Analysis of impact factor of reservoir loose bank collapse in mountain valley reservoir

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Abstract. The safety of the reservoir construction and the normal reservoir as well as the normal operation of the power station is affected by the phenomena of reservoir bank slopes’ instability and failure. Nowadays there is a lot of research about plain reservoir bank collapse, but the research about mountain valley reservoir bank collapse is not very perfect. Because of the various material characteristics and complex structure of mountain valley reservoir bank collapse, the influencing factors, mechanisms and types of mountain valley reservoir bank collapse is complex. According to a mountain valley reservoir site in southwest China, the bank collapse influencing factors are summarized, which are the formation lithology of the bank, the topography, the geologic structure, the hydrodynamic condition of the reservoir and the wave effect. The sensitivity of impact factors of the bank collapse is achieved by the orthogonal analysis. By contrast to single factor sensitivity, the cohesion in natural state and the wave height are the main impact factors.

Keywords: Bank collapse; Influencing factors; orthogonal analysis; Single factor sensitivity analysis

1. Introduction
Reconstruction of reservoir bank slope caused by unstable slope of reservoir bank slope and siltation on the bank is an engineering geological problem commonly encountered during reservoir construction [1]. Reservoir bank slope collapse refers to damages caused by the impact of the bank's internal and external factors, such as the dynamic action of reservoir water, wave erosion, surface water erosion and groundwater landslide, during reservoir construction, water storage and operation. After the bank slope of the reservoir collapses, under the influence of geological camps, the water bank slope and the underwater shoal will evolve continuously until a relatively stable new landform is formed. The collapse of the reservoir bank slope has played a dual role in destroying and reconstructing the original landform. During the reservoir impoundment process, the geological and hydrological environment of the reservoir area will change. With the change of the water level in the bank slope, especially loose bank slope, bank collapse generally occurs, which has a great impact on the normal water storage, operation of power station, facilities around the reservoir and personal and property safety [2].
From the construction to the storage and operation of the reservoir, change of water level mainly refers to the rising and falling of water level. The change of water level will lead to significant changes in the geological conditions of rock and soil near the range of water level. During the water storage process, the rising water level leads to the elevation of the base surface of the bank slope erosion and groundwater level. Under the dual influence of reservoir water and groundwater, the underlying rock and soil body will be humidified, and at the same time, the hydrodynamic conditions of the bank slope reservoir will be changed [3], and the main external force such as wave force will be continuously transformed. As for loose soil bank slope, due to its weak anti-scour ability, it is easy to loosen, soften, slump and slide and its shape continuously changes and moves backward [4]. The instability of the bank slope will damage the surrounding buildings, such as facilities, houses, roads, factories, and farmland. Besides, the collapsed soil and stone bodies will be deposited at the bottom of the reservoir, which will reduce the effective storage and threaten the safety of ships and personnel.

The hydropower projects in the southwestern mountainous areas of China have developed vigorously. Researchers have conducted research on the Three Gorges[5,6], Ertan[6,7], Baozhu Temple[7,8], achaoshan, Tianshengqiao, Zipingpu, Manwan, Xiaowan[7] and other hydropower projects, which indicates that the bank slope instability of valley reservoirs differs enormously from that of plain reservoirs, including formation mechanism, developing process, slope mode and prediction methods. The instability of bank slopes of plain reservoirs is mainly reflected in the reconstruction of the bank slope under the action of wave wash. By contrast, as for the bank slopes of valley reservoirs, the material characteristics are diverse and the structures are complicated, which results in the complexity of its instability mode and formation mechanisms. It is meaningful to study the weight of the influence of different factors on the failure of bank slopes, as well as predict the probability of collapse under different factors and evaluate the stability of bank slopes during water storage. These help to ensure the safety of projects and reduce the loss of personnel and property. Taking an operating valley reservoir as the research object, this paper analyses the Impact Factors of the bank slope of the valley reservoir and its sensitivity.

