

# Research on progressive failure process of Baishuihe landslide based on Monte Carlo model

Fasheng Miao<sup>1</sup> · Yiping Wu<sup>1,2</sup> · Yuanhua Xie<sup>1</sup> · Feng Yu<sup>1</sup> · Lijuan Peng<sup>1</sup>

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**Abstract** To the progressive landslide, development of the internal deformation and failure situation can't be accurately reflected by the overall stability of coefficients and failure probability. But this problem can be solved by utilizing the principle of progressive failure by slices. Taking the warning area of Baishuihe landslide as an example, 5 days accumulated rainfall in different reappearing period is computed by Gumbel model. The failure probability of each slice is calculated by progressive failure principle, which is based on Monte Carlo model. The following results can be revealed through calculation: Overall stability and failure probability can't reflect real situation of Baishuihe landslide warning area. Through building the calculation of progressive failure model of each slice, the stability of each part in the Baishuihe landslide warning area is quite different. Unstable region mainly lies in vicinity of the middle and posterior warning area. The front of the warning area remains stable. Deformation characteristics of the warning area are consistent with the investigation report. The scope of unstable area increased gradually with rainfall and the decline of reservoir water. Under 5 day's accumulated rainfall of 50 years, the poor stable and unstable region reached 75 %, there is a large possibility of local deformation slip. Under the joint action of rainfall and reservoir water level, the warning area of Baishuihe landslide shows a progressive failure mode from top to bottom.

**Keywords** Landslide · Monte Carlo · Numerical simulation · Progressive failure · Reservoir level · Rainfall

## 1 Introduction

Rainfall (rain gush) is one of the most important factors of landslide. From the twentieth century, the catastrophic landslides statistics throughout the country show that the landslide induced by rainfall is the most (Huang 2008). Combining with the conditions of the Three Gorges Reservoir Region, the failure of slope is usually caused by the fluctuation of reservoir level (Lu et al. 2014a). With the decline of reservoir level, groundwater level in the slope falls. If the slope rock has low permeability, groundwater cannot discharge in time. As a result, groundwater level falls more slowly than reservoir level (Lu et al. 2014b), which will reduce the stability of slope.

For the different characteristics in development process of landslide deformation and failure, landslide is divided into two categories (Shouyi 1996): Sudden failure and progressive failure. Deformation and failure time of the former is extremely short. And it often happens when stress state of slope breaks out great changes, such as heavy rainfall, sudden drawdown of reservoir level and earthquake. Process of the latter usually takes longer time. The progressive failure landslide caused by the shear strength of slope rock reducing gradually, and it's a progressive process of the slip surface which is formed from partial failure extending to run-through gradually (Li et al. 1998). The concept of progressive failure is first proposed by Bishop (1967, 1971). Taking the progressive failure mechanism of slope reliability into consideration, which is gradually expanded becomes one of the most important research topics. Chowdhury et al. (1982, 1987) establishes

✉ Yiping Wu  
ypwu1971@163.com

<sup>1</sup> Faculty of Engineering, China University of Geosciences, Wuhan 430074, China

<sup>2</sup> Three Gorges Research Center for Geo-hazard, Ministry of Education, Wuhan 430074, China

the failure analysis of failure probability model for progressive slope, which merely considered the shear strength parameters of the cohesive force, and the influence of the friction coefficient of the soil is neglected. Wang (2000; Wang et al. 2005) analyze the slope stability during the progressive failure process, which indicates definitely that taking progressive failure process into account could get 5–10 % smaller stability coefficient than not.

The reliability analysis of slope engineering is a new method which is developed to evaluate the state of slope engineering for nearly 20 years. It takes multi-elements, such as properties of rock, load, groundwater, failure and calculation model as uncertainty factors. Combine the theoretical method of the structural engineering reliability and the particular cases of the slope engineering, and use reliability index and probability of failure to evaluate the slope safety (Tan and Cai 2009). Chowdhury and Xu (1993) confirm the probability distribution of the slope safety factor and failure probability by applying the rational polynomial technique to the Landslide reliability analysis. Xu and Zhang (1995) put forward the method of landslide failure probability and reliability analysis, and calculate the Shuibuya Dam site big rock pond landslide as a case. Dodagoudar and Venkatachalam (2000), Giasi et al. (2003) and Tan et al. (2003) have not only considered random uncertain of the slope, but also studied fuzzy uncertainty of the slope, and used the fuzzy random reliability theory to study slope stability. Adarsh and Reddy (2013) presents reliability analysis of composite channels, considering uncertainty associated with various design parameters. Wu et al. (2014) finds that the landslide random-fuzzy reliability is the smallest at the process of high water level slowly dropping to low water level. Lian et al. (2014) uses ensemble empirical mode decomposition (EEMD) based extreme learning machine (ELM) ensemble learning paradigm to forecast the displacement of Baishuihe landslide. Li et al. (2014) presents the BP neural network forecasting model and the corresponding programs for bank destruction. Su et al. (2014) determines the evaluation index system of rock slope stability in hydropower projects based on multiple factors. Travis et al. (2011) finds that a log (base 10) normal distribution to adequately describe the SF data. Mohammed (2013) addresses the integration of reliability-based design in the design of embankments founded on soil improved by lime-cement columns. Jiao et al. (2013), Jiao et al. (2014) tests three extensions to the traditional discontinuous deformation analysis (DDA) method to simulate the entire process describing the behavior of landslides induced by reservoir impoundment. Jiao et al. (2015) presents a methodology for evaluating the safety of slopes threatened by strong earthquakes.

Based on the theory of Monte Carlo and the mechanical analysis of progressive failure process, taking the warning

area of Baishuihe landslide as an example, two aspects are elaborated: overall stability and progressive failure process. Come to the conclusion through the calculation and comparison. The process of full text is shown as Fig. 1.

## 2 Methods and materials

### 2.1 Calculation-analysis model

#### 2.1.1 Mechanical analysis of progressive failure process

The force of each slice is decomposed into two components, one is parallel to the sliding surface and the other is perpendicular. As shown in Fig. 2, the sliding force of the slice  $i$  is:

$$S_i = (W_{i1} + W_{i2}) \sin \alpha_i + P_{wi} \cos(\theta_i - \alpha_i) + F_{i-1} \cos(\alpha_{i-1} - \alpha_i) - F_i \quad (1)$$

$$R_i = N_i \tan \varphi_i + c_i l_i \quad (2)$$

The sliding resistance force of the slice  $i$  is

$$N_i = (W_{i1} + W_{i2}) \cos \alpha_i + P_{wi} \sin(\theta_i - \alpha_i) + F_{i-1} \sin(\alpha_{i+1} - \alpha_i) \quad (3)$$

