Analysis and numerical simulation of toppling deformation and failure characteristics of anti-dipping rock slope under impoundment

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Abstract. High dam engineering is characterized by high water head, steep slope and complex geological conditions. Excavation or water storage will destroy the original equilibrium state of the bank slope and induce the deformation of the bank slope. Based on the monitoring data, this paper analyzes the spatio-temporal evolution of slope deformation during the impoundment of a reservoir bank in China. On this basis, considering the influence mechanism of water pressure, temperature, rainfall, seepage, rock mass rheology and other factors on slope deformation in the process of water impoundment, a statistical regression model of slope deformation is established, and the regression analysis of the deformation process of typical measuring points is carried out, and the main influencing factors of slope deformation are analyzed. Based on regression analysis, the slope deformation and failure process under impoundment are simulated and the influence degree of effective stress change and parameter weakening of rock mass on bank slope deformation and failure in the process of seepage field change is studied to reveal the main inducement of slope deformation under impoundment through the fractured rock mass seepage-stress-rheology coupling finite element analysis method. The results show that the slope deformation is the rheologic deformation triggered by the decrease of effective stress at slope toe caused by the rise of water level and the softening of rock mass, and the toppling form is the dominant one in space.

1. Introduction

In recent years, many large reservoirs with high dams in our country have successively entered the impoundment period and operation period, which may destroy the original balance of the bank slope, induce disturbance to deform the bank slope when reservoir filling due to the prominent characteristics of high dam engineering such as high head, steep slope, and complex geological conditions, resulting in an important impact on the overall safety of hydropower projects, and having been attracting widespread attention from the dam engineering community. As a typical form of anti-dipping rock slope deformation, toppling deformation is commonly seen in hydropower projects in our country, such as the left bank slope of Jinping I Hydropower Station¹², the toppling deformation...
slope of Changma Reservoir [3], Yinshuigou slope, Xiaowan Hydropower Station [4], left bank slope, Longtan Hydropower Station [5], left bank slope, Yangwumiao dam site, Wuqiangxi Hydropower Station [6], and Guobu side slope, Laxiwa Hydropower Station [7], etc. These phenomena appearing in actual engineering have exceeded the general engineering experience and understanding of laws, which is difficult to explain with conventional analysis methods and understandings.

Practical engineering phenomena and existing research results have shown that the deformation of the anti-dipping rock slope is mainly controlled by the structural plane in the reverse steep-dipping with a similar slope surface direction [1-6] and the disturbance of impoundment on the rock mass underneath the bank slope soaking in water may induce toppling deformation [7,8], which is very different from the shear sliding deformation in terms of deformation characteristics and mechanical mechanism. Moreover, anti-dipping rock slopes generally do not have a deterministic sliding surface, their deformation and failure evolution is more complicated, and it is difficult to evaluate the stability of the slope with the limit equilibrium method. In hydropower projects, deformation starts at many reservoir-bank rocky anti-dipping slopes after impounding water. Although not suffered from landslide and unstable failure, such slopes have been in a state of rheological deformation for a long time with large time-dependent deformation [7,9-11], which may result in the risk of large-scale landslide disasters. At present, the research on the deformation and failure of the anti-dipping rock slope of the reservoir bank under the effect of impoundment focuses mostly on the mechanism explanation and qualitative analysis [12-20], lack of research on the trigger mechanism and deformation evolution of the impoundment effect on the slope deformation.

Based on the deformation monitoring data, taking into consideration of the influence mechanism of the factors such as the water head, temperature, aging (seepage, rock mass rheology) on the deformation of the rocky slope of the reservoir bank during the impoundment process, a statistical regression model for the slope deformation has been established in this paper to analyze the main influencing factors of slope deformation. On the basis of the results from regression analysis, a finite element analysis method for the fractured rock mass seepage-stress-rheological coupling has been used to numerically simulate the deformation and failure process of the slope under the effect of water storage, revealing the leading causes of the deformation of the bank slope under the effect of water storage.