2. Determination of Impact Factors of bank collapse

The bank collapse of reservoirs is influenced by various factors, including geological environment factors, hydrological factors and others. Through the investigation of collapsed banks in the reservoir area, based on previous research results, this paper proposes the main Impact Factors of the collapse of bank slopes with loose structures in the valley reservoir [9, 10].

2.1. Lithology of bank slopes

The slope lithology is the decisive factor of bank collapse, which directly affects the width, height, failure mode and developing range of the bank collapse. The soil has fine particles, large porosity and loose structure. It is easy for bank slopes with such soil, like artificial fill and strongly weathered residual soil, to collapse widely in a short time under the action of water level change, wave erosion and rainfall. On the contrary, rock masses with better physical and mechanical properties and undeveloped joint fissures, such as sandstones with good integrity and unweathered granite, are less likely to be affected by external forces.

The values of the cohesion c and the friction angle φ are the main parameters determining the properties of rock and soil masses. With regard to slope rocks and soil, since part of the slopes are below the reservoir water level, the analysis of rock and soil properties should be divided into two parts based on natural strength parameters above the waterline and saturation strength parameters below the waterline.

2.2. Topography of bank slopes

Forms and topography have a great impact on the stability of the bank. Under the lateral erosion of the reservoir bank, rock and soil masses at the foot of the bank slope will be destroyed, and grooves will be formed by the erosion, which will cause the masses in the upper part of the bank to be unstable under
gravity. The steeper the bank slope is, the larger the range of collapsed soil formed by the erosion of water will be. In addition, when other geological conditions remain the same, the higher the bank slope is, the higher the stress value of the slope near the surface and the more concentrated the shear stress at the foot of the slope will be. And because the foot is the part most influenced by hydrodynamics, the slope will be more easily eroded by water. Therefore, the main factors causing bank collapse are the gradient and height of the bank slope.

2.3. Geological structure
The geological structure also has a decisive influence on the stability of the bank slope, especially the fault structure, which makes the rock masses incomplete and greatly reduces the integrity of the bank slope structure and the strength of rock masses. According to the investigation on the collapse site of a reservoir area, the slope is more likely to collapse and the range is larger when the angle between the tectonic line strike (mostly the strike of the fault zone) and the shoreline strike is smaller; and in contrast, when the angle is larger (maximum = 90°), the slope is less likely to collapse and the range is smaller. Therefore, the angle between the tectonic line strike and the shoreline strike can be used to analyze the degree to which the geological structure influences the range of collapse.

2.4. Hydrodynamic conditions
The action of water is the leading factor in the bank collapse. The effect of water immersion, softening, erosion, abrasion and dissolution on the bank slope is the direct cause of bank collapse. The water level changes during storage and operation due to the need of power generation and the changing climatic environment, going through dry season and flood period. The water level is lower during the dry season and gradually rises during the rainy season or water storage period, so that the slope above the original waterline is submerged, and the rock and soil masses are transformed from natural state to saturated state and the mechanical properties of the masses are reduced. When the water level drops due to flood discharge, etc., a saturation line of groundwater will be formed, resulting in seepage water pressure. At the same time, because of the change of soil properties and pore water pressure, the slope morphology changes due to the decrease in stability. Different water levels and amplitudes of water level changes have different degrees of influence on rock masses and groundwater level. Therefore, the main factor influencing the hydrodynamic conditions of the reservoir is the amplitude of the water level change.

2.5. Waves
The wave mainly reconstructs the bank slope by transferring its own energy to the slope. There are two main forms of reconstruction. One is the erosion effect of the wave directly on the bank slope, which mainly occurs in the shore where the slope angle is steep. The other is the erosion caused by the wave slamming the bank slope. Since the wave energy is proportional to the square of the wave height, the higher the wave is, the greater the wave energy will be, the greater the impact on the bank slope will be and the stronger the extent of reconstruction will be. Therefore, the evaluation of the degree of influence of the wave on the bank slope is mainly to evaluate the wave height. Wave height is also an important factor causing bank collapse.

