Stability analysis of the reservoir bank landslide with weak interlayer considering the influence of multiple factors

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ABSTRACT

There are many factors that induce landslides on the reservoir banks, including periodically changing reservoir water level, rainfall and micro-seismic in the reservoir area. To study the evolution process of the reservoir bank landslide with a weak interlayer under the combined action of multiple factors, this article adopts a combination of field investigation, indoor tests and numerical simulation to analyze the Zhaoshuling landslide in the Three Gorges Reservoir Area. The fluctuations of the reservoir water level and real-time rainfall are used to establish the seepage field of the landslide, and earthquakes are introduced to investigate the instability of landslides. Furthermore, the indoor tests are used to determine the parameters of the rock with different numbers of dry-wet cycles, then the evolution trend of the landslide can be analyzed. The results indicate that the stability of landslides is lowest in June during a typical hydrological year. Moreover, the landslide would be in a critical state under the 0.05 g seismic peak acceleration. Due to the changing reservoir water level, the strength reduction of weak interlayers would accelerate the instability of the Zhaoshuling landslide. This study could provide guidance for the prevention and mitigation of the reservoir bank.

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Introduction

Landslide is one of the most frequent geological disasters, causing huge losses to human life and property safety (Jiang et al. 2018; Huang et al. 2020; Zhuang et al. 2021). As for the large-scale landslide, the bedding landslide (a type of landslide sliding along an existing structural surface) with a weak interlayer is common worldwide (Wen and Aydin 2005; Zhang et al. 2021). Generally, the weak interlayer is an important boundary condition in the stability analysis of rocky landslides (Barton 1986). Xu et al. (2013) analyzed the stability of the artificial slope in Jiuding Mountain by field shear test, laboratory soil test and limit equilibrium

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method. It can be found that the mechanical characteristics of weak interlayers are key factors affecting overall stability. After the disturbance of external factors (e.g. reservoir water, rainfall and earthquake), the deflection and sliding of the slope would be accelerated (Tan et al., 2022; Wang et al. 2021a).

The distributions of geological hazards are regular to a certain extent because they have similar geo-mechanical models or inducing factors (Chang et al. 2020; Wang et al. 2022; Schneider-Muntau et al. 2022). There are many factors that induce landslides on the reservoir bank, including periodically changing reservoir water level, rainfall and micro-seismic in the reservoir area (Wang et al. 2021b; Huang et al., 2020b; Huang et al., 2020c). Specifically, taking the uncertainty of earthquakes into consideration, the seismic coefficient can be regarded as a random variable by the pseudo-static method in a certain range (Zhang et al. 2021). The fluctuation of the reservoir water plays a vital role in inducing slope failures, for the minimum stability coefficient occurs at the rapid decline of water level (Zhang et al. 2020b; Mao et al. 2020; Zhang et al., 2022a). Wang et al. (2020a, 2020b) and Zhang et al. (2022b) found that the dry-wet cycles caused obvious damage to the base rock mass.

According to the existing research, it can be found that the effective link of multiple factors is very important in analyzing the evolution process of reservoir banks with weak interlayers. In this study, the Zhaoshuling landslide is taken as an example. Based on the actual reservoir water level fluctuation, rainfall monitoring data and seismic data, the stability study of the Zhaoshuling landslide is performed. Furthermore, the dry-wet cycle tests are used to determine the evolution trend of the landslide.

**Study area**

The Zhaoshuling landslide is located in Badong county, Hubei Province (Figure 1). It is 1 km away from the Badong Yangtze River Bridge in the west and 74 km away from the Three Gorges Dam in the east (Chen et al. 2011). It is a typical large-scale bedding rock landslide with a weak interlayer in the Three Gorges area. The Zhaoshuling landslide is about 1200–1500 m long and 600 m wide. The elevation of the trailing edge of the landslide is about 500 m, and the elevation of the leading edge is about 60–100 m (Figure 2).

![Figure 1. Overview of the Zhaoshuling landslide: (a) Location of the Zhaoshuling landslide in China and (b) remote image of the Zhaoshuling landslide.](image)
The reservoir water level fluctuates between 145 m and 175 m every year since the normal operation of the Three Gorges Hydropower Station. The study area is a subtropical monsoon climate with high temperatures and abundant rainfall. The groundwater levels are affected by the precipitation recharge and changing reservoir water levels. According to the earthquake intensity zoning map of China (Shi et al. 2014), the seismic intensity of the study area is VI, and the peak acceleration is 0.05 g.