$W_{i1} = \gamma V_{iu}$ ,  $W_{i2} = \gamma' V_{id}$ ,  $P_{wi} = \gamma_w i V_{id}$ ,  $i \approx \sin \theta_i$ ;  $F_i$ ,  $F_{i-1}$  represent adjacent strips' force of the slice  $i$ .  $F_i$  is squeezing action to the slice  $i$  from the  $i + 1$  to the  $n$  slice. In accordance with active force and passive force law, slices from  $i + 1$  to the  $n$  can't squeeze the upper slice actively. So  $F_i$  reflects the maximum squeezing capacity of the upper slice that from the  $i + 1$  to the  $n$ .  $F_{i-1}$  is the residual thrust which acted on the slice  $i$  by the slices from the first to  $i - 1$ . As a result,

$$F_{i-1} = \sum_{j=1}^{i-1} \left[ W_j \sin \alpha_j + P_{wj} \cos(\theta_j - \alpha_j) - c_j l_j - N_j' \tan \varphi_j \right] \quad (4)$$

$$F_i = \sum_{j=i+1}^n \left[ \left( c_j l_j + N_j' \tan \varphi_j \right) - W_j \sin \alpha_j - P_{wj} \cos(\theta_j - \alpha_j) \right] \quad (5)$$

$$W_j = W_{j1} + W_{j2} \quad (6)$$

$$N_j' = (W_{j1} + W_{j2}) \cos \alpha_j + P_{wj} \sin(\theta_j - \alpha_j) \quad (7)$$

$(j = 1, 2, \dots, n)$

From formula (1)–(7), security redundant form's state function of the slice  $i$  is

$$Z_i = c_i l_i + N_i \tan \varphi_i - S_i \quad (8)$$

$N_i$  and  $S_i$  refer to formula (3) and (1) respectively. Use the peak strength unless the slice  $i$  has been destroyed. Otherwise use the residual strength.

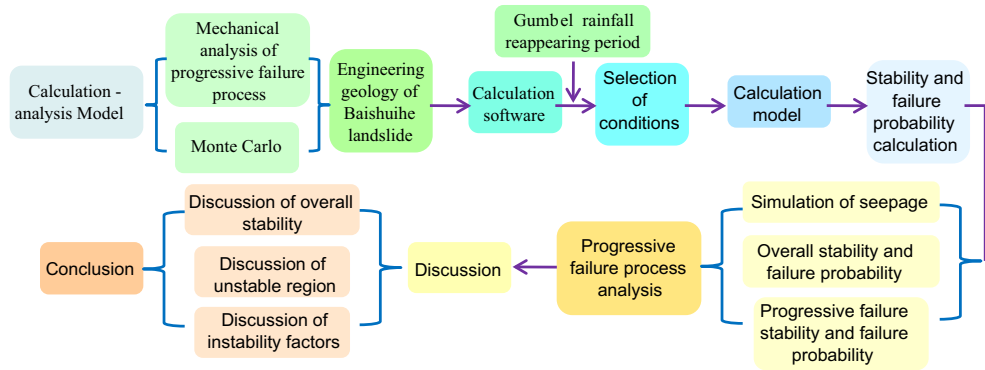
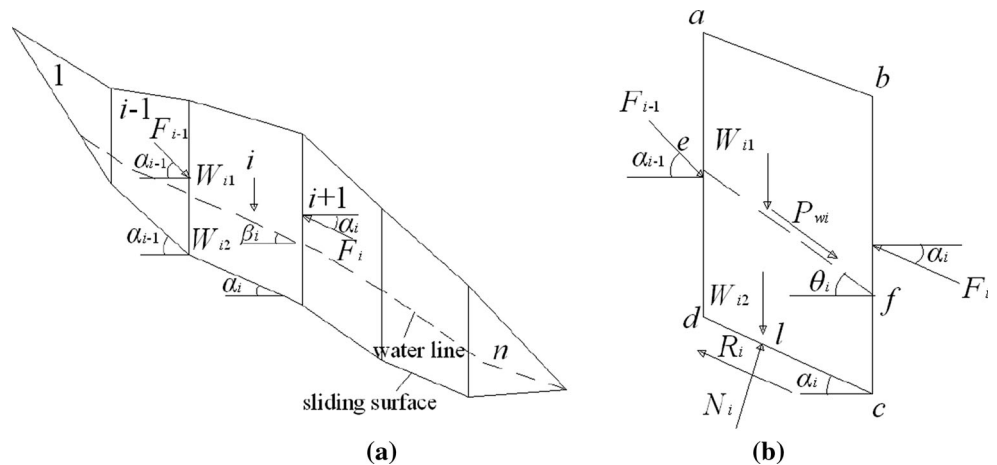


Fig. 1 Flow diagram of the paper

Fig. 2 Strength analysis of the landslide. a The overall slices. b The slice *i*



Above all,  $c_i$ (kN/m)—the cohesion of rock and soil on the sliding surface of the slice *i*.  $\varphi_i$  (°)—Sliding soil friction angle of the slice *i*.  $l_i$  (m)—the length of the sliding surface of the slice *i*.  $\alpha_i$  (°)—Ground inclination of the slice *i*, take a negative value when the inclination is in the reverse direction.  $\theta_i$  (°)—average angle of groundwater flow, take the average inclination angle of saturation line and the slip surface in general, and take a negative value when the inclination is in the reverse direction.  $W_i$  (kN/m)—Sum of ground loads of weight and architecture of the slice *i*.  $P_{wi}$  (kN/m)—Osmotic pressure of the slice *i* unit width, direction is  $\theta_i$ .  $V_{iu}$  (m<sup>3</sup>/m)—The volume of unit width rock and soil above saturation line of the slice *i*.  $V_{id}$  (m<sup>3</sup>/m)—The volume of unit width rock and soil under saturation line of the slice *i*.  $\gamma_w$  (kN/m<sup>3</sup>)—Unit weight of water.  $\gamma$  (kN/m<sup>3</sup>)—Natural unit weight of rock and soil.  $\gamma'$  (kN/m<sup>3</sup>)—Floating unit weight of rock and soil.  $\gamma_{sat}$  (kN/m<sup>3</sup>)—Saturated unit weight of rock and soil.

2.1.2 Monte Carlo model

The main idea of Monte Carlo method is: if the probability distribution of state variable is known, we can use Monte Carlo method to get a set of random datum  $c_1, \varphi_1, \rho_1, h_1,$

$u_1, \dots$  conforming to the state variable probability distribution. According to the limit state of landslide  $F_s = f(c, \varphi, \rho, h, u, \dots) = 1$ , a random number of state functions can be calculated with the set of datum into state function  $F_s = f(c, \varphi, \rho, h, u, \dots)$ . And using the same method gets *N* random numbers. According to theorem of large numbers, if there are *M* numbers not more than 1, frequency is similar to probability when *N* is large enough, Which can get the damage probability of landslide:

$$p_f = p(F_s \leq 1) = \frac{M}{N} \tag{9}$$

where *M* is the number which is not more than 1, and *N* is total number of random numbers.

