



Effect of climate change induced extreme precipitation on landslide activity in the Three Gorges Reservoir, China

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Abstract

Climate change has caused an increase in extreme rainfall and snowfall in many parts of the world. For example, in the Three Gorges Reservoir area, annual precipitation has gradually increased and the occurrence of heavy precipitation events has become more frequent. As the reservoir water level rises in October, the high water combined with heavy precipitation creates a “special hydrological environment,” which recently caused the Yanguan landslide. The Yanguan landslide is a large-scale soil landslide that has undergone two slides, pushed the Yanguan Road Bridge into the reservoir, and caused serious damage to roads and buildings. In the present study, the combined effects of high water and heavy precipitation on landslide deformation characteristics (movement patterns and evolution processes) have been analyzed and a stability evaluation was conducted through a field investigation and numerical simulation. To comparatively analyze these combined effects of high water and heavy precipitation, a two-dimensional finite element model was created, and four cases of the hydrological environment were calculated with the model. Results show that the factor of safety was maintained in the range of 1.013 to 1.059 before the precipitation conditions changed. However, as heavy precipitation increased in October 2017 (reaching 356.4 mm in 1 month), this “special hydrological environment” potentially decreased the FoS to 0.948, which is 9.6% lower than that observed under normal conditions, and helped drive the Yanguan landslide activity. The analysis of these various combined effects can also indicate the impacts of climate change on landslides in other areas of the Three Gorges Reservoir.

Keywords Global climate change · Special hydrological environment · Landslide · Stability evaluation

Introduction

In recent years, global warming has raised the world’s average temperature, resulting in an augmentation of extreme rainfall and snowfall in many parts of the world (Donat et al. 2016). The increase in extreme precipitation has not only caused a large number of floods (Chen and Zhai 2013; Easterling et al. 2000; Yao et al. 2008) but also had a direct impact on landslide

disasters (Crozier 2010; Huggel et al. 2010), which have resulted in a large number of casualties and economic losses.

The relationship between global climate change and increased landslide disasters has been studied by many scholars worldwide, and many of those studies have focused on the impacts of climate change on landslides in mountain areas (Huggel et al. 2012). With the accelerated melting of alpine glaciers and increasing precipitation due to global warming, disasters have become increasingly common (Huggel et al. 2010; Evans and Clague 1994; Shang et al. 2003). Crozier (2010) discussed the global climate change–induced temperature effects on landslides in New Zealand. Biasutti et al. (2016) and Chen et al. (2019) discussed the relationship between rainfall conditions and landslide characteristics along the West Coast of the USA and in northern Taiwan. Huang (2009) reported that global climate change was one of the most important factors inducing catastrophic landslides in the southwest mountain area of China. By using downscaled synthetic rainfall series obtained from the Global Circulation Model (GCM), Dixon and Brook (2007), Jakob and Lambert

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(2009), and Chiang and Chang (2011) have investigated the effect of climate change on landslides on a large scale.

The influences of climate and its variations on landslides can also be classified broadly by region (Gariano and Guzzetti 2016). In this regard, landslides in the Three Gorges Reservoir area have attracted special attention. Based on a long-term analysis of monitoring data, the combined effects of seasonal precipitation conditions and periodic water level fluctuations can influence the slope deformation and stability conditions over time (Wang et al. 2008; He et al. 2008; Xia et al. 2013). With the precipitation increase and the water level decline between May and August, many landslides were reactivated or caused destruction during this period (Song et al. 2018; Tang et al. 2015). However, with the precipitation decrease in the dry season, in order to ensure the requirements for flood control and improve the economic benefit of hydropower stations, it is necessary to raise the reservoir water level from September to March of the following year. This period is called the “sleeping period” in the Three Gorges Reservoir area, with fewer geological disasters.

With the precipitation conditions in the Three Gorges Reservoir area changing in recent years (Zhao and Shepherd 2012; Li et al. 2011; Lü et al. 2018), some landslides in the reservoir area have also “woken up” during the “sleeping period.” For instance, the Dahe landslide in Wuxi County, Chongqing Province, occurred on October 21, 2017 (the volume was approximately 6,000,000 m³, and 9 people were missing), and the Yanguan landslide in Zigui County, Yichang City, occurred in the Three Gorges Reservoir area on October 27, 2017 (the volume was approximately 2,100,000 m³, and no casualties were reported).

Why did the Yanguan landslide occur during the “sleeping period” of geological disasters in the Three Gorges Reservoir? Has climate change led to landslide activity, and what is the connection between them? To explore these questions, this paper first discusses the variations in precipitation conditions in this area based on data extracted from unusual periods of precipitation from September to October in 2003 to 2018. Then, a large number of geological surveys were conducted to describe the landslide deformation characteristics in detail. Furthermore, this study also analyzed landslide stability under the combined influence of various rainfall and reservoir water levels by using a numerical simulation method. In addition, it should be noted that the aim of this paper is not only to discuss the variation in precipitation conditions but also more importantly to consider the combined effect of abnormal precipitation conditions and reservoir water level on landslide stability. Thus, the reservoir operating mechanisms should be strengthened for similar situations in the foreseeable future.

Changes in precipitation conditions

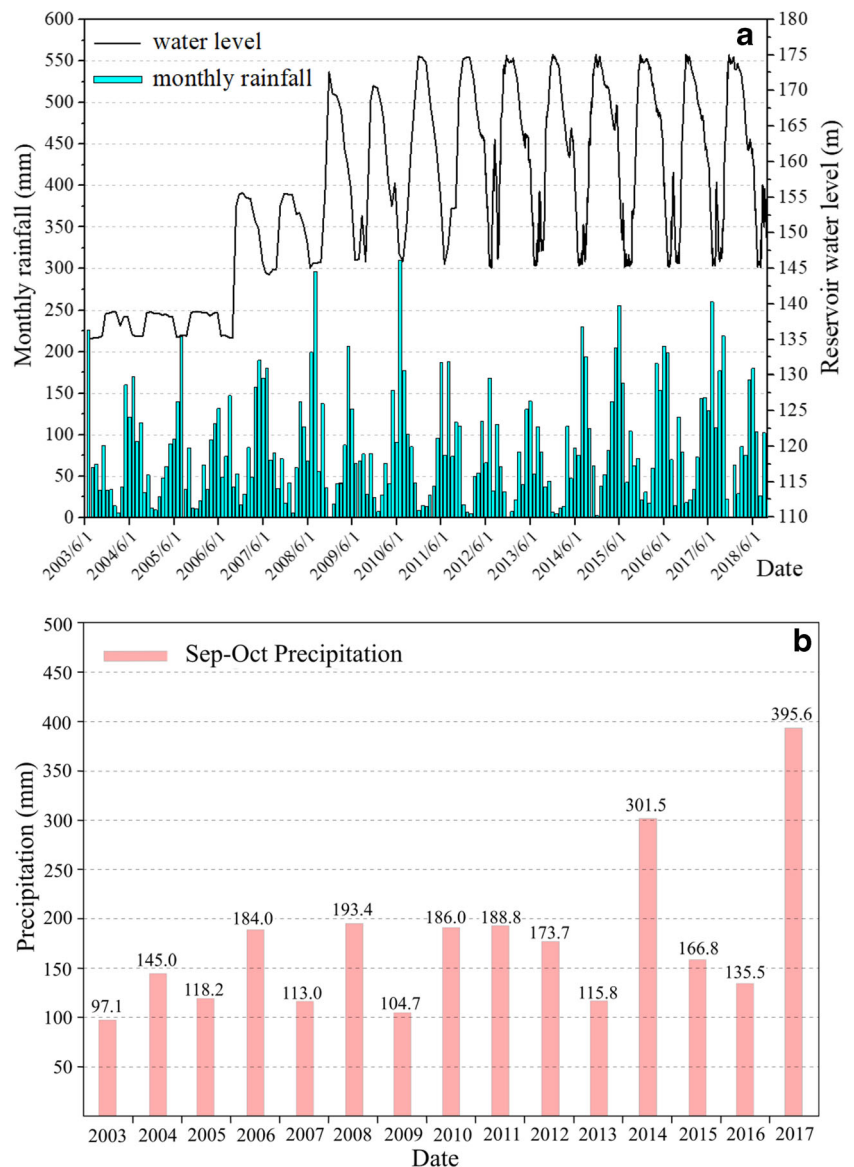
Climate change has caused an increase in extreme rainfall and snowfall in many parts of the world (Donat et al. 2016). Over the last few decades, extreme weather events have become more significant in countries in South Asia, such as Afghanistan, Bangladesh, Bhutan, India, and Sri Lanka (Naveendrakumar et al. 2019). In Europe, anomalies of extreme rainfall are also considered to have a strong connection with climate change (Tabari and Willems 2018). Similarly, in China, there are many extreme precipitation events, resulting in a large number of casualties and direct economic losses (Zheng 2016), especially in the Three Gorges Reservoir area, a region that typically responds positively to climate change (Li et al. 2011).

