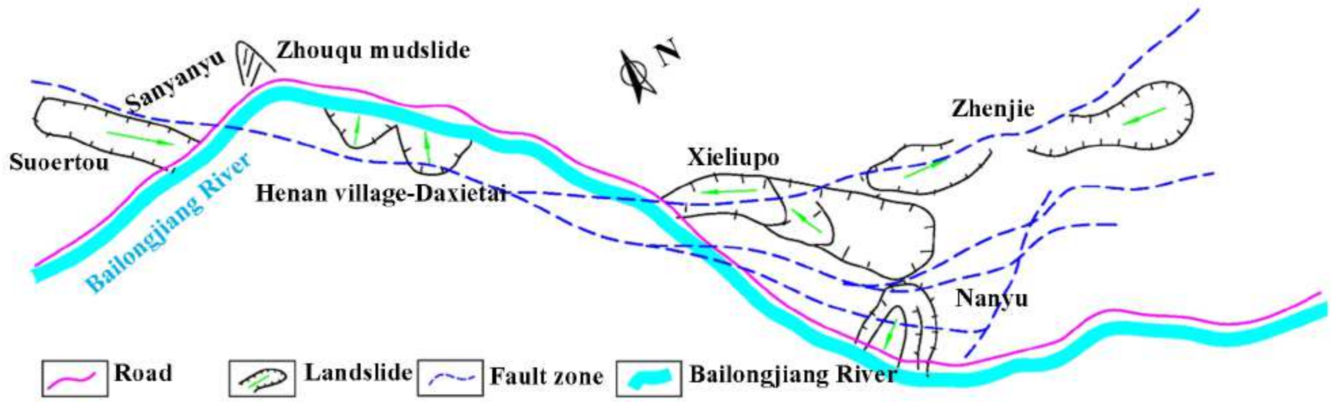


Figure 1

Landslide group in Bailongjiang River Basin. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

The resurrected Jiangdingya landslide (H1 landslide) in 2018. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

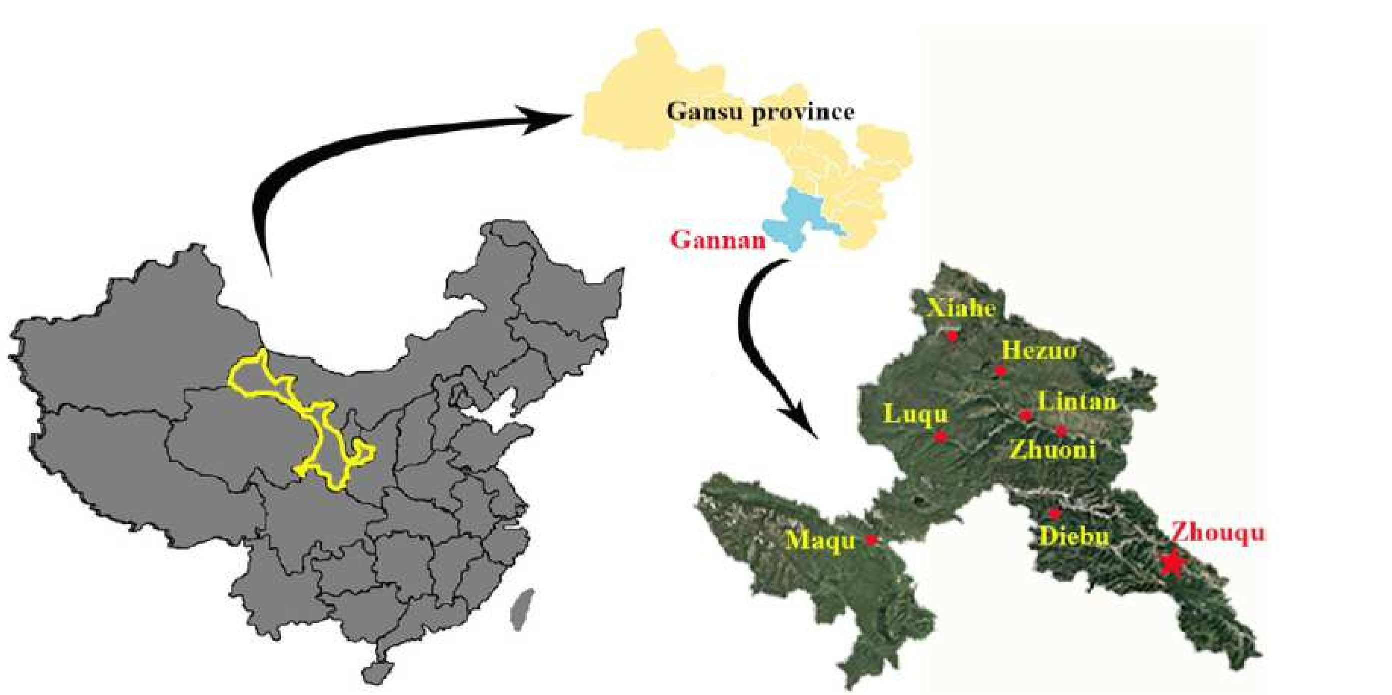


Figure 3

Geographical location of landslide Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