The exposed strata in the study area are the second and third sections of the middle Triassic Badong Formation (T\textsubscript{2}b\textsuperscript{2} and T\textsubscript{3}b\textsuperscript{3}). These strata are layered structures and the sequence is normal. There are more than 90% of the landslides in Badong County developed in T\textsubscript{3}b\textsuperscript{3} which is affected by slope deformation and giant deep-seated landslides (Wen et al., 2020; Chai et al. 2013; Li et al. 2016).

The Zhaoshuling landslide can be simplified into three sections: sliding mass, sliding zone and bedrock (Wang and Lin 2011; Oh et al. 2015; Shinoda et al. 2015). Notably, on-site investigations of the Zhaoshuling landslide are conducted. There are 21 boreholes performed in the study area, and the characteristics of the landslide are determined through the drilling tests (Figure 2; Chen et al. 2011). The sliding mass, mainly from T\textsubscript{3}b\textsuperscript{3}, can be classified into two types: limestone and marlstone. The sliding zone is located at the junction of T\textsubscript{3}b\textsuperscript{3} and T\textsubscript{2}b\textsuperscript{2}, which is a weak interlayer of landslide. Besides, the shape of the weak interlayer is consistent with the topography, becoming the potential sliding surface of the landslide and controlling the stability of the landslide. Referring to the existing papers (e.g. Chen et al. 2011; Shi et al. 2014; Li et al. 2016), the deformation of the Zhaoshuling landslide keeps getting smaller. In this case, there is no long-term monitoring curve for this landslide.

**Methods**

Based on the lithologic interface and geological tectonics of the Zhaoshuling landslide, a numerical model is established by SLIDE2 that can analyze the stability of slip
surfaces using the Morgenstern-Price method. SLIDE2 also includes finite element groundwater seepage analysis built into the program, for both steady state and transient conditions. The seepage modules can be calculated independently or coupled with slope stability analysis. The model is divided into five sub-areas including sliding mass, weak interlayer, silty mudstone, argillaceous siltstone and limestone (Figure 3).

The field surveys show that the stability of the Zhaoshuling landslide is controlled by the weak interlayer where the sliding surface of the slope develops. There are many secondary sliding belts and bedding fracture zones in the sliding mass, and the lowest sliding belt is located near the interface between the strata of T2b2 and T2b3. Meanwhile, multiple layers of weak fractured zones in the section are exposed by the drilling tests. Therefore, it is speculated that these weak fractured zones constitute the sliding zones of the Zhaoshuling landslide. During the numerical simulation, the sliding zone can be specified in the software, as shown in the red line in Figure 3. Compared with the automatic search of the sliding surfaces, this calculation method is in line with the actual situation of the landslide and the calculation efficiency is higher. Considering the fluctuation of the reservoir water level between 145 m and 175 m, there is a dry-wet cycles zone with a 30 m height on the bank slope. The dry-wet cycles could affect the sliding mass and weak interlayer. Thus, the sliding mass and weak interlayer can be divided into three sections: underwater saturated zone, dry-wet cycles zone, and unsaturated zone. The changing seepage field of the landslide is analyzed by introducing the rainfall and the reservoir water level.

The Mohr-Coulomb model is selected to characterize the mechanical properties of the landslide. The physical and mechanical parameters of the Zhaoshuling landslide are adapted from the relevant literature and engineering geologic analogy (Chen et al. 2011; Wen et al., 2021). The effect of negative pore water pressure on shear strength in the unsaturated zone is considered during water level fluctuation. All relevant calculation parameters are shown in Table 1. It should be noted that the physical parameters of the dry-wet cycle zone are the reduction values after 10 dry-wet cycles.

![Figure 3. Model of Zhaoshuling landslide.](image-url)
The length of the study area is more than 1 km. To speed up the calculation, the rock mass with a discontinuous seepage grid can be regarded as an equivalent continuous seepage medium (Barton 1973; Priest and Hudson 1981; Huang et al. 1992). Hydraulic parameters of rock and soil of the Zhaoshuling landslide are adapted from the relevant literature and engineering geologic analogy (Spencer 1967; Bishop 1955; Hodge and Freeze 1977), as listed in Table 2. Notably, this article focuses on the influence of multiple inducing factors on the stability of the bank landslide; thus, the proposed methods can be used for the qualitative evaluation of its evolution trend. If the absolute factor of safety (FOS) is required, it is suggested to confirm the relevant hydraulic parameters by the specific tests (Zhang et al. 2020a).

