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Research Article

Failure Mechanism of Colluvial Landslide Influenced by the Water Level Change in the Three Gorges Reservoir Area

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The stability of the reservoir bank landslide is affected by a variety of external factors, and the fluctuation of reservoir water level is one of the important influencing factors. The Erdaohe landslide is a typically colluvial landslide in the Three Gorges Reservoir area with periodic reservoir water level fluctuations. According to landslide displacement data, the displacement of the Erdaohe landslide exhibits the significantly stepwise feature. Its failure mechanism was analyzed using strength reduction method by the FLAC^{3D} package in the case of reservoir water level changes. The results indicate that the hydrodynamic pressure has an important impact on the initialization of the landslide failure. When reservoir water level rises rapidly or maintains constant at the lower level, the landslide stability would be higher. When the reservoir water level decreases rapidly or maintains constant at the higher level, the landslide stability will be smaller. When the reservoir water level was in the lowest elevation, the factor of safety (FS) reached the minimum value of 1.11. Findings in this paper can provide guidelines for the risk assessment of colluvial landslides.

1. Introduction

Lots of landslides have been reported in the reservoir area, with the increased number of the large-scale hydraulic projects [1–7]. In addition, the fluctuation of reservoir water level has an important impact on the landslide stability [7–10]. The Three Gorges Reservoir area (TGRA) is significantly affected by catastrophic landslides, and the colluvial landslides often occur in this area due to reservoir water level changes [11]. Since June 2003 when the Three Gorges Pro-

ject was completed, around 2619 landslides have failed due to the fluctuation of the reservoir water level, and 670 mountains are under unstable status [5–7, 12–20]. Therefore, it is important to study the failure mechanism to provide guideline for the risk assessment of the landslides.

A number of engineering cases and researches have been conducted to survey the influences of the reservoir and groundwater levels on the initialization of the landslide. Jiang et al. [21] established a 3D geological model to simulate the Qiaotou landslide and survey the impact of reservoir

water level using the FLAC^{3D} package, where the saturation-unsaturated fluid-solid coupling theory was considered for the landslide deformation mechanism. Based on the findings obtained by the in-depth engineering geological survey of the Liangshuijing landslide, Wang and Xu [22] proposed that the rapid change of reservoir water level was the key influential factor to the landslide stability. He et al. [23] developed a predictive model for the dynamic incremental displacement considering the impact of the groundwater level. Maihemuti et al. [24] surveyed the impact of the velocity of the periodic reservoir water level changes on the landslide stability. Sun et al. [25, 26] used a genetic algorithm to consider the deformation and failure mechanism of the landslide affected by rainfall and reservoir water level. Gu et al. [27] reported the deformation characteristics and failure mechanism of the Quchi landslide according to four-year hydrological data, which reveals that the evolution process of the Quchi landslide was governed by the reservoir water level. Shen et al. [28] studied the deformation mechanism of the Liujiaba landslide by considering the change of reservoir water level. Many studies in the past mainly considered the influence of reservoir water level changes on the landslide stability. Herein, the variation of the groundwater level may affect the seepage and stress of the landslide. However, few studies have discussed the cracked mechanism of the colluvial landslide influenced of reservoir water level.

In this paper, four reservoir water level conditions are considered, using the unsaturated fluid-solid coupling numerical method. Seepage field, stress field, and the factor of safety (FS) are obtained considering the variation of reservoir water level, using the strength reduction method by the FLAC^{3D} package. And the failure mechanism of the landslide was further discussed.

2. Project Overview of the Erdaohe Landslide

2.1. Geographical Location and Geological Conditions. The Erdaohe landslide area is near the Daxi River in Wushan County, with longitude 109°35′57″ and latitude 30°57′57″ (Figure 1(a)). The floor plan of the landslide area is shown in Figure 1(b). In addition, the layout of the monitoring points is also presented. As can be noted from Figure 1, the landslide scar is surrounded by the gullies and steep landslide, and the front end of the scar is close to the Daxi River. The elevation of the toe is 138 m, and the highest part of the upper boundary of the landslide is 225 m in elevation. In addition, the average depth of the rupture surface is about 55 m, with the area of the landslide scar equal to 5.43×10^4 m^2 and the volume of the sliding mass equal to 147×10^4 m^3 [29].

The most critical section I-I′ of the landslide is shown in Figure 1(c). The angle of the landslide varies from 15° to 30°, with an averaged value of 27°. Generally, the front part of the landslide is steeper (the averaged angle is around 30°), and the back part of the landslide is gentler (the averaged angle is around 20°). The soil profile of the study area is constructed by the silty clay and gravel, and the main lithology is the argillaceous limestone, with size ranging from 5 cm to 10 cm. The soils within slip zone are mainly made up by the

clay, and the bedrock is mainly made up by the turquoise siltstone from the Triassic formation in the middle Badong formation.

2.2. Sliding History. According to the geological survey, the landslide in the study area firstly failed in August 1998. A tension crack had been observed in the back end of the landslide site. The length of the crack was around 20 m, and the width was generally in 1 mm–3 cm. From 2000 to 2002, the landslide deformation developed continuously, and the local displacement increased rapidly. Besides, tension cracks had also been found around the landslide site (e.g., the nearby buildings). Due to the impoundment activities in 2003, a number of bank collapses had happened in the front portion of the landslide. The landslide displacement monitoring results showed that the landslide in the study area is still under the continuously uniform creep state.

