Stability and Failure Analysis of Zhaoshuling Landslide under the Reservoir Water and Earthquake

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Abstract. Due to the reservoir impoundment, the geological environment in Three Gorges Reservoir area deteriorates, consequently inducing a series of geological hazards. Zhaoshuling landslide is one of the most important landslides in Three Gorges Reservoir area, and its safety seriously affects the planning and construction of the new-established Badong city. The unfavourable change of hydraulic condition, accompanied with earthquake, may cause landslide instability. In this paper, the stability and failure features of Zhaoshuling landslide under the reservoir water and earthquake are researched by discontinuous deformation analysis (DDA) method. The simulated results show that Zhaoshuling landslide is globally stable under the reservoir water and VII earthquake, while considering the degradation effect of rainfall and reservoir water on the strength of the sliding zone, the landslide may be damaged. The landslide damages more seriously at a low water level, the failure mode is creep and traction, and the failure mainly happens at the head and middle of landslide. Therefore, the head and middle of landslide is the key section of prevention and treatment.

Keywords. Landslide failure, three Gorges Reservoir, earthquake, DDA.

1. Introduction
Zhaoshuling landslide, a bedding landslide discovered in 1992, is located at the east of Badong county, Three Gorges Reservoir area. This region lies in the transitional wide valley between Wu Gorge and Xiling Gorge. The landform of landslide alternately changes in a zigzag way, i.e., its head and tail are rather steep, while its middle distributes a few gentle slope flatlands with the average gradient of 10° - 15°, among which are steep slopes with the gradient greater than 35°. The fold direction of rock mass in this region is nearly EW, consistent with the slope. The bedrock is mainly argillaceous limestone, marl, silt mudstone and siltstone of Triassic Badong formation (T₂b), which is the typical sliding-prone stratum in Three Gorges area. Some researchers found that Zhaoshuling landslide is generally stable, but the degree of stability is not high, under the action of reservoir water and earthquake, its stability may be further reduced [1-5]. In this study, discontinuous deformation analysis (DDA) method [6-8] is adopted to analyze the stability and failure features of Zhaoshuling landslide under combined condition of reservoir water and earthquake.
2. Landslide Characteristics

2.1. Landslide Boundary and Shape

As a whole, Zhaoshuling landslide is a huge spoon-like complexive landslide, formed after multi-times of local collapse and bending-toppling slide. The landslide plane looks like an irregular oblong of 550 m in width, 900-950 m in length and 5 million m$^2$ in area. The landslide head is near the bank of Yangtze River. The landslide surface wholly presents ladder form, and two gentle slope flatlands appear on it. The first one is at the altitude of 150-200 m, the second one is at the altitude of 350-400 m, and the other section is steep slopes with the gradient of 25°-50°, as shown in figure 1.

![Figure 1. Zhaoshuling landslide generalized model.](image)

2.2. Landslide Material Composition

The material structure in this region gradually transits from surficial collapse body to intact bedrock. The bedrock is mostly aubergine silty mudstone and argillaceous siltstone in the second member of Badong formation(T$^2_{2b}$). The surficial collapse body is mainly made up of cataclasite, shaly breakstone and breakstone from the third member of Badong formation(T$^3_{2b}$). The cataclasite distributes at the altitude of 225-350 m, the rock mass is grey or lark argillaceous limestone and marl of layered structure with roughly normal sequence, and the geological structure is a rather entire anticline. The shaly breakstone, distributing at the middle of landslide, generates from eluvial layer. The breakstone distributes broadly, especially at the head of landslide, and its genesis is mainly from colluvium of different period. Unparallel multilayer weak-fracture zones, exhibiting the features of discontinuity and great variation in thickness, appear in the stratum T$^3_{2b}$ outcropped in this region. These weak-fracture zones compose the multistage sliding surface, the lowest one of which is near the interface of T$^2_{3b}$/T$^3_{2b}$ with the same shape of landform and has control action on the global stability of landslide.

2.3. Landslide Deformation State and Its Influencing Factors

Five small-scale rockfalls with different volume and thickness have happened at excavation slope, gully and steep slope along the river bank. The features of rockfalls are summarized as follows: they are almost local shallow soil slump, and occurred in recent years owing to landform, rainfall and excavation. Among the influencing factors of landslide stability, the hydrogeology condition is the important one, especially reservoir water storage and water level fluctuation. In addition, rainstorm and earthquake also have major effects on landslide stability, and they are important inducing factors for triggering landslide [9-12].

