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ORIGINAL PAPER

# Influence of Morphology of Sliding Surface on Its Seepage Characteristics and Slope Stability Under Fluctuations in Reservoir Water Level

**Jian Chen · Yubo Zhu · Lei Lv · Hairong Huang**

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**Abstract** The fluctuation in reservoir water level is one of the key external factors affecting the stability of slopes. Finite element models are established for four typical slope types in the Three Gorges Reservoir area (line-shaped, arc-shaped, polyline-shaped, and chair-shaped), and the seepage characteristics and slope stability under different permeability coefficients are simulated. The results reveal the following: (1) The shape of the infiltration line is closely related to permeability. The infiltration line presents a convex shape when the permeability coefficient is lower than the rate of reduction in the reservoir water level, and a concave shape when the coefficient is higher than this rate. However, the infiltration line always presents a convex shape under the condition of increasing reservoir water level. (2) The wetting rate decreases with the increase in the permeability coefficient and attains its minimum value under the conditions of line- and arc-shaped slopes. (3) The slope safety factor first decreases and then increases with the decrease in the reservoir water level. Meanwhile, the converse occurs when the reservoir water level increases. (4) When the reservoir water level decreases, the line-shaped slope with a marginal permeability coefficient is the most hazardous, whereas the chair-shaped slope with a high permeability coefficient is the safest. (5) When the reservoir water level increases, the slope becomes unstable after the stable stage of the reservoir water level.

**Keywords** Reservoir water level fluctuations · Sliding surface morphology · Seepage · Slope stability · Numerical simulation

## 1 Introduction

Landslides, earthquakes, and volcanic eruptions are regarded as three of the major geological disasters worldwide (Squarzoni et al. 2020; Guo et al. 2020). Among these, landslides are the most frequent and hazardous geological disasters, accounting for 50–60% of the total number of geological disasters (Huang et al. 2020; Peng et al. 2019; Yan et al. 2019). Slope instability has many forms and is influenced by numerous factors such as adverse geological conditions and extreme climatic changes. For example, the 1963, Vaiont landslide killed over 1900 individuals and injured over 700 (Li et al. 2019) (see Fig. 1a). In 2013, a landslide in China's Yunnan province destroyed numerous residential buildings, leaving residents displaced (see Fig. 1b). Landslide disaster causes permanent damage to engineering structures and poses a severe threat to the safety of human lives and property. Therefore, it is of great importance to

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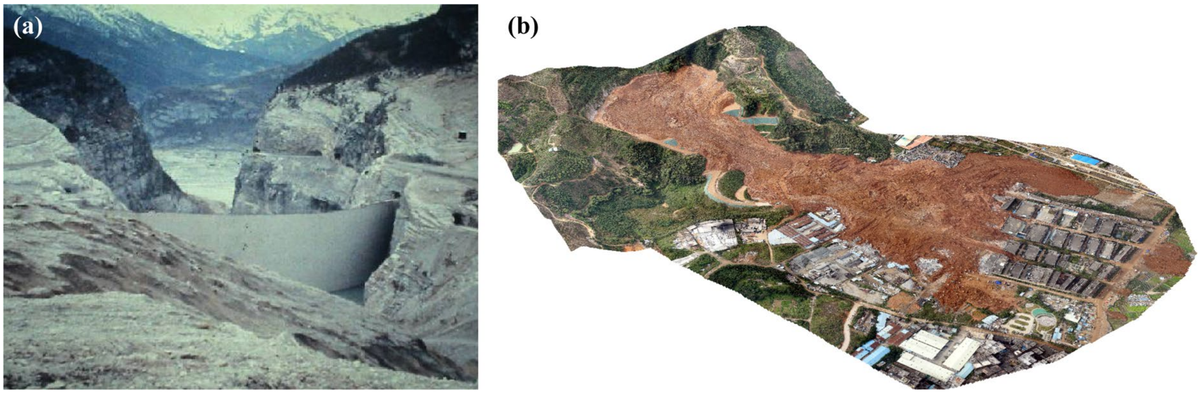


**Fig. 1** Geological disasters caused by typical landslides. **a** Vaiont Landslide, Italy, 1963; **b** landslide in Yunnan, China, in 2013

identify the seepage laws and determine the critical parameters for slope instability.

Research on the mechanisms of seepage stability under fluctuations in reservoir water level has focused mainly on three aspects: experimental studies, theoretical studies, and numerical simulation. Experimental studies are the most direct and important means to explore landslide mechanisms. For example, Jia et al. (2009) analysed the causes and modes of instability of loosely-filled slopes caused by an abrupt reduction in water level using a model test. Wang et al. (2011) focused on the characteristics of bank collapse under an increase in water level. Li et al. (2012) analysed the variation in the slope seepage field and its influence on stability under a reduction in water level. Liang et al. (2013) analysed the deformation development characteristics of soil bank slopes under the fluctuation in reservoir water level. However, laboratory tests can only perform small scale experiments. Theoretical research focuses mainly on the criteria of landslide instability. For example, Lin et al. (2001) discussed the spatio-temporal relationship between rainfall and landslides in the Three Gorges Reservoir area. They also summarised the critical rainfall and rainfall intensity of landslides at different scales. Li et al. (2010a; b) explored the deformation and failure modes of landslides with stepped displacement characteristics in the Three Gorges Reservoir area. They also obtained comprehensive criteria by combining a single factor criterion. Li et al. (2010a; b) discussed the mechanisms of progressive landslide failure and presented quantitative prediction criteria for different evolution stages based on the prediction of deformation time series. However, the accuracy of the theoretical criteria remains to be examined. Numerical simulation is an important means to verify and reveal landslide mechanisms in experimental and engineering practice. For example, Lu et al. (2017) conducted numerical simulation of the seepage field and stress strain of the Baijibao landslide under the condition of daily reduction in different reservoir water levels. Zhong et al. (2012) calculated the stability coefficient of the upstream dam slope of a clay core dam under the condition of abrupt reduction in the reservoir water level based on the unsaturated theory. Compared with experimental research, numerical simulation is inexpensive and convenient in terms of parameter adjustment, and has gradually become one of the important tools for researchers to study landslide stability.