Figure 1 shows the precipitation data of Zigui County in the Three Gorges Reservoir area from 2003 to 2018. Zigui County is the first county in the upper reaches of the Three Gorges Dam, and it is in a subtropical monsoon climate zone in Central and Western China. The monthly precipitation data in this area can reflect the changes in precipitation conditions and seasonal characteristics in the Three Gorges Reservoir area in recent years.

The precipitation in Zigui County has typical seasonal characteristics. Affected by this, the regulation and control of the reservoir water level also show periodic variation to achieve flood control, power generation, and navigation of the Three Gorges Project (Fig. 1a). Before the annual rainy season (from January to May), the precipitation is weak, and the reservoir water level drops from 175 to 145 m. In the rainy season from June to August (summer), the precipitation is concentrated and ample, especially in 2005, 2008, 2010, and 2014. The reservoir water level is basically maintained at approximately 145 m. However, after the rainy season ends (from September to October), there is less precipitation, and the reservoir water level is increased from 145 to 175 m and then basically remains approximately 175 m from December to January in the following year (winter). From 2003 to 2018, the average monthly precipitation was approximately 40 mm in winter, and the lowest was only 4 mm.

However, under the influence of global climate change, precipitation is more intense and sustained on the north side of the Three Gorges Reservoir area (Li et al. 2014). Such abnormal changes have occurred more frequently after 1980 (Zhao et al. 2010). Generally, the precipitation is relatively less intense after the end of the rainy season (September to October), but this intensity has increased in recent years. As shown in Fig. 1b, the cumulative precipitation from September to October fluctuated, increasing between 100 and 200 mm, and the higher cumulative precipitation in 2014 and 2017 reached 301.5 mm and 395.6 mm, respectively. As the reservoir water level was rising in this period (Fig. 1a), it led to a “special hydrological environment” where heavy precipitation and a high water level coexisted.

Fig. 1 Precipitation and reservoir water level fluctuations in the Three Gorges Reservoir area. **a.** monthly precipitation in the Three Gorges Dam area; **b** cumulative precipitation from September to October



Extreme precipitation-induced landslide events

Climate change has caused heavy precipitation more frequently from September to October, and the reservoir water level has risen during this period. Under these coexisting conditions, there have also been many major landslide disasters, such as the Shanshucao landslide on September 2, 2014 (Huang et al. 2018), the Dahe landslide in Wuxi County on October 21, 2017, and the Yanguan landslide in Zigui County on October 27, 2017. To better understand the impact of this “special hydrological environment” on the deformation behavior of landslides, the Yanguan landslide was analyzed in depth as a case study.

Description of the Yanguan landslide features

The Yanguan landslide is located on the right side of the Xiangxi River, a tributary on the north bank of the Yangtze River in Zigui County, Hubei Province, China. The landslide is approximately 12 km below the mouth of the Xiangxi River, and the geographical coordinates are N 31° 3' 18", E 111° 44' 45" (Fig. 2).

The topography of the Yanguan landslide before and after sliding is shown in Fig. 3 and Fig. 4, respectively. The landslide plane is a “tongue” type, which lies between 156 and 328 m elevation, and the accumulation body elevation range is between 150 and 280 m (Fig. 3). The landslide covers an area of approximately 70,000 m² with a volume of 2,100,000 m³ and is approximately 374-m long and 175-m wide. Figure 4

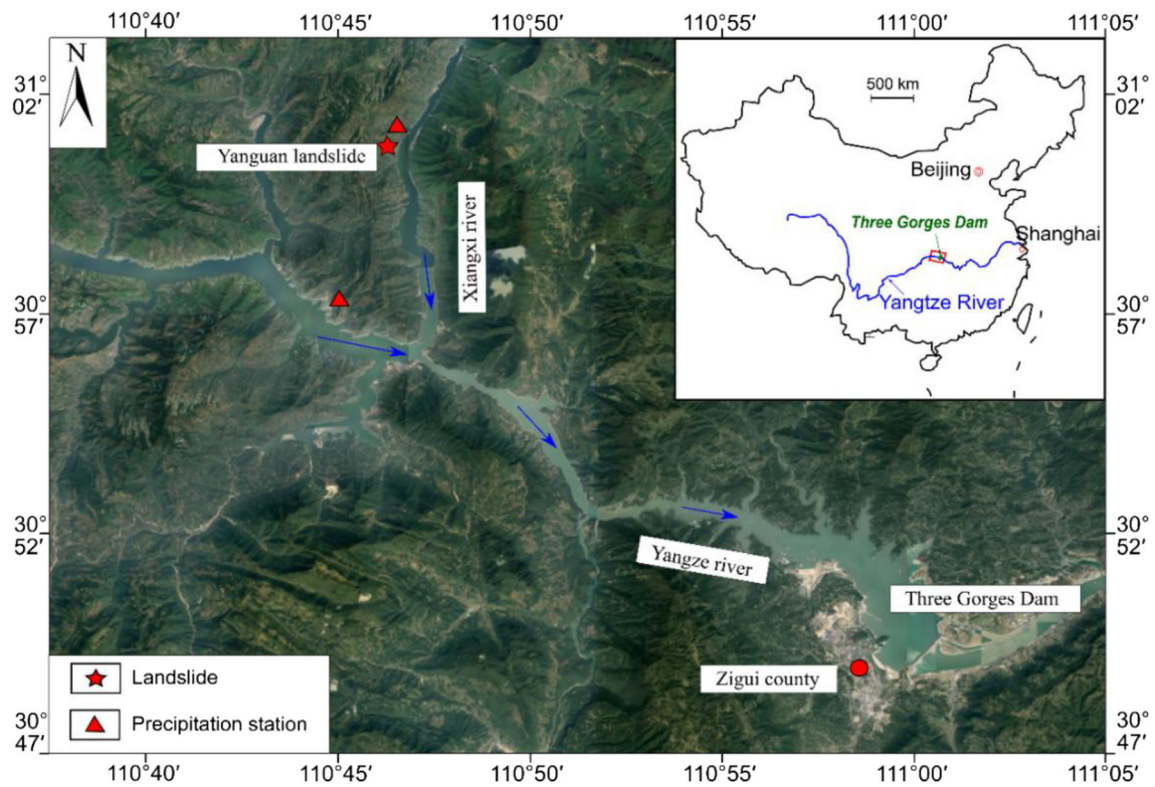


Fig. 2 Location of the Yanguan landslide (the precipitation monitoring station in Zigui County is also shown in the figure)