2.2 Engineering geology of Baishuihe landslide

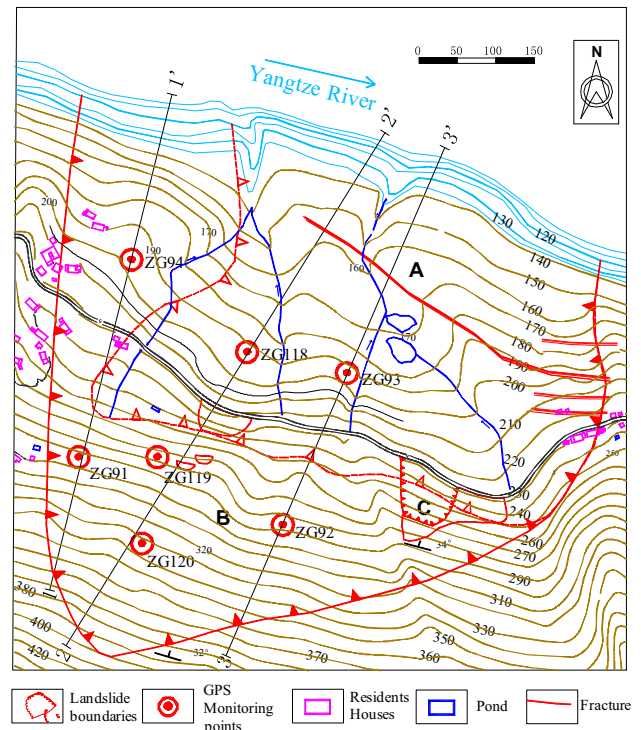
2.2.1 Landform

Baishuihe landslide is located in the right bank of the Yangtze River, 56 km away from the three gorges dam site, as shown in Fig. 3. As a large thick layer of soil slope, the main sliding direction of the landslide is 20°. The landslide has 500 m length from north to south, 430 m

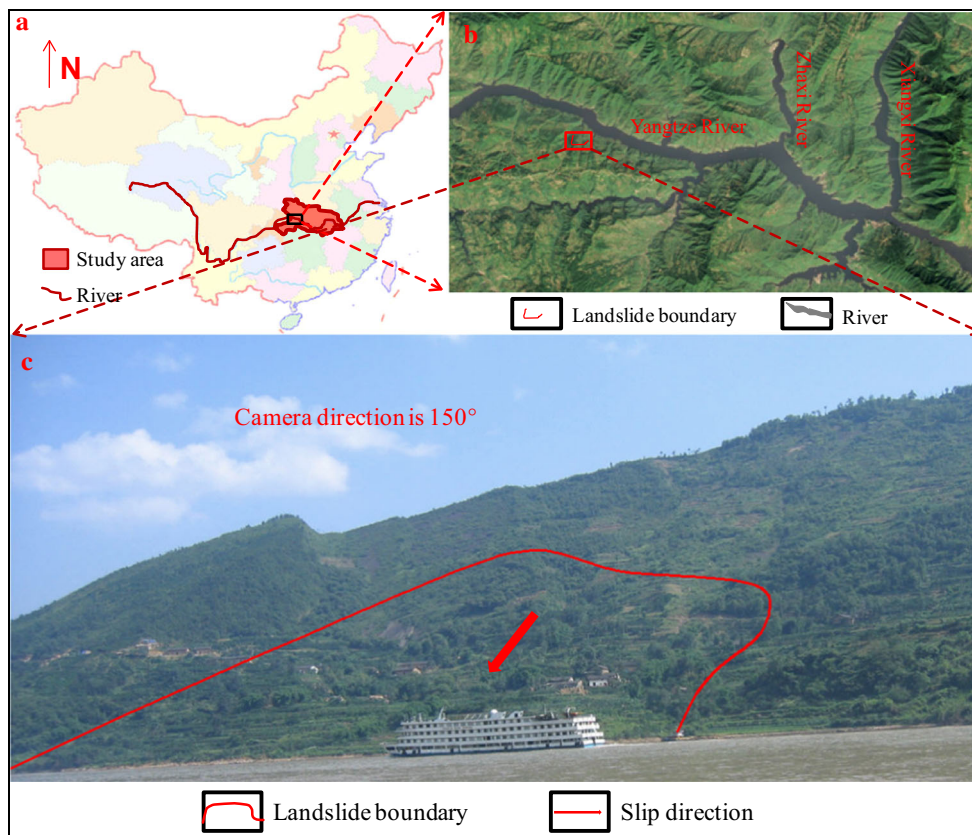
width from east to west and about 30 m average thickness. The volume of the landslide is  $645 \times 10^4 \text{ m}^3$ , covering an area of  $21.5 \times 10^4 \text{ m}^2$ . The rear elevation is in 450–500 m and the front elevation in 120–130 m, as shown in Fig. 4. Baishuihe landslide formed in the nearly north–south gully with the south higher than the north and spreading into the Yangtze River. The gradient of the landslide leading edge and trailing edge is big while the central is flat. Morphology shows irregular flat concave terrain that in the east and west sides of the landslide are slightly higher and the middle is lower. Due to Baishuihe landslide is in an unstable state for a long time, since the flood season in 2003, the landslide has been warning for many times because of intense deformation. By the end of July 2012, the accumulated maximum displacement of Baishuihe landslide reaches 3108.5 mm.

Cross-section 2-2' locates in the middle of Baishuihe landslide. And it could reflect the sliding direction of the landslide. Comparing with the other two sections, the deformation of cross-section 2-2' is more obvious. Therefore, we choose cross-section 2-2' in the analysis and calculation. As shown in Fig. 5.

According to the investigation report (Three Gorges University, 2013), the crack occurred after the first reservoir impoundment in July 2003. Eastern slip body appeared



**Fig. 4** Topographical map of Baishuihe Landslide, with the location of the monitoring network



**Fig. 3** a Location of the study area. b Location of the Baishuihe Landslide. c Geomorphological of the Baishuihe landslide

a more than 300 meters transverse tensile crack with a trend of 330°, which lead to 4 farmers housing crack and be forced to move. Macroscopic deformation of Baishuihe landslide is shown in Fig. 6.

### 2.2.2 Physical properties of rock and soil

The sliding body of Baishuihe landslide consists of colluvium, slope wash and landslide debris, the materials of which consists of gravel, rubble, breccia, silty clay and clay. The average thickness of sliding is about 30 m. The sliding zone is breccia silty clay, plastic—soft plastic, particle size of 0.5–2.0 cm, with a rounded, ratio of 9:1–7:3, and the collection of average thickness is 0.70 m. Slide bed is formation of dark grey siltstone and thin laminated shale, coal in the Lower Jurassic XiangXi group, and a little clip feldspar quartz sandstone, the structure of which is compact and rigid with a monoclinial structure. The rocks tend to 15–20°, and the inclination is 32–36°. There is no big fault fracture zone in the area.

The primary value of landslide shear strength parameters is based on the shear strength confirmed in the investigation report about Baishuihe landslide which is submitted by China Three Gorges University in the end of 2013. Other physical and mechanics parameters of the landslide are obtained by regional statistical law and engineering geological analogy method. The physical and mechanics parameters of rock and soil are shown in Table 1.