The eroded structural alpine landform. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a) The front edge of the second terrace of the valley **(b) The river is turbulent and the bank wall is upright**

Figure 5

The eroded accumulation valley terrace landform. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

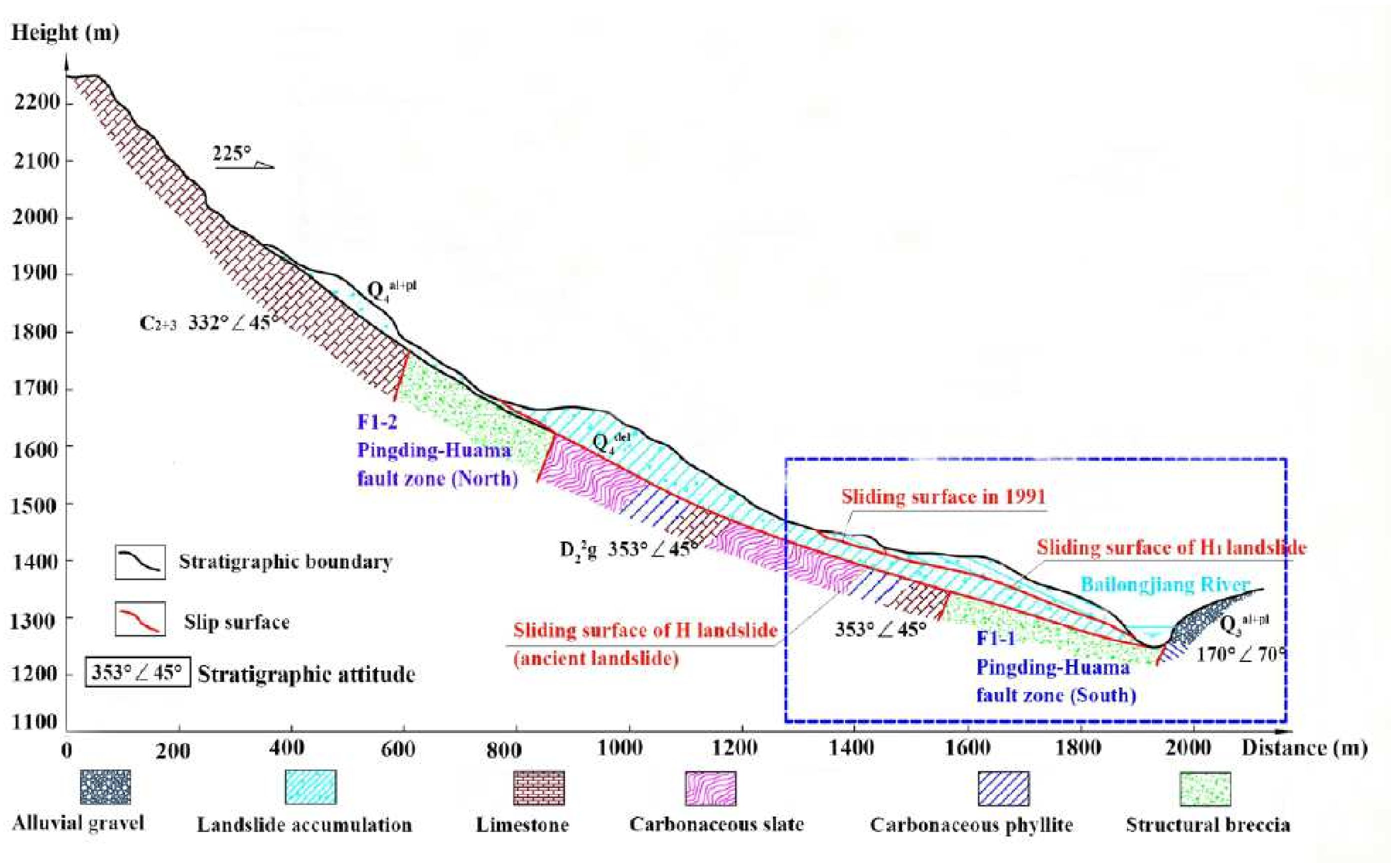


Figure 6

Stratigraphic structure section (section1-1’)