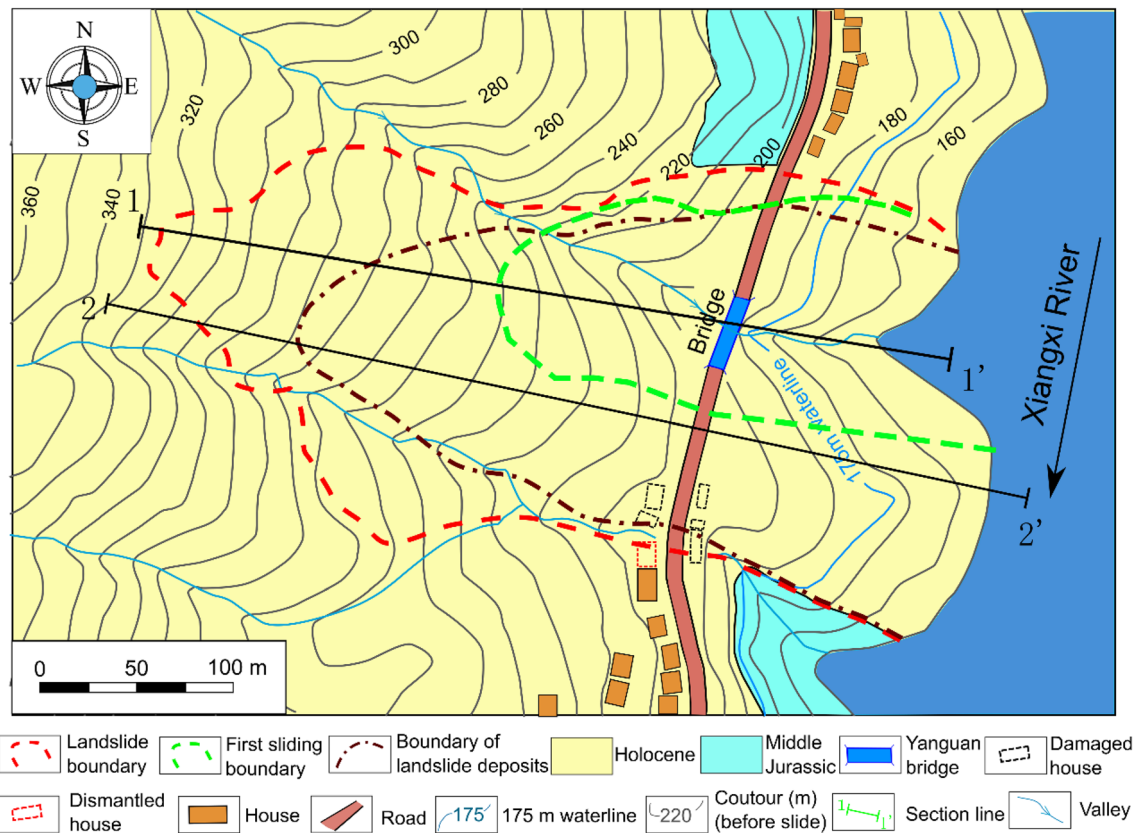


Fig. 3 Topography (before sliding) and associated geological map of the Yanguan landslide area

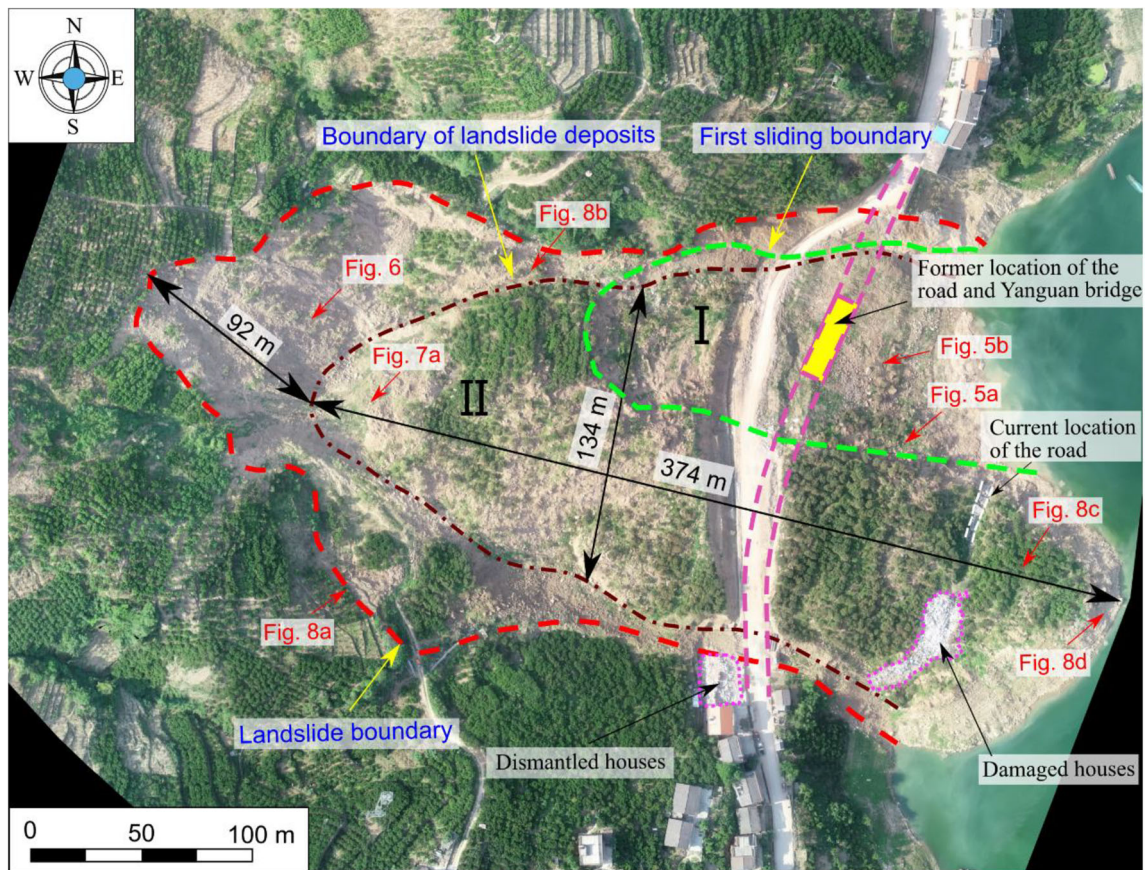


Fig. 4 Yanguan landslide image taken by Unmanned Aerial Vehicle in June 2018

shows the landslide mass after sliding, incorporating a damaged road and ruining several houses. In this figure, the red dotted line represents the landslide boundary, the green dotted line indicates the first sliding boundary, and the brown dotted line indicates the landslide deposit boundary.

The material of the slide body was identified as Holocene deposits based on previous research. The deposits are mainly composed of purple-red and yellow-brown silty clay and mudstone gravel blocks. The gravel content is between 20 and 40%, and the parent rocks are mainly composed of sandstone, mudstone, and bits of argillaceous siltstone. The gravel structure is angular, and the particle size is generally between 30 and 50 cm, but the maximum particle size is approximately 3 m.

Field geological investigation indicates that the underlying bedrock is purple-red, thick-layered, and mainly composed of Middle Jurassic mudstone, sandstone, and silty mudstone. It is exposed along the road at the left boundary of the landslide and in the front gully of the right boundary (Fig. 3). The rock formation strikes approximately 295° , dipping 31° , and the bedding planes are clearly visible in outcrops.