## 3 Calculation and results

### 3.1 Calculation process

#### 3.1.1 Calculation software

The Canadian geotechnical software GEO-Studio is used to calculate the seepage and stability analysis. Landslide seepage analysis is studied by the SEEP/W program, and

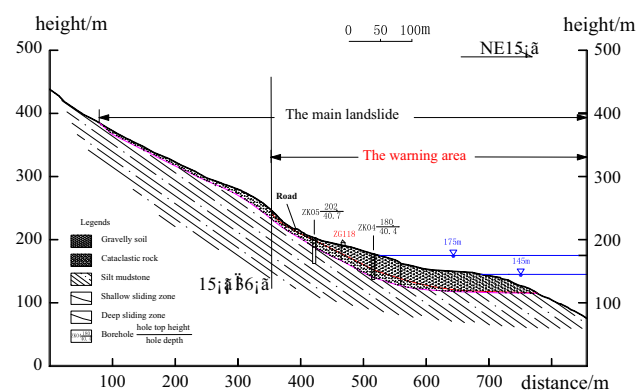


Fig. 5 Schematic geological cross-section (2-2') of Baishuihe landslide

the stability is calculated by SLOPE/W program. In the application, firstly, the SEEP/W program is used for transient analysis of seepage problem, which can get seepage field distribution under different time and water head. Then the SEEP/W module for the transient seepage analysis of different time steps is introduced into SLOPE/W module, when calculating the transient seepage field coupling of stability.

In addition, it is assumed that the parameters of geotechnical parameters are subject to normal distribution. Based on the Monte Carlo Model, using Matlab to generate a large number of random combination of geotechnical parameters. Then compile the formula shown in mechanical model and calculate the landslide stability coefficient of each slice. The block can't take the initiative to the upper bar extrusion force. So if  $F_i/F_{i-1}$  is less than zero, assigning zero to them.

#### 3.1.2 Selection of conditions

The stability of Baishuihe landslide is mainly affected by the reservoir water level variation and rainfall. The Three Gorges reservoir water level variation and rainfall in Zigui County was shown in Fig. 7. During normal operation, the water level dropped from the highest of 175 m to 145 m with the maximum speed of 0.6 m/d. Due to the Baishuihe landslide warning area deformation mainly occurred during the period of falling water, the water pressure of the front of the slope body is larger when the water level is high, and the stability is good. Considering the most unfavorable factors, take the process of the water level decline from 148 m to 145 m, and the falling speed is 0.6 m/d.

Rainfall probability statistical analysis is an important part on the rainfall type landslide's probability study, mainly concentrated on the largest correlation between landslide and rainfall distribution characteristics of the maximum. Assume  $Y_1, Y_2, \dots, Y_n$  is a random sample of a random variable  $\chi$ , the maximum  $Y_{\max} = \max\{Y_1, Y_2, \dots, Y_n\}$  is a random variable. The distribution is called extreme value distribution. Because  $Y_1, Y_2, \dots, Y_n$  is independent random variable, the distribution function of  $Y_{\max}$  is:

$$\begin{aligned} \theta(y) &= P(Y_{\max} < y) \\ &= P(Y_{\max} < Y_1, Y_{\max} < Y_2, \dots, Y_{\max} < Y_n) \\ &= P(Y_1 < y) \cdot P(Y_2 < y) \dots P(Y_n < y) \\ &= F(Y_1 < y) \cdot F(Y_2 < y) \dots F(Y_n < y) = [F(y)]^n \end{aligned} \tag{10}$$

$F(y)$  is the original distribution function of  $\chi$ . There are three types of maximum distribution function: Exponential type, Cauchy type and Bounded type. When the original



**Fig. 6** Macroscopic deformation of Baishuihe landslide

**Table 1** Value table to calculate physical and mechanics parameters of rock and soil mass

Medium	Gravity (KN/F <sub>i</sub> )	Cohesion (KPa)	Internal friction angle (°)	Elasticity modulus (Pa)	Poisson ratio	Saturated volatile water content (%)	Residual volatile water content (%)	Saturated infiltration coefficient (m/s)
Silty clay with gravelly soil	20.7	32.4	18	3.65E+07	0.31	43	2	1.27E-6
Siltstone	24.8	228	34.2	6.8E+09	0.26	24	0	5.79E-8
Slip soil	22	24.5	16	1.22 E+07	0.334	0.35	15	6.48E-7

distribution is exponential distribution, its sample extremum is exponential distribution of asymptotic distribution (Gumbel distribution). Gumbel distribution is used for extreme value distribution in the meteorological and hydrological research. It can be written as the following form:

$$A(y) = P(\chi < y) = e^{-e^{-a(y-u)}} \tag{11}$$

To calculate the extreme value of rainfall, the parameter  $a, u$  in the formula should be estimated first. Gumbel method is used to estimate the parameters in this paper.

$$a = \frac{\sigma_x}{\sigma_y}, \quad u = \bar{y} - \frac{\bar{x}}{a} \tag{12}$$

$$x_m = -\ln \left[ -\ln \left( 1 - \frac{m}{N+1} \right) \right], \quad m = 1, 2, \dots, N \tag{13}$$

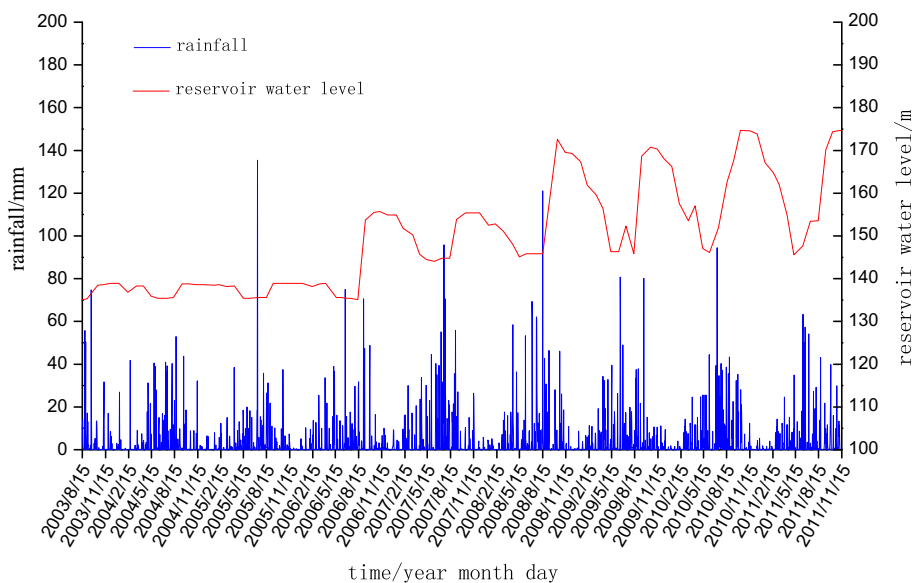
$$\bar{x} = \frac{\sum x_m}{N} \tag{14}$$

$$\sigma_x = \sqrt{\frac{\sum (x_m - \bar{x})^2}{N}} \tag{15}$$

$\bar{y}$  and  $\sigma_y$  are the mean and standard deviation of sample  $\chi$ . We can get T rainfall reappearing period of extreme rainfall intensity  $R_T$ :

$$R_T = u - \frac{1}{a} \left[ \ln \left( \ln \frac{T}{T-1} \right) \right] \tag{16}$$

**Fig. 7** Rainfall and water level elevation monitoring curves



Rahardjo et al. (2001), Rahardjo et al. (2008), Rahimi et al. (2011) studied the Singapore 4 slopes in pore water pressure distribution after rainfall through the field observation experiment, and found that 5 days antecedent precipitation have larger influence on the stability of the slope. According to it, we count 54 years rainfall data from 1960 to 2013, and the average of 5 days cumulative rainfall among 54 years is 134 mm. Using the method of calculation, the results are  $a = 0.02751$ ,  $u = 113.9182$ . We can get  $T$  rainfall reappearing period of extreme rainfall intensity, which is shown in Fig. 8.