2.3. Analysis of the Surface and Deep Accumulative Displacement of the Landslide. Six GPS devices were installed in the study area to monitor the landslide deformation. Figure 2 shows the changes of the measured landslide displacement, reservoir water level, and rainfall in the study area between January 2007 and December 2013. It can be seen that the landslide displacement exhibits a pronouncedly stepwise feature, and the landslide displacement is correlated to the reservoir water level. Generally, when the reservoir water level decreases, the landslide displacement would increase faster. From May to September, when the annual rainfall is relatively concentrated, the accumulative displacement of the landslide increases rapidly, which indicates the possible relationship between the concentrated rainfall and the displacement change.

According to the different setup of each GPS monitoring point, the accumulative displacement of the monitoring points (GPS-1, GPS-3, and GPS-5) is much larger than that of the monitoring points (GPS-2, GPS-4, and GPS-6), which verifies that the Erdaohe landslide exhibits the characteristics of traction landslide displacement.

As shown in Figure 3, the QZK1 borehole deformation at the middle and rear edges is not obvious; the QZK2 borehole at the middle and front edge of the landslide mass shows sliding deformation at a depth of 22.4–25 m, with a deformation of nearly 25 mm, which is consistent with the deformation characteristics of a traction landslide.

3. Methods and Numerical Model

3.1. Computation Theory. The landslide instability governed by the variation of reservoir water level is essentially a fluid-solid coupled problem. The flowing in porous media obeys the Darcy law and Fourier-Biot theory, which connects the volume strain (ε_v), pore-water pressure (u_w), and saturation degree (s) as follows:

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{1}{s} \frac{\partial \zeta}{\partial t} - \frac{1}{M} \frac{\partial u_w}{\partial t} - \frac{n}{s} \frac{\partial s}{\partial t}, \tag{1}$$

where M is the Biot modulus, ζ is the change of fluid volume, and n is the porosity.
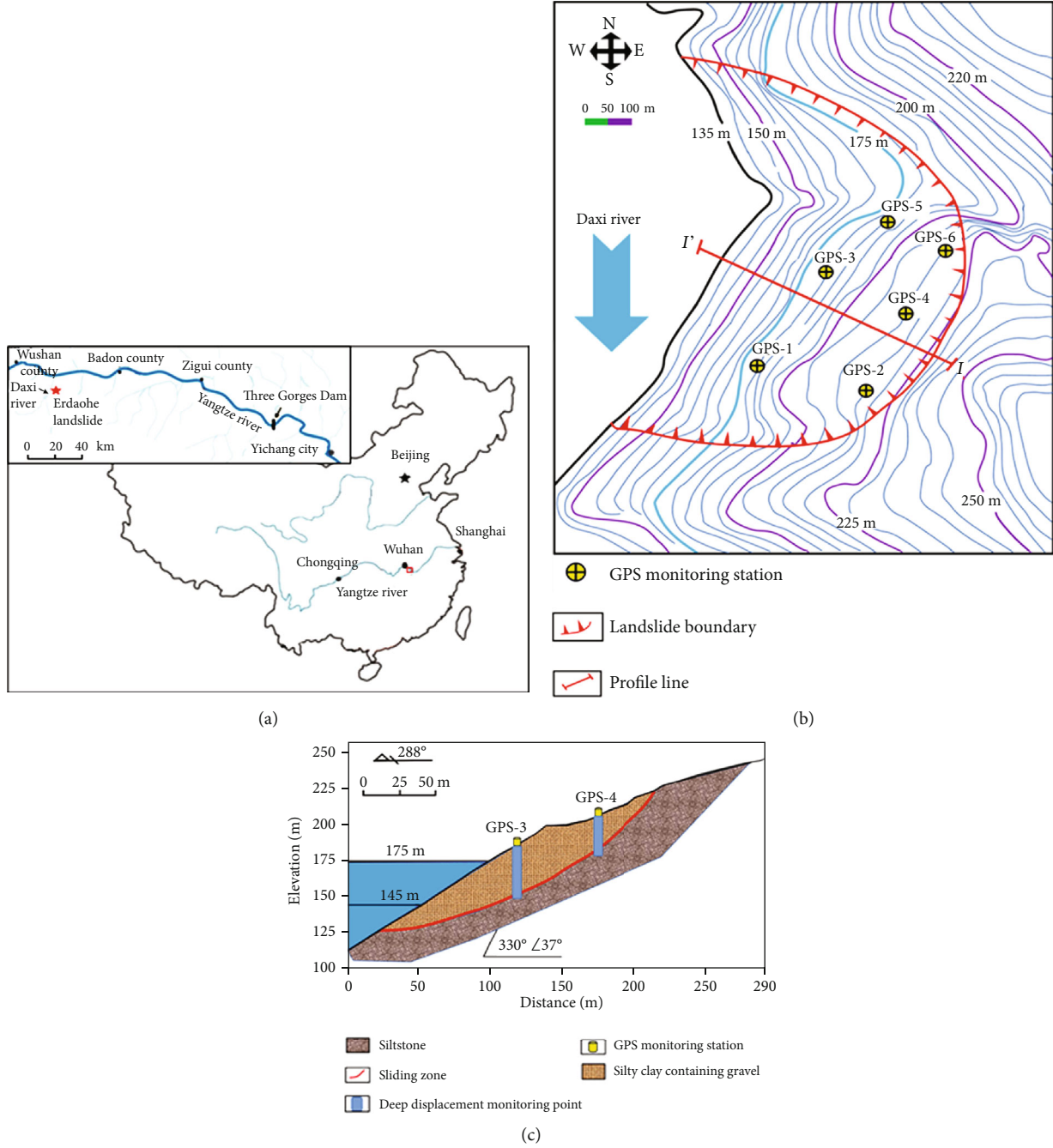
(a)

(b)

(c)

FIGURE 1: (a) Location of the Erdaohe landslide. (b) Floor plan of the Erdaohe landslide with monitoring. (c) Cross section along the I-I$'$ profile.