Investigation of surface deformation

As shown in Fig. 5a, a clear dividing line can be observed in the right boundary after the first sliding. The upper part is the

slide body and is mainly composed of a silty clay layer with a thickness of approximately 12 m. Some local soil collapses downward, as shown in the figure. The lower part of the dividing line is the landslide deposits after the first sliding (Fig. 5b), which contain a large amount of broken stones that are heaped irregularly at the gully mouth in front of the river. The main sliding direction is in the range of $85\text{--}100^\circ$.

After the second sliding, a main scarp with a height of approximately 48 m and a slope of 44° was formed at the backslope (Fig. 6). There are two springs on the slope surface, one in the middle and the other at the bottom of the main scarp. The water flow measured on site is approximately 0.6 L/min.

The head of the landslide is a stacking platform with a length of approximately 58 m and a width of 49 m (Fig. 7a). Affected by the downstream flow of the spring, a puddle exists on the head surface (Fig. 7b), and water flows to the right side of the platform. The flow rate is approximately 0.5 L/min (Fig. 7c).

A large number of tensile cracks with strikes in the NW direction are exhibited on the right boundary of the landslide deposits. These cracks have a total length of approximately 300 m, among which a single section can be up to 10 m, and the maximum width is 2.6 m (Fig. 8a). In the left boundary, there are also many broken rock masses heaped irregularly along a gully with a length of 350 m, a depth of 2 m, and an average groove width of 3.5 m. As shown in Fig. 8b, the

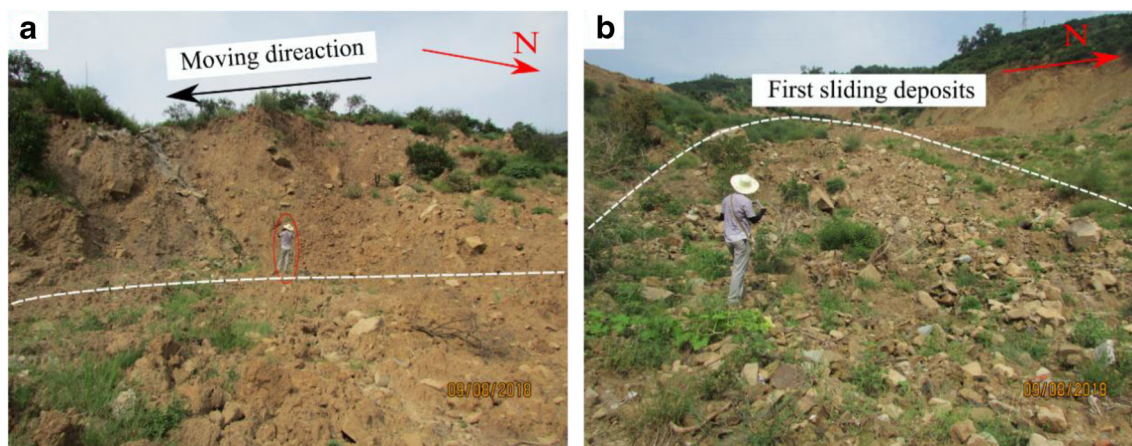


Fig. 5 Right flank and deposits of the landslide after the first sliding: **a** right flank; **b** landslide deposits

gravel size grade is very different, and the maximum particle size is 3 m, but the minimum is only 10 cm. At the leading edge of the landslide, the soil is mainly composed of silty clay and gravel inclusions, and the soil-rock ratio is approximately 8:2. Under the effect of rapid fluctuation in the reservoir water level, many tensile cracks formed at the leading edge and roughly parallel to the Xiangxi River. The maximum width of a single crack is 1.5 m (Fig. 8c). With erosion by the river, a steep slope also formed on the toe of the landslide (Fig. 8d).

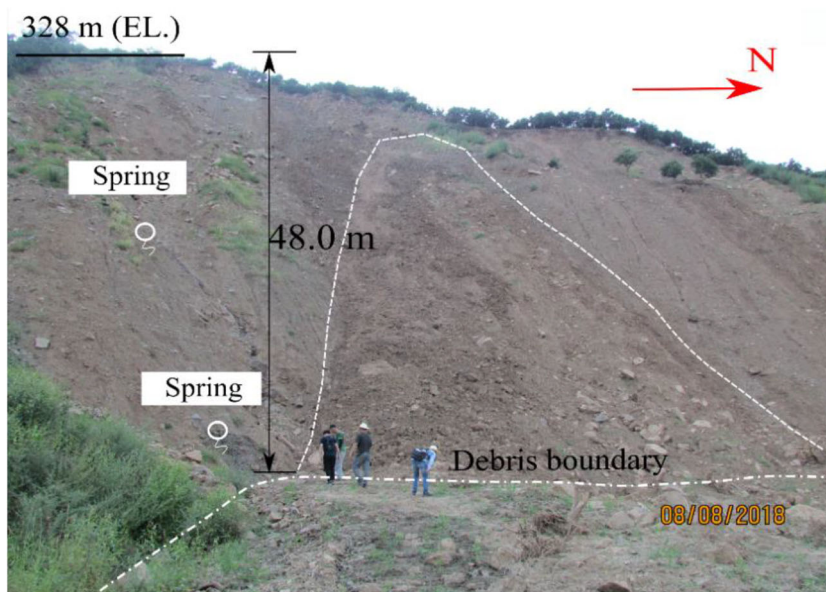
Investigation of motion characteristics

Through on-the-spot investigation after the sliding and high-resolution images taken by a drone, the motion characteristics analysis map is compiled in Fig. 9. The figure mainly shows the range, the moving direction, and the sliding distance of the landslide; and it also includes the motion damage characteristics of surface structures and some typical site photos.

As shown in Fig. 9a, the Yanguan landslide had two slips in succession; the first sliding is mainly near the Yanguan Road Bridge, which is indicated with the green dotted line, and the second sliding zone is marked by the red dashed line. Figure 9b is taken by a local villager during the first sliding. In this figure, it can be observed that several shear cracks grow on the bridge surface and continue to extend across the bridge. The rock mass on the west side also began to slide downward. Ultimately, the first sliding, with a sliding distance of approximately 70 m and a direction of $N82^{\circ} W$, destroyed a 50 m road and deformed one building (Fig. 9b).

The second sliding moved in the $N75^{\circ} W$ direction, causing extensive damage to the concrete pavement. According to the field investigation, the damaged road was stacked at the leading edge (Fig. 9c), but the residue of the Yanguan Road Bridge was submerged in the river, which means that the broken bridge could move further than the damaged road. In other words, it can be concluded that the deposits of the first