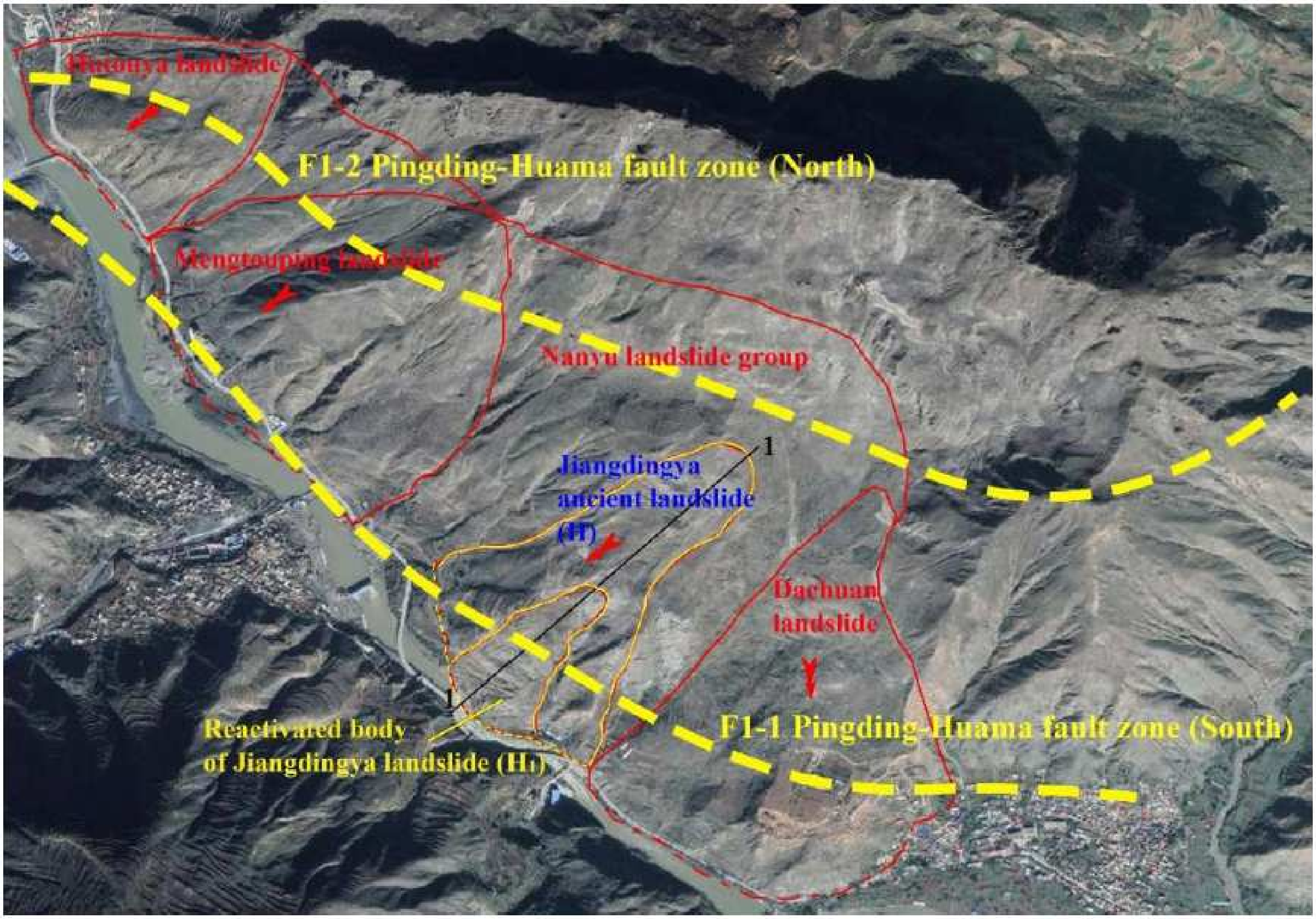
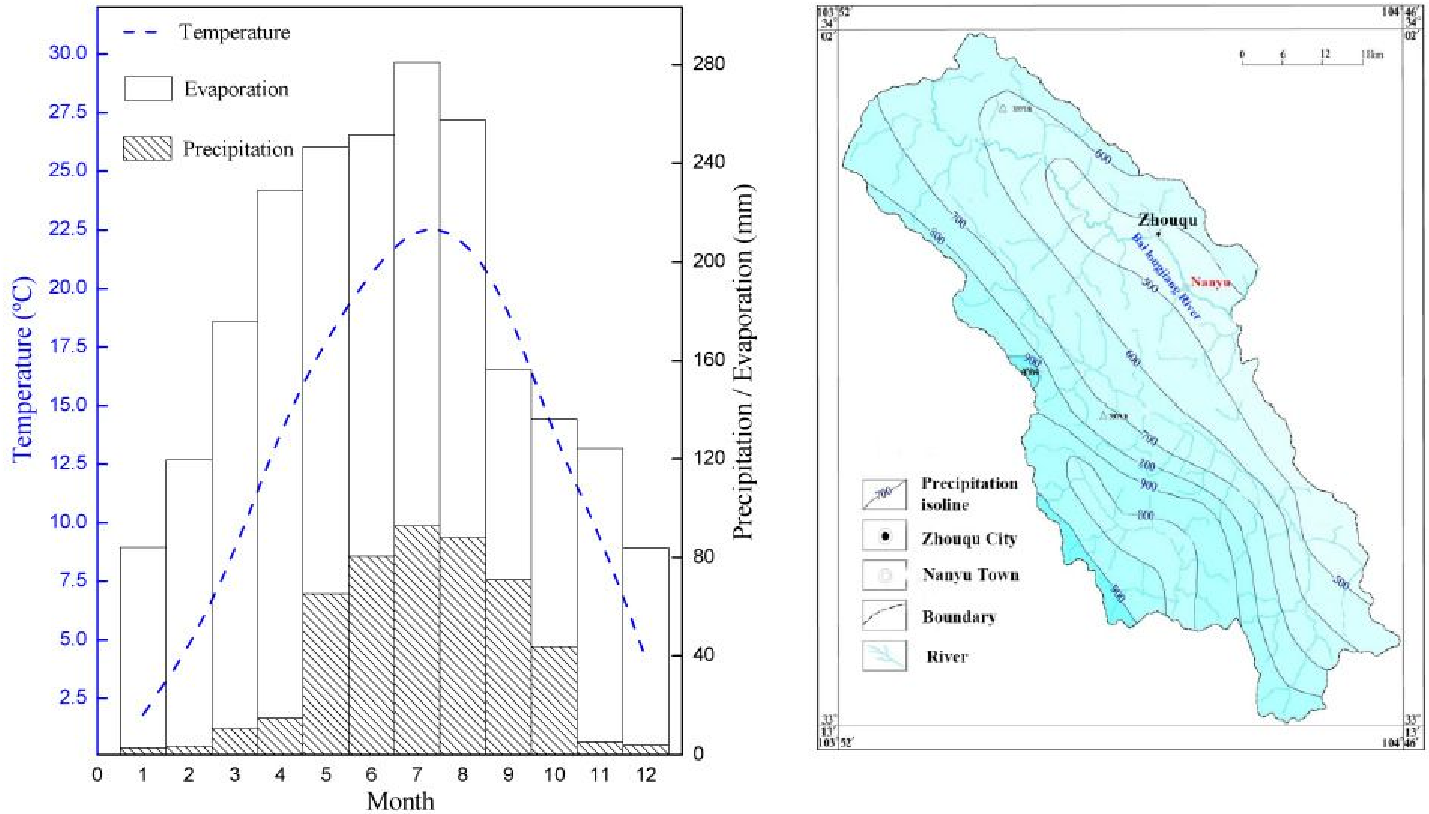