During reservoir water level fluctuation, the moisture movement in unsaturated porous soil follows Darcy's law:

$$q_i = -K_{il}k(s)\left(u_w - \rho_f x_j g_j\right)_{il},\qquad(2)$$

where q_i denotes the vector of unit flow, ρ_f the fluid density, K_{il} the tensor of permeability of coefficient, and $k(s)$ the component of gravity acceleration.

The reservoir water level changes will also lead to the groundwater level changes. The unsaturated antishear strength should be considered when the unsaturated zone is above the phreatic line. Based on the twin stress strength theory, the expression of the unsaturated antishear strength is as follows [5–7]:

$$\tau_f = c' + (\sigma_f - u_a)_f \tan \varphi' + (u_a - u_w)_f \tan \varphi^b,\qquad(3)$$

where c' and φ' represent the effective cohesive strength and the friction angle, respectively, $(\sigma_f - u_a)_f$ represents the net
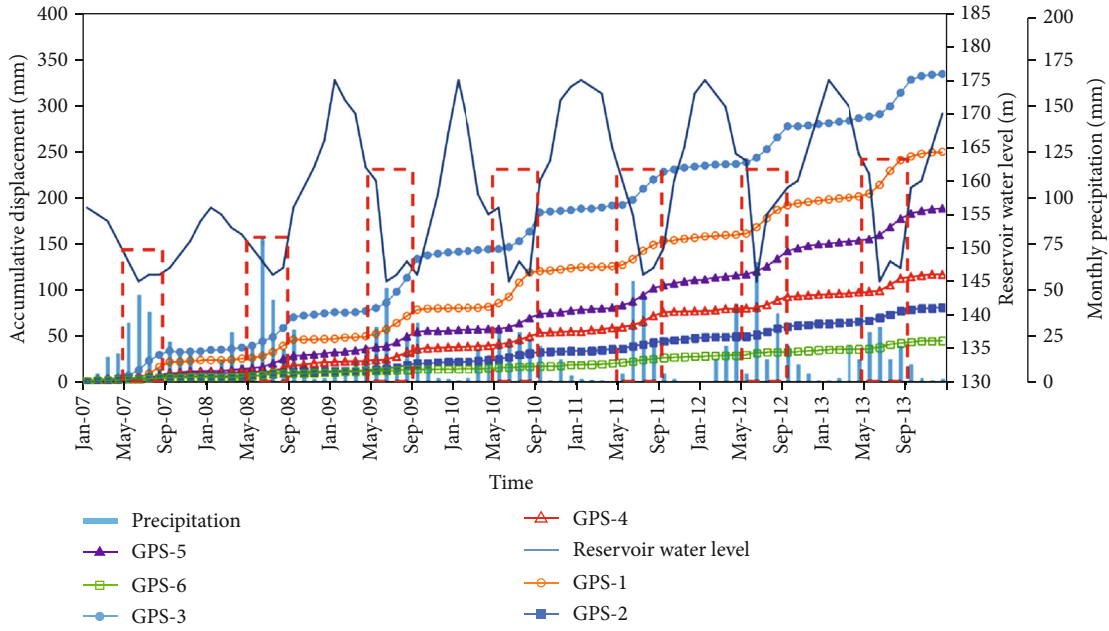
Figure 2: Changes of the accumulative displacement as reservoir water level and precipitation in the Erdaohe landslide.
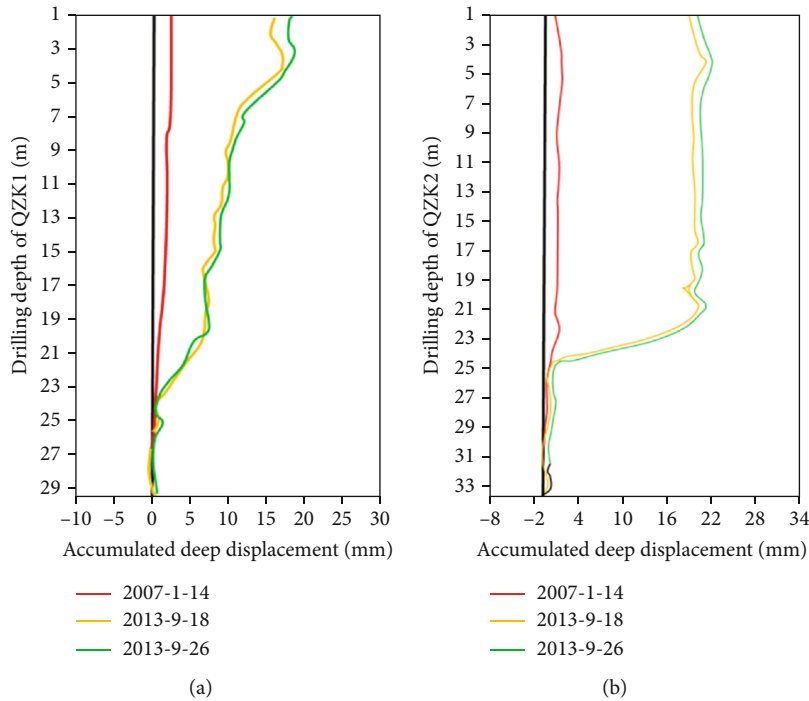

Figure 3: (a) Deep accumulated displacement monitoring curves of QZK1. (b) Deep accumulated displacement monitoring curves of QZK2.

normal stress, $(u_a - u_w)_f$ is the matrix suction, and φ^b is the inclination of the antishear strength and matrix suction curve.

