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Study on the Response of Slope Stability to Its Influencing Factors Based on a Simple Model

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Abstract: The stability of the water bank slope and the reservoir bank slope along the mountain river is affected by the change of water level. In addition, the inclination angle of the overburden layer and the bedrock surface is also one of the important factors affecting the stability of the bank slope. In order to evaluate the stability of the water bank slope and the reservoir bank slope under the condition of the change of water level and the dip angle of the sliding surface, this paper selects a simple model: the limit equilibrium method is used to calculate the stability coefficient of the given water level and the dip angle of the sliding surface. The results show that the change of the dip angle of the sliding surface is positively correlated with the change of the amplitude of the stability coefficient. The larger the dip angle, the easier it is for the slope to change from a stable state to an unstable state during the change of the reservoir water level, and the slope stability is more sensitive to the change of the water level. The influence of reservoir water level on the stability coefficient is related to the inclination angle of the sliding surface. Although the inclination angle is large and small, it can cause a sharp change in the stability coefficient, but it is not the most unstable state. The slower or steeper the inclination angle of the sliding surface, although it can sensitively affect the slope stability, it is still in a stable state. The most unstable state is within a certain inclination angle of the sliding surface.

1. Introduction

Landslide near water is a common geological disaster in China. It will not only cause a series of problems such as river blockage and rapid increase of reservoir water level[1-3], but also cause the ecological environment along the line to be destroyed[4-5], causing serious harm to the safety of the people downstream of the river and around the dam. A large number of engineering examples have shown that the hydro-geological conditions of the near-water slope and the reservoir bank slope along the river will change significantly under the condition of water level fluctuation, which will not only cause the original stable old landslide to lose stability again, but also lead to the instability of the near-water slope, forming new landslides and collapses[6-7]. On June 24, 2017, a large mountain high-level collapse disaster occurred on the left bank of Songpinggou in Xinmo Village, Diexi Town, Maoxian County, Sichuan Province. The accumulation body blocked the Songpinggou

River, which had a serious impact on the safe flood discharge of the river during the flood season[8]. According to statistics, nearly 40% of the waterside slopes in Japan are unstable during the rise of reservoir water level[9]. In addition, the landslide events[10,11] occurred in the Vajont reservoir in Italy and the Qianjiangping reservoir in the Three Gorges reservoir area in China in 1963 and 2003 respectively are typical disasters caused by the rise of reservoir water level, causing serious losses to the national economy and people 's lives and property.

The change of water level is closely related to the occurrence of reservoir landslide. Lane P A et al.[12-13] used the strength reduction method to analyze the influence of water level change on the slope stability coefficient, and found that the slope stability coefficient decreased first and then increased with the rise of the reservoir water level, and the slope stability was not monotonously related to the rise of the water level. In addition, some scholars[14-18] studied the influence of reservoir water level rise on the stability of reservoir bank slope through some deformation monitoring and numerical simulation methods, and also obtained the same results. Cai et al.[17-19] analyzed that the stability of the water slope is the worst at the water level of about 1/4-1/3 of the slope, indicating that there is the most dangerous water level range in the stability analysis of the water slope. Shi Dingkang[20] studied the influence of soil-rock interface inclination on the stability of ideal binary structure slope based on the limit equilibrium method, and obtained that the larger the inclination of soil-rock interface, the higher the stability coefficient, but when the inclination of soil-rock interface is small, the stability coefficient is not sensitive to the inclination of soil-rock interface. Based on numerical simulation and stability calculation, Luo Shilin[21] revealed the influence of the change of the dip angle of the base-cover interface on the stability of the linear-like base-cover interface accumulation body. It was found that the stability of the linear-like base-cover interface landslide developed from rapid decline to slow decline with the increase of the dip angle. The larger the dip angle of the linear-like base-cover interface, the more sensitive the stability coefficient to the change of strength parameters.

The above scholars mostly study the influence of water level change or base-cover interface inclination change on slope stability coefficient. There are few studies on the influence of both factors on the stability of landslide and the degree of change. In this paper, a simple geological model is selected: the limit equilibrium method is used to calculate the change of the stability coefficient in a certain range of water level and the dip angle of the sliding surface. The research results can provide reference for the prevention and stability evaluation of water slope.