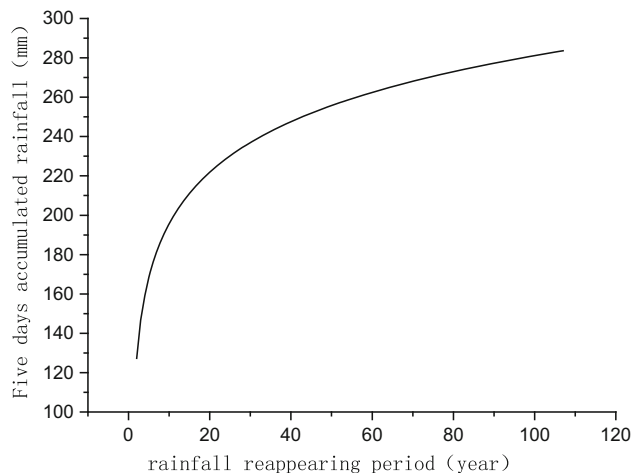
$$R_T = 113.92 - 36.35 \left[ \ln \left( \ln \frac{T}{T-1} \right) \right] \quad (17)$$

According to the above formula, 5 days accumulated rainfall of 10 years, 20 years and 50 years as shown in Table 2.

Considering two aspects of water level fluctuation and rainfall factors, four conditions are chosen as shown in Table 3.

### 3.1.3 Calculation model

Professional monitoring data of many years shows that Baishuihe Landslide deformation occurred in warning area, and there is no obvious deformation outside the warning area (Three Gorges University. Faculty of civil and construction 2013). Select warning area part of cross-section 2-2' as the calculation section, and regard bedrock as aquiclude. Boundary conditions of the model are: Left is boundary of fixed water level. Sliding surface is confining boundary. Under water is boundary of fixed water level, and it change into variable water head boundary when the



**Fig. 8** Five days accumulated rainfall of different rainfall reappearing period

water level range. Above water is boundary of fixed flow under the condition of rainfall. Calculation model is shown in Fig. 9.

## 3.2 Stability and failure probability calculation

### 3.2.1 Simulation of seepage

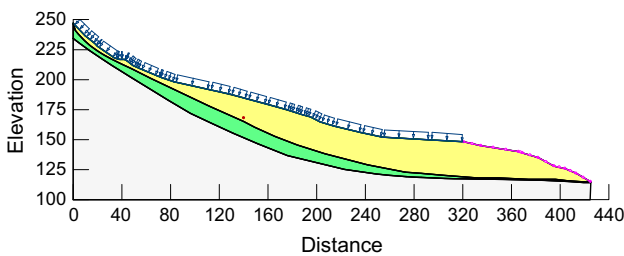
According to the boundary conditions and initial state of the existing water level monitoring data, analyse transient seepage problem in the SEEP/W program. In order to research on the change of landslide's seepage field clearly, 7 observation points are set in the model of calculation, among which 2 observation points are at different levels above the reservoir water level (observation point 150 and

**Table 2** Five days accumulated rainfall of different rainfall reappearing period

Calculated parameters		Rainfall reappearing period/year	Rainfall capacity/mm
a	0.00916	10	195.72
u	379.9505	20	221.886
		50	255.755

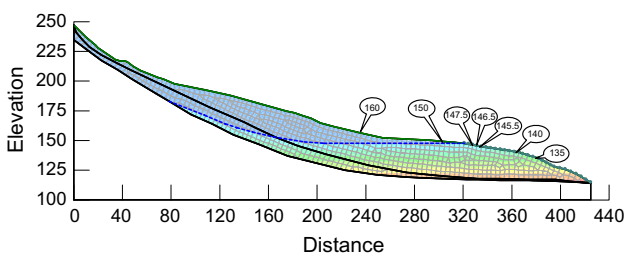
**Table 3** Condition choose

Condition	Rainfall reappearing period/year	Falling speed of water level m/d
1	–	0.6
2	10	0.6
3	20	0.6
4	50	0.6



**Fig. 9** Seepage calculation model

160), 3 observation points are in the variation range of reservoir water level (observation point 145.5, 146.5, 147.5), and the rest of 2 observation points are under the reservoir water level (observation point 140 and 135). Get the initial seepage field distribution, as shown in Fig. 10. Add water level drop of 0.6 m/d and the boundary conditions of different rainfall intensity, calculating the water

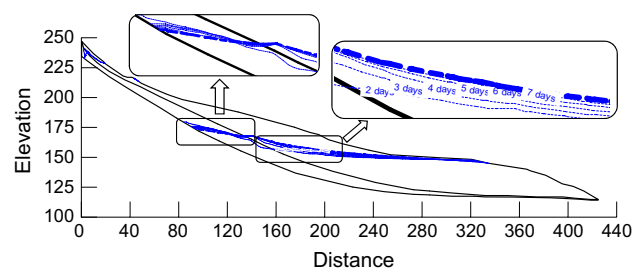


**Fig. 10** Initial moment seepage of landslide

head distribution of seepage field under different time, get in the water level decline and seepage field under the action of rainfall distribution. Taking condition 1 and condition 3 as examples, the saturation line at different moment are shown in Figs. 11 and 12, and the Figs. 13 and 14 express the change of pore water pressure of every observation point over time.

Under condition 1, the middle of landslide’s saturation line have a slight rise while the leading edge and trailing edge both descend gradually, which means groundwater of trailing edge supply that of middle’s, then supply the reservoir water level. With the increase of time, the angle between saturation line and reservoir water level decrease gradually, which indicate that the change of saturation line lags behind that of reservoir water level while reservoir level falls. Under condition 3, saturation line of slide mass above that of condition 1, which suggests that groundwater recharge comes from infiltration of precipitation before reservoir water level get recharged. And the falling range of the trailing edge’s saturation line is slight that of condition 1, because infiltration of precipitation raise the middle of saturation line, and head difference between trailing edge and leading edge decrease, which lead hydraulic gradients’ decrease while penetrating path is invariability. On the basis of Darcy law  $V = KI$ , seepage flow velocity decreases, and the range of saturation line decreases at the same time.