2. Features of toppling deformation of bank slope of reservoirs

The bank slope of a certain reservoir studied in this paper is located in the upper reaches of a hydropower station in Western China, where the bank slope is 650~700m in height, the river valley takes shape of "V", with the steep bank slopes and narrow river valley, generally in the texture of granite rocky. Figure 1 is a schematic diagram of the No. 3 ridge rock mass division and the location of monitoring points, where there is a faulted rock mass on the upper part of the bank slope, and its bottom control surface is the large-scale low-angle dip fault HF104, and the rear edge of the faulted rock mass is bounded by the LF1 fault at the rear edge of the top platform. The bank slope rock mass is divided into 4 types of structures from the surface to the inside as the loose structure, fragmented structure, block-fractured structure, and original rock. The fault structure in the bank slope granite body is relatively developed, large in scale, and poor in character with 4 groups of structures that play a major role in controlling the formation process of the bank slope and the deformation and destruction of the later bank slope.
2.1. Spatial characteristics of bank slope deformation

Since the reservoir was filled in March 2009, a new toppling deformation has been monitored on the platform on the top of the bank slope, where the front edge of the top platform has a downward deformation pointing to the valley, taking out the failure characteristics that the rear edge has significantly subsided, and there have been deformations such as flanging ridge and collapse on the platform as shown in Figure 2 and Figure 3. The spatial characteristics of bank-slope deformation are as follows: ① it was mainly in the form of toppling deformation in terms of the bank slope space, accompanied by the bank slope surface collapse, rolling, and the deformation of a large number of internal tension cracks, and shear dislocation; ② the deformation of bank slope was gradually increasing from the bottom to the top, and gradually decreasing from the surface to the inside; ③ the surface deformation of the platform at the top of the bank slope was featured by the large front edge and small rear edge while deformation of the front edge was mainly featured by toppling and the rear by faulted deformation. As of June 2017, the measured displacement at K1 at the top of the bank slope was 41.16m; ④ The bank-slope deformation was dominated by horizontal displacement, where the horizontal displacement was greater than the vertical displacement. Generally speaking, the lower the elevation, the greater the ratio between the horizontal displacement and the vertical displacement.

2.2. Time characteristics of bank slope deformation

Fig. 4 and Fig. 5 are the comprehensive deformation process lines of the No. 3 mountain ridge K1 and LS05 measuring points of the bank slope, respectively. It can be seen that ① there is a strong correlation between the bank-slope deformation and the reservoir water level. When the reservoir water level rises in the early stage, the deformation rate at the bank slope measurement points starts to increase after 1 to 7 days and continues to develop. When the water level stabilizes, the deformation...
The rate decreases again. After the water level rise rate is controlled in the later period, the increment in the deformation rate of the measuring point is also controlled; ② When the water level stabilizes at 2448m, the bank-slope deformation is still deformed at a deformation rate of about 1.8mm/d per day, which indicates that the bank-slope deformation caused by the change of previous water level has not completely converged, and the deformation has a certain time effect; ③ Seen from the trend of the deformation process line of the measuring points, the bank-slope deformation tends to converge.

3. Influencing factors of toppling deformation from bank slope

The observed deformation of the bank slope should only be related to the changes in the load received during the monitoring period. In order to further analyze the influencing factors of the bank-slope toppling deformation, a regression analysis will be performed on the monitoring data as follows. During the impoundment period, the main factors affecting the deformation of the rocky slope of the reservoir bank are the water head, temperature, aging (seepage, rock mass rheology), etc, through which the influence mode of the above factors on the slope deformation of the reservoir bank has been analyzed, and a slope deformation regression model is established considering the deformation mechanism during the impoundment period as follows:

$$\delta = \delta_{HW} + \delta_{TW} + \delta_{TD}$$

(1)

Of which \(\delta\) —— measured deformation at the monitoring points of the reservoir bank slope during the impoundment period; \(\delta_{HW}\) —— deformation component caused by water head; \(\delta_{TW}\) —— deformation component caused by temperature; \(\delta_{TD}\) —— deformation component caused by aging.

(1) Component of water head \(\delta_{HW}\): The deformation component triggered by the impoundment can be expressed as the quartic polynomial of the water head, namely:

$$\delta_{HW} = \sum_{i=0}^{4} b_{hi} H^i$$

(2)

Of which \(b_{hi}\) —— the regression coefficient of head component; \(H\) —— water head.

(2) Temperature component \(\delta_{TW}\): the temperature variation will affect the deformation of the bank slope, which is expressed by a periodic function or polynomial, namely:

$$\delta_{TW} = \sum_{i=1}^{2} \left[ b_{ti1} \sin \frac{2\pi it}{365} + b_{ti2} \cos \frac{2\pi it}{365} \right]$$

(3)

Of which \(t\) —— the cumulative number of days from the displacement observation date to the initial monitoring date; \(b_{ti1}, b_{ti2}\) —— The regression coefficient of temperature component.