2. Model establishment

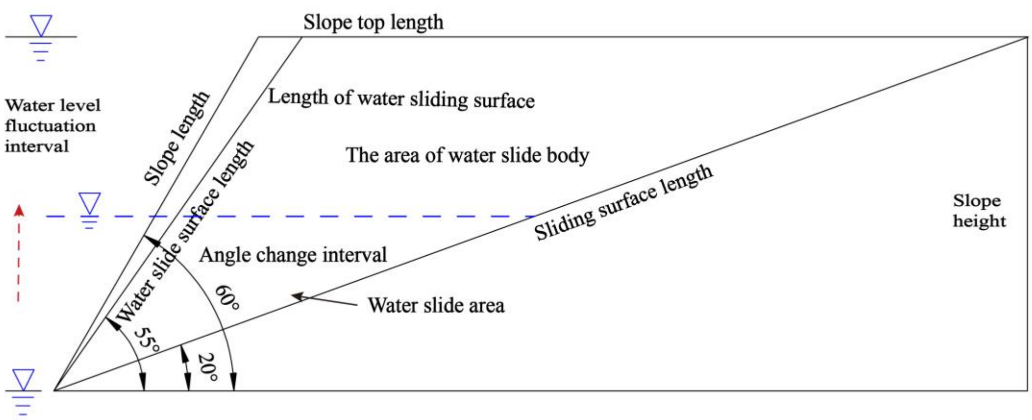

Figure 1: Ideal slope profile

The slope height of the water slope is 50m, the slope inclination angle is 60°, the sliding surface type is set to be linear, and the sliding surface inclination angle is uniformly increased from 20° as the starting angle to 55° at an interval of 5°. The front edge of the slope is the relative current water level (0m), and the water level rises evenly to the relative maximum water level (50m) at an interval of 5m to reach the top of the slope. The simple model is shown in Figure 1.

It is assumed that there is no obvious fracture structure in the slope area near the water. The slope material is mainly composed of loess loam, and the composition is silty clay. The slope stability mainly depends on the strength of loess loam. The test soil samples are taken from the western mountainous area. Because the process time of slope instability is short in the case of sudden rise of water level on both sides of the river and reservoir bank, which is equivalent to the direct shear stress condition, the fast shear test is carried out to determine the effective strength index. Considering that the landslide body is partially submerged under the water and partially on the water during the rise of the reservoir water level, the shear test of the landslide soil under natural water content and saturated water content is carried out to obtain its effective shear strength index. The strength indexes measured by the test are shown in Table 1.

Table 1: Slope stability calculation index under natural and saturated state

lithologic characters	State	Gravity γ(kN/m^3)	Force of Cohesion c(kPa)	Angle of Friction φ(°)
Loessial loam	natural	18.9	48.0	22.6
	saturation	20.1	26.5	22.3

3. Calculation Method

It is known that the vertical height of slope near water source is $H = 50\text{m}$, and the slope angle is $\alpha = 60°$. The slope length A can be obtained from Equation (1). Setting the inclination angle of the sliding surface as β, the length B of the slope top can be obtained by the sine theorem (2), and the length L of the sliding surface can be obtained by the cosine theorem (3). The water level is set to rise xm from the relative current water level (0m), and the length $L_{\text{below the water level}}$ and $L_{\text{above the water level}}$ below and above the water level of the sliding surface can be obtained by the similar triangle principle formula (4) and (5). The area S of the potential sliding area is obtained by Equation (6), and then the area $S_{\text{below the water level}}$ and $S_{\text{above the water level}}$ of the potential sliding area below and above the water level can be obtained according to the similar triangle principle Equation (7) and (8).