The influence degree of each of the above factors on the bank collapse varies, and some factors affect the collapse obviously, while some factors have little influence. In other words, the contribution of these factors to the range of bank collapse is different, which requires evaluation of the sensitivity of these factors. The sensitivity analysis of the factors of bank collapse is to quantitatively analyze the correlation between the factors and the stability coefficient of the bank slope. That is to analyze the influence degree of the factors of each bank collapse on the stability coefficient of the slope. In the study of collapse prediction methods, the sensitivity degree of bank collapse factors is extremely important. The sensitivity analysis provides a theoretical basis for proposing a suitable bank collapse prediction method.
3. Orthogonal analysis

At present, single factor analysis is a widely used method. The orthogonal analysis method is a multi-factor analysis method that uses normalized tables to design orthogonal test schemes. The results of this method can be used to derive the primary and secondary relationships of the factors, that is, the order of contribution of each factor to the survey indicators; the relationship between factors and indicators, that is, the change of indicators when factors change.

The steps of the orthogonal analysis method are as follows,

i. Select the appropriate orthogonal analysis table based on actual situations and record it as Ln(rm).

In the table, L is the symbol of the orthogonal table; r is the number of evaluation levels, that is, the number of evaluation factors; n is the number of rows in the table, that is, the times of calculation; m is the number of columns in the table, that is, the number of factors that can be included at most. Place each evaluation factor above the orthogonal table.

ii. Design schemes using orthogonal tables at a given level of each factor.

iii. Solve the results of the analysis based on the schemes above.

iv. Analyze the calculation results and draw the conclusion of sensitivity evaluation. There are several methods to analyze the results, such as range analysis method, variance analysis method, regression analysis method and covariance analysis method. In this paper, the range analysis method is utilized, that is, the difference between the maximum and minimum values in the average effect. Using the extremes, the main factors affecting the indicators and the best combination of factors can be determined.

Suppose that the orthogonal table Ln (rm) is used for the test. The number of trials of the same level in each column is marked as t, and then n=rt can be obtained. Let the results of the experiment be Yi (i=1, 2, 3, …, n), which are independent of each other and satisfy the normal distribution of the variance σ2, that is, Yi~N(μi, σ) (i=1,2,3,…, n). This paper uses the variance method to analyze the results of Yi, that is, to make a significant analysis of the hypothesis H0: μ1=μ2=…=μn.

The steps of range analysis are as follows,

i. Calculate the average effect and range of each factor at each level.

ii. Analyze the calculation results and the primary and secondary relationships of each factor, and find the optimal test scheme.

4. Sensitivity analysis

For the stability evaluation of bank slope, it is predicted whether it may collapse. This paper uses Sarma method to calculate the sensitivity degree [11, 12, 13].

For the influencing factors of bank slope, the lithology and structure of the rock masses determine the mechanical strength; the slope height and gradient determine the shape of the bank slope; the water level change and wave action determine the effect of water pressure on the slope.

The orthogonal analysis method is used to design the orthogonal table. The stability coefficient of the bank slope under each factor is calculated and analyzed by Sarma method. The variance of the calculation results is analyzed, and the influence degree of each factor on the stability of the bank slope is obtained. According to the previous analysis, the main Impact Factors of the bank slope of the valley reservoir are as follows: the natural strength parameters of the rock masses above the waterline (cohesion c and friction angle φ), the saturation strength parameters of the rock masses below the waterline (saturated soil cohesion c and friction angle φ), slope gradient α, slope height h, angle between the tectonic line and shoreline θ, water level change ΔH, wave height d, etc. The evaluation is only related to the strength parameters of the rock and soil masses, regardless of the interaction between factors. In order to reduce systematic errors due to horizontal order, the order of the various factor levels should be randomly arranged. The orthogonal table is designed based on these Impact Factors [14, 15].