Several landslide accidents occurred in the Three Gorges Reservoir area from 2003 to 2015. Based on the data of 463 old water-related landslides with significant deformation or instability (Zhou et al. 2016), four typical slide surface forms are summarised according to the sliding surface position, shapes, and landslide deformation mechanisms: line-shaped, arc-shaped, polyline-shaped, and chair-shaped (see Fig. 2). Lu et al. (1993) studied the influences of the four typical slides on slope stability. Qian et al. (2016) analysed the correlation between landslide deformation and slip surface morphology. They also explained the variations in seepage characteristics of different slip surface morphologies during water level fluctuations in a reservoir area from a macro perspective. However,

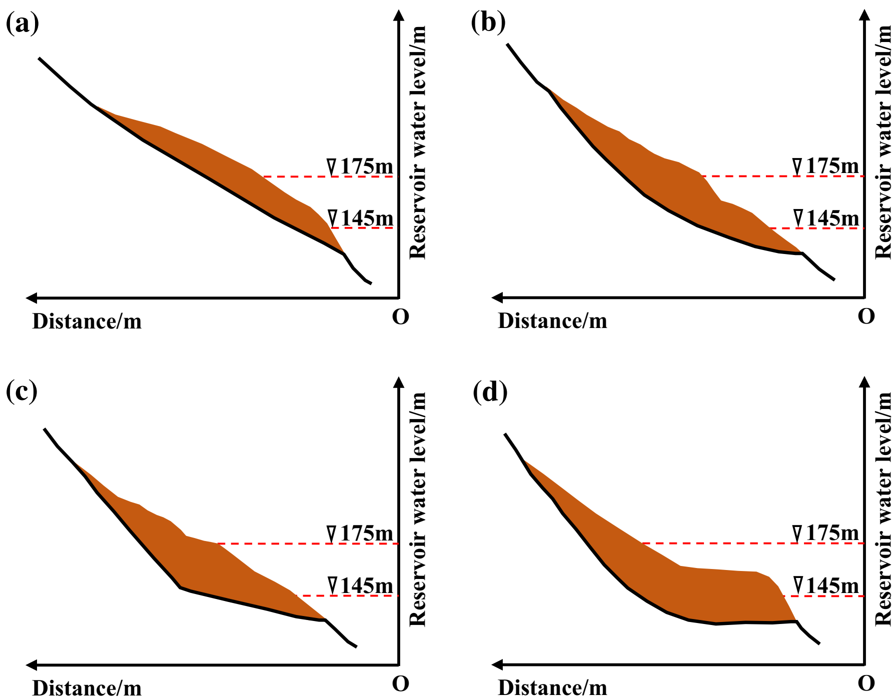


**Fig. 2** Different sliding surface morphologies. **a** Line-shaped; **b** arc-shaped; **c** polyline-shaped; **d** chair-shaped

these studies used only data analysis or engineering experience rather than numerical simulation to systematically analyse and examine the variation laws of the seepage field and factors influencing stability.

Considering the shortcomings of previous studies, this study mainly analyses the influences of different permeability coefficients and fluctuations in reservoir water level on the seepage and stability of slopes. In addition, it examines the mechanisms of landslide instability. Two-dimensional numerical models are established for four types of slide surface morphologies using Geostudio software. The Seep/w and Slope/w modules are utilised to simulate the seepage characteristics and slope stability under different conditions. Then, the influences of the relationship between fluctuations in reservoir water level and different permeability coefficients on seepage variation and stability of landslides are discussed. The research results can provide certain references for comprehending the seepage characteristics of different sliding surface morphologies and the prevention and control of landslide disasters under reservoir water fluctuations.

## 2 Unsaturated Theory and Numerical Models

### 2.1 Unsaturated Theory

The unsaturated theory considers the variations in the seepage field in the landslide body under fluctuations in the reservoir water level. Additionally, it is used to characterise the seepage characteristics of unsaturated soil bodies. The governing equation of unsaturated seepage is established in the following form in accordance with Darcy's law (Song et al. 2015):

$$\frac{\partial}{\partial x_i}\left[k_{ij}^s k_r\left(h_c\right)\frac{\partial h_c}{\partial x_j} + k_{i3}k_r\left(h_c\right)\right] + Q = \left[C\left(h_c\right) + \frac{\theta}{n}S_s\right]\frac{\partial h_c}{\partial t} \tag{1}$$

where $k_{ij}$ is the saturated permeability tensor, $k_r$ is the relative water permeability, $h_c$ is the pressure head, $Q$ is the source and sink term, C($h_c$) is the water capacity, $\theta$ is a function of pressure head, $n$ is the internal porosity of the soil, and $S_s$ is the water storage per unit.

The range of the unsaturated and saturated areas in landslides varies under the action of fluctuations in the reservoir water level. Therefore, it is more reasonable to adopt the unsaturated theory according to relevant studies. In this section, the Fredlund double stress variable formula is adopted (Fredlund et al. 1994):

$$s = c' + \sigma_n \tan \phi' + (u_a - u_w) \tan \phi^b \quad (2)$$

where $c'$ and $\phi'$ are the effective strength parameters, $\sigma_n$ is the difference between the total normal stress and pore gas pressure, $u_a$ is the pore air pressure, $u_w$ is the pore water pressure, and $\phi_b$ is the strength increased by negative pore water pressure.

### 2.2 Numerical Models and Boundary Conditions

Four typical landslide models are established based on the Wshaxi landslide in the Three Gorges Reservoir area: line-shaped; arc-shaped; polyline-shaped, and chair-shaped. The resistance sections of the four landslide surfaces increases successively. The reservoir water level ranges from 175 to 145 m. The numerical model consists of tetrahedral elements and triangular elements. The subdivision of the sliding body region is refined effectively to improve the calculation accuracy. The line-shaped slope is divided into 883 nodes and 835 elements. The arc-shaped slope is divided into 1040 nodes and 996 elements. The polyline-shaped slope is divided into 992 nodes and 948 elements. The chair-shaped slope is divided into 963 nodes and 923 elements (Fig. 3).

The reservoir water level ranges from 175 to 145 m. The boundary conditions are as follows: AE represents the 185 m fixed water-head boundary, ABCD denotes the reservoir water level fluctuation boundary, and ED represent the impervious boundaries. The rate of increase and reduction in the reservoir water level is 1 m/*d*, and the calculation time is 60 d.

### 2.3 Model Parameters and Calculation Conditions

The Fredlund and Xing model is adopted to describe the soil–water characteristics of the slope (Fredlund et al. 1994). It can accurately describe the

