Slope stability and dynamic stability analysis during the process of reservoir water level decline

Naidong Sun, Lingqiang Yang* and Zhenyu Wang

School of Civil Engineering and Architecture, University of Jinan, Jinan, Shandong, 250022, China

*Corresponding author’s e-mail: cea_yanglq@ujn.edu.cn

Abstract. In order to study the stability of the slope during the reservoir water level decline, the finite element analysis is carried out by using Seep/w, Slope/w and Quake/w modules in Geo-slope software, to analyze a self-designed slope during the process of that under normal conditions and occasional earthquakes. The variation curve of safety factor is obtained in the process under different working conditions. The results show that: (1) Under normal circumstances, during the process of reservoir water level decline, the safety factor of the slope will decrease firstly and then slowly increase. There is one most dangerous water level at the water level slope ratio of 1/2~1/3; (2) When adjusting the different water level decline rate and keeping the same water level drop elevation, the higher the water level decline rate is, the lower the stability of the bank slope is, and the smaller the minimum safety factor is during the water level drop process; (3) In the case of an earthquake, the seismic load does not change the overall change trend of the slope safety factor during the process of the reservoir water level drop. What goes beyond the normal pattern of cognition is that, the peak acceleration of the earthquake and the minimum safety factor generally do not occur simultaneously. It can be clearly seen that the seismic intensity plays a more important role in affecting the stability of the slope compared to the reservoir water level decline rate. The research results have certain guiding significance for the regulation of reservoir water level and the safety control of slope under earthquake conditions.

1. Introduction

The change of reservoir water level has a great influence on the stability of dam and slope. The stability of the bank slope is not only related to the reservoir water level, but also affected by the reservoir water level rise and fall [1]. In recent years, major accidents caused by water level changes and earthquakes have occurred frequently, which not only poses a huge threat to the personal and property safety of surrounding residents, but also affects the normal safety of the reservoir system to a certain extent. Therefore, it is of great significance to analyze the slope stability during the process of reservoir water level decline and the dynamic stability under seismic conditions.

In recent years, many domestic and foreign scholars have carried out a lot of research on reservoir water level changes and slope stability under earthquake loads. For example, Lei Guangyu et al. simulated the transient groundwater seepage field change of the slope after the reservoir water level fluctuation, and analyzed the change of slope stability coefficient under different time steps [2]. Zhang Kefeng combined the submerged working conditions of the reservoir water level with the rainfall conditions [3], analyzed the variation of pore pressure and safety coefficient of the slope body, and analyzed in detail the stability effects of reservoir water level changes on various parts of the slope.
This article combines existing research results, and the Seep/w, Slope/w and Quake/w modules in the Geo-slope software are used to analyze the stability of the slope during the process of reservoir water level descent. At the same time, the dynamic stability analysis of the slope is also carried out. The analysis results have important reference significance for the construction and safety protection of the slope.

2. Calculation principle

2.1. Unsaturated seepage theory
The governing equation for unsaturated seepage is

\[ \frac{\partial}{\partial x} [k_i \cdot k_j \cdot h_j \cdot \frac{\partial h_i}{\partial x} + k_{ij} \cdot h_j] + Q = [C(h_i) + \frac{\theta}{n} S_i] \frac{\partial h_i}{\partial t} \]  

(1)

Among them, \( k_i \) is the relative water permeability; \( k_{ij} \) is the saturated permeation tensor; \( h_i \) is the pressure head; \( Q \) is the source sink; \( C(h_i) \) is the water capacity; \( \theta \) is the pressure head function; \( n \) is the porosity; \( S_i \) is the unit water storage.

2.2. Dynamic safety factor calculation method
The dynamic stability analysis of slopes under seismic conditions requires consideration of the dynamic safety factor of the slope [5]. \( F(t) \) is used to represent the safety factor of the slope. The calculation expression is:

\[ F(t) = \frac{\int \tau_f(t) dA}{\int \tau(t) dA} \]  

(2)

In the formula, \( \tau_f(t) \) and \( \tau(t) \) are the anti-slip and the slip force of the point on the sliding surface at time \( t \). When numerical methods are used to calculate, the calculation area must be discretized. Equation (2) can be written as:

\[ F(t) = \frac{\sum (c_i + [\sigma_{s,i} + \sigma_{a,i}(t)] \tan \phi_i) A_i}{\sum (\tau_{s,i} + \tau_{a,i}(t)) A_i} \]  

(3)

Among them, \( c_i \) and \( \phi_i \) are Cohesion and internal friction angle of the i-th type of rock and soil mass; \( A_i \) is the area of the discrete potential sliding surface; \( \sigma_{s,i} \) and \( \tau_{s,i} \) are normal and shear stress under gravity; \( \sigma_{a,i}(t) \) and \( \tau_{a,i}(t) \) are the additional normal stress and additional shear stress at time \( t \) under the action of earthquake, and is calculated by dynamic finite element.

2.3. Dynamic stability evaluation method
The law of the change of the safety factor on the potential sliding surface with time is expressed by the dynamic safety factor method to guide the dynamic stability analysis of the slope [6].

\[ F = \frac{1}{T} \int_0^T F(t) dt \]  

(4)

Among them, \( T \) is the power duration; \( F(t) \) is the dynamic safety factor.