3.2. Computation Conditions. The change of reservoir water level from 2013 to 2014 is illustrated in Figure 4. The average reservoir water level fluctuated in the range of 145 m to 175 m with a maximum variable rate of around 1.5 m/d. The highest

reservoir water level was in the winter season while the lowest was in summer.

It has been revealed that the colluvial landslide is at high risk when the reservoir water level drop rate exceeds 0.8 m/d [30]. According to the reservoir water level fluctuation, the maximum variable rate is chosen to simulate the reservoir water level change. Four reservoir water level conditions are designed (Figure 5): (1) rapid rise: the reservoir water
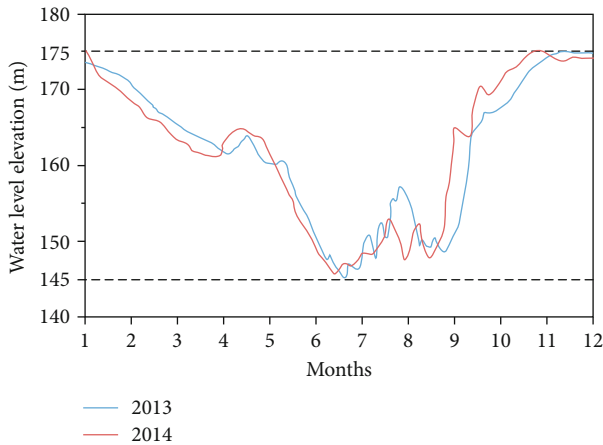
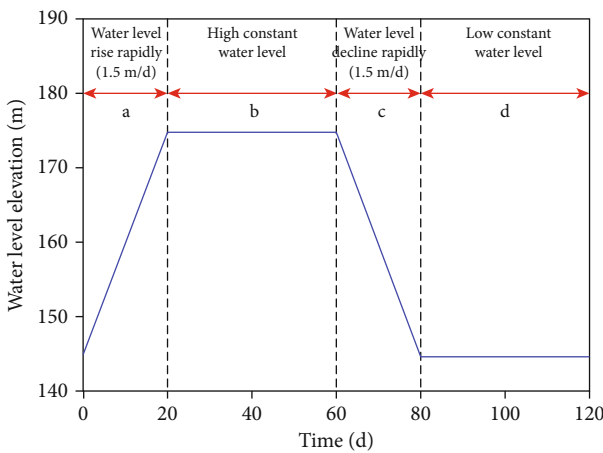FIGURE 4: The fluctuation of reservoir water level from 2013 to 2014.

FIGURE 5: Fluctuation conditions of reservoir water level in different stages, respectively.

FIGURE 6: FLAC^{3D} numerical model.

level rise rapidly at 1.5 m/d and lasted 20 days; (2) constant at a high level: the reservoir water level keeps constant at 175 m for 40 days; (3) rapid decline: the reservoir water level drops rapidly at 1.5 m/d and lasted 20 days at the third stage; and (4) constant at a low level: the reservoir water level maintains at 145 m.

3.3. Numerical Model. According to the topography map of Erdaohe landslide, a 3D numerical model was built, as shown in Figure 6. The model was divided into tetrahedral mesh with 293,006 nodes and 1,645,367 elements. For the calculation of the unsaturated seepage, the negative pore water pressure was set as 1. The unsaturated seepage analysis method was used in the variation law simulation of unsaturated seepage under the change of reservoir water level. Then, the stress module was invoked to generate initial stress filed by the iteration between unsaturated seepage filed and stress filed. The simulation of the unsaturated fluid-solid coupling under the impact of the reservoir water level changes was further conducted.
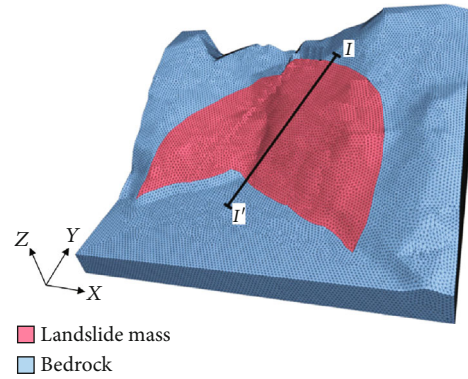
Through experiments and field tests, the material modeling parameters of various parts of Erdaohe landslide are shown in Table 1. The landslide mass and the bedrock below the landslide mass use linear elastic materials to plastic materials, and the plastic materials can meet the Mohr Coulomb failure criterion [31]. There is a slip zone before the landslide mass and the bedrock in contact with it, and the slip zone part uses strain softening material for numerical modeling. An impervious interface is set between the bedrock and the sliding zone, and the part of the bedrock below the interface does not consider seepage.

Speeds in the *x*, *y*, and *z* directions were constrained at the bottom and the east-west and north-south boundaries. The surface of the landslide was set free. The sliding surfaces, the bottom of the model, and the periphery surface were set as the no-flow boundary. The boundary treatment is a key step for landslide simulation considering reservoir water level fluctuation. FLAC^{3D} provides flow quantity boundary, stress boundary, and seepage boundary. The rational utilization of flow quantity boundary and stress boundary could achieve the numerical simulation of water infiltration and exudation of landslide during reservoir water level fluctuation period.

To save the convergence time of iterative solution and strength reduction, the 2D landslide profile of I-I$'$ section was selected to present the change law of groundwater level, displacement response, plastic damage, and FS. Initially, the groundwater level and reservoir water level were on the same plane, with an elevation of 145 m. The initial pore water pressure ranged from -800 kPa to 200 kPa, as shown in Figure 7.