(3) Aging deformation component \(\delta_{TD}\): When the reservoir is impounded, the reservoir water infiltrates into the rock masses on both banks, inside which the seepage field...
gradually transitions from non-constant to constant and the effective stress change and material softening of the rock mass caused by seepage will cause time-dependent deformation of the bank slope. In addition, the stress state of the bank slope rock mass changes after water storage, which will induce rheological deformation of the rock mass. Therefore, the time-dependent deformation components of the bank slope caused by the factors such as seepage and rheology can be expressed in the form of an exponential function, namely:

\[
\delta_{TD} = \sum_{i=1}^{n} \left[ \alpha_{i} \tau_{i} + \alpha_{2i} (1 - e^{-\beta_{i} \tau}) \right]
\]  

(4)

Of which \( t \) — the number of days from the displacement observation date to the initial monitoring date; \( \alpha_{i}, \alpha_{2i}, \beta_{i} \) — The regression coefficient of aging deformation component.

In summary, the slope deformation regression model considering the deformation mechanism during the impoundment period can be expressed as:

\[
\delta = \sum_{i=0}^{1} b_{i} H' + \sum_{i=1}^{2} \left[ b_{1i} \sin \left( \frac{2 \pi it}{365} \right) + b_{2i} \cos \left( \frac{2 \pi it}{365} \right) \right] + \sum_{i=1}^{2} \left[ \alpha_{i} \tau_{i} + \alpha_{2i} (1 - e^{-\beta_{i} \tau}) \right]
\]  

(5)

The established bank-slope deformation regression model is used to perform regression analysis on the monitoring data of the bank-slope deformation to extract the deformation components under the action of various influencing factors. Figure 6 and Figure 7 are the regression analysis results of the comprehensive deformation at the K1 measuring point and the LS05 measuring point, respectively, from which it can be seen that the comprehensive deformation process line obtained by the regression fits well with the measured comprehensive deformation process line, of which the maximum value of the aging deformation component at the K1 measuring point is 35.30m, and that of the water head deformation component is 3.81m, and the aging deformation accounts for about 99% of the total deformation, indicating that the instantaneous deformation caused by the fluctuation of the water level in the deformation of the bank slope during the observation period is relatively small, and most of them are time-dependent deformations.

According to the deformation and failure characteristics of the bank slope and the results of the deformation regression separation, it is believed that the bank-slope deformation mechanism after the impoundment is that: when the rock mass under the bank slope is infiltrated by the reservoir water after the water storage, the effective stress of the rock mass is reduced, and the rock mass material is softened in contact with water, causing continuous deformation of the rock mass and local cracking, dislocation, and collapse. The deformation of the lower part of the bank slope makes room for the toppling deformation at the middle and upper part, and the deformation gradually enlarges from the bottom to the top. The obvious aging deformation of the upper part of the bank slope is mainly due to the rheological deformation of the rock mass caused by the traction effect from the lower part of the bank slope, where the rheological deformation of the structural plane of the rock mass plays a major role. The numerical simulation is performed to further verify the bank-slope deformation mechanism as follows.
4. Numerical simulation of toppling deformation failure of reservoir bank slope

4.1. Finite element mesh
A two-dimensional finite element model is established according to the typical geological profile at the No. 3 mountain ridge of the bank slope, as shown in Figure 8. The calculation of the model considers bank-slope rock mass division, controlling structural planes, and faults, which is divided into 28,225 units and 4016 nodes in total.

Figure 8. The finite element model of the typical section at No. 3 mountain ridge of the bank slope

4.2. Method for numerical simulation
A finite element analysis method for the fractured rock mass seepage-stress-rheological coupling is used to numerically simulate the failure process of the slope as follows.

(1) Taking into account the dead weight load and the initial water load (the original riverbed water level is 2240.0 m elevation), the geostatic stress of the bank slope is calculated;

(2) The stress calculated in the previous step is taken as the initial stress. The impact of water level changes on the bank-slope deformation is simulated based on the inversion parameters, and in accordance with the actual impoundment process and boundary conditions.