Figure 7

Remote sensing image of Nanyu landslide group. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



(a) Meteorological element

(b) Multi-year rainfall isogram

Figure 8

Climate characteristic of the Bailongjiang River Basin. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a) Scarp formed by road construction (b) Slope cultivation

Figure 9

Human activity in Jiangdingya landslide area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

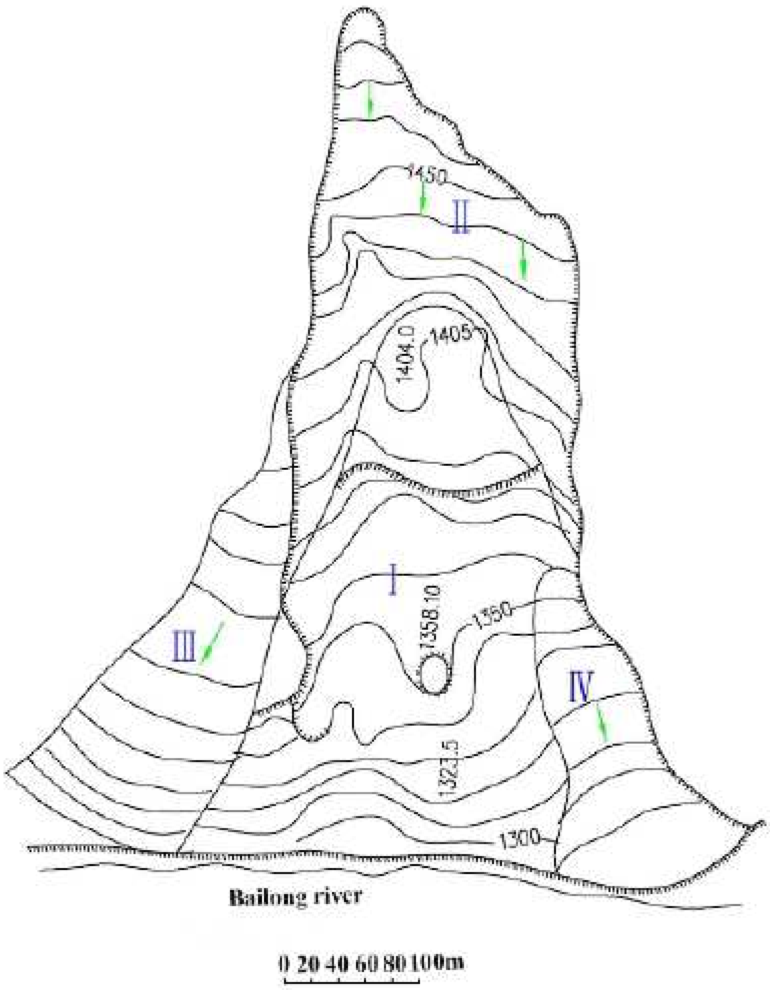


Figure 10

Jiangdingya landslide in 1991. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