The permeability coefficients and volumetric water contents are constants when rock and soil are saturated, and change with the pore water pressure when rock and soil are unsaturated. Therefore, the saturation unit weight is used in the saturated zone; the natural unit gravity is used in the unsaturated zone; the cohesion and internal friction angle in the dry-wet cycles zone are reduced according to the specific number of cycles. The Van Genuchten model is selected to characterize the soil-water characteristic curve and permeability coefficient curve.

### Slope stability analysis under reservoir water level and rainfall

According to water level data for the Three Gorges Reservoir from 2011 to 2018, the reservoir water levels vary periodically. And the annual variation can be divided into five representative periods: January to March (slow descending stage), the water level drops from 175 to 165 m; April to June (rapid descending stage), the water level drops from 165 to 145 m; June to August (steady state), the water level stays 145 m and 155 m; September to October (ascending stage), the water level increases from 145 to 175 m; November to December (steady state), water level stabilizes at 175 m. The daily monitoring data of reservoir water level for 2017 are used as the water level in the annual stability analysis, as shown in Figures 4a–b.

| Parameter                              | Parameter Sliding mass | Weak interlayer | Silty mudstone | Argillaceous siltstone | Limestone |
|----------------------------------------|------------------------|-----------------|----------------|-------------------------|-----------|
| Natural unit gravity (kN/m³)            | 20                     | 21              | 23             | 25.5                    | 25.8      |
| Saturated unit weight (kN/m³)           | 22                     | 23              | 25.9           | 26.9                    | 26.8      |
| Cohesion (kPa)                          | 130                    | 12              | 120            | 200                     | 350       |
| Cohesion of dry-wet cycle zone (kPa)    | 117.42                 | 6.9             | /              | /                       | /         |
| Friction angle (°)                      | 22                     | 18              | 21             | 30                      | 32        |
| Friction angle of dry-wet cycle zone (°)| 21.6                   | 5.92            | /              | /                       | /         |
| Tensile strength (kPa)                  | 1                      | 1               | 30             | 100                     | 150       |

Table 1. Physical and mechanical parameters of the Zhaoshuling landslide.

| Parameter                              | Sliding mass | Weak interlayer | Silty mudstone | Argillaceous siltstone | Limestone |
|----------------------------------------|--------------|-----------------|----------------|------------------------|-----------|
| Saturated permeability coefficient (m/s)| 1.157E-4     | 3.472E-5        | 5.787E-6       | 5.785E-5               | /         |
| Saturated volumetric water content     | 0.25         | 0.35            | 0.25           | 0.35                   | /         |
| Residual volumetric water content      | 0.09         | 0.05            | 0.12           | 0.12                   | /         |

Table 2. Hydraulic parameters of rock-soil mass of Zhaoshuling landslide.
Figure 4. The factors affecting the seepage field of landslide. (a) The reservoir water level of Three Gorges Reservoir in 2017; (b) the fluctuation speed of reservoir water; and (c) the daily precipitation of Badong County in 2017.
Determination of rainfall, the daily rainfall data in 2017 are also used as the transient rainfall boundary conditions, date from China Meteorological Data Service Centre (V3.0). The precipitation cloud image is interpolated into grid data, and then the daily precipitation of Badong county is calculated according to the administrative division, as shown in Figure 4c.

The recording data show that rainfall is concentrated between April and October, with more than 87.28% of the annual precipitation. Annual rainfall in 2017 is 1362.46 mm, slightly larger than the average annual rainfall of 1073.29 mm in Badong County. According to the classification of the China Meteorological Administration, the rainfall can be divided into light rain, moderate rain, heavy rain and rainstorm, at rainfall intensity thresholds of 10, 25, 50, and 250 mm/d. Accordingly, the year of 2017 can be determined as a year with typical rainfall patterns.

Results

The changing groundwater level within one year can be divided into five stages, as shown in Figure 5.

Stage I (January 1–March 20). The groundwater level decreases with the reservoir water level, and there is no obvious change in the seepage field of the shallow slope. The FOS is basically unaffected by the slow descending of reservoir water level and rainfall.