Fig. 6 The main scarp of the Yanguan landslide



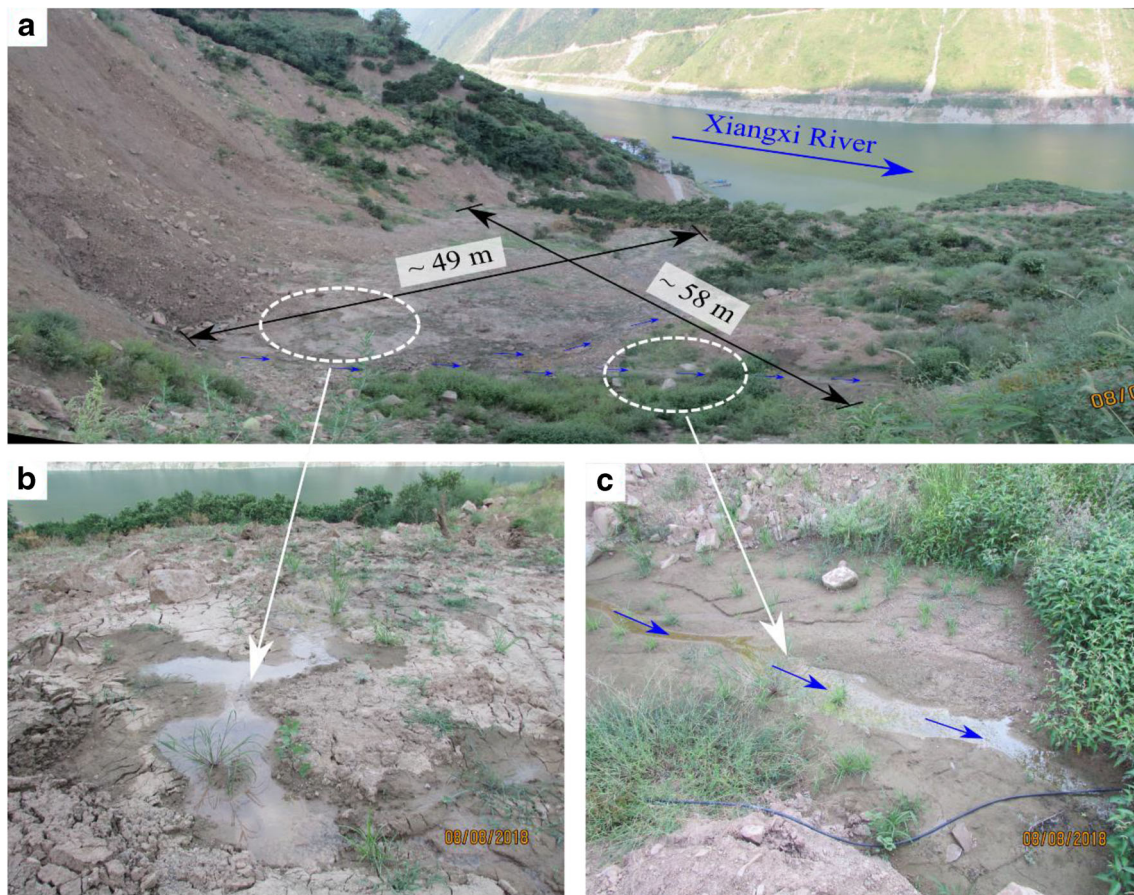


Fig. 7 Platform at the head of the Yanguan landslide: **a** panorama; **b** puddle; **c** flowing water

sliding were pushed by the second sliding slope. Affected by the shear stress between the landslide and the surrounding rocks, a residential building on the right boundary was destroyed and pushed to the bank of the river (Fig. 9e); another building also developed a large number of cracks on the surface, and it was dismantled by the local government to protect the villagers' safety (Fig. 9d).

Evolution process of the landslide

Before the Yanguan landslide occurred, climate change caused the rainfall to increase abnormally in this area. Affected by this, many cracks appeared at the leading edge and the surface of the landslide on October 27, 2017. In addition, as the reservoir water level rose, the overburdened soil gradually became saturated, and a gradually extending shear developed on the contact surface between the bedrock and the overlying formation (Fig. 10b). As the cracks on the slope continued to extend deeper and eventually through the overburden, the Yanguan landslide occurred for the first time at approximately 12:00 AM on October 28, 2017. In addition, cracks at the backslope were continuously stretched by traction (Fig. 10c).

After the first sliding, the leading edge of the landslide formed a large free surface and broke the original equilibrium state of the slope. The weak side of the backslope continued to extend, and, finally, it contacted the weak side of the leading edge to form a complete shear zone. The second large-scale sliding occurred at 17:00 on October 29, 2017 (Fig. 10d). After the landslide failure, there were two platforms with gentle angle slopes in the geomorphology of the deposits (Fig. 10e), and the front one was excavated into an emergency road during the rescue construction process.

Impact of climate change on the stability of the Yanguan landslide

The Yanguan landslide occurred in the "special hydrological environment" (October 27, 2017), where heavy precipitation caused by climate change coincided with the high reservoir water level of the Three Gorges Reservoir. To better analyze the impact of the "special hydrological environment" on the landslide stability, the groundwater seepage field with different hydrological conditions (the combination of the reservoir water level fluctuation and rainfall change) was calculated by the finite element method (FEM), and then the limit



Fig. 8 Surface deformation behavior of the Yanguan landslide: **a** tensile cracks near the right flank of the landslide; **b** the gully near the left flank; **c** tensile cracks in the foot of the landslide; **d** the toe of the landslide

equilibrium method was used to calculate the factor of safety of the Yanguan landslide. The overview of this process is given in the flowchart in Fig. 11.

Landslide finite element model

Based on the geological characteristics of the landslide, a two-dimensional finite element model with the quadrilateral mesh element size of 4×4 m (Fig. 12) is established by using the Seep/W in Geo-studio software. The model mainly consists of the upper silty clay with a gravel layer and the lower bedrock. Silty clay with a gravel band is assumed to be a homogeneous material with equivalent parameters, and the spatial variability and anisotropy of the gravel with silty clay are ignored. A numerical test is conducted by applying a time-dependent total head, H_w , on the slope surface below the reservoir water level (C-D). A boundary flux, equal to rainfall intensity, I , is applied to the slope surface above the reservoir water level (B-D). The node flux Q with a value of zero is applied to other boundaries of the landslide, such as the left and bottom (B-E, A-C), to simulate a no-flow zone.

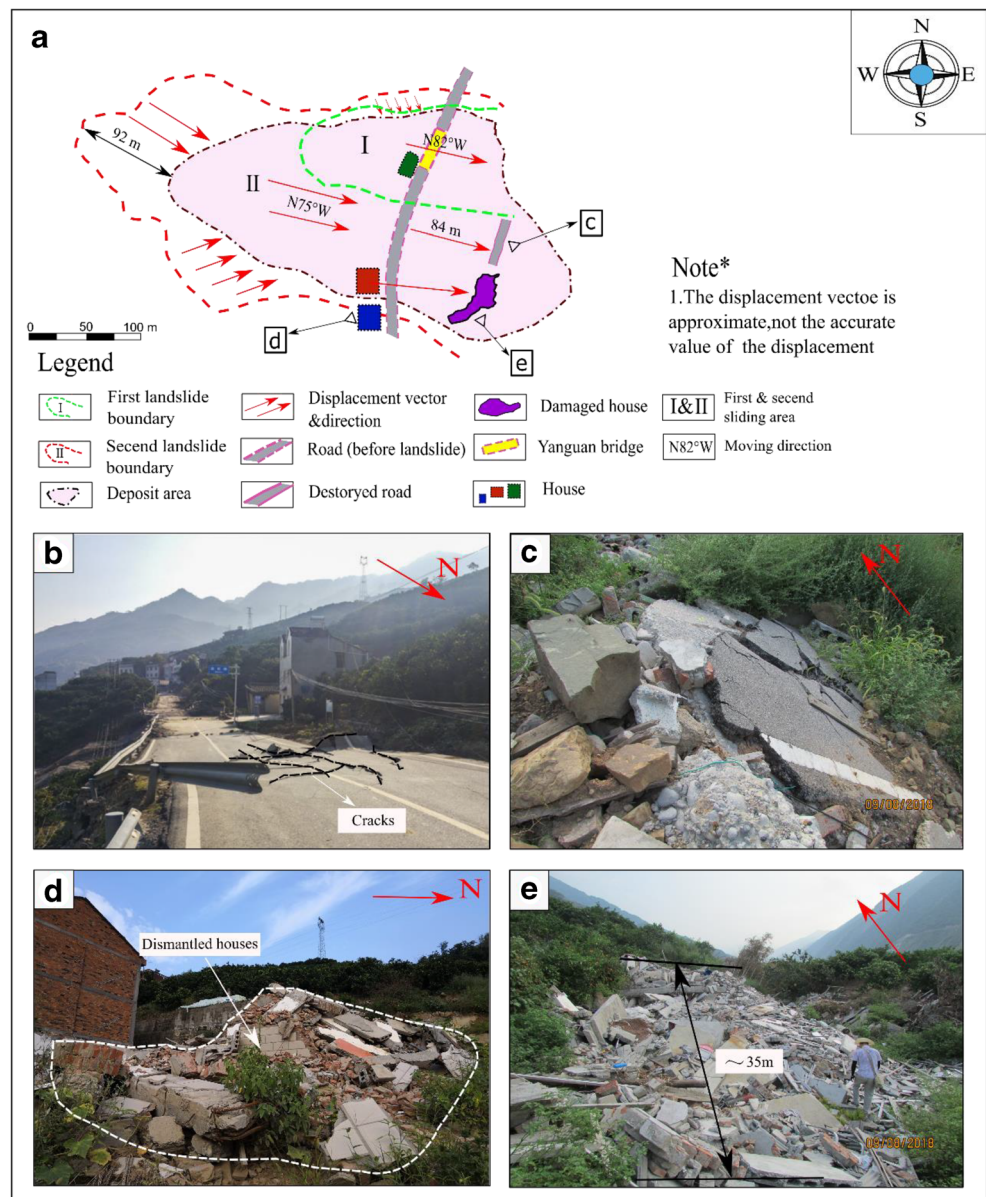
According to the field laboratory test results, the soil hydraulic parameters for seepage calculation are determined as