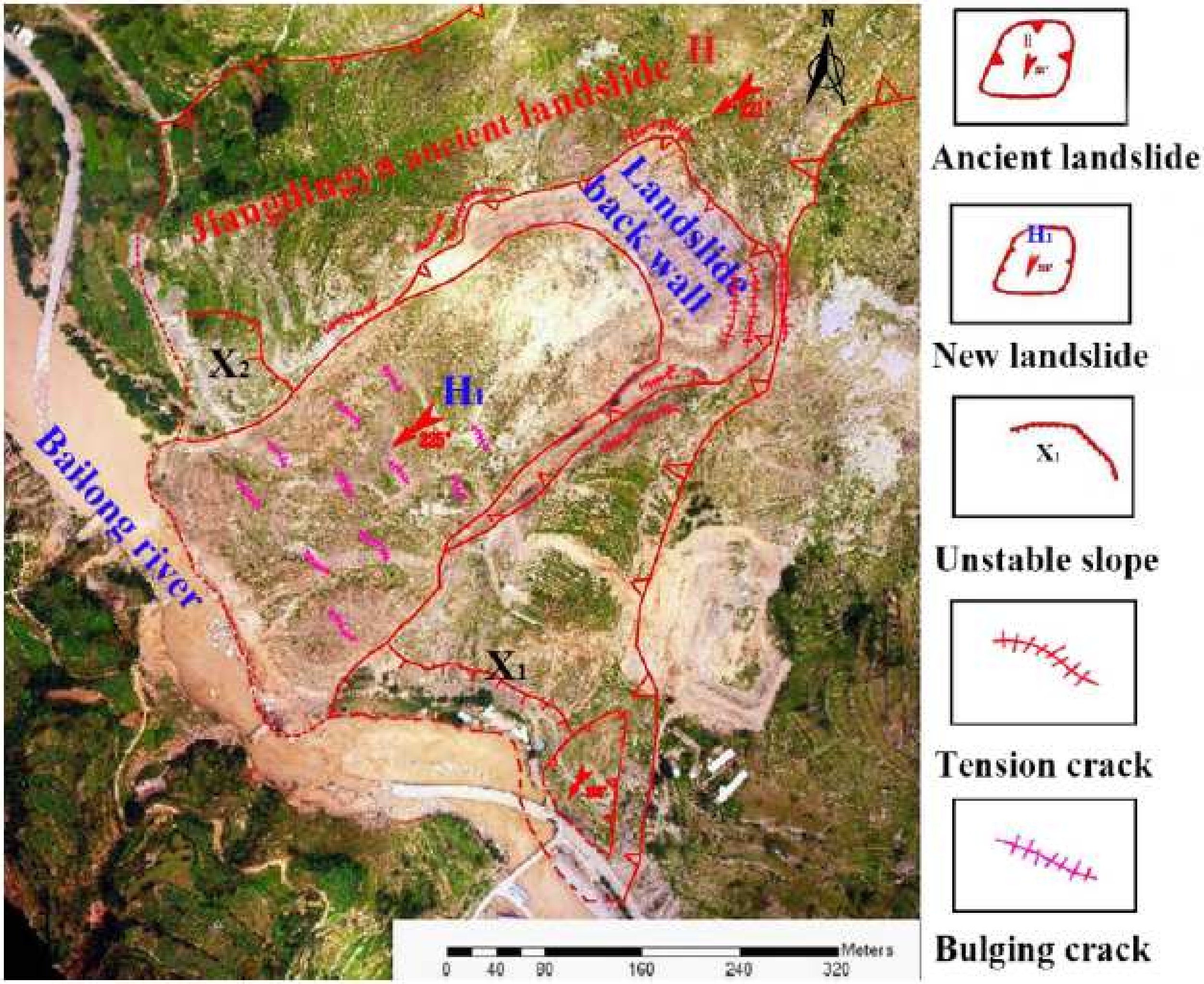


Figure 11

Remote sensing image of Jiangdingya landslide landform. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

