Long-Term Deformation Simulation of Reservoir Bank Slope Considering the Effect of Creep Degradation

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Abstract. Long-term deformation and failure of bank slope are main geological hazards in engineering. Many studies focused on the strength degradation of rock mass and the stability of bank slope under the condition of reservoir water level fluctuation. However, few studies analyzed the time-dependent deformation of rock mass under this condition. Based on the creep degradation characteristics revealed by existing creep tests of rock mass with different water contents, a creep damage constitutive model considering water degradation is established. Then, this constitutive model is incorporated into FLAC3D software and verified. Moreover, the model is implemented to simulate the time-dependent deformation of the Majiagou landslide in the Three Gorges Reservoir area during the impoundment period. Based on the displacement–time curve of the observation point in the initial stage of impoundment, the creep parameters of rock mass are obtained through back analysis. Subsequently, the time-dependent deformation of the bank slope during impoundment is simulated. The results of numerical simulation reveal the deformation mechanism of the Majiagou landslide considering the effect of creep degradation. This study serves as a reference for preventing geological disasters of relevant reservoir banks.

1. Introduction

Long-term deformation and failure of bank slope caused by water level fluctuation are geological hazards. More than 5000 landslides were reactivated and induced by the completion and subsequent impoundment of the Three Gorges Reservoir Project. The Majiagou landslide was triggered by the first impoundment of the reservoir behind the Three Gorges dam. The largest average annual deformation was approximately 183 mm/year during the monitoring period between 2007 and 2009 [1]. Numerous studies have investigated the strength degradation of rock mass and the stability of slope under the condition of water level fluctuation [2,3]. Biaxial creep tests were carried out to determine the effects of water content on the mechanical characteristics of greenschist [4]. The creep properties of saturated and dry rocks were studied by comparing the creep rule of saturated and dry samples [5]. Nevertheless, the time-dependent deformation of rock mass during impoundment needs to be further studied. In the present study, a creep damage constitutive model considering water degradation is
established. Then, this constitutive model is incorporated into FLAC3D software to study the deformation mechanism of the Majiagou landslide during impoundment.

2. Constitutive model considering water degradation

2.1. Improved constitutive model

An improved generalized Kelvin model is proposed, as shown in Figure 1. This creep damage constitutive model considering water degradation consists of a modified Hook body and a modified Kelvin body. The constitutive equation is

$$
\epsilon = \epsilon_0 + \frac{\sigma_0}{E_M (1 - D_\omega)} + \frac{\sigma_0}{E_k (1 - D_\omega)} \left(1 - e^{-\frac{E_k}{\eta}}\right),
$$

(1)

where $D_\omega$ is the water damage variable.

$$
D_\omega = 1 - \frac{E_\omega}{E_0},
$$

(2)

where $E_0$ is the initial elastic modulus, and $E_\omega$ is the elastic modulus when the water content is $\omega$.

![Figure 1. Creep constitutive model considering water degradation](image)

2.2. Verification

The creep test of mudstone with different water contents [6] shows that the creep strain increases significantly with the increase in water content. The parameter identification of creep curves is conducted using the generalized Kelvin model, as shown in Figure 2. In Figure 2(a), the $G_M$ values are 12.7, 12.0, 11.9, and 11.0 when the water contents are 0, 2.03%, 6.17%, and 8.28%, respectively, which show a linear decreasing trend with the increase in water content. The regularities of the change in $G_K$ and $\eta$ are the same, as shown in Figure 2(b), (c). The relationship between parameters and water content is expressed using the least square method:

$$
G_M = 12.91423 - 0.20188 \omega,
$$

$$
G_K = 11.09101 - 0.20049 \omega,
$$

$$
\eta = 50.11205 - 1.78691 \omega.
$$

(3)
The constitutive model considering water degradation is incorporated into FLAC3D software. Uniaxial creep numerical experiments have been performed via laboratory tests to verify this constitutive model[6]. Similar to the mudstone used in the laboratory tests, the numerical model is cylindrical, 25 mm in diameter, and 50 mm in height.