In order to truly simulate the physical and mechanical properties of structural planes in rock masses, the finite element method is used to simulate the mechanical properties of structural planes in rock masses based on the contact elements with thickness and strength. The local coordinate system is established based on the normal-tangential direction of the contact elements, as shown in Figure 9.

Figure 9. Schematic diagram of the bottom contact element in the local coordinate system

In the local coordinate system, the relationship of the stress-nodal displacement of the contact element is:

\[
\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \frac{\Delta u}{h} \\ \frac{\Delta v}{h} \end{bmatrix} = \frac{1}{h} [K][N] \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix}
\]

(6)

Of which \( \sigma_x, \sigma_y \) is the thickness of the joint element; \( \Delta u, \Delta v \) is the

\( h \) is the
displacement of the contact element, respectively; \( \{ \delta \} \) is the element node displacement; \([\mathbf{N}]\) is the shape function matrix; \([\mathbf{K}]\) is the stiffness matrix of the element.

When the normal stress of the contact element reaches its tensile stress threshold, that is when \( \sigma_n > f_{nt} \), the element is pulled apart; when the shear stress of the contact element reaches the Mohr-Coulomb strength failure criterion, that is when \( F = |\tau| - (C_o + f_s \sigma_n) \geq 0 \), the element generates shear slippage.

In addition to the existence of faults at the macro-scale, the bank-slope rock mass has also a large number of micro-cracks outside of structural planes and inside the rock mass, therefore, the Drucker-Prager yield criterion is used to simulate the physical and mechanical properties of the rock mass, namely:

\[
F(I_1, J_2) = \alpha I_1 + \sqrt{J_2 - k} = 0
\]  
(7)

Of which \( \alpha, k \) —— a constant; \( I_1 \) —— the first invariant of the stress tensor; \( J_2 \) —— the second invariant of stress deflection.

Since the rock mass is a viscoelastic-plastic body with elasticity, plasticity and viscosity, that is, it has rheological properties, the rheological model of the rock mass is adopted in this paper as:

\[
\varepsilon^\tau (t) = \Delta \sigma_0 C(t_0) + \int_{t_0}^{t} C(\tau) \frac{d\sigma}{d\tau} d\tau
\]  
(8)

\[
C(\tau) = \frac{\tau}{\eta_m} + \frac{1}{E_k}(1 - e^{-\frac{\eta_k}{\eta_m} \tau})
\]  
(9)

Of which \( \varepsilon^\tau (t) \) —— rheological strain; \( \Delta \sigma_0 \) —— Incremental stress applied at time \( t_0 \); \( E_k \) —— elasticity modulus; \( \eta_m, \eta_k \) —— viscosity constant.

### 4.3. Physical and mechanical parameters of rock mass

The mechanical parameters of the rock mass were inversely analyzed based on the design mechanical parameters of the rock mass and the results of the monitoring deformation regression analysis to obtain the mechanical parameters of the bank-slope rock mass, structural planes, and main faults, as shown in Tables 1 to 3.

**Table 1. Mechanical parameters of rock mass in different zones**

| Rock structure type            | Deformation modulus (GPa) | Poisson's ratio | Bulk density (g/cm³) | Shear strength f'/c' (MPa) |
|-------------------------------|---------------------------|-----------------|----------------------|---------------------------|
| Loose structure               | 0.35                      | 0.43            | 2.35                 | 0.50                      | 0.05                      |
| Scattered structure           | 0.75                      | 0.37            | 2.50                 | 0.65                      | 0.40                      |
| Faulted structure             | 2.50                      | 0.33            | 2.65                 | 0.80                      | 0.60                      |
| Original rock                 | 12.50                     | 0.25            | 2.71                 | 1.20                      | 1.50                      |

**Table 2. Mechanical parameters of structural planes in different partitions**

| Group | f' | c' (MPa) | f' | c' (MPa) | f' | c' (MPa) | f' | c' (MPa) | f' | c' (MPa) |
|-------|----|----------|----|----------|----|----------|----|----------|----|----------|
|       |    |          |    |          |    |          |    |          |    |          |
| Loose mass | 0.50 | 0.07 | 0.50 | 0.07 | 0.49 | 0.06 | 0.49 | 0.05 |
| Scattered | 0.59 | 0.23 | 0.59 | 0.24 | 0.60 | 0.25 | 0.61 | 0.27 |
| Faulted mass | 0.66 | 0.38 | 0.67 | 0.39 | 0.69 | 0.44 | 0.71 | 0.48 |
| Original rock | 0.87 | 0.86 | 0.89 | 0.90 | 0.95 | 1.02 | 1.00 | 1.14 |
Table 3 Mechanical parameters of faults

|       | Deformation modulus /GPa | Poisson's ratio | Bulk density /(g/cm³) | Shear strength f' | c'/MPa |
|-------|--------------------------|----------------|-----------------------|-------------------|--------|
| LF1   | 0.30                     | 0.30           | 2.35                  | 0.49              | 0.05   |
| HF104 | 0.30                     | 0.30           | 2.35                  | 0.40              | 0.05   |