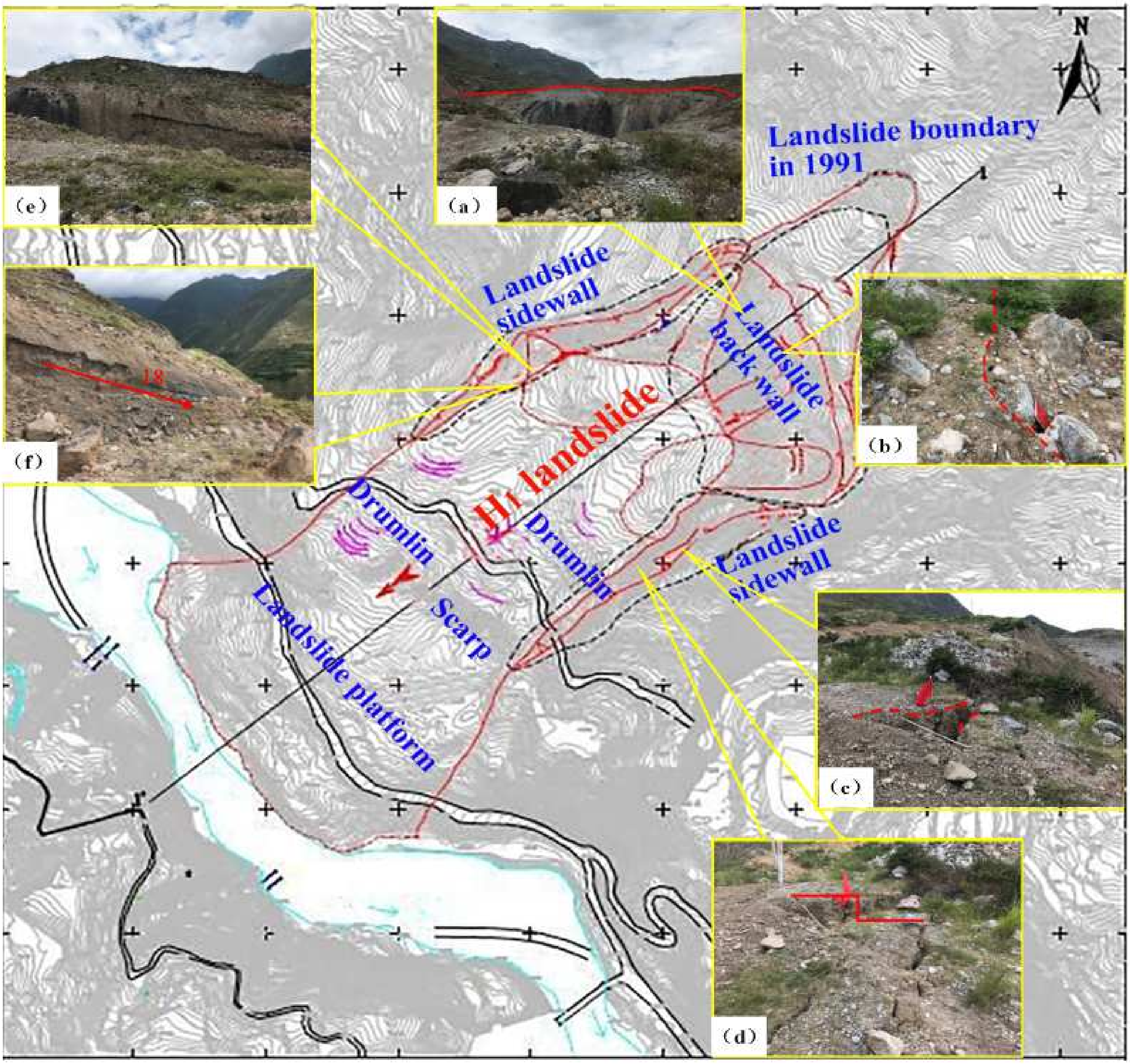


Figure 12

Morphological characteristics of the Jiangdingya landslide. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a) Soil layer distribution of landslide body