shown in Table 1. The soil-water characteristic curve (SWCC) is estimated by the equation proposed by Fredlund et al. (1994), and the unsaturated permeability function is predicted from the SWCC (Fredlund et al. 1994), where a , n , and m are the parameters that define the SWCC; K_s is the saturated hydraulic conductivity; θ_s is the saturated volumetric water content; and θ_r is the residual water content.

In the SEEP/W analysis module, because of the absence of effective groundwater monitoring data, it was first determined that the initial groundwater table, as shown in Fig. 12, is equal to the reservoir water level, and the hydraulic gradient is equal to zero (Song et al. 2016). Then, the different combinations of boundary conditions (headwater boundary and flow boundary) were formulated to reflect the different hydrological environments of the Yanguan landslide before and after the change in rainfall conditions. The simulated conditions are shown in Table 2.

Before the rainfall conditions changed, there were three cases of hydrological environment in the Three Gorges Reservoir area, i.e., case (b), case (c), and case (d). Case (b) is a high water level superimposed with weak precipitation, that is, the cumulative precipitation is approximately 120 mm (e.g., the average cumulative precipitation from September to

Fig. 9 Analysis of the movement characteristics of the Yanguan landslide: **a** the moving direction and the moving distance; **b** the damaged road after the first sliding; **c** the damaged road after the second sliding; **d**, **e** the damaged houses after the second sliding



October (2003–2005) is 120 mm, as shown in Fig. 2). Case (c) is a low water level superimposed with heavy precipitation (such as the heavy rainfall that appeared in the traditional rainy season with a water level of 145 m), and case (d) is a low water level superimposed with weak precipitation. However, after the rainfall conditions changed, the area presented a “special hydrological environment”, such as case (a) where the cumulative precipitation reached 356.4 mm in the month from September 18 to October 18, 2017 (Fig. 13).

Landslide stability analysis

After the seepage calculation, the consequences for each working condition were introduced into the SLOPE/W analysis module (GEO-SLOPE International Ltd 2008) to calculate

the corresponding FoS of the Yanguan landslide. In this module, the residual shear strength properties of the soil used were based on similar landslide laboratory tests of soil from the slip zone. The unit weight of the soil, $\gamma = 19.2 \text{ kN/m}^3$; effective cohesion, $c' = 19.0 \text{ kPa}$; effective angle of friction, $\varphi' = 17.9^\circ$; and the rate of increase in shear strength caused by matric suction, $\varphi_b = 1.2^\circ$, were used in the landslide stability analysis, and were kept constant for all cases.

In 2017, an extended period of heavy rainfall occurred following the change in rainfall conditions. Figure 14 indicates the variation of the FoS of the Yanguan landslide in this year. During the period from January to June 2017, with the reservoir water level gradually decreasing, the FoS increased slowly from 1.002 to 1.069, and the average monthly growth rate was 1.0%. With the increase in precipitation intensity

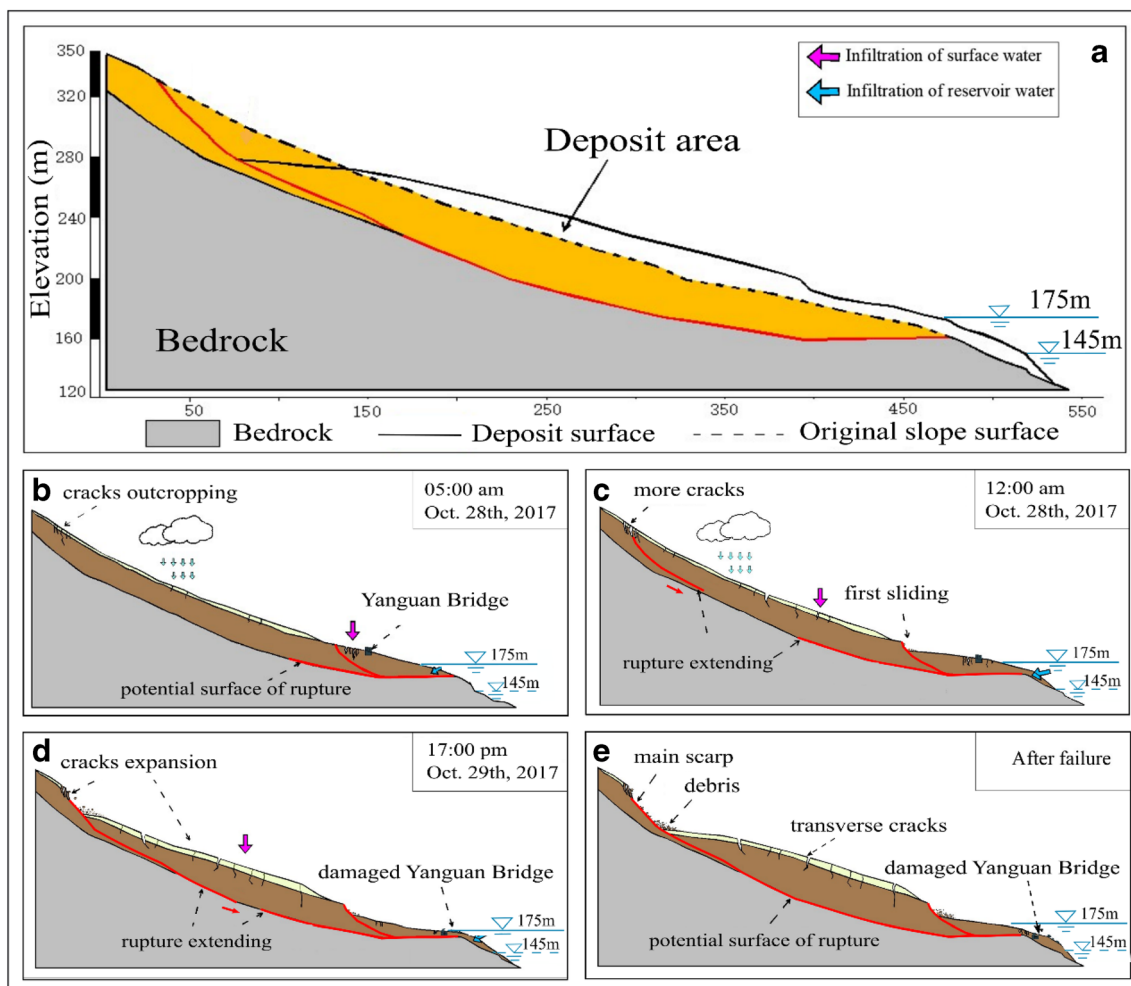


Fig. 10 The evolution process of the Yanguan landslide: **a** longitudinal section of the landslide (2–2' in Fig. 3); **b, c, d, e** evolution process of the cracks and rupture surface expansion

during the rainy season, that is, from June to August 2017, the FoS gradually decreased, and the average monthly decline rate was 0.9%. However, in the period from September to October 2017, the FoS dropped sharply, with an average monthly decrease of 8.7%. By October 27, 2017, the FoS was 0.958, and the landslide was activated. After that, the FoS continued to decrease to 0.948. However, as the slope reached equilibrium again, the FoS gradually increased and approached 1.000.