4. Numerical Calculation and Analysis

4.1. Seepage Characteristics. Figure 8(a) illustrates the evolution rule of groundwater phreatic line in the rapid rise stage and constant high reservoir water level stage. It can be seen that the elevation of phreatic line was positively related to the elevation of landslide front water level. The pore water pressure of landslide increased rapidly with increasing landslide front water level, and then, the elevation phreatic line was gradually uplifted over time. The pore water pressure was inversely related to the landslide elevation in the initial state, which means that the initial pore water pressure and

TABLE 1: Material parameters of the Erdaohe landslide.

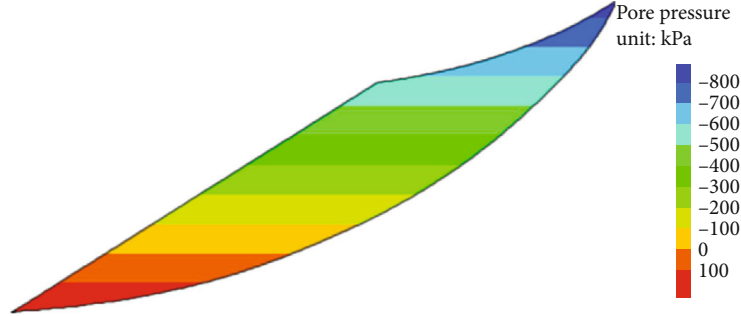| Material	Unit weight (kN/m³)	Saturated unit weight (kN/m³)	Elastic modulus (GPa)	Poisson ratio	Friction angle (°)		Cohesion force		Permeability	Coefficient porosity
					Natural	Saturated	Natural	Saturated		
Landslide mass	20.0	22.1	0.30	0.29	20	18	0.20	0.08	7×10^{-11}	0.35
Slip zone	18.0	19.2	0.25	0.31	18	15	0.10	0.04	9×10^{-11}	0.4
Bedrock	25.0	26.2	4.10	0.18	40	40	2.50	2.50	—	—

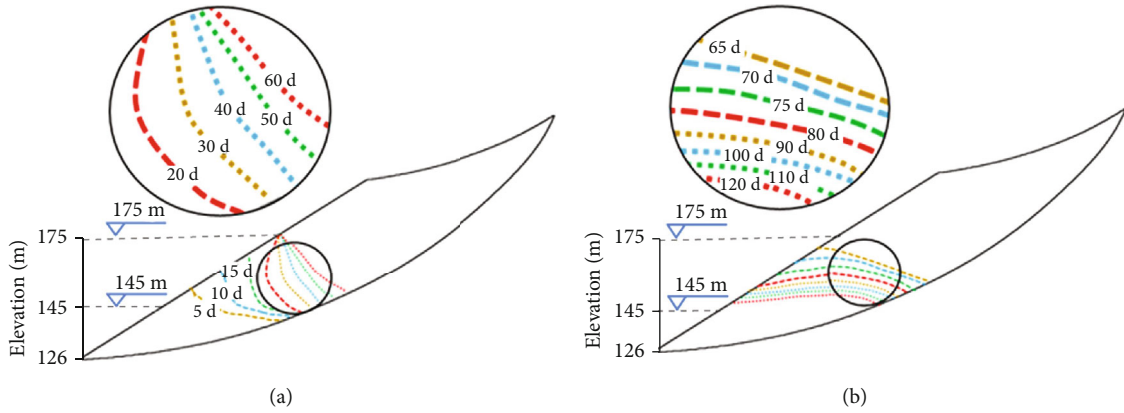FIGURE 7: Distribution of initial pore water pressure.

FIGURE 8: Distributions of phreatic line: (a) in the reservoir water level rising and constant high reservoir water level period; (b) in the reservoir water level falling and constant low reservoir water level period.

permeability became smaller when the water level was farther away from the initial value. In the process of groundwater lifting, it is more difficult to transform the landslide from unsaturated state to saturated state. The amplitude of phreatic line lifting gradually decreased, and the velocity of phreatic line was relatively slower than that of the groundwater.

The evolution rule of phreatic lines in the rapid decline stage and constant low water level stage is shown in Figure 8(b). When the landslide was in the rapid decline stage and constant low reservoir water level stage, the elevation and reduction rate of the phreatic line gradually reduced over time, and the reduced amplitude lagged behind that of the groundwater level. As the front reservoir water level drops, water inside the landslide gradually flows outside, which results in the decrease of pore water pressure inside the landslide mass. After

60 days of reservoir water level fluctuation, the pore water pressure was in inverse relation with the elevation. When the positive pore water pressure of the leading edge was too high, the dissipation velocity of pore water pressure became slow. With increasing duration for reservoir water level decreasing stage and low reservoir water level stage, the falling magnitude of phreatic line gradually reduced due to the constant decrease of permeability coefficient.