$$A = \frac{H}{\sin\alpha} \tag{1}$$

$$\frac{B}{\sin(\alpha - \beta)} = \frac{A}{\sin\beta} \quad \text{Get} \quad B = \frac{A\sin(60° - \beta)}{\sin\beta} \tag{2}$$

$$L^2 = A^2 + B^2 - 2AB\cos(180° - \alpha) \quad \text{Get} \quad L = \sqrt{A^2 + B^2 - 2AB\cos(180° - \alpha)} \tag{3}$$

$$L_{\text{below the water level}} = \frac{x}{H} L \tag{4}$$

$$L_{\text{above the water level}} = \frac{H - x}{H} L \tag{5}$$

$$S = \frac{1}{2} AB\sin(180° - \alpha) \tag{6}$$

$$S_{\text{below the water level}} = \frac{x^2}{H^2} S \tag{7}$$

$$S_{\text{above the water level}} = \frac{H^2 - x^2}{H^2} S \tag{8}$$

Finally, the stability coefficient under different water level and sliding surface inclination is obtained by the stability coefficient calculation formula (9). Where *i* represents two different states of underwater and water.

$$F_s = \frac{\sum c_i L_i + \sum \gamma_i S_i \cos\beta \tan\varphi_i}{\sum \gamma_i S_i \sin\beta} \tag{9}$$

In the formula: γ——Soil weight /kN/m^3
c——Force of Cohesion /kPa
φ——Angle of internal friction / °
L——Sliding surface length /m
α/β——Slope angle, Sliding surface angle / °

4. Result Analysis and Evaluation

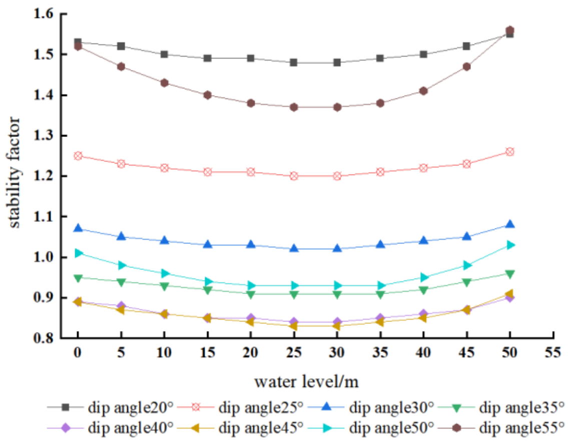

Figure 2: Relation curve between stability coefficient and water level and dip angle

In this paper, a simple geological model is established based on the limit equilibrium method, and the slope stability coefficient is calculated by Equation (9). The calculation results of the slope stability coefficient considering the continuous rise of the water level and the change of the potential sliding surface are shown in Figure 2.

In the slope stability analysis, the shear inlet, shear outlet and sliding surface position of the landslide are determined under different sliding surface inclination angles. With the rise of the reservoir water level, the stability coefficient is roughly divided into two sections with the rise of the reservoir water level, namely the descending section and the ascending section. When the dip angle of the sliding surface is 20 °, the stability coefficient under the reservoir water level of 50m is greater than that under other dip angles. The initial stability coefficient is 1.53, and the minimum is 1.48 at the water level of 25m~30m, which is about 1/2~3/5 of the slope. When the dip angle of the sliding surface is 40 °~45 °, the stability coefficient in the process of reservoir water level change is less than the stability coefficient under other dip angles. The initial stability coefficient is 0.89, and the minimum is 0.83~0.84 at the water level of 25m~30m, which is located at 1/2 ~ 3/5 of the slope, and the rest of the dip angle is roughly in this interval. The analysis shows that there is the most dangerous water level in the water slope, which is between the ideal model and the actual slope. There are some errors in the most dangerous water level interval due to the complex shape and stress of the slope and sliding surface.

The change trend of stability coefficient under different sliding surface inclination angles is the same. The decrease and increase of the descending and ascending segments are shown in Figure 3. Both stages increase with the increase of the inclination angle of the sliding surface, and the increase of the ascending segment is larger than that of the descending segment. When the inclination angle of the sliding surface is up to 55 °, the former is 9.86% and the latter is 13.92%. It shows that the change of the inclination angle of the sliding surface is positively correlated with the amplitude change of the stability coefficient, that is, the larger the inclination angle of the sliding surface, the slope is easy to change from a stable state to an unstable state during the change of the reservoir water level, and the slope stability is more sensitive to the change of the water level.