3. Landslide Stability and Failure Analysis

At present, Zhaoshuling landslide is globally stable under various geological factors, but it may become unstable or even damaged under Three Gorges Reservoir's water level fluctuation, rainfall and earthquake. Among them, water has a great effect on the stability of landslide. On the one hand, water will change the mechanical properties of rock-soil mass and sliding surface, and reduce their strength. On the other hand, water will produce hydrostatic and hydrodynamic pressures acting on sliding body.
Both the two effects mentioned above will deteriorate the landslide stability. In a word, the hydrogeology condition is an important influencing factor of landslide stability. The water level of Three Gorges Reservoir varies periodically between 145 m and 175 m. It will pose significant influence on the landslide stability, especially accompanied with earthquake. In this section, by using DDA method, the stability and failure features of Zhaoshuling landslide under combined condition of reservoir water and earthquake are researched to provide evidence for landslide treatment.

3.1. The DDA Formulations

DDA is a novel discontinuous numerical method proposed by Shi. Similar to discrete element method, the equation of motion is adopted to describe the movement of single block, and the penetration between blocks isn’t allowed. The implicit solution of governing equations is employed based on the principle of minimum potential energy, which is similar to finite element method.

In DDA, each block with arbitrary shape and size has six degrees of freedom, i.e., three rigid body motion terms and three constant strain terms. The generalized displacement vector of block \( i \) can be expressed as

\[
\mathbf{D}_i = (u_0, v_0, r_0, e_x, e_y, \gamma_{xy})^T
\]

(1)

where \( u_0 \) and \( v_0 \) respectively are the translations in \( x \) and \( y \) directions at block centroid \((x_0, y_0)\); \( r_0 \) is the rigid rotation around block centroid; \( e_x, e_y \) and \( \gamma_{xy} \) are the strain components of block.

The displacement at any point within block \( i \) is calculated by a complete first-order approximation function:

\[
U = \mathbf{T} \mathbf{D}_i
\]

(2)

\[
\mathbf{T} = \begin{bmatrix}
1 & 0 & -(y - y_0) & x - x_0 & 0 & (y - y_0)/2 \\
0 & 1 & x - x_0 & 0 & y - y_0 & (x - x_0)/2
\end{bmatrix}
\]

(3)

in which \( \mathbf{T} \) is the displacement transformation matrix.

By minimizing the total potential energy contributed by different mechanisms, the following governing equations for \( n \)-block system can be derived:

\[
\begin{bmatrix}
K_{11} & K_{12} & \cdots & K_{1n} \\
K_{21} & K_{22} & \cdots & K_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
K_{n1} & K_{n2} & \cdots & K_{nn}
\end{bmatrix}
\begin{bmatrix}
\mathbf{D}_1 \\
\mathbf{D}_2 \\
\vdots \\
\mathbf{D}_n
\end{bmatrix}
= 
\begin{bmatrix}
\mathbf{F}_1 \\
\mathbf{F}_2 \\
\vdots \\
\mathbf{F}_n
\end{bmatrix}
\]

(4)

where \( \mathbf{D}_i \) and \( \mathbf{F}_i \) respectively are the generalized displacement and force vectors; \( K_{ij} \) is defined by the material properties of block \( i \); \( K_{ij} \) (\( i \neq j \)) is related to the contact state between blocks \( i \) and \( j \), if no contact happens, \( K_{ij} = 0 \).

The solution of equation (4) must satisfy a kinematic condition, that is, one block can’t penetrate into another. This can be carried out by using penalty spring method. Once penetration occurs, the penalty springs with high stiffness are applied between the contact blocks. By minimizing the energy of penalty springs, their contributions to the global matrix of equation (4), \( K_{ij} \), can be obtained. The equation (4) will be solved repeatedly until all penalty springs are applied correctly. In addition, the sliding along contact interface should satisfy Coulomb friction criterion.