4.2. Displacement Response Analysis. Figure 9 shows the distribution law of landslide displacement at different reservoir water levels. At the reservoir water level increasing stage, the maximum displacement was 10.3 mm, and local deformation was observed at the trailing edge. At the constant high reservoir water level stage, displacement concentration was
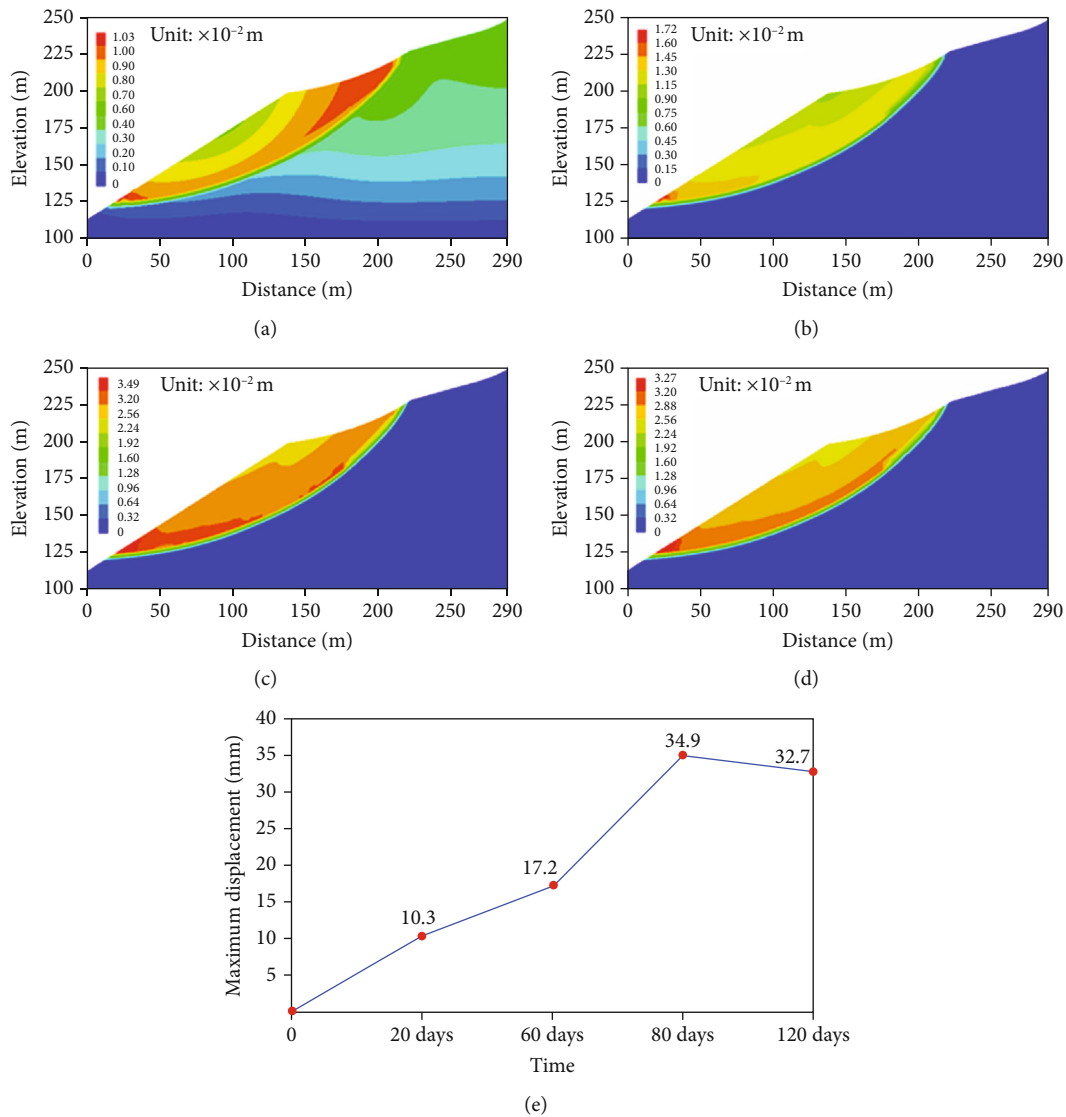
Figure 9: Maximum displacement distribution with the changing of reservoir water level: (a) 20 days, (b) 60 days, (c) 80 days, and (d) 120 days; (e) trend of maximum displacement over time.

observed at the leading edge, with a maximum displacement of 17.2 mm, which shows the characteristic of gradually retrograde mode. As the reservoir water level declines, the maximum displacement increased from 17.2 mm to 34.9 mm, and the integral displacement of landslide significantly increased as the reservoir water level dropped. The abrupt change of displacement led to the instability of the landslide. In the constant low reservoir water level period, the integral displacement of landslide went down to 32.7 mm, which indicates that the stability of the landslide was slightly improved.

When the reservoir water level increased from 145 m to 175 m, hydrodynamic pressure was applied to the toe of landslide and the antisliding force increased. Meanwhile, the tensile failure that occurred inside the trailing edge would induce local deformation and failure of landslide. When the 175 m reservoir water level lasted 40 days, the reservoir water level was continuously replenished into the