Assuming that there is no interaction between the various factors, a 9-factor orthogonal table is chosen for the test. Taking a bank slope in the reservoir as an example, the orthogonal experiment is carried out. The parameters of the bank slope are as follows: the natural cohesion c of the soil is 40.0 kPa and the friction angle φ is 28°; below the waterline the saturated cohesion c is 32.0kPa and the
Sensitivity analysis chart is shown in Figure 1. Compared with it, the results are shown in Table 3. According to data of the single-factor analysis, the width of the collapsed bank is influenced by the factors, and the multi-factor analysis method is the main impact factors.

The factors are selected according to the parameters of the hierarchical levels of each scheme in the orthogonal table, and stability coefficient $F_s$ of the bank slope is calculated using the Sarma method.

According to the design criteria of the orthogonal test, $L_{49} (78)$ is selected as the orthogonal table, and the test is carried out with the correct head design. According to the experimental design, 64 tests should be arranged to obtain the sensitivity of each factor.

The stability coefficients are obtained by calculating 64 different combinations. The test results of each factor at the same level are averaged, and the range is the difference between the maximum and the minimum of the average value at each level. The large range indicates that there are huge differences between different levels. The test results of the above table are analyzed by the range, as shown in Table 2.

It can be seen from Table 2 that the order of sensitivity to the collapse factor is as follows: natural cohesion $c$ > wave height $d$ > saturated cohesion $c^*$ > saturated friction angle $\phi^*$ > natural friction angle $\phi$ > bank slope gradient $\alpha$ > angle between the tectonic line and the shoreline $\theta$ > water level change $\Delta H$ > slope height $h$. Among them, the huge differences in the wave height $d$ and the natural cohesion $c$ are the main impact factors.

At the same time, the traditional single factor analysis method is used to analyze the degree to which the width of the collapsed bank is influenced by the factors, and the multi-factor analysis method is compared with it. The results are shown in Table 3. According to data of the single-factor analysis, a sensitivity analysis chart is shown in Figure 1.
Table 2. Orthogonal Result Range Analysis Table

| Level | Natural cohesion c′(kPa) | Natural friction angleφ° | Saturated cohesion c′(kPa) | Saturated friction angleφ° | Slope angle α° | Slope height h(m) | Angle between the tectonic line and shoreline θ(°) | Water level change ΔH(m) | Wave height d(m) |
|-------|--------------------------|--------------------------|----------------------------|-----------------------------|----------------|-------------------|---------------------------------|------------------------|----------------|
| 1     | 1.258                    | 1.111                    | 1.099                      | 1.121                       | 1.074          | 1.170             | 1.154                          | 1.133                  | 1.193          |
| 2     | 1.174                    | 1.198                    | 1.100                      | 1.076                       | 1.185          | 1.123             | 1.118                          | 1.121                  | 0.973          |
| 3     | 1.130                    | 1.160                    | 1.095                      | 1.237                       | 1.139          | 1.095             | 1.153                          | 1.070                  | 1.112          |
| 4     | 1.095                    | 1.074                    | 1.150                      | 1.109                       | 1.134          | 1.109             | 1.065                          | 1.196                  | 1.086          |
| 5     | 1.010                    | 1.075                    | 1.220                      | 1.093                       | 1.094          | 1.085             | 1.046                          | 1.130                  | 1.087          |
| 6     | 1.044                    | 1.124                    | 1.084                      | 1.112                       | 1.042          | 1.104             | 1.117                          | 1.049                  | 1.131          |
| 7     | 1.075                    | 1.077                    | 1.094                      | 1.102                       | 1.109          | 1.092             | 1.098                          | 1.067                  | 1.112          |
| 8     | 1.076                    | 1.030                    | 1.022                      | 1.093                       | 1.087          | 1.085             | 1.113                          | 1.127                  | 1.111          |
| Range | 0.248                    | 0.168                    | 0.178                      | 0.161                       | 0.143          | 0.085             | 0.108                          | 0.087                  | 0.220          |
| Order | 1                        | 5                        | 3                          | 4                           | 6              | 9                 | 7                              | 8                      | 2              |