4.4. Deformation of bank slopes at different stages of water storage

Figure 10 shows the deformation cloud map of the bank slope when the water level was at 2430 m on December 20, 2011. Figure 11 shows the deformation cloud map of the bank slope when the water level was at 2440 m on April 20, 2012. Figure 12 shows the deformation cloud map of the bank slope when the water level was at 2448 m on December 20, 2014, from which it can be seen that after the impoundment, a downward deformation incurs in the bank slope that points to the river valley, of which the deformation at the front edge of the platform on the top of the bank slope is the largest, and the horizontal deformation is greater than the vertical deformation, while obvious subsidence deformation incurs along the LF1 Fault at the rear edge of the platform and the longitudinal deformation is greater than the horizontal deformation, and laws of these deformations are consistent with reality. The calculated maximum comprehensive deformation at the front edge on the top of the platform of the bank slope on December 20, 2011 (with water level at 2430 m) was 32.16 m while the measured comprehensive deformation was 33.84 m; the calculated maximum comprehensive deformation at the front edge on the top of the platform of the bank slope on April 20, 2012 (with water level at 2440 m) was 34.61 m while the measured comprehensive deformation was 35.19 m; the calculated maximum comprehensive deformation at the front edge on the top of the platform of the bank slope on December 20, 2014 (with water level at 2448 m) was 40.94 m, while the measured comprehensive deformation was 39.48 m. The bank-slope deformations obtained by numerical calculation fit well with the measured values.

Figure 10. Deformation cloud map of bank slope with water level at 2430 m on December 20, 2011 (unit: m)
Figure 11. Deformation cloud map of bank slope with water level at 2440 m on April 20, 2012 (unit: m)

Figure 12. Deformation cloud map of bank slope with water level at 2448 m on DEC 20, 2014 (unit: m)

Figure 13 shows the shape of the bank-slope deformation obtained by numerical simulation, from which it can be seen that there is obvious toppling deformation in the upper and middle surface rock blocks of the bank slope, especially the strongest toppling deformation at the front edge on the top of the platform, and obvious subsidence deformation.
incurs along the LF1 Fault at the rear edge of the platform on top of the platform on the bank slope. Due to the creeping effect of HF104, the rocks are extruded near the exposure of Hf 104, and may even roll-off. The overall deformation shape of the bank slope obtained by numerical simulation is consistent with the actual situation.

Figure 13. Deformation of bank slope obtained by numerical simulation

5. Conclusions

Based on the deformation monitoring data of anti-dipping rock slope at a reservoir bank of a domestic hydropower station, taking the typical profile as the research object, the failure characteristics of the toppling deformation of the bank slope under impoundment has been analyzed, and a numerical simulation has been performed on of the process of the bank-slope deformation and failure in this paper, whose numerical simulation results are consistent with those of the actual situation. On the other hand, the main influencing factors of bank-slope deformation have been analyzed, and the toppling deformation mechanism of the bank slope during the impoundment period has been studied according to the regression analysis and numerical simulation of bank-slope deformation. The research results indicate that there is a strong correlation between bank-slope deformation and water level variation, and impoundment is the main inducing factor for bank slope deformation; during the observation period, the bank-slope deformation directly caused by water level variation is relatively smaller, and most of them are time-dependent deformation; the reduction in the effective stress and the weakening of the material properties of the rock mass under the bank slope caused by infiltration of reservoir water may firstly lead to the deformation at the bottom of the lower bank slope that can make room for toppling deformation at the middle and upper parts of the bank slope, where the deformation is gradually enlarged from the bottom to the top and the obvious time-dependent deformation at the upper part of the bank slope is mainly due to the rheological deformation of the rock mass induced by the traction effect at the lower part of the bank slope.

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