landslide with the gradual lifting of underground phreatic line; as a result, the displacement of leading edge, which was caused by the water-absorption softening and continuous lifting of groundwater level, gradually led to the destruction of landslide trailing edge. In the third stage, the reservoir water level fell rapidly from 175 m to 145 m and the underground phreatic line of landslide lagged behind reservoir water level. Also, the seepage pressure acting on the landslide surface gradually disappeared and the direction was gradually shifted outside the landslide. When the 145 mm reservoir water level lasted 40 days, water in the leading edge continuously flew out of the landslide, which led to the decline of underground phreatic line, the rebound of matrix suction, and the slow recovery of antishear strength. Furthermore, the displacement response was less than that in the rapid dropping period. The characteristic of landslide was transitioned from the thrust-load-caused failure with local failure in the trailing edge (condition 1) into progressive retrogressive failure of which the landslide leading
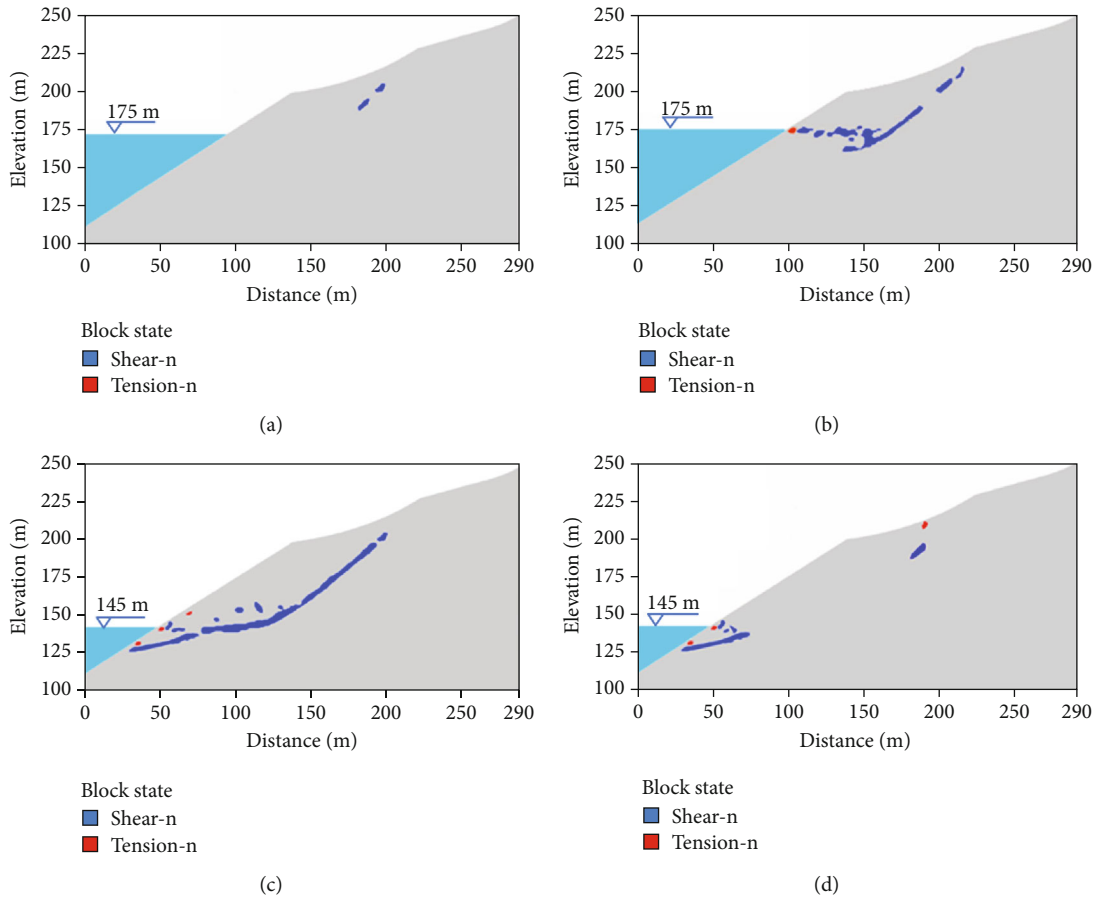
(a)

(b)

(c)

(d)

Figure 10: The change rule of plastic zone with the time: (a) 20 days; (b) 60 days; (c) 80 days; (d) 120 days.

edge drags the trailing edge (conditions 1, 2, and 3). The main reason for this transition is as follows: (1) in the high constant reservoir water level stage, the leading edge was saturated due to the increase of groundwater level; (2) in the reservoir water level decline stage and a low constant reservoir water level stage, the hydrostatic pressure disappeared and the matrix suction recovered.

The numerical results of the landslide displacement verify the correctness and rationality of the flow-solid coupling method. Under different reservoir water level fluctuations, the displacement of the landslide leading edge was bigger than that in the medium and rear zone. The rapidly falling reservoir water level induced abrupt change of displacement at the toe of the landslide. Therefore, reasonable control measures should be taken to protect and reinforce the landslide toe.

4.3. Failure Mechanism Analysis. In order to further study the impact of periodic water fluctuations on reservoir bank landslides in the Three Gorges Reservoir area, the distribution of plastic zones and the variation of safety coefficient with water fluctuation are illustrated in Figures 10 and 11, respectively.

When the reservoir water level rose to 175 m, no plastic zone was observed in the leading edge and local plastic failure occurred in the trailing zone, as shown in Figure 10(a). The safety coefficient increased from the initial value of 1.28 to

1.62, with an increasing amplitude of 26.6%; it is believed that the whole landslide mass was in a stable state. In the rapidly lifting process of reservoir water level, the groundwater level lagged behind the change of reservoir water level, and the hydrostatic pressure of front landslide kept increasing, which was beneficial to the stability of landslide leading edge. As shown in Figure 10(b), when the reservoir water level remained at 175 m for 40 days, large amounts of shear plastic zone were generated in the landslide leading edge and medium areas, and the tension fracture appeared around the high reservoir water level zone; however, not all the plastic zones were connected. The safety coefficient was reduced to 1.49, which was 8.7% lower than that in condition 1. Though the safety coefficient presented the rapid descending trend, the landslide was still in the stable state. With the continued lifting of reservoir water level in the landslide submerged area, the increase of hydrostatic pressure was beneficial to the landslide stability. Meanwhile, around the high reservoir water level zone, the water-immersion softening effect was obvious; the antisliding force and antishear strength were reduced, resulting in the plastic damage in the landslide and the gradual development of plastic zone to the trailing edge.