Table 3. Table of Stability Coefficient for Single Factor Change

| Parameter change | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------------------|---|---|---|---|---|---|---|---|
| Natural cohesion c′(kPa) | (+20%) | (+15%) | (+10%) | (+5%) | (0%) | (-5%) | (-10%) | (-15%) |
| Stability factor | 1.621 | 1.598 | 1.536 | 1.478 | 1.413 | 1.348 | 1.287 | 1.231 |
| Natural friction angleφ° | (+20%) | (+15%) | (+10%) | (+5%) | (0%) | (-5%) | (-10%) | (-15%) |
| Stability factor | 1.512 | 1.498 | 1.465 | 1.432 | 1.398 | 1.365 | 1.333 | 1.306 |
| Saturated cohesion c′(kPa) | (+20%) | (+15%) | (+10%) | (+5%) | (0%) | (-5%) | (-10%) | (-15%) |
| Stability factor | 38.4 | 36.8 | 35.2 | 33.6 | 32.0 | 30.4 | 28.8 | 27.2 |
| Saturated friction angleφ° | (+20%) | (+15%) | (+10%) | (+5%) | (0%) | (-5%) | (-10%) | (-15%) |
| Stability factor | 1.475 | 1.458 | 1.425 | 1.396 | 1.365 | 1.332 | 1.298 | 1.272 |
| Slope angle α° | (+20%) | (+15%) | (+10%) | (+5%) | (0%) | (-5%) | (-10%) | (-15%) |
| Stability factor | 20.4 | 19.6 | 18.7 | 17.9 | 17 | 16.2 | 15.3 | 14.5 |
| Wave height d(m) | (+20%) | (+15%) | (+10%) | (+5%) | (0%) | (-5%) | (-10%) | (-15%) |
| Stability factor | 42 | 40.3 | 38.5 | 36.8 | 35 | 33.3 | 31.5 | 29.8 |

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It can be seen from Fig. 1 that the wave height and the natural cohesive force of the rock and soil masses are the main factors affecting bank collapse, while the others are secondary factors, but the sensitivity of each factor is similar.

Comparing the results obtained by single factor analysis with those of orthogonal analysis, it is found that the wave height and the natural cohesion of rock and soil masses of the bank slope are the main influencing factors, indicating that the sensitivity analysis of factors affecting slope stability by orthogonal design is reliable.

However, in the comparison of the sensitivity of other factors, the two methods are slightly different. The differences of the sensitivity of each factor in the orthogonal analysis are obvious, and the sensitivity of secondary factors of the single factor analysis is not easy to distinguish. Orthogonal analysis considers the simultaneous changes of various factors and is in line with reality. Therefore, the conclusions obtained by this method have certain reliability.

5. Conclusion
Based on the investigation on the collapsed bank of a reservoir, the Impact Factors of the loose bank slope of the valley reservoir are mainly the natural strength parameters of the rock and soil masses above the waterline (natural parameters of the soil: cohesion $c$ and friction angle $\phi$), saturated strength parameters below the waterline (saturated parameters of the soil: cohesion $c'$ and friction angle $\phi'$), bank slope gradient $\alpha$, slope height $h$, angle between the tectonic line and shoreline $\theta$, water level change $\Delta H$, and wave height $d$.

Based on an example of a bank slope in the reservoir, the sensitivity of the Impact Factors to the collapse of the loose bank slope of the valley reservoir is obtained by orthogonal analysis. The order is as follows: natural cohesion $c >$ wave height $d >$ saturated cohesion $c' >$ saturated friction angle $\phi' >$ natural friction angle $\phi >$ bank slope gradient $\alpha >$ angle between the tectonic line and shoreline $\theta >$ water level change $\Delta H >$ slope height $h$. Among them, the huge differences in the wave height $d$ and the natural cohesion $c$ are the main Impact Factors, which is consistent with the results of the single factor analysis.

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