In unsaturated zone of slope, pore water pressure is negative while in saturation zone it is positive. The pore water pressure of the 3 observation points, which are below the elevation of 146 m, show a trend of decrease, and the other 4 points are in the process of slightly rise. Thus the saturation line of the slope in the part of more than 146 m elevation is slightly raised while the following parts of 146 m are decreased. Until the end of calculation, the pore water pressure of each observation point under condition 4 is higher than that of condition 1, and with the increase of the observation point’s elevation, the differences become bigger. When the water level drop below



**Fig. 11** Saturation line at different time under condition 1



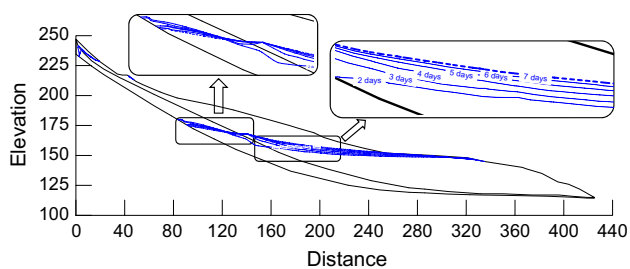


Fig. 12 Saturation line at different time under condition 3

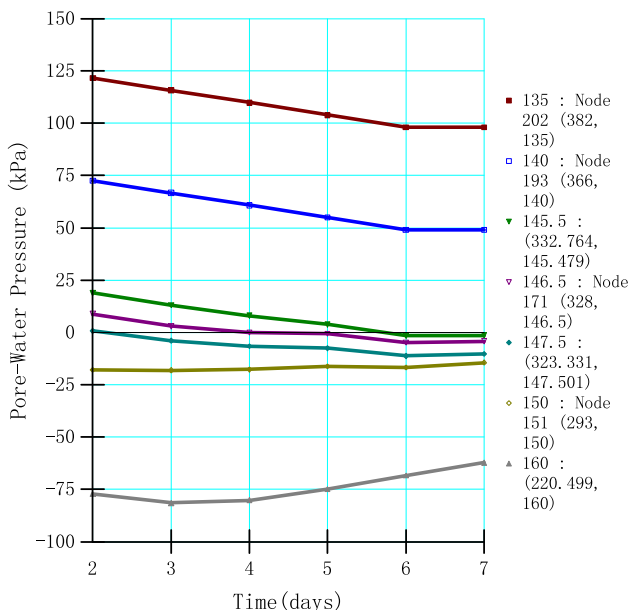


Fig. 13 Pore pressure of observation point varying under condition 1

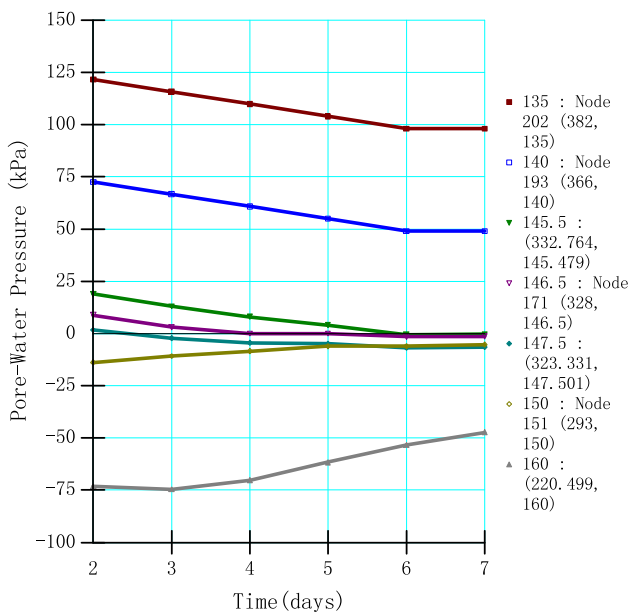


Fig. 14 Pore pressure of observation point varying under condition 3

observation points, the pore water pressure will keep 0 for a period of time in the process of reducing, which means the observation point is transited from saturated to unsaturated, then decrease gradually. Due to the volume of soil skeleton and the effective stress have a transition process from initial state to the new state, and the permeability coefficient of soil is small, the soil skeleton transition to the new void ratio when discharge groundwater, the pore water pressure remains the same in the process.

### 3.2.2 Overall stability and failure probability calculation

Import the seepage state of different time into SLOPE/W program to calculate the stability. Then obtain the overall stability coefficient of Baishuihe landslide warning area under different conditions. Choose one day for a time step. The stability coefficient, failure probability is shown in Tables 4, 5 and Fig. 15.

The calculation result shows that under four different conditions, stability coefficient of the warning area show a trend of decreasing and probability increases gradually with the rain and the water continue to decline. But the whole process of the warning area stability coefficients are between 1.2 and 1.4, and the probability are less than 5 %, the overall stability is good. It is different with the actual situation of the warning area in the investigation report of Baishuihe landslide. Therefore, the overall stability and failure probability can't reflect real situation of Baishuihe landslide warning area.

### 3.2.3 The progressive failure stability and failure probability calculation

The warning area of Baishuihe landslide is divided into 32 blocks from top to bottom. Based on the process of progressive failure analysis model, the stability coefficient and failure probability of each slice under each condition can be calculated. According to the size of the landslide failure probabilities, stability of landslide is divided into five levels as shown in Table 6.

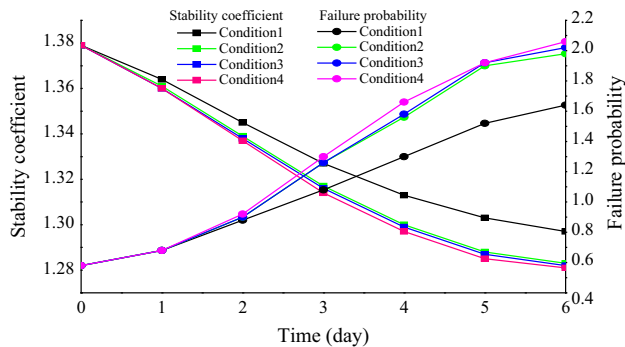
The warning area slice stability diagram are shown in Figs. 16, 17, 18, 19.

Table 4 Stability coefficient under different conditions and time

Conditions	0	1	2	3	4	5	6
Condition 1	1.379	1.364	1.345	1.327	1.313	1.303	1.297
Condition 2	1.379	1.361	1.339	1.317	1.300	1.288	1.283
Condition 3	1.379	1.360	1.338	1.316	1.299	1.287	1.282
Condition 4	1.379	1.360	1.337	1.314	1.297	1.285	1.281

**Table 5** Failure probability under different conditions and time

Conditions	0	1	2	3	4	5	6
Condition 1	0.58	0.68	0.88	1.08	1.30	1.52	1.64
Condition 2	0.58	0.68	0.90	1.26	1.56	1.9	1.98
Condition 3	0.58	0.68	0.90	1.26	1.58	1.92	2.02
Condition 4	0.58	0.68	0.92	1.30	1.66	1.92	2.06