As shown in Figure 3, multistage creep tests are carried out on four samples with different water contents (0, 2.03%, 6.17%, and 8.28%). The stress is applied in three levels: 7.92, 8.72, and 9.52 MPa, respectively. Under the same stress level, the strain increases significantly with the increase in water content. For example, at the stress level of 7.92 MPa, the strains of the samples with water contents of 0, 2.03%, 6.17%, and 8.28% are 4.40, 4.59, 4.95, and 5.16, respectively. The simulation results are in good agreement with the laboratory test results. Meanwhile, the simulation results confirm that this proposed model can simulate the long-term deformation of rock mass considering water degradation.
3. Long-term deformation of the Majiagou landslide

3.1. Numerical model

The Majiagou landslide is located on the left bank of the Zhaxi River in the Three Gorges Reservoir. The landslide moved after the first impoundment of the Three Gorges Reservoir in 2003. The toe of this landslide is 135 m above sea level, and the crown is at an elevation of 280 m \[^7\]. Superficial deposits and sedimentary bedrock are the main material of the Majiagou landslide. The superficial deposits are silty clay and gravel soil. The bedrock consists of interbedded argillaceous siltstone and silty mudstone. The mudstone can be easily softened by water. Therefore, to study the time-dependent deformation of the Majiagou landslide during impoundment and provide technical support for the operation of the reservoir are important.

3.2. Determination of parameters

Monitoring data show that the water level was 145 m in October 2008. The water level rose to the maximum height of 175 m in December. With the rising of water, the deformation of blocks at the elevation of 145–175 m increased significantly. Thus, the constitutive model considering water degradation is used to simulate the creep behavior of the Majiagou landslide during impoundment. The numerical model is depicted in Figure 4. The model consists of 543 elements and 1180 nodes. G01 is taken as the observation point. The rock mass consists of three groups: superficial deposits, deformed rock mass, and bedrock. The physical and mechanical parameters, which are obtained by geological test and inversion \[^1,7\], are shown in Table 1.
Figure 4. Model of the Majiagou landslide

The range of parameters is obtained using engineering examples to identify the creep parameters of rock mass [8,9]. Then, the analytical expression is deduced from Equation (1). Back analysis is carried out on the basis of the displacement–time curve of the observation point during impoundment. The iteration processes are as follows:
1. Design variable is
   \[ X = \{ G_M, G_K, \eta \} \]  

2. A group of design variables \( X' \) is selected to obtain the displacement of the observation point. The simulation result of displacement at \( t_i \) is \( w(X', t_i) \), and the measured displacement at \( t_i \) is \( w_m(t_i) \). In this paper, \( t_i \) should be selected from the calibration interval, which is from August to December 2008.
3. The objective function is established as follows:
   \[ Q = \min \sum_i [w(X', t_i) - w_m(t_i)]^2 \]  

4. The iterative solution is conducted by optimization. The objective function is adjusted by modifying the value of the design variable. The iteration can be terminated when the objective function arrives at a minimum value.

The creep parameters are obtained following the above steps, as listed in Table 1.

| Group                  | Density \( \rho \) (kg/m\(^3\)) | Bulk modulus \( K \) (MPa) | Permeability coefficient (cm/s) | \( G_M \) (MPa) | \( G_K \) (MPa) | \( \eta \) (MPa·s) |
|------------------------|-------------------------------|---------------------------|-------------------------------|----------------|----------------|----------------|
| Bedrock                | 2500                          | 750                       | \( 10^4 \)                    | 600            | 400            | \( 4.4 \times 10^9 \) |
| Deformed rock mass     | 2450                          | 58                        | \( 10^4 \)                    | 600            | 400            | \( 4.4 \times 10^9 \) |
| Superficial deposits   | 2110                          | 9.3                       | \( 10^4 \)                    | 40             | 30             | \( 4.4 \times 10^9 \) |

3.3. Simulation results

The saturation nephograms of slope under the water levels of 145 and 175 m are shown in Figure 5. The saturation of rocks at an elevation of 145–175 m increases significantly along with the rising of water level.
The creep curve of G01 is obtained, as shown in Figure 6. In the initial stage of the calibration interval, the displacement increases slowly, and the maximum creep rate is 0.3 mm/day. Affected by the rising water level, the creep rate increases significantly after October, and the maximum rate is 10.4 mm/day. The prediction interval is after December 2008. The creep curve at this interval is obtained by the calibrated parameters. Results show that the displacement and the creep rate are in good agreement with the monitoring data, which further verifies the constitutive model and the selection of parameters. Importantly, the results indicate that impoundment increases the water content of the rock, which further causes creep degradation and then increases deformation.

4. Conclusion
To study the effect of creep degradation on the bank slope in the reservoir area, the long-term deformation of the Majiagou landslide is simulated. The main conclusions are as follows:
(1) According to the degradation of creep parameters and damage evolution equation, a creep constitutive model considering water degradation is proposed and incorporated into FLAC3D software.
(2) The long-term deformation of the Majiagou landslide after impoundment is simulated using the proposed constitutive model. The creep curve of the observation point obtained by simulation agrees well with the measured value. Impoundment increases the water content of the rock, which further causes creep degradation and then increases deformation.

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