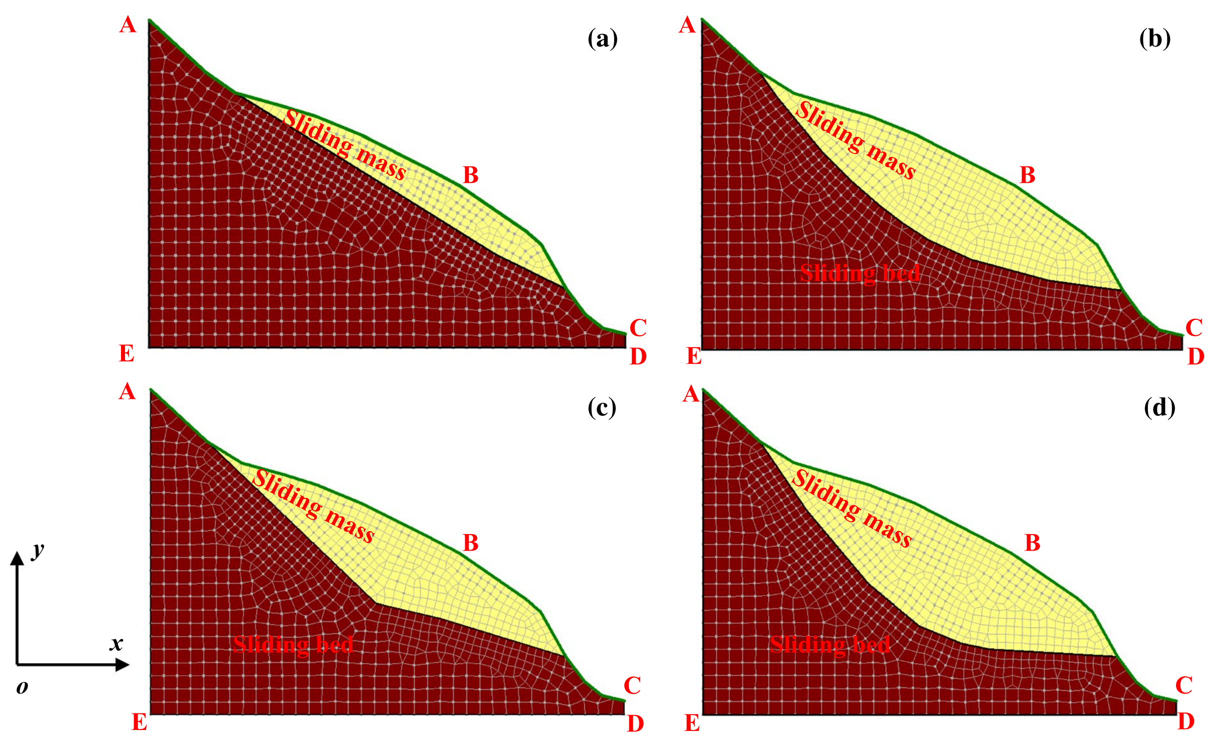


**Fig. 3** Mesh divisions and boundary conditions of four types of slopes. **a** Line-shaped; **b** arc-shaped; **c** polyline-shaped; **d** chair-shaped

relationship between the permeability coefficient (volumetric water content) of soil and matric suction. The governing equation is as follows:

$$\theta_w = C_\phi \frac{\theta_s}{\left\{\ln\left[e + \left(\frac{\phi}{a}\right)^n\right]\right\}^m} \tag{3}$$

where $\theta_w$ is the volumetric water content of the soil, $C_\phi$ is set to 1 in accordance with Leong et al. (1997), $\theta_s$ is the saturated volumetric water content, and $\phi$ is the negative pore pressure. $a$, $m$, and $n$ are the fitting parameters and are expressed as follows:

$$a = \phi_i \tag{4}$$

$$m = 3.67 \ln\left(\frac{\theta_s}{\theta_i}\right) \tag{5}$$

$$n = \frac{1.31^{m+1}}{m\theta_s} 3.72 s\phi_i \tag{6}$$

where $\phi_i$ is the matric suction at the inflection point and $s$ is the slope at the inflection point.

The permeability coefficient function is calculated using the following equation based on the volumetric water content (which is calculated by Eq. (3)):

$$k_w = k_s \frac{\sum_{i=j}^{N} \frac{\theta(e^y)-\theta(\psi)}{e_i^y} \theta\left(e_i^y\right)}{\sum_{i=1}^{N} \frac{\theta(e^y)-\theta_s}{e_i^y} \theta^0\left(e_i^y\right)} \tag{7}$$

where $k_w$ is the permeability coefficient corresponding to the water content, $k_s$ is the saturated permeability coefficient, $y$ is the dummy variable, $i$ is the numerical spacing, $j$ is the minimum negative pore pressure, $N$ is the maximum negative pore pressure, $\Psi$ is the negative pore pressure at step $j$, and $\theta^0$ is the initial value.

The saturated permeability coefficient of the slope is set as $k_s$=1.9e−3m/$d$, 0.11m/$d$, 1.84m/$d$, and 7.38m/$d$ separately according to the range of the hydrogeological permeability coefficient of the Three Gorges Reservoir area (Li et al. 2017). The other soil parameters are set as follows: soil mass $\gamma$=22 kN/m$^{-3}$, effective cohesion $c'$=25 kPa, internal friction angle $\varphi'$=28°, and $\varphi_b$=11°. The curves of the volumetric water content and permeability coefficient of the slope under different permeability coefficients are depicted in Fig. 4.

Different slide surface morphologies are selected in our calculation conditions: (1) line-shaped; (2) arc-shaped; (3) polyline-shaped; (4) chair-shaped. Furthermore, the seepage and stability characteristics of different permeability coefficients under the fluctuations in the reservoir water level are investigated (see Table 1).

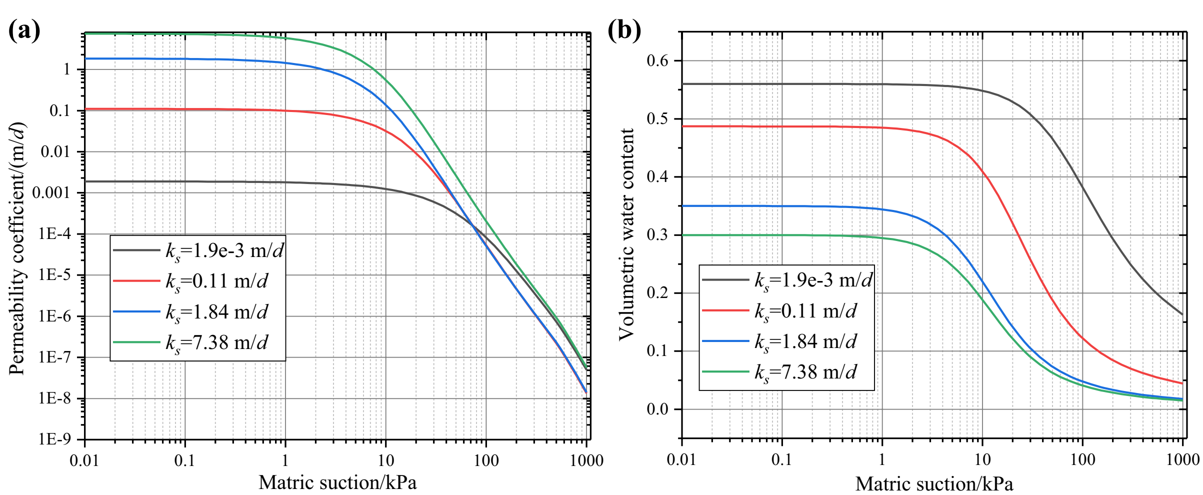


**Fig. 4** Soil–water characteristic curve. **a** Permeability coefficient function; **b** volumetric water content function