3.2. Landslide Calculation Model

A typical geological section (figure 1) along the primary sliding direction of landslide is selected to establish the calculation model. The length of model is 1200 m, and the height is 475 m. As displayed in figure 2, two sets of parallel joints are contained in the model, one of which has the dip angle of 24°
and the dip direction of 35°, and the other has the dip angle of 45° and the dip direction of 145°. Two monitoring points are set on the sliding body.

3.3. Calculation Parameters and Conditions

According to some relevant test results, the physical and mechanical parameters of rock mass used in the simulation are given as follows: density $\rho=2450$ kg/m$^3$, elastic modulus $E=3$ GPa, and Poisson ratio $\gamma=0.3$. The parameters of saturated rock mass below the water level are: density $\rho=2590$ kg/m$^3$, elastic modulus $E=2$ GPa, and Poisson ratio $\gamma=0.3$. The strength of the first joint set takes the values as: inner friction angle $\varphi=23^\circ$, cohesion $c=0.19$ MPa, and tensile strength $T_0=0.03$ MPa. The strength of the second joint set takes the values as: inner friction angle $\varphi=32^\circ$, cohesion $c=0.36$ MPa, and tensile strength $T_0=0.1$ MPa. The sliding surface has the following strength parameters: inner friction angle $\varphi=20^\circ$, cohesion $c=0.02$ MPa, and tensile strength $T_0=0.001$ MPa.

The outer big block is fixed to confine the boundary displacements of the model. In-situ stress measurement results show that self-weight stress is predominant and horizontal tectonic stress has gradually released, so initial stress state is not considered in the computation. The earthquake intensity is set to VII, the corresponding acceleration peak is 0.125g, and the assumed seismic wave is plotted in figure 3. Two cases are analyzed: water level of 145 m combined with earthquake and water level of 175 m combined with earthquake. After obtain the seepage field in the slope (see figure 4), set the rock mass below the water level as saturated, apply seismic load, and calculate the failure process of the landslide.

![Figure 2. Calculation model of Zhaoshuling landslide.](image)

![Figure 3. The assumed seismic wave.](image)

![Figure 4. The seepage field in slope.](image)
3.4. Calculation Results and Discussions

When adopting the above strength parameters, the sliding body produces small creep deformation but not obvious collapse and slide, indicating that Zhaoshuling landslide is stable globally. Under the periodic change of reservoir water level, the sliding zone is subjected to repeated dry and wet state, and its strength deteriorates. The authors’ group performed some indoor tests and found that under dry and wet cycles, the cohesion of sliding zone reduced $1/4$-$1/3$, and the inner friction angle reduced $1/6$-$1/3$[13-15]. In this study, we reduce the shear strength of sliding surface by half and the tensile strength to 0. The landslide becomes unstable. The obtained results are given in figures 5-7.

**Figure 5.** The displacement evolution during landslide failure under 145 m water level combined with earthquake.

**Figure 6.** The displacement evolution during landslide failure under 175 m water level combined with earthquake.
From the simulated results, we can obtain the following conclusions:

1. Collapse and slide mainly happen at the head and middle of landslide. Other studies also prove that the head and middle of landslide exhibits poor stability.

2. The failure of landslide is dominated by tensile fracture, and its failure mode is creep-traction. Firstly, the head of landslide produces creeping deformation and slippage, then it provides tensile force for the subsequent creeping slide of adjacent part, and finally it results in large-scale failure.

3. When the water level ascends from 145 m to 175 m, the displacement of sliding body decreases, and the failure area becomes smaller. It demonstrates that water applies uplift force on the sliding body, which can restrain the earthquake force.

4. What noted above suggests that the optimal position of reinforcement measures should be at the head and middle of landslide. One is that the reinforcement measures can prevent its creep deformation and resultant tensile force, and the other is that it can make full use of the anti-warping effect.

4. Conclusions

In this paper, the DDA method is employed to study the stability and failure features of Zhaoshuling landslide under the reservoir water and earthquake. The simulated results indicate that Zhaoshuling landslide is globally stable under the reservoir water and VII earthquake, while considering the degradation effect of rainfall and reservoir water on the strength of the sliding zone, the head and middle of landslide may be failed. The failure mode is creep-traction, and the impact area is large at a low water level. In terms of prevention and treatment, the head and middle of landslide is the key section.

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