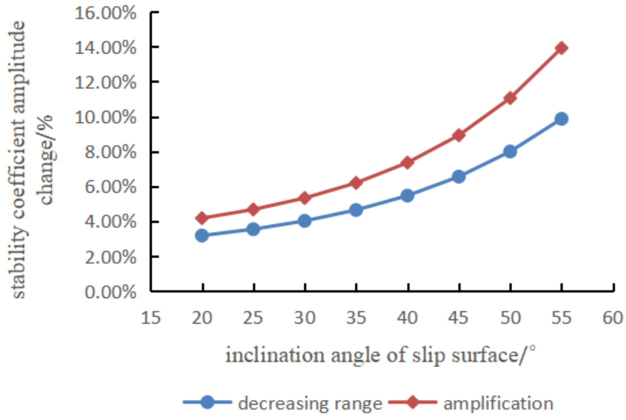

Figure 3: Variation amplitude of stability coefficient under different dip angles

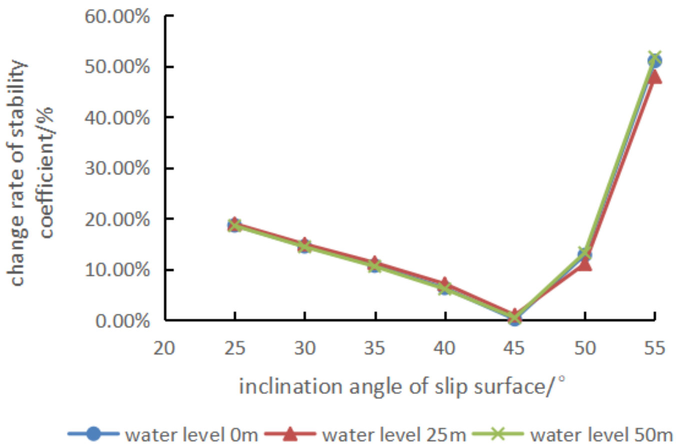

Figure 4: The variation curve of slope stability coefficient under different water levels

With the increase of the inclination angle of the sliding surface, the stability coefficient is also roughly divided into two sections, namely the descending section and the ascending section. The change trend of the stability coefficient under different water levels is the same. The stability coefficient of the sliding surface dip angle near 35 ° and 50 ° is close to 1, but the change rate of the stability coefficient of the sliding surface dip angle near 40 °~45 ° is close to 0, and the stability coefficient is generally the smallest, all below 1. The change trend of the stability coefficient caused by the change of the sliding surface dip angle is shown in Figure 4. The maximum change rates of the stability coefficient corresponding to the change of the two sliding surface dip angles are 18.95% and 51.75%, respectively, and the stability coefficient is still above 1.3. It shows that the influence of reservoir water level on the stability coefficient is related to the inclination angle of the sliding surface. Although the inclination angle is large and small, it can cause a sharp change in the stability coefficient, but it is not the most unstable state, that is, the slower or steeper the inclination angle of the sliding surface, although it can sensitively affect the slope stability, it is still in a stable state. The most unstable state is within a certain inclination angle of the sliding surface.

5. Conclusions

In this paper, the response of the stability of the water bank slope and the reservoir bank slope to its influencing factors under a simple geological model is studied. The influence of water level change and sliding surface inclination change on its stability is analyzed. The following conclusions are obtained:

(1) The stability coefficient in the process of reservoir water level rising is roughly divided into two sections, namely the falling section and the rising section, and the corresponding water slope has the most dangerous water level.

(2) The change of the dip angle of the sliding surface is positively correlated with the change of the amplitude of the stability coefficient, that is, the larger the dip angle of the sliding surface is, the easier the slope is to change from a stable state to an unstable state during the change of the water level. When the dip angle of the sliding surface is up to 55 °, the former is 9.86% and the latter is 13.92%.

(3) The influence of reservoir water level on the stability coefficient is related to the inclination angle of the sliding surface. Although the inclination angle is large and small, it can cause a sharp change in the stability coefficient and then sensitively affect the slope stability, but it is not the most unstable state. The maximum change rate of stability coefficient corresponding to the change of the dip angle of the two sliding surfaces is 18.95% and 51.75% respectively, and the stability coefficient is still above 1.3. The most unstable state is in the vicinity of the sliding surface inclination angle of 40 °~45 °, and the change rate of the stability coefficient is close to 0, which is the smallest.

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