**Table 1** Calculation conditions

| Calculation | Reservoir water level fluctuation rate | Slide surface morphologies | Permeability coefficient |
|---|---|---|---|
| Reservoir water level rise: 145→175 | 1 m/*d* | (a) Line shape; (b) arc shape; (c) polyline shape; (d) chair shape | 1.9e−3 m/*d*<br>0.11 m/*d*<br>1.84 m/*d*<br>7.38 m/*d* |
| Reservoir water level drop: 175→145 | 1 m/*d* | (a) Line shape; (b) arc shape; (c) polyline shape; (d) chair shape | 1.9e−3 m/*d*<br>0.11 m/*d*<br>1.84 m/*d*<br>7.38 m/*d* |

## 3 Calculation Results

### 3.1 Variations in Infiltration Line

#### *3.1.1 Reduction in Reservoir Water Level*

The variations in the infiltration lines under different conditions in the case of a reduction in the reservoir water level are depicted in Fig. 5. As is evident, the relationship between the permeability coefficient and rate of reduction in the reservoir water level is one of the important factors affecting the groundwater level. When the permeability coefficient is lesser than the rate of reduction in the reservoir water level (implying that the permeability of the slope is relatively marginal), the infiltration lines of the four types of slides are convex upward. The hydrodynamic pressure is directed towards the exterior of the slope body. Furthermore, there is a difference in the water head between the interior and exterior of the slide, and the infiltration line of the slide presents a lag effect. Under a reduction in the reservoir water level, the groundwater level of the slope body does not decrease immediately. Thus, the infiltration line is convex upward. When the permeability coefficient is higher than the rate of reduction in the reservoir water level,

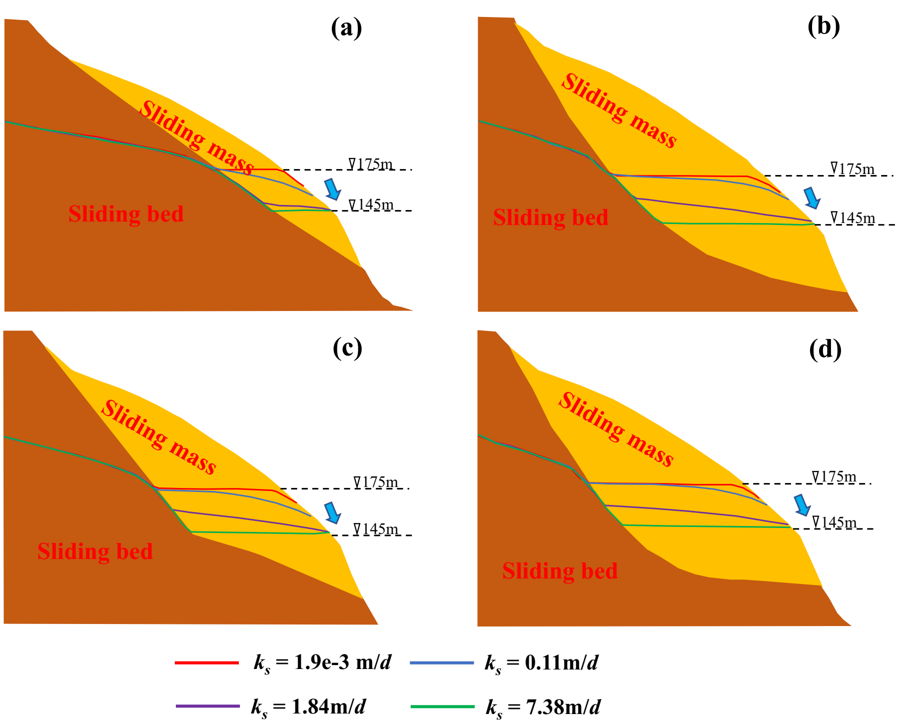


**Fig. 5** Variations in infiltration lines under reduction in reservoir water level. **a** Line-shaped; **b** arc-shaped; **c** polyline-shaped; **d** chair-shaped

the water-permeable capacity of the sliding body increases gradually and the water-holding capacity decreases. The hydrodynamic pressure characteristics are apparent, and the groundwater level presents a gradual downward trend. The difference in the water head between the sliding body and reservoir water level is almost zero. However, when the permeability coefficient increases to a certain extent, the variation trend of the groundwater level is no longer apparent.

As the strength of the infiltrated part of the slope decreases significantly, the proportion of the infiltrated part of the slope plays a key role in the stability analysis of the landslide. To quantitatively characterise the infiltration proportion of the slope, the wetting rate is defined as the ratio of the volume of soil under the infiltration line to the total volume of the slope (see Fig. 6a). Figure 6b depicts the wetting rate under different slip surface morphologies. As can be observed, the wetting rate decreases gradually with the increase in the permeability coefficient. This indicates that a lower position of the infiltration line in the landslide body is more favourable to the stability of the slope. Meanwhile, the wetting rate is minimum for the polyline-shaped landslide among the different slip surface morphologies.

### *3.1.2 Increase in Reservoir Water Level*

The variations in the infiltration lines under different conditions in the case of an increase in the reservoir water level are depicted in Fig. 7. As can be observed, when the reservoir water level increases at a rate of 1 m/*d*, the shape of the groundwater level varies with the increase in the permeability coefficient. When the permeability coefficient is lesser than the rate of reduction in the reservoir water level, as the permeability coefficient increases, the curve curvature reduces and the difference in the water head between the interior and exterior of the slope decreases gradually. Another consequence of the low permeability of the slope body is that the water level in the slide body increases gradually even when the reservoir water level increases rapidly. Meanwhile, it can observed that the curvature of the groundwater level and difference in the water head decrease gradually with the increase in the permeability coefficient. When the permeability coefficient is higher than the rate of reduction in the reservoir water level, the shape of the infiltration line exhibits a downward concave trend, and the bending angle of the curve increases. The infiltration line trend is almost constant when the permeability coefficient increases to 7.38 m/d.

Similar to the condition of the reduction in the reservoir water level, statistics are made on the laws of the wetting rate under the condition of an increase in the reservoir water level (see Fig. 8). In contrast to the condition of the reduction in the reservoir water level, the wetting rate decreases gradually with the increase in the permeability coefficient. The position of the infiltration line is higher in the arc-shaped and polyline-shaped slopes among the different slide surface morphologies.