(b) Gravel soil

Figure 13

Structural and mechanical characteristics of landslide body

Figure 14

Scratch marks of sliding zone soil

Figure 15

Sliding bed soil

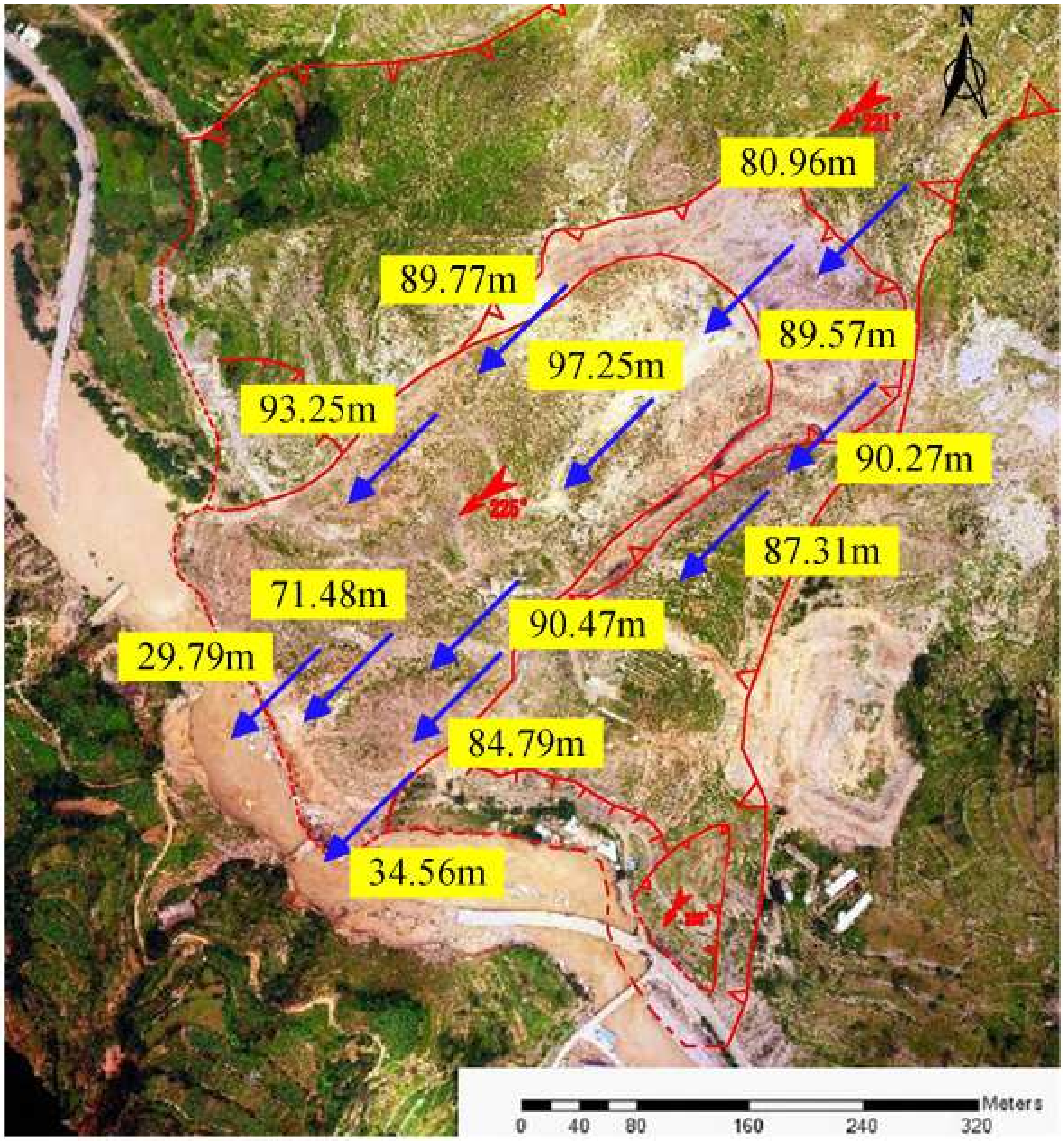


Figure 16

Sliding distance of the landslide Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