The FoS of all the cases is presented in Table 3. The initial FoS is from 0.948 to 1.059. It should be noted that the case-based rainfall data might contain significant uncertainties because only four different combined situations were simulated, and the variation between each situation changed only one condition. Moreover, the uncertainties in the selection of rock and soil mass parameters also lead to some deviation in the calculation results. In this regard, we propose an indicator and

Fig. 11 Flow chart of the numerical modeling procedure

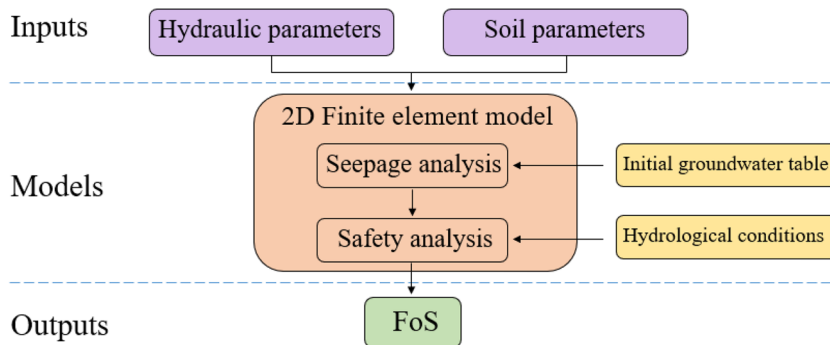
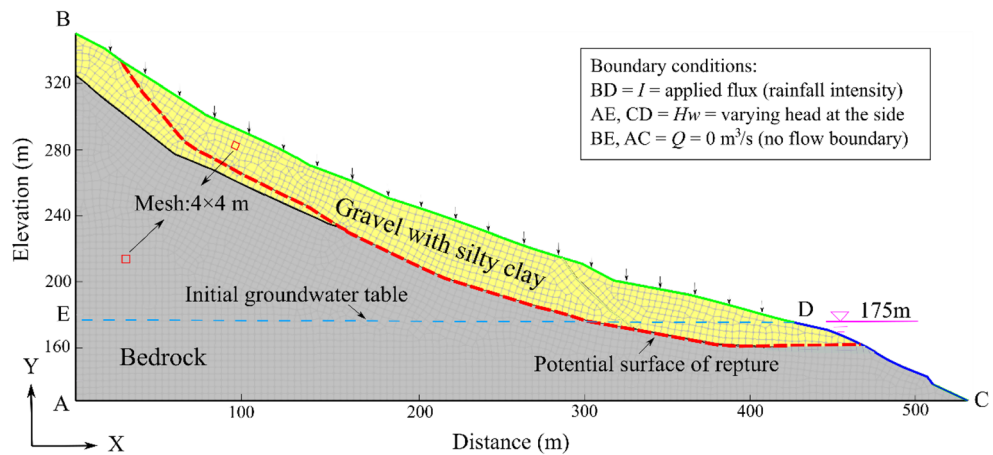


Fig. 12 Two-dimensional finite element method (FEM) model and boundary conditions of the Yanguan landslide



make a comparative analysis of the results and select relative values as the basis for evaluation, which will reduce the impact of such uncertainty to a certain extent. The relative change rate of the FoS is defined as follows (Song et al. 2016):

$$\delta = \frac{F_{si} - F_{s0}}{F_{s0}} \times 100\%$$

where δ is the relative change rate; F_{s0} is the FoS of case (a), which is the failure condition of the Yanguan landslide; and F_{si} is the FoS for cases (b)–(d).

Before the precipitation conditions changed, the Yanguan landslide was in a stable state in which the FoS of case (b) was 1.013, the FoS of case (c) was 1.059, and the FoS of case (d) was 1.049. However, with the “special hydrological environment” that occurred after the precipitation conditions changed, the FoS of case (a) was only 0.948. Compared with case (a), the FoS of case (b), case (c), and case (d) increased by 0.065, 0.111, and 0.101, respectively. By controlling the variable method analysis, comparing case (b) with the increasing precipitation intensity, and case (c) with the increasing reservoir water level, the magnitude δ is 6.4% and 10.5%. Moreover, compared with case (d), the magnitude δ of the “special hydrological environment” in case (a) is approximately 9.6%. It can be seen that increasing the precipitation intensity or

Table 1 Hydraulic properties of soil materials in the numerical simulation

Material	SWCC			K_s (m/s)	θ_s	θ_r
	a (kPa)	n	m			
Gravel with silty clay	10	0.4	0.5	4.2E-05	0.5	0.1
Bedrock	/	/	/	9.9E-10	/	/

The a , n , and m are the parameters that defined the soil-water characteristic curve (SWCC)

The K_s is the saturated hydraulic conductivity; θ_s is the saturated volumetric water content; and θ_r is the residual water content

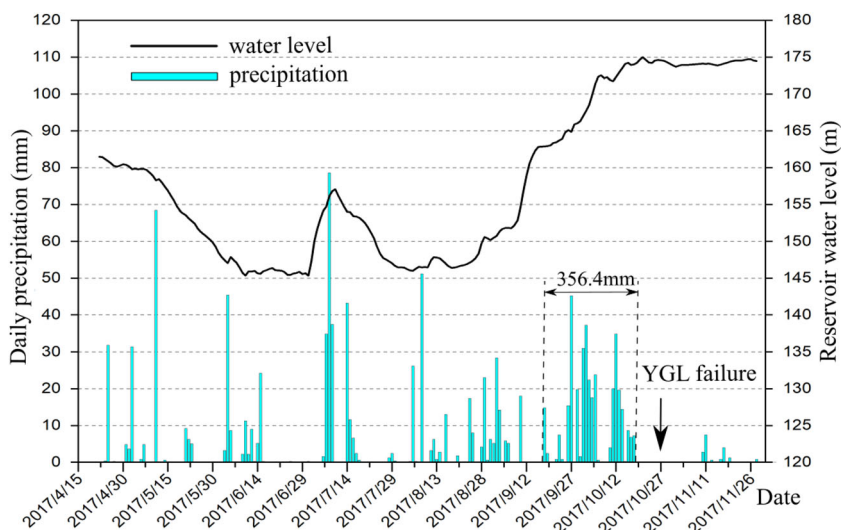
Table 2 Calculated conditions of seepage in the numerical simulation

Case no.	Reservoir water level H_w (m)	Cumulative precipitation (mm)	Rainfall intensity I (mm/d)	Description
a	175	356.4	I^a	Climate change has caused a prolonged heavy precipitation period, which is the real condition from Sept. 18 to Oct.18, 2017, is also the failure condition of the Yanguan landslide.
b	175	60	I^b	There may be a non-rainy hydrological environment before the change in precipitation conditions, such as the hydrological conditions in October from 2003 to 2005.
c	145	356.4	I^a	The hydrological environment of the rainy season that may occur before climate change. The rainfall intensity is assumed to be the same as in case (a), which is convenient for comparison with case (a).
d	145	60	I^b	The rainy season with few precipitation, and the precipitation intensity is assumed to be the same as in case (b), which is convenient for comparison with case (b).