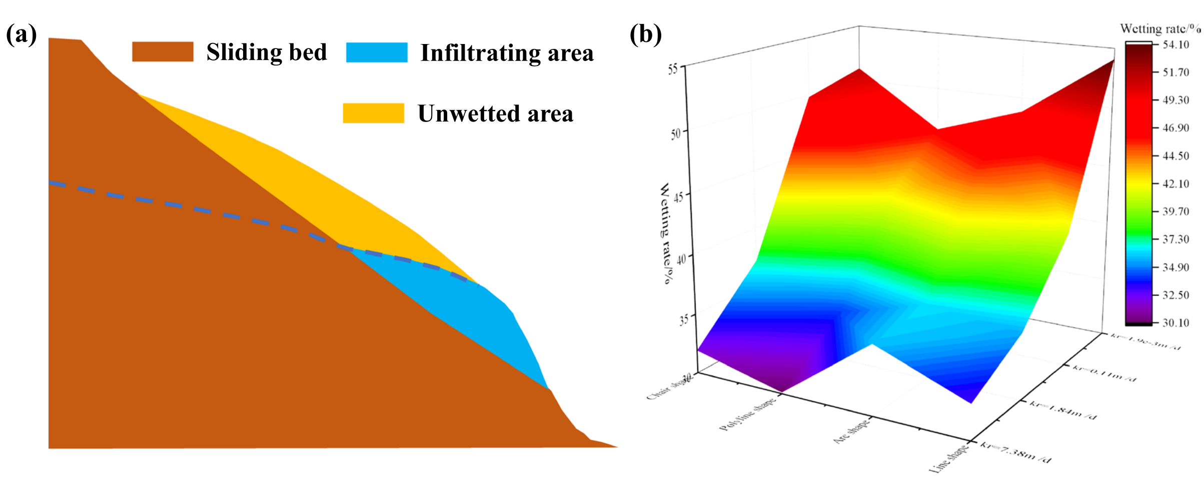


**Fig. 6** Variations in wetting rate under reduction in reservoir water level. **a** Definition of wetting rate; **b** variations in wetting rate

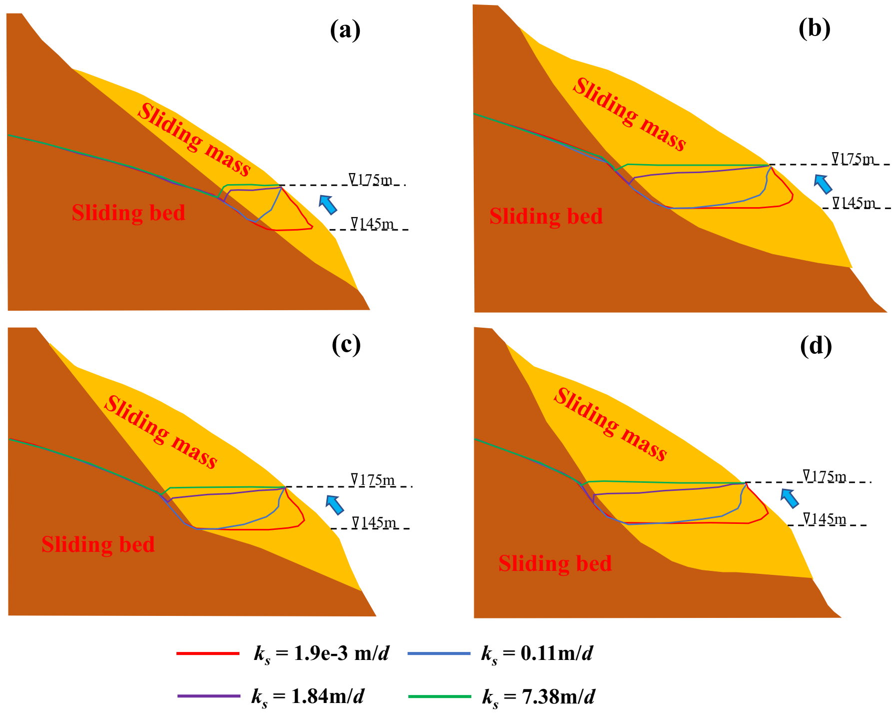


**Fig. 7** Variations in infiltration lines under increase in reservoir water level. **a** Line-shaped; **b** arc-shaped; **c** polyline-shaped; **d** chair-shaped