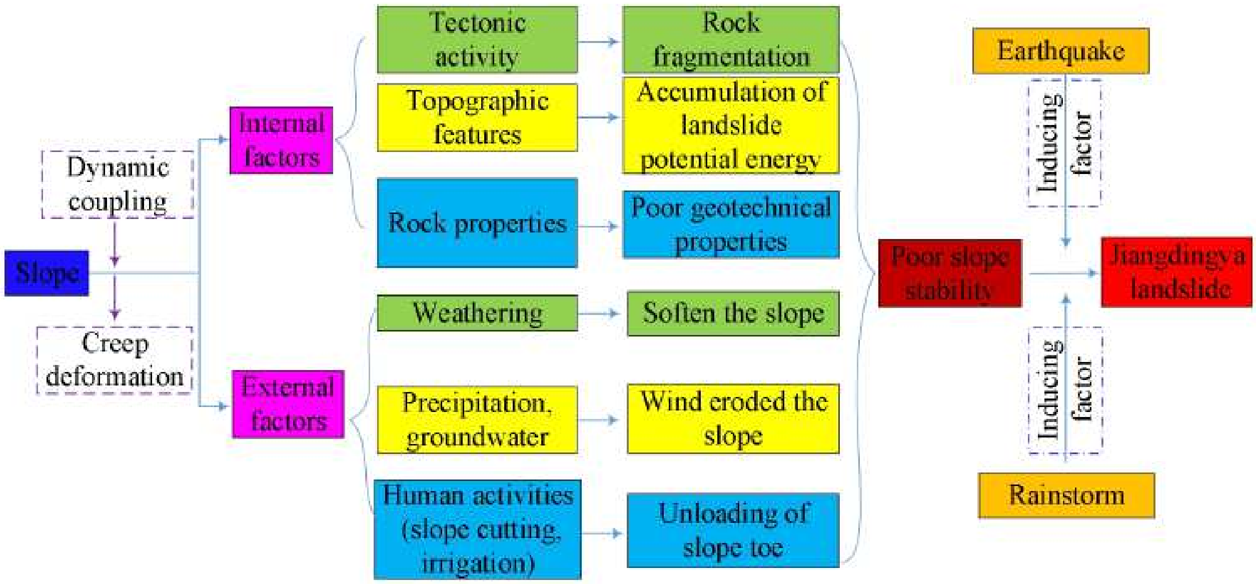
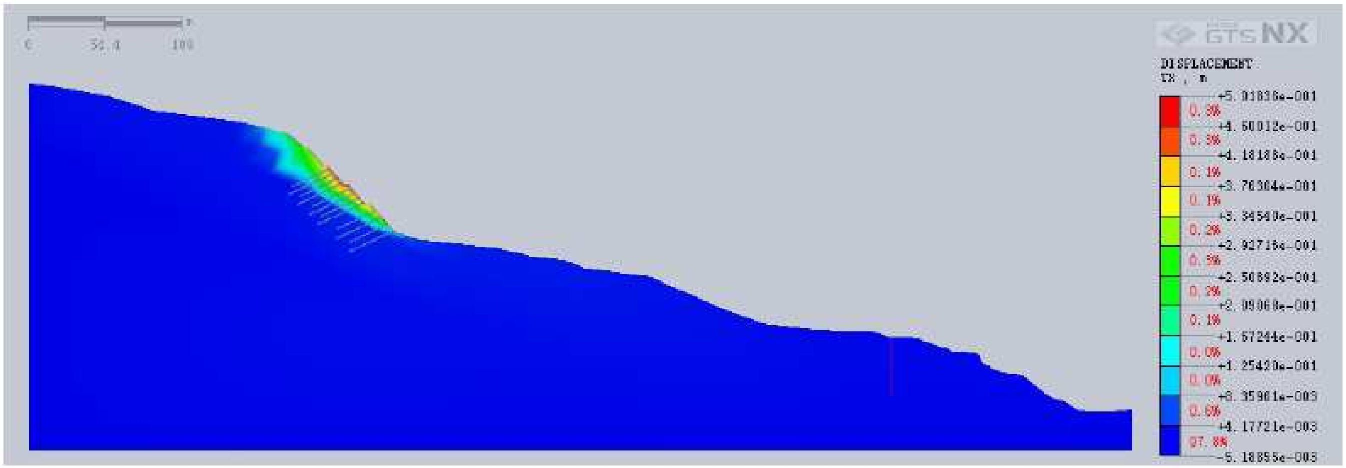
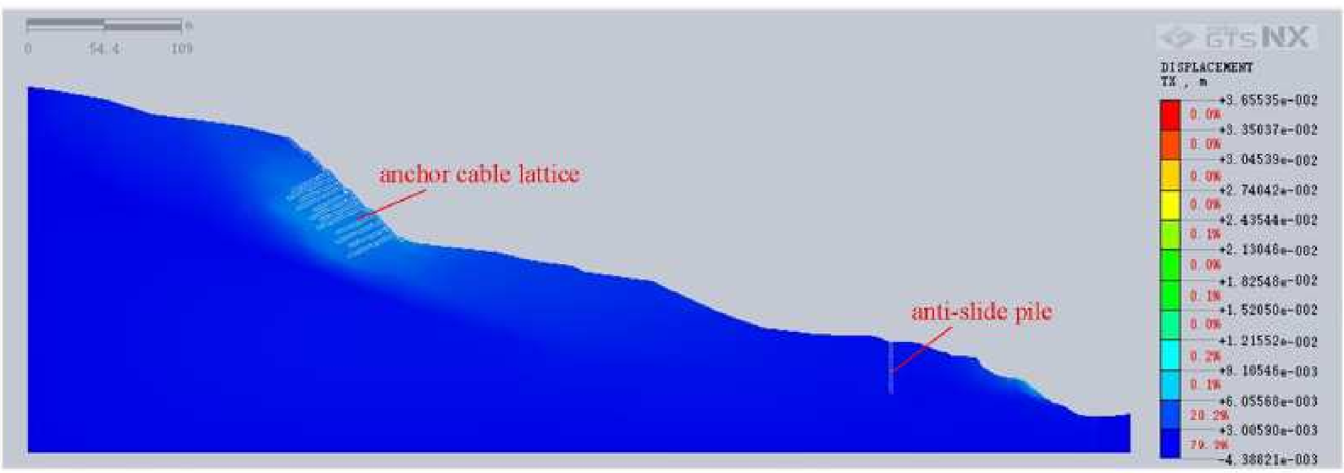


Figure 17

Catastrophe mechanism of landslide



(a) before the safety treatment



(b) after the safety treatment

Figure 18

Displacement nephogram of slope