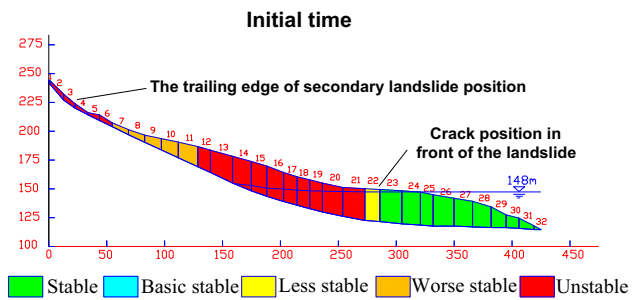


**Fig. 15** Stability coefficient and failure probability under different conditions

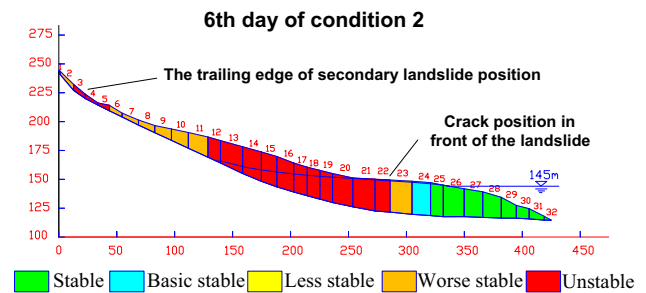
Above charts show that Baishuihe landslide warning area slope stability of each part have large differences. Because the front of sliding zone is relatively flat and slippery body thickness is relatively large, the front of the warning area is in a stable state. The rear sliding slope is large, so the unstable region—failure probability is greater than 90 % part mainly concentrated in the vicinity of middle and posterior warning area. According to the investigation report (Three Gorges University. Faculty of civil and construction 2013), from august 2005 to august 2006, several landslides occurred in the elevation of 220 m, and the scale was small generally. Large area of landslide surface appeared sinking cracks. On the morning of June 30, 2007, there were about 100000 m<sup>3</sup> of highway landslide sliding piled on the road in posterior of warning area, and the trailing edge of warning area boundary mainly connected. The west boundary cracks were intermittent plumes spread. By comparison, progressive failure model can reflect the actual situation of warning areas in real. In addition, there is a large possibility for warning area to slip or slide along the shallow sliding surface. Therefore, focus of the prevention and control measures

**Table 6** Different failure probability of landslide stability (Zhang et al. 1994)

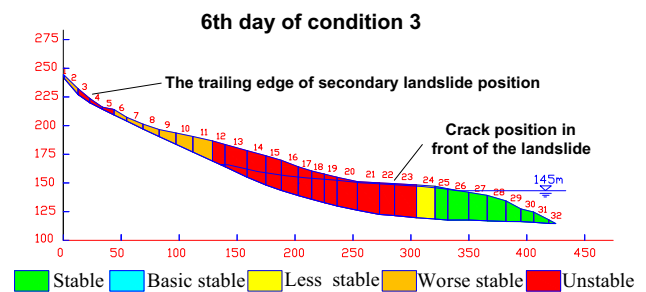
Failure probabilities	<5 %	5–30 %	30–60 %	60–90 %	>90 %
Stability	Stable	Basic stable	Less stable	Worse stable	Unstable



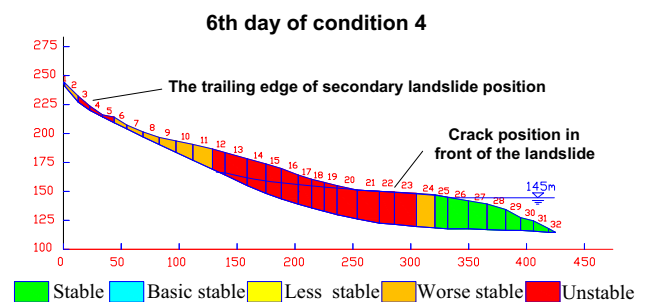
**Fig. 16** Landslide stability of the initial time



**Fig. 17** Landslide stability of the 6th day under condition 2



**Fig. 18** Landslide stability of the 6th day under condition 3



**Fig. 19** Landslide stability of the 6th day under condition 4

should be given to the trailing edge and central warning areas.

Four kinds of conditions landslide failure probability distribution are shown in Figs. 20, 21, 22, 23.

Only under the action of water drop, there is 49 % area unstable region of warning area. With the rainfall intensity increases gradually, unstable and worse stable area ratio increase. Under the condition of 5 days accumulated rainfall of 50 years, the unstable region reaches 59 %, and only 25 % of the area is in a stable state. The possibility of local deformation slip is large.

### 3.3 Progressive failure process analysis

According to the results of failure probability calculation, the warning area is divided into 4 sections. In order to research on the progressive failure process, 6 observation points are set in the calculation model, among which 1 observation point is at section 1 (observation point 1 at 230 m), 1 observation point is at section 2 (observation point 2 at 201 m), 2 observation points are at section 3 (observation point 3,4 at 188 m, 152 m), and the rest of 2 observation points are at section 4 (observation point 5,6 at 145 m, 135 m). As shown in Fig. 24.

SIGMA/W program is used to calculate stress and strain of the warning area. Take condition 4 as an example.

The change of XY-displacement of each observation point over time is shown in Fig. 25.

Obviously, each observation point cumulative displacement shows a trend of gradual increase. At the beginning of the calculation, the displacement of the observed points 1-4 are significantly larger than that of the observation points 5 and 6. To the end of the calculation, each observation point displacement increases with the elevation decreases. It can be seen that strain is produced from the upper part of the warning area. Under the joint action of rainfall and reservoir water level, the sliding zone of section 1 and 3 appeared weakening first, which lead to local deformation. And then section 2 sliding zone began weakening. At this time, the upper part of the warning area showed a trend of deformation. Section 2 sliding zone weakened after the second day. As a result, the sliding zone