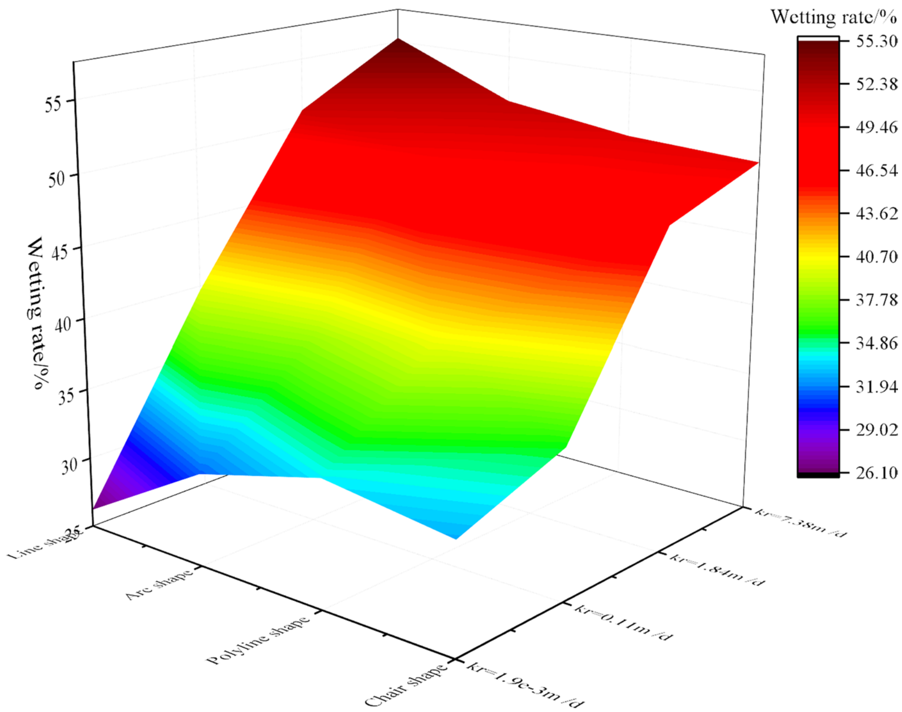


**Fig. 8** Variations in wetting rate under increase in reservoir water level

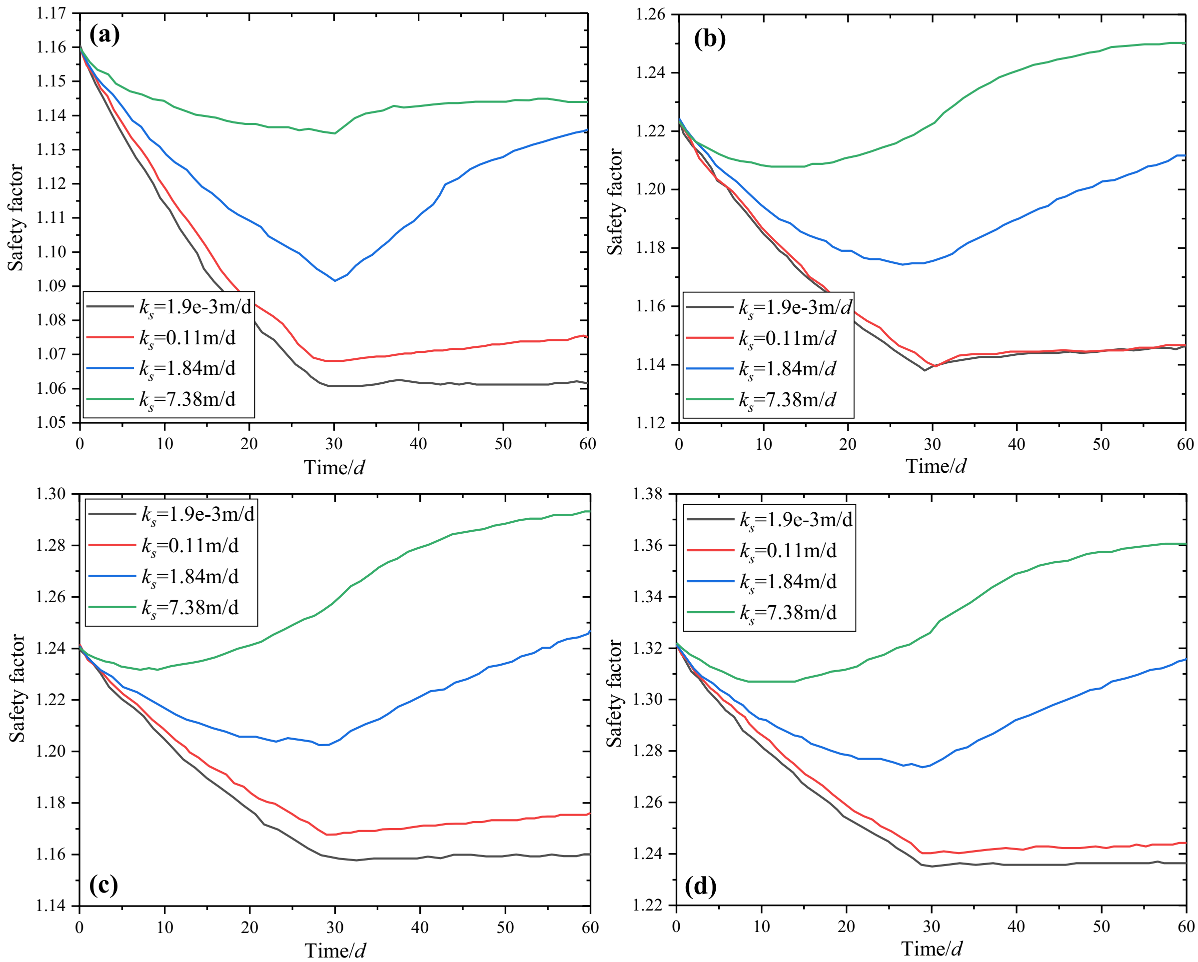


**Fig. 9** Variations in safety factor under reduction in reservoir water level. **a** Line-shaped; **b** arc-shaped; **c** polyline-shaped; **d** chair-shaped

## 3.2 Variations in Safety Factors

### *3.2.1 Reduction in Reservoir Water Level*

Figure 9 depicts the variations in safety factors of different landslide shapes under a reduction in the reservoir water level. In the initial state, the safety factors of the chair-shaped, polyline-shaped, arc-shaped, and line-shaped slopes decrease gradually. This implies that under identical initial conditions, the line-shaped slope exhibits the worst stability owing to the marginal volume of the slip-resisting section. Meanwhile, the chair-shaped slope exhibits the largest slip-resisting section and consequently, the highest safety factor.

When the permeability coefficient is lesser than the rate of reduction in the reservoir water level ($k_s = 1.9\text{e}{-3}$, 0.11 m/*d*), the seepage force is directed towards the exterior of the slope owing to the apparent “hysteresis effect” under a reduction in the reservoir water level (Yu et al. 2020). Thus, a “convex” shape is presented. Meanwhile, it is evident from Sect. 3.1 that the wetting rate is relatively higher, and the strength parameters of the soil are weakened substantially. In addition, the slope water pressure unloading effect is superplaced. Therefore, the slope stability of the four types of sliding surfaces decreases rapidly, and the safety factor attains its minimum value on the 30th day. Once the reservoir water level decreases to the lowest position, the hydrodynamic pressure effect in the sliding body weakens gradually. Furthermore, the safety factor tends to be stable and then increases gradually. However, the magnitude of increase is moderate.

When the permeability coefficient is higher than the rate of reduction in the reservoir water level ($k_s$ = 1.84, 7.38 m/$d$), the decrease in the safety factor is marginal owing to the high water discharge rate inside the landslide. In addition, after the reservoir water level decreases to the lowest position, the safety factor increases gradually, and the magnitude of increase is moderate.

The evaluation of slope stability generally addresses two questions: (1) Will the slope be unstable? (2) When would the slope fail? Corresponding to the law of the safety factor in this section, it is necessary to pay attention to two important indexes: minimum safety factor of the landslide (MSF) and the day when the landslide occurs (MSFD). The variations in MSF and MSFD are shown in Fig. 10. As is evident from the laws of MSF, the minimum safety factor decreases substantially with the decrease in the permeability coefficient. Meanwhile, under identical permeability coefficients, the following is the order of slopes in terms of MSF: line-shaped < arc-shaped < polyline-shaped < chair-shaped. Therefore, a line-shaped slope with a smaller permeability coefficient is the most hazardous condition, whereas a chair-shaped slope with a larger permeability coefficient is the safest condition. As is evident from MSFD, for a line-shaped slope, the MSFD does not vary with the permeability coefficient. That is, the minimum safety factor occurs on the day when the reservoir water level reduces to the lowest position (30th day). For other types of slopes, the time of occurrence of the minimum safety factor advances with the increase in the permeability coefficient.

### 3.2.2 Increase in Reservoir Water Level

Figure 11 depicts the variations in the safety factors for different slope types under the condition of an increase in the reservoir water level. In the initial state, the safety factor of the polyline-shaped, chair-shaped, arc-shaped, and line-shaped slopes decreases gradually. This implies that under the condition of a low reservoir water level, the polyline-shaped slope is more stable, whereas the line-shaped slope is more hazardous.