The distribution of plastic zone is drawn in Figure 10(c). When the reservoir water level was in the lowest elevation, the safety coefficient of landslide mass was 1.11, which was close to the threshold value. The stability of the whole
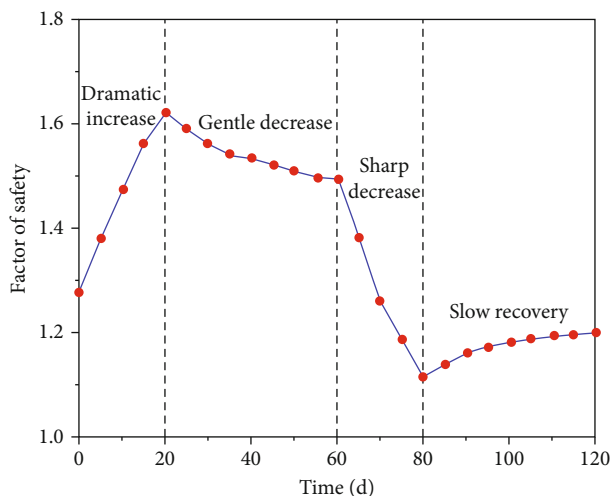
Figure 11: The safety coefficient variation rule versus the time.

landslide became worse, and a nearly connected plastic zone formed. It suggests that with falling groundwater, the hydrostatic pressure of front landslide water acting on the landslide mass was evanished, while large hydraulic gradient was produced inside the landslide mass. The reservoir water level difference was formed due to the velocity lagging of groundwater level relative to the front landslide reservoir water level. The hydrodynamic pressure was also lagged, which led to the direction deflection of excess pore water pressure and seepage force. The pulling force, pointing to the outside of the landslide, induced the tension fracture around the landslide surface at the leading edge, which threatened the stability of landslide. Figure 10(d) illustrates the distribution of landslide plastic zone when the reservoir water level was 145 m. In the constant low reservoir water level period, the reduced amplitude of reservoir water level became slow and the matric suction of unsaturated zone gradually recovered. The safety coefficient rebounded to 1.20, with 8.1% rise. The plastic area, which was previously located in the medium area and the trailing edge, was vanished.

To sum up, the safety coefficient experienced four stages: dramatic increase, gentle decrease, sharp decrease, and slow recovery. The landslide stability increased in the reservoir water level rise rapidly stage and also in the low constant reservoir water level stage and dropped when the reservoir water level was in the high constant reservoir water level stage and also in the reservoir water level decline stage.

5. Discussion

The landslide formation is mainly caused by the internal and external factors. The internal factors include the structural zone, the lithological composition and distribution of the strata, and the topographical conditions. The Erdaohe landslide is located in the Badong Group landslide belt, where landslides occur frequently. The sliding surface is a weak layer, and the effect of gravity can easily cause creep deformation of the weak layer, resulting in tensile and sliding deformation of the internal rock and soil. In addition, the Erdaohe landslide

has a steep front edge, which is more prone to landslides under unfavorable terrain conditions.

The external main influencing factor of the landslide is the reservoir water level change. In particular, when the reservoir water level in the reservoir area drops, SF of the landslide decreases significantly, which is likely to cause deformation and movement of the landslide.

When the reservoir water level drops rapidly, due to the presence of soil particles inside the landslide mass, it will hinder the groundwater seepage inside the landslide mass. Large hydraulic gradients are often formed inside and outside the landslide mass, and large excess pore pressure appears inside the landslide mass. When the groundwater inside the landslide is discharged outwards, high penetration force is applied to the surface of soil particles, causing instability to the landslide.

6. Conclusions

The colluvial landslide influenced by the reservoir water level was discussed using the strength reduction method by the FlAC^{3D} package. Four kinds of groundwater level conditions were considered, including rapid increase of reservoir water level, constantly higher reservoir water level, rapid decrease of reservoir water level, and constantly lower reservoir water level. The main conclusions are as follows:

(1) When considering the rapid increase of reservoir water level and the constantly higher reservoir water level, the reservoir water level within the landslide mass would increase after the increase of the reservoir water level at the front end of the landslide. When the reservoir water level increases rapidly, the landslide would exhibit the style induced by thrust load, where the local failure and plastic zone can be observed in the trailing edge. When considering the constantly higher reservoir water level, the landslide would exhibit the progressive and retrogressive failure manners, where the trailing edge would be driven by the leading edge

(2) When considering the rapid decrease of reservoir water level and maintaining the constantly lower reservoir water level, the groundwater level within the landslide mass would decrease after the decrease of the reservoir water level at the front edge of the landslide, and the magnitude of the change would reduce gradually. When the reservoir water level decreases rapidly, the landslide displacement would change abruptly, which induces a nearly connected plastic zone. This indicates that the landslide is under the unstable stage. When maintaining the constantly lower reservoir water level, the magnitude of the change of the landslide displacement was smaller than that considering the decrease of the reservoir water level

(3) The landslide stability is mainly influenced by the leading edge. The rapid decrease of reservoir water level can cause the abrupt change of displacement around the landslide toe, with the maximum displacement of 32.7 mm. Therefore, it is significant to

protect and stabilize the landslide toe in engineering practice in the reservoir area

(4) There are four main stages for FS with the reservoir water level changes: dramatic increase, gentle decrease, sharp decrease, and slow rebound. The landslide stability would be higher, when the reservoir water level rises rapidly or maintains constant at the lower level. On the other hand, the landslide stability will be smaller, when the reservoir water level decreases rapidly or maintains constant at the higher level. When the reservoir water level was in the lowest elevation, FS reached the minimum value of 1.11

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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