I^a , the real rainfall intensity from Sept. 18 to Oct.18, 2017, which is time-dependent, and shown in Fig. 12

I^b , the average rainfall intensity, $I^b = 2.0$ mm/d

Fig. 13 Real-time precipitation and reservoir water level in the Yanguan landslide area



raising the reservoir water level individually could not cause Yanguan landslide instability. Only after the precipitation conditions change will the “special hydrological environment” cause instability in the Yanguan landslide.

Discussion

The Yanguan landslide was a unique landslide that followed a “special hydrological environment”: the combination of heavy precipitation and the high reservoir water level of the Three Gorges Reservoir. Intensive study of the field geological investigation and numerical simulation of this landslide can therefore provide strong evidence for research on slope instability mechanisms under the “special hydrological environment.” These issues will be discussed in the context of two related aspects: the adverse geological conditions and the hydrological environment.

According to the outcrop of the steep wall on the landslide leading edge, a landslide shear outlet can be observed at approximately 160 m elevation (Fig. 8d). The lower unit bedrock is composed of sandstone, mudstone, and argillaceous siltstone with alternating weak (mudstone) and hard layers (sandstone). The hard layer is a thick sandstone layer with poor water permeability, while the weak layer is a mudstone, characterized by a large number of joint cracks, and the mudstone easily soaks and deforms. This alternating strata is the material foundation of the landslide and is the controlling factor of landslide formation. As shown in Figs. 5 and 7, the upper material of the Yanguan landslide body is mainly composed of residual soil and mudstone gravels with a loose structure. Both materials have good water permeability, indicating that precipitation could easily permeate through the surface into the landslide. Additionally, the left boundary of the gully (Fig. 8b) and several slope surface cracks (Fig. 8a and c) can also provide a preferential flow path for the penetration of rainwater.

In previous studies, the stability of reservoir landslides was generally affected by the combination of reservoir water level fluctuation and rainfall intensity, such as the Huangtupo landslide, Quchi landslide, and Shuping landslide (Tang et al. 2015; Huang et al. 2018; Song et al. 2018). For example, Huang et al. (2018), through the analysis of displacement time series, found that the Quchi landslide movement appears as a

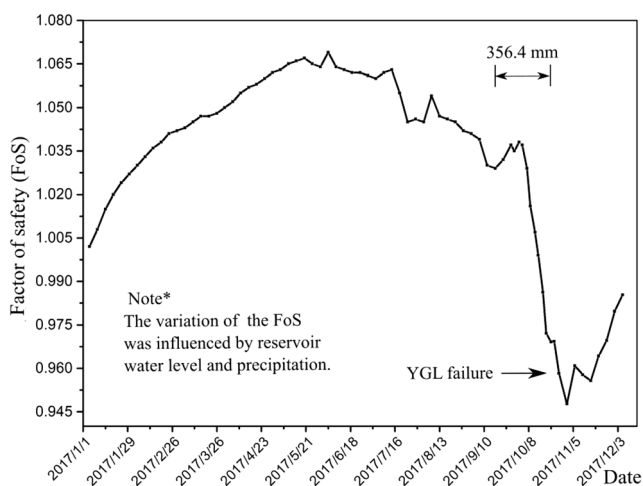


Fig. 14 Factor of safety (FoS) variation of the landslide in 2017

Table 3 Factor of safety (FoS) of the Yanguan landslide

Case no.	Factor of safety (FoS)	δ (%)
a	0.948	–
b	1.013	6.4
c	1.059	10.5
d	1.049	9.6

seasonal cycle correlating with hydrological factors (rainfall and reservoir operation), and faster seasonal displacements are synchronous with low reservoir levels and high precipitation between June and September. Similarly, Tang et al. (2015) and Song et al. (2018) considered that most reservoir landslide cumulative displacement curves show “step-like” characteristics during the rainy season due to the increase in rainfall and the drawdown of the reservoir water level.

However, with varying climate change-induced precipitation conditions, regional precipitation is becoming increasingly intense and sustained (Li et al. 2014). As shown in Fig. 1b, the monitoring data showed that the cumulative precipitation from September to October exhibited a fluctuating increasing trend in recent years. As the reservoir water level rose, a “special hydrological environment” appeared in this area and eventually induced a significant impact on the Yanguan landslide.

The high reservoir water level first penetrated the cracks of the rock mass and acted on the weak sliding surface at the leading edge; in addition, the heavy precipitation permeated into the landslide through the gully and cracks. This combined effect not only increased the slope body weight but also increased the pore water pressure in the slope body, which could have rendered the weak landslide surface soft and promoted the first sliding of the Yanguan landslide on the leading edge. The following numerical simulation results of different hydrological conditions, listed in Table 3, can also prove this statement. In the four different cases, only the FoS of case (a) is less than 1, which means that the “special hydrological environment” decreased the FoS sharply, with an average monthly decrease of 8.7% (Fig. 14). It can be seen that the “special hydrological environment” caused by climate change is the triggering factor for sliding in the Yanguan landslide.

Although the field investigation and finite element method are effectively combined in this study for the climate change-induced landslide deformation characteristics and stability analysis, some limitations still exist, i.e., the numerical simulation is relatively simple, and only four different combined situations were simulated. In addition, it is essential to mention that the lack of a field soil test will directly affect the accuracy of the simulation results. Therefore, the input parameters in this study were determined by some empirical and similar landslide laboratory tests, and the reliability and accuracy of this method were validated by some other similar research studies (i.e., Nguyen and Likitlersuang 2019; Wang et al. 2020).

Conclusions

This study discusses the evolutionary characteristics of the Yanguan landslide caused by extreme precipitation considering the combined effect with reservoir water level from the perspective of climate change. The analyses are helpful to

further understand the relationship between climate change and variations in slope stability. The following main conclusions can be drawn:

1. Due to the impact of global climate change, the rainfall characteristics in the Three Gorges Reservoir area have undergone some changes. The cumulative precipitation from September to October shows a fluctuating increasing trend as the reservoir water level is rising in this period, which will lead to a “special hydrological environment” where heavy precipitation and high water levels coexist. In particular, this “special hydrological environment” has become more frequent in recent years. Therefore, climate change should be considered in a future study as a key factor to compare with other similar areas.
2. The Yanguan landslide is a large-scale soil landslide with a maximum sliding distance of 90 m, which has undergone two slides. The first sliding was near the Yanguan Road Bridge and formed a free surface at the leading edge of the landslide; then, the subsequent free surface caused the entire failure of the landslide. Ultimately, the Yanguan Road Bridge was pushed into the reservoir as a whole, and roads and buildings incurred serious damage.
3. The Yanguan landslide occurred on October 27, 2017, accompanied by the “special hydrological environment” in the Three Gorges Reservoir Area. The stability was analyzed under the combined influence of various rainfall and reservoir water levels. Before the change in precipitation conditions, the FoS was maintained in the range of 1.013 to 1.059. However, with the global climate change-induced “special hydrological environment,” the FoS dropped sharply to 0.948, which was a 9.6% decrease compared with normal conditions. This combination of high water level and heavy precipitation was identified as the triggering factor of Yanguan landslide destruction.

After the water impoundment of the Three Gorges Reservoir, since 2003, the fluctuation of water level was thought to be an important contributing factor for landslide stability and deformation. By contrast, the effects of precipitation have received less attention in the early phase. However, some of the recent landslides (i.e., the Dahe landslide, the Shanshucao landslide and the Yanguan landslide) induced by the combined effect with high water level and intense precipitation, due to global climate change, prove that the “special hydrological environment” of the Three Gorges Reservoir needs more attention. Therefore, it is still necessary to incorporate more climate change scenarios in future work and use ensemble methods to obtain more reliable results.

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