When the permeability coefficient is lesser than the rate of reduction in the reservoir water level ($k_s$ = 1.9e−3, 0.11 m/$d$), an apparent "concave" characteristic is observed under an increase in the reservoir water level. This is owing to the lower permeability coefficient of the slide. The infiltration inside the landslide is relatively marginal, whereby the weakening effect of the soil is less. Thus, the water pressure acting on the slope surface plays a decisive role. Consequently, there is a large increase in the safety factor of the slope. However, the safety factor decreases gradually after the reservoir water level

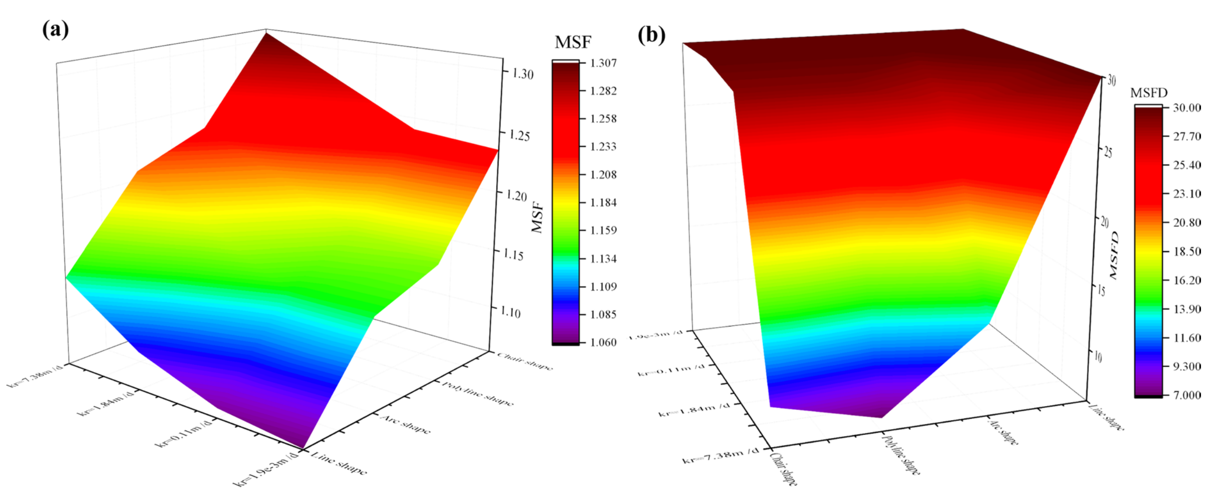


**Fig. 10** Variations in MSF and MSFD. **a** Variations in MSF; **b** variations in MSFD

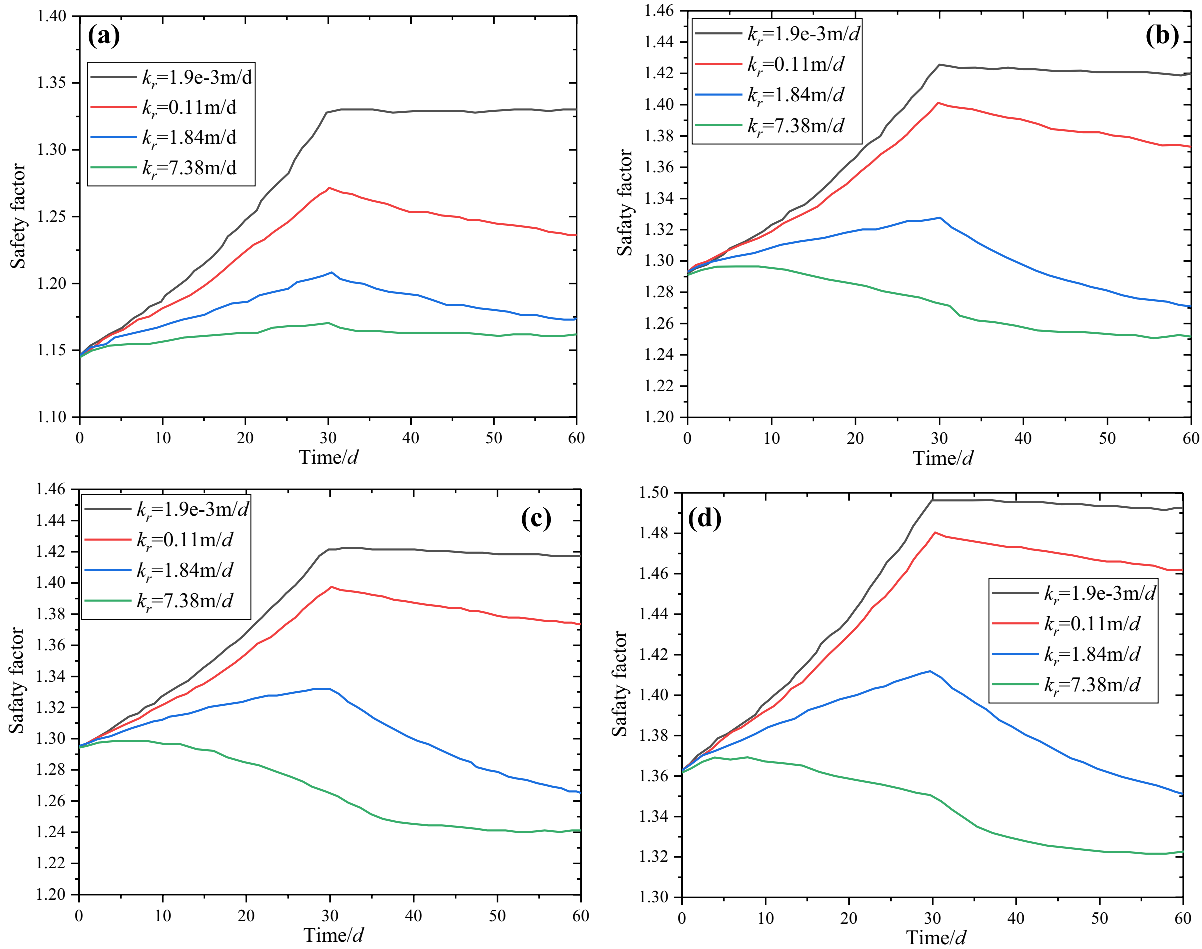


**Fig. 11** Variations in safety factor under increase in reservoir water level. **a** Line-shaped; **b** arc-shaped; **c** polyline-shaped; **d** chair-shaped

increases to the highest position (175 m), although the range of decrease is moderate.

When the permeability coefficient is higher than the rate of reduction in the reservoir water level ($k_s = 1.84$, 7.38 m/*d*), the water level inside the landslide increases rapidly owing to the high permeability coefficient of the landslide. The strength of soil decreases substantially compared with the water pressure acting on the slope surface. Thus, the safety factor of the landslide increases marginally and then decreases substantially. Therefore, in the case of an increase in the reservoir water level, the instability generally occurs after the reservoir water level continues to increase for a long time.

Similar to that in Sect. 3.2.1, the maximum safety factor of the landslide (MASF) and the day when the MASF occurs (MASFD) are depicted in Fig. 12. As is evident, the maximum safety factor increases substantially with the decrease in the permeability coefficient. Meanwhile, under identical permeability coefficients, the order of slopes in terms of increasing order of MASF is line-shaped < arc-shaped < polyline-shaped < chair-shaped. For a line-shaped slope, the MASFD does not vary with the variation in the permeability coefficient. However, for the other types of slopes, the MASFD is advanced in the case of a large permeability coefficient.