Stage II (March 21–June 10). The groundwater level gradually decreases in this stage. The FOS stabilizes at first and then decreased. Moreover, the FOS began to decrease on May 15, several days after the decline of the reservoir water level. It shows that the fluctuation of reservoir water level has a lagging effect on slope stability.

Figure 5. Groundwater infiltration line. (a) Stage I; (b) Stage II; (c) Stage III; (d) Stage IV; and (e) Stage V.
Stage III (June 11–August 20). The reservoir water level fluctuates up and down rapidly, and the groundwater infiltration lines are convex. Notably, there is still a certain lag inside the landslide. The FOS shows a good coincidence trend with the landslide stability coefficient. Due to the increased rainfall on 6 July, the growth rate of FOS decreases when the reservoir water level rises uniformly.

Stage IV (August 21–October 20). The reservoir water level rises rapidly, and the groundwater level before the slope is the same as the reservoir water level. The groundwater infiltration line sags slightly. Except for local drops due to rainfall, the FOS increases with rising water levels.

Stage V (October 21–December 31). Due to the lag phenomenon of groundwater level compared with reservoir water, the leading-edge groundwater infiltration line does not reach a stable state in a short time after the reservoir water level rises.

The FOS fluctuates periodically when the landslide is subjected to rainfall and water level declination (Figure 6). These results indicate that the fluctuation of reservoir water level plays a dominant role in controlling landslide stability, and rainfall has a less important impact on the overall landslide stability. Notably, the reservoir water only exists at the foot of the landslide. Accordingly, its effect on the overall sliding along the weak interlayer is limited.

Slope stability analysis under reservoir water level rainfall combined with earthquake

Material parameters obtained by indoor triaxial tests are applied to the numerical simulation, and the simulation of rainfall and reservoir water level conditions are in line with the actual situation. Under the combined action of reservoir water level and rainfall, the lowest FOS is 1.233 on June 10. Notably, the earthquake is an accidental
factor and a very short external effect on the slope. To explore the most dangerous situation of the slope, earthquakes are introduced to the numerical simulation on June 10.

The pseudo-static method is used to perform the seismic stability analysis. The critical states of landslides under horizontal seismic coefficients are determined. The calculation results of Zhaoshuling landslide stability under different seismic levels are shown in Figure 7. It can be found that the seismic coefficients corresponding to the FOS of 1.20 and 1.0 under seismic action are 0.028 g and 0.224 g, respectively. With the increase of seismic coefficient, the FOS decreases linearly and rapidly. Thus, compared with reservoir water level fluctuation and rainfall, earthquakes pose a greater threat to the stability of the Zhaoshuling landslide.

**Discussion**

A dry-wet cycle zone is formed on the reservoir bank between 145 m and 175 m. Furthermore, the dry-wet cycles would deteriorate the shear strength parameters more seriously than long-term immersion. Therefore, the influence of dry-wet cycles on slope stability should be considered.

The groundwater level at the trailing edge of the landslide is basically the same during the fluctuation of reservoir water which only affects the groundwater infiltration line on the leading edge of the landslide. Therefore, the influence of the dry-wet cycles on the leading edge is analyzed, involving the sliding mass and the weak interlayer. The dry-wet cycle area is mainly caused by periodic fluctuation of reservoir water level. In this case, the influence of dry-wet cycles on landslide stability is analyzed under the combined action of reservoir water level and rainfall. The most dangerous situation is June 10, when the FOS is the lowest. Mechanical parameters in dry-wet cycles are adopted as listed in Table 3, and the parameters are selected based on the references (e.g. Fredlund and Xing 1994; Chaney et al. 1996; Cokca et al. 2004; Wang et al. 2020b; He 2020). Specifically, He (2020) took soil samples from the
Zhaoshuling landslide and conducted indoor triaxial tests. Wang et al. (2020b) collected the weak interlayer from the base rock mass for dry-wet cycle testing. The influence of dry-wet cycles on the long-term stability of landslides is discussed by considering the simultaneous reduction of parameters of sliding mass and weak interlayer. Moreover, the degradation of sliding mass and weak interlayer on landslide stability under the action of dry-wet cycles are compared.