3. Calculation profile

3.1. Calculation model
The upstream slope of a certain earth-rock dam is used in this calculation as the analysis object. In this model, three water level decline rates are set from 39.2m elevation to 32.8m water level elevation. The finite element model is established, and the grid is encrypted to improve the calculation accuracy. The model has 5725 nodes and 5548 units. The finite element model is shown in Figure 1.
3.2. Boundary conditions
The boundary condition of this model is set to: abc is the boundary of the reservoir water level change, mainly including the boundary where the reservoir water level drops at different rates; gh is the downstream water level boundary; cdef and agi are impervious boundaries.

3.3. Calculation parameter
After studying the previous research results [4–6] and referring to the corresponding rock geotechnical specification, to determine the material parameters required for this model, as shown in Table 1.

| Lithology        | ρ (g·cm⁻³) | μ  | E_s (10⁹Pa) | E_d (10⁹Pa) | C   | φ (°) | ε   | φ_f (°) |
|------------------|------------|----|-------------|-------------|-----|------|-----|--------|
| Deposit          | 2.2        | 0.2| 5.62        | 7.20        | 130 | 32   | 0.05| 0      |
| Fragmented rock  | 1.9        | 0.2| 2.69        | 3.50        | 112 | 20   | 0.05| 0      |
| Sandstone        | 2.6        | 0.2| 9.54        | 12.4        | 280 | 54   | 0.05| 0      |

3.4. Calculation condition
In order to carry out the stability analysis and dynamic stability analysis of the slope in the process of the reservoir water level falling, three reservoir water level decline rates have been set: 1.5m/day, 2m/day and 3m/day respectively. In addition, Seismic waves with peak accelerations of 0.05g and 0.1g were applied on our analysis object respectively, so as to conduct dynamic stability analysis of slopes under seismic loading.

4. Calculation results
4.1. Slope stability analysis under normal conditions
The instantaneous safety factor of the slope is shown in Figure 2. Under normal circumstances, the case of 3m/day was taken as an example. During the decline of the reservoir water level, the safety factor of the slope decreased from 3.85 to 2.65, and then slowly rose to around 2.70. And it is obvious that in this process, the safety factor has a minimum: The most dangerous position of the slope. Compared with the other two working conditions, this rule also exists.

When setting the reservoir water level to drop at different rates, the greater the rate of decline of the reservoir water level, the earlier the safety factor of the slope reaches the minimum value, the lower the stability of the bank slope, and the lower the minimum safety factor corresponding to the decline process.
4.2. Analysis of dynamic stability of slope under earthquake conditions

The dynamic response of the slope in first 20s of the whole process was taken as the analysis object. The change of the safety factor of the slope during this time is shown in Fig.2.

Under the action of a seismic wave with a duration of 20s, we took the drop rate of the reservoir water level at 1.5m/day as an example. The water level drop rate was set to a fixed value. When the seismic load with a peak acceleration of 0.1g was applied, the safety factor of the slope reduced from 2.035 to 2.005. When the seismic load with a peak acceleration of 0.05g was applied, the safety factor of the slope reduced from 2.662 to 2.615; On the other hand, we took seismic conditions with a peak acceleration of 0.1g as an example. The intensity of the seismic load was set to a fixed value. When the reservoir water level decreased at a rate of 1.5 m/day, the slope safety factor decreased from 2.035 to 2.010. When the reservoir water level decreased at a rate of 3 m/day, the slope safety factor decreased from 2.015 to 1.975. Obviously, compared with the drop rate of the reservoir water level, the seismic dynamic load is more likely to affect the stability of the slope.

In addition, regardless of the type of seismic load, the dynamic safety factor of the slope was generally decreasing in addition to the local fluctuation during the 20s seismic time. In other words, the dynamic safety factor of the slope will change with the intensity of the earthquake during the process of reservoir water level decline. The larger the peak acceleration of the seismic wave is, the smaller the safety factor is as a whole and the lower the slope stability is. However, the seismic load does not affect the overall trend of the safety factor during the process. The minimum value of the safety factor will still appear at a certain level of water level slope ratio and will not appear at the same time as the peak acceleration.

Fig.2. Slope safety factor change chart

Fig.3 (a) Peak acceleration with 0.1g
Fig.3 (b) Peak acceleration with 0.05g

Figure 3. Slope safety factor change chart
5. Conclusion

(1) Slope safety factor, regardless of the impact of other factors, will quickly reduce to a minimum at a height ratio of 1/2 to 1/3 and then slowly rise during the process of reservoir water level decline. Therefore, when the reservoir water level drops to a dangerous location, we can appropriately slow down the water level and avoid slope instability.

(2) When setting the elevation of decline of the reservoir water level to a fixed value and increasing the rate of that, the safety factor of the slope will have a significant decline as a whole, that is, the stability of the slope will decrease as the rate increases. Therefore, in the actual drainage process of the project, the sudden drop of the reservoir water level is very unfavorable to the stability of the slope, and there are certain safety hazards. Whether it is in the drainage of the reservoir or in the process of water storage, the speed of the water level change should be limited, and the speed of the water level of the reservoir should be slowed down as much as possible to improve the stability of the slope.

(3) When the earthquake occurs during the reservoir water level decline, the safety factor of the slope will decrease significantly overall, but the whole change trend of the safety factor is constant, and there may be local fluctuations in the change process of safety factor. Therefore, when encountering an earthquake during the process of that, it is necessary to properly control the drainage time of the reservoir.

(4) Compared with other factors affecting slope stability, such as the water level decline rate, the change of seismic load intensity is more likely to affect the stability of slope. Therefore, when an earthquake comes or before it comes, it is necessary to recognize the primary and secondary relationship of each influencing factor, arrange the work reasonably, and take precautions in advance.

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