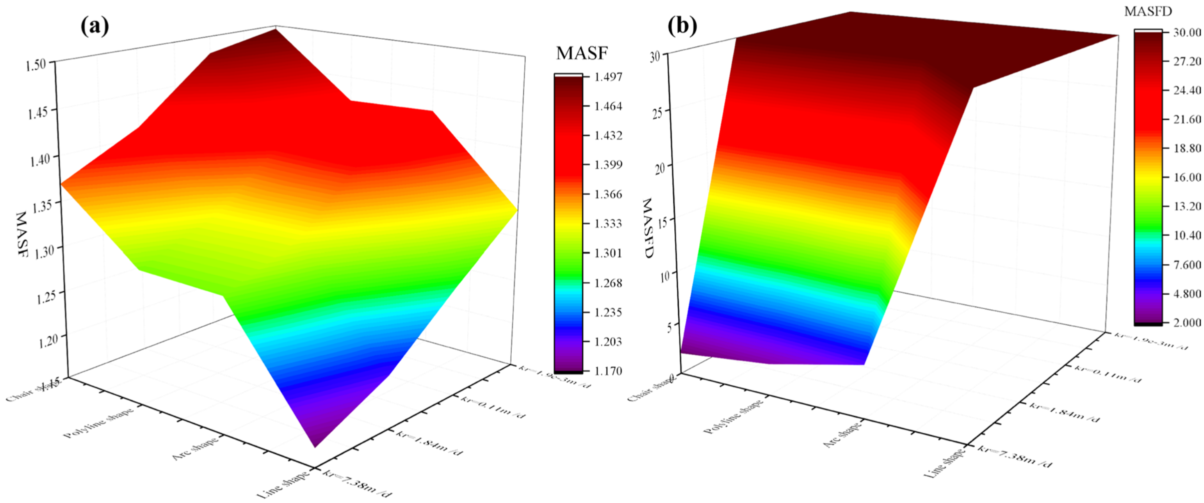


Fig. 12 Variations in MASF and MASFD. **a** Variations in MASF; **b** variations in MASFD

## 4 Discussion

In this paper, by establishing the numerical models of four typical slope types in the Three Gorges Reservoir area (line-shaped, arc-shaped, polyline-shaped, and chair-shaped), the influences of different permeability coefficient of different landslide under the reservoir water level fluctuations are investigated. The failure mechanisms are summarized as follows:

(1) Line-shaped slope. Since the sliding surface of line-shaped slope is flat and there is no obvious concentrated anti-sliding section, anti-sliding force is dispersed in the whole sliding surface. When the reservoir water rises to the high level, the reservoir water begins to infiltrate into the slope body, forming a seepage field pointing into the slope. The slope body is subjected to high osmotic pressure, which leads to the increase of the slope stability; When the reservoir water level remains high, the groundwater seepage gradually changes from transient to steady state, the seepage pressure gradually dissipates, and the stability decreases gradually; When the reservoir water level gradually decreases from the high water level to low water level, the groundwater seepage field forms a high seepage pressure pointing out of the slope, which increases the sliding force and decreases the slope stability.

(2) Arc-shaped slope. Due to the uniform radian of the sliding surface, the dip angle of the sliding surface at the front of the slope body is larger than that of the chair shape, therefore the normal stress is smaller, which leads to the smaller the normal stress. When the reservoir water rises, except for the high osmotic pressure pointing into the slope, the weight reduction effect of buoyancy is more obvious for the reduction of slip resistance, which is not conducive to the stability of landslide. When the reservoir water drops, due to the dissipation of weight reduction effect, the anti-sliding force increases, which is beneficial to the stability of landslide.

(3) Polyline-shaped slope. The dip angle below the inflection point of the polyline-shaped slide surface is small, which is mainly the anti-slide section. The dip angle of the slide surface above the inflection point is steep, which constitutes the main slide section of the landslide. Its overall stability change characteristics are similar to those of the chair-shaped slope.

(4) Chair-shaped slope. The front part of the chair-shaped slide has a gentle dip angle, and some even turn up to form the leading edge of the anti-warping section, so the front part of the slide body constitutes the main anti-sliding section of the landslide. When the reservoir water rises to the front of the landslide and infiltrates into the slope, the sliding body is subjected to the float-

ing support force of the reservoir water, forming the floating support weight reduction effect, the normal stress of the sliding surface decreases, the slide resistance decreases, and the overall stability decreases. When the reservoir water level gradually rises, the seepage pressure and buoyancy act on the middle and rear of the sliding body, namely the sliding section of the slope, the sliding force of the landslide decreases and the stability of the landslide increases. When the water level drops, the stability of landslide will increase gradually because the floating support effect dissipates and the anti-sliding force increases.

## 5 Conclusions

(1) Under the condition of a reduction in the reservoir water level, the shape of the infiltration lines are closely related to the permeability coefficient of the soil slope: the infiltration line is “convex upward” when the permeability coefficient is lower than the rate of reduction in the reservoir water level, and “concave” when it is higher than this rate. The wetting rate exhibits a decreasing trend with the increase in the permeability coefficient and is minimum for the polyline-shaped slope.

(2) The infiltration lines of the landslide body present a “concave” shape under the condition of an increase in the reservoir water level. The wetting rate decreases gradually with the increase in the permeability coefficient and is maximum for the arc-shaped and polyline-shaped slopes.

(3) Under the condition of a reduction in the reservoir water level, the decrease in the safety factor is large when the permeability coefficient is lesser than the rate of reduction in the reservoir water level, and the increase in the safety factor is marginal after the reservoir water level is stabilised. For the line-shaped slope, the MSFD appears on the 30$^{th}$ day, which does not vary with the variations in the permeability coefficient. However, the MSFD of the other types of slope is advanced.

(4) Under the condition of an increase in the reservoir water level, the safety factor increases significantly when the permeability coefficient is lesser than the rate of reduction in the reservoir water level. Meanwhile, the decrease in the safety factor is marginal after the reservoir water level is stabilised. The safety factor increases negligibly when the permeability coefficient is lesser than the rate of increase in the reservoir water level. However, the large decrease in the safety factor occurs when the reservoir water level is stabilised. The MASF increases significantly with the decrease in the permeability coefficient. Meanwhile, for the same permeability coefficient, the slopes can be ranked in the following order in terms of their maximum safety factor: line-shaped slope < arc-shaped slope < polyline-shaped slope < chair-shaped slope. The MASFD is advanced when the permeability coefficient is relatively large.

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**Data Availability** Enquiries about data availability should be directed to the authors.

**Declarations**

**Conflict of interest** The authors declare that there are no known conflicts of interest associated with this publication.

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