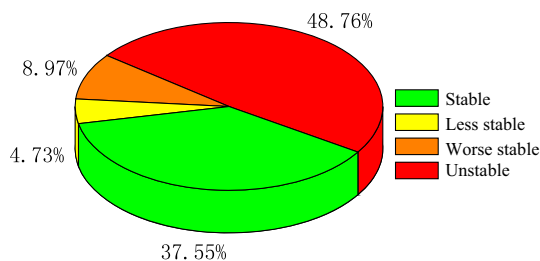


Fig. 20 Failure probability distribution of condition 1

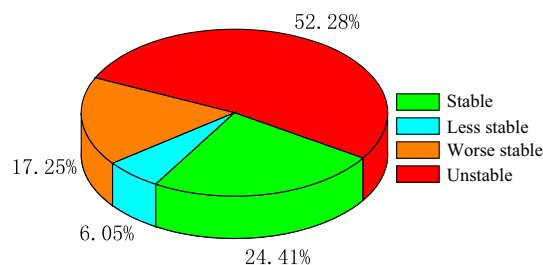


Fig. 21 Failure probability distribution of condition 2

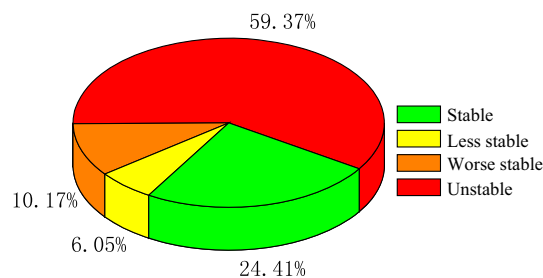


Fig. 22 Failure probability distribution of condition 3

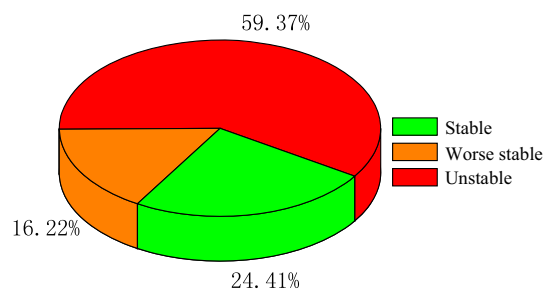


Fig. 23 Failure probability distribution of condition 4

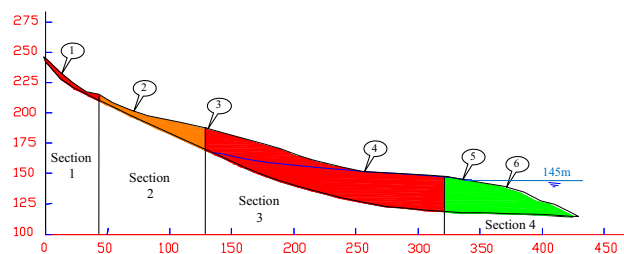
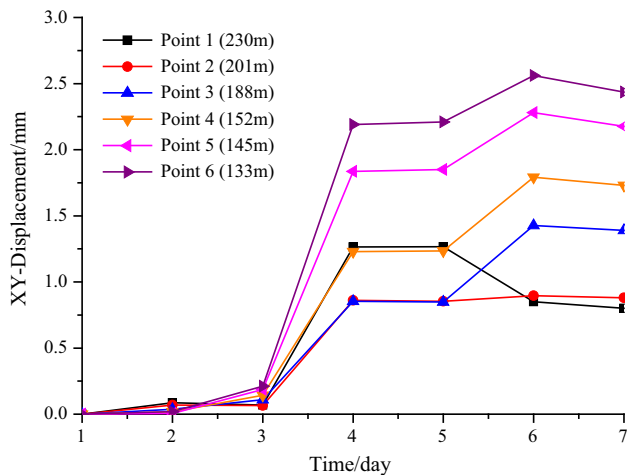


Fig. 24 4 sections partition of the warning area

of the warning area linked completely and overall creep appeared. Displacement obviously increased.

In conclusion, under the joint action of rainfall and reservoir water level, the warning area of Baishuihe Landslide’s sliding zone experienced a weakening process, which is section 1,3—section 2—section 4. The landslide shows a progressive failure mode from top to bottom which is basically consistent with the results of previous calculation.



**Fig. 25** XY-Displacement of observation point varying with time

## 4 Discussion

### 4.1 The discussion of overall stability

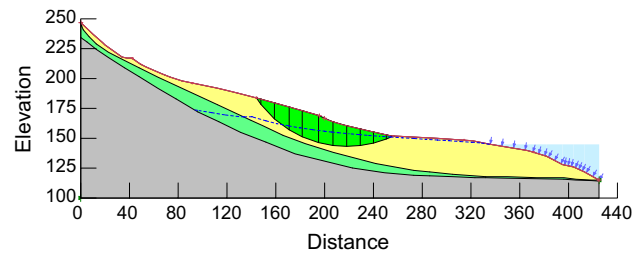
On the basis of monitoring data, the deformation of the warning area of Baishuihe Landslide mainly happened during the period of low water level, which means the uplifting of the reservoir water level is conducive in the overall stability of slope. Therefore, the time from June to August should be attached great importance in daily warning.

In the process of whole calculation, the probability of damage under the conditions of rainfall (condition 2, 3, 4) is obviously higher than no rain (condition 1). The former three condition of rainfall don't have apparent differences among each other. However, the difference of three condition of rainfall appeared clearly in the calculation of progressive failure model of each slice. By comparison, the difference of rainfall can't be responded very well when calculating the overall stability, while it can be responded the influence well by calculation of progressive failure.

### 4.2 The discussion of unstable region

The entire landslide probability of damage can't be used any more when assessing the stability of Baishuihe landslide warning area. Through the calculation of progressive failure model of each slice, Baishuihe landslide warning area stability of each part has large differences. Therefore, it's necessary to find the most dangerous area. By using auto search function in Geo-studio, choosing the 6th day of condition 4 as the condition, the most dangerous area of whole warning area can be found after 10,000 times calculation of Monte-Carlo, as Fig. 26 shows.

It has been found that the most dangerous area is on the middle of warning area, which is consistent with the result



**Fig. 26** Schematic diagram of the most dangerous area in landslide of calculation of progressive failure. The stability of the coefficients is 0.931 and the probability of damage is 63.74 % in most dangerous area. Thus, this area should be attach great importance when forecasting the slope and preventing the project.

### 4.3 The discussion of instability factors

In practice, geotechnical parameter will have characteristic of time-varying along with the change of saturation line. So researching on the time-varying reliability of landslide will be more accurate. In addition, the road building in the middle of landslide and other human engineering activities have adverse effect on the landslide stability. To simplify the calculation process, this paper only considers the influence of reservoir water level change and rainfall infiltration. The calculation result shows that Baishuihe Landslide is induced by reservoir water level and rainfall, of which the dominant factor is reservoir water level while rainfall infiltration results in the deformation of landslide. When the reservoir level decreased, the change of saturation line lags the reservoir level, which leads that the decrease of the pore water pressure lags that of leading edge's water pressure. As a result, deformation of the landslide is accelerated. And on the one hand, rainfall infiltration softens the slip soil, which makes geotechnical parameters of slip soil reduce. On the other hand, saturation line is raised which lead to the rise of pore water pressure of landslide. Under the joint action of water and rainfall, the deformation of slope will further increase.

## 5 Conclusion

- (1) The analysis of seepage shows that the change of saturation line lags the change of reservoir water level. In unsaturation zone, pore water pressure is negative while the pore water pressure is positive in saturation area. When the water level drop below observation points, the pore water pressure will keep 0 for a period of time in the moment of the observation point is transited from saturated to unsaturated, then decreased gradually.

- (2) By calculating the overall stability coefficient and failure probability, the whole process of the warning area stability coefficients are between 1.2 and 1.4, and the failure probability are less than 5 % under four conditions. The overall stability is good. It is different with the investigation report of Baishuihe Landslide actual situation. Therefore, overall stability and failure probability can't reflect real situation of Baishuihe Landslide warning area.
- (3) Through the calculation of progressive failure model of slice, Baishuihe Landslide warning area slope stability of each part has large differences. The unstable region mainly concentrated in the vicinity of the middle and posterior warning area. Front of the warning area is in a stable state. The deformation characteristics are consistent with investigation report<sup>[14]</sup>. There is a large possibility for landslide warning area to slip or slide along the surface of shallow slip.
- (4) Under four conditions, unstable area increases gradually with the rain continues and the water continues to decline. Under the condition of 5 days accumulated rainfall of 50 years the unstable region reaches 59 %, only 25 % of the area is in a stable state. The possibility of local deformation slip is large.
- (5) Under the joint action of rainfall and reservoir water level, the warning area of Baishuihe landslide shows a progressive failure mode from top to bottom.
- (6) Method for analysis of landslide based on local failure probability can be more comprehensive, more practical understanding the landslide deformation and failure of the most prone to initial position. And the prediction of potential damage initial position, could instruct laid monitoring points in the landslide deformation phase detection prediction, and guide prevention projects in control work.
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