The strength parameters of sliding mass and weak interlayer are reduced in accordance with Table 3, and the calculation results of slope stability within 30 dry-wet cycles are shown in Figure 8. With the dry-wet cycles, the FOS of the landslide decreases rapidly at first, especially in the first five cycles. After 10 dry-wet cycles, the FOS of the landslide basically remains unchanged. It can be found that the reduction of strength parameters under dry-wet cycles has a negative impact on landslide stability.

The strength parameters of sliding mass and weak interlayer are considered respectively under the action of dry-wet cycles (Figure 9). It can be observed that the parameter reduction of weak interlayer has a significant impact on landslide stability. Although the dry-wet cycle area of the weak interlayer is much smaller than that of the sliding mass, the weak interlayer is the key area in controlling the overall stability of the Zhaoshuling landslide. The FOS is unchanged by only considering the parameter reduction of the sliding mass.

Table 3. Mechanical parameters of sliding mass and weak layers with different numbers of dry-wet cycles.

| Numbers of Dry-wet Cycles | Cohesion of Sliding Bodies (kPa) | Friction Angle of Sliding Bodies (°) | Cohesion of Weak Interlayer (kPa) | Friction Angle of Weak Interlayer (°) |
|---------------------------|----------------------------------|--------------------------------------|-----------------------------------|---------------------------------------|
| 0                         | 130                              | 22                                   | 12                                | 18                                    |
| 5                         | 122.27                           | 21.73                                | 6.95                              | 7.16                                  |
| 10                        | 117.42                           | 21.6                                 | 6.90                              | 5.92                                  |
| 15                        | 112.59                           | 21.46                                | 6.90                              | 5.92                                  |
| 20                        | 109.50                           | 20.31                                | 6.90                              | 5.92                                  |
| 25                        | 108.13                           | 19.74                                | 6.90                              | 5.92                                  |
| 30                        | 106.78                           | 19.17                                | 6.90                              | 5.92                                  |

Figure 8. Influence of dry-wet cycles on the FOS considering the degradation of sliding mass and weak interlayer.
Among many factors, the reservoir water level and rainfall will affect the seepage field of the landslide. On this basis, the earthquakes and dry-wet cycles are introduced to investigate the most dangerous state and long-term stability of the landslide. The results show that earthquakes have the most significant impact on the FOS of the landslide. Moreover, the dry-wet cycles will lead to the continuous decrease of the FOS of the landslide in the long-term evolution process.

Figure 9. Influence of dry-wet cycles on the FOS considering the degradation of a single region.

Among many factors, the reservoir water level and rainfall will affect the seepage field of the landslide. On this basis, the earthquakes and dry-wet cycles are introduced to investigate the most dangerous state and long-term stability of the landslide. The results show that earthquakes have the most significant impact on the FOS of the landslide. Moreover, the dry-wet cycles will lead to the continuous decrease of the FOS of the landslide in the long-term evolution process.

Conclusion

The numerical calculation of the Zhaoshuling landslide is performed based on the monitored data of the reservoir water level fluctuation, rainfall and regional seismic intensity. The sliding mass and weak interlayer are divided into three parts: saturated zone, dry-wet cycle zone and unsaturated zone. According to the stability of the Zhaoshuling landslide, several conclusions can be obtained as followings:

The fluctuations in reservoir water levels and the seasonal rainfall can cause changes in the seepage fields of the bank landslides. Due to the reservoir water only existing at the foot of the slope, the affected area is limited to the overall stability of the landslides. The stability of the Zhaoshuling landslides is lowest in June during a full hydrological year. When the earthquakes are taken into consideration at this time, the FOS of the landslide decreases rapidly with the increase of the seismic coefficient. Earthquakes pose a greater threat to the stability of the Zhaoshuling landslide than reservoir water level fluctuation and rainfall.

The dry-wet cycles have a certain negative impact on the long-term stability of bank landslides. With the increase in the number of dry-wet cycles, the FOS gradually decreases. Comparing the calculation results of the strength parameters of the sliding mass and the weak interlayer, it can be found that the parameter reduction of the weak interlayer has a significant impact on landslide stability. Correspondingly, the FOS of landslide is unchanged only considering parameter reduction of sliding mass. It can be proved that the control effect of weak interlayer on the overall stability of landslide.
Disclosure statement
No potential conflict of interest was reported by the authors.

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Data availability statement
The data related to all the numerical simulation performed during the study are available from the corresponding author on request.

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