Research on the Stability of Dam Foundation of a Sluice Dam Project in the Pearl River

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Abstract. In water conservancy projects, the safety and stability of sluice dams are worth exploring due to the fact that they are subject to a wide variety of loads and the physical and mechanical properties of the dam foundation are easily weakened. This paper focuses on the study of the stability of the foundation of a dam project on the Pearl River when the strength and deformation characteristics of the weak interlayer are weakened. Through geomechanical model tests, two methods of overloading and strength reduction are used to explore the stability of the dam foundation of the sluice dam. Whether the instability of the dam foundation of the sluice dam is deep sliding or shallow sliding, the deformation characteristics of weak interlayers in various parts under different overload multiples are explored. Tests show that only the weak interlayer at the surface is cracked and penetrated, and the deep weak interlayer is not obvious. It shows that when the weak interlayer and rock layer are weakened, only shallow damage occurs to the dam foundation and only targeted reinforcement measures are required. The research is not only critical to the safe operation of the sluice dam project, but also serves as a reference for other similar sluice projects.

1. Introduction

The Pearl River is a large river in the south, and its runoff length ranks third in China and its annual runoff is second only to the Yangtze River. The floods in the Pearl River Basin are characterized by peak height, large volume, and long duration, and are prone to flooding in summer due to heavy rain. As early as 1993, according to the characteristics of the Pearl River Basin, the State Council proposed that the flood control plan should adopt the principle of "combining dykes and reservoirs, with drainage as the main, and both storage and drainage". The Pearl River Basin is the main production area of grain and subtropical crops in China, with dense population on both sides of the river. Therefore, a number of water conservancy projects with comprehensive benefits such as flood control, water supply, hydropower, shipping, and irrigation have been built in the Pearl River Basin, such as Feilaixia, Changzhou, and Baise sluice dam projects¹⁻³. However, the foundation lithology of the Pearl River Basin is often dominated by fine sandstone, muddy fine sandstone and mudstone. Weak rock layers are interbedded and interlaced and complex, and muddy interlayers are developed. In addition, the thrust of the sluice dam is relatively large, and the structure is relatively thin. It is easy to cause sliding damage under adverse geological conditions, which poses a great threat to the safety of
people’s lives and properties along the coast and downstream. Therefore, it is necessary to study the foundation stability of these dam projects.

Geomechanical model test \([4]\) is a method to simulate the possible failure situation of actual project through model destruction, and there are many successful examples in the practice of water conservancy and hydropower engineering\([5-10]\). For the study on the stability of dam foundation in dam project, Yang Gengxin et al\([11]\) explored the stability of dam foundation of Danba Hydropower station by using two-dimensional geomechanical model test. Tang Maoying et al\([12]\) used geomechanical model tests to explore the effect of deep overburden on the overall stability of high dam dams. The geomechanical model test uses materials with high bulk density, low strength and low deformation modulus, which can better simulate the actual situation of the dam foundation under the action of water and sand load, temperature load, seepage water pressure, seismic load and other forces. The overload method, strength reserve method or comprehensive method to explore the failure process and destruction form of the model, so as to reasonably simulate the possible status of the prototype and make a safety assessment of stability.

The sliding instability of dam and dam is usually divided into three kinds: sliding along the dam foundation, shallow sliding and deep sliding. The geological conditions of the dam are complex, with multiple weak interlayers in the rock mass, alternating staggered soft and hard rocks, and complex structural fissures of the dam. These adverse geological conditions affect the stability of the dam, as well as the dam failure process and form waiting for further research. In this paper, the comprehensive method of geomechanical model test is used to test the dam foundation of the typical dam section with the most unfavorable geological conditions. The displacement characteristics of the sluice foundation in the normal condition, the strength reduction phase and the overload phase are obtained, and the damage process and the damage form of the foundation are proved. The research results can provide a scientific basis for the foundation treatment.

2. Geological conditions

The sluice dam project, located at the Qianjiang section of the Pearl River Basin, is the last step in the cascade plan of the Hongshui River. The project is for comprehensive utilization of flood control, navigation, power generation, water supply, reducing salinity, and irrigation. The normal water storage level of the project is 61.00m, and the installed capacity of the power station is 1600MW. The main dam is a concrete dam dam with a maximum height of 80 and a length of 1243m.

Figure 1. Geological profile of typical dam section
The geological conditions of dam foundation are complex (as shown in Figure 1), with the following characteristics: (1) The dam foundation rocks are lower Devonian Lianhuashan formation, Nagaoling Formation (D1n11-7~D1n13-3) and Yujiangian nearshore and littoral neritic sedimentary rocks (D1y1-1~D1y1-3). The lithology is mainly fine sandstone, muddy fine sandstone, argillaceous siltstone and mudstone. The interbedding and interlacing changes of soft and hard rocks are complex. (2) Weak interlayers and faults are developed and have good continuity. The occurrence of weak interlayers is basically the same as that of rock layers. The faults are steeply inclined, and the rock mass of the dam foundation is easy to form a complete failure along the layer or weak interlayer. (3) The complex structural fracture system exists in the dam foundation rock mass, which greatly reduces the integrity of the rock mass under the influence of multi-period tectonic movement, and the lower shear strength parameter also provides the possibility for the integrity failure of the rock mass. (4) The dam site is mainly exposed from the 11th to 13th layers of the Nagaoling Formation, with muddy interlayers developed, and the rock strata is inclined to the left bank on the downstream. Due to the development of the soft interlayer, and the occurrence of the soft interlayer is basically consistent with the occurrence of the rock layer, the slip failure of the dam foundation is easy to occur. The main physical and mechanical parameters of the dam foundation rock mass are illustrated in Table 1 and 2.

### Table 1. Geological parameters of the weak interlayer

| Structural plane | Shear (break) strength | Deformation modulus/GPa |
|------------------|------------------------|-------------------------|
|                  | \( f' \) | \( c / \text{MPa} \) | \( f \) |
| D1n11-7          | 0.26   | 0.015                 | 0.25 |
| D1n13-1~D1n13-3  | 0.28   | 0.02                  | 0.26 |
| D1y1-1           | 0.32   | 0.04                  | 0.26 |
| D1y1-2           | 0.3    | 0.03                  | 0.24 |

The sluice dam have 11 sections. Among these 11 dam sections, the typical dam section selected in this article has certain particularities, that is, the dam foundation rock body near the sluice dam is jointed and cracked. The large size and a considerable proportion of joint cracks are parallel to the axis of the sluice dam. These structures play a controlling role in the stability of the dam foundation rock mass, which is easy to constitute an outlet for the destruction of the dam foundation rock mass. Therefore, it is necessary to study the stability of the dam foundation.

### Table 2. Mechanical parameters of rock formation

| Number | Weathered state | Density g/cm³ | Rock/Concrete Modulus GPa | Rock/Rock Modulus GPa | Deformation modulus GPa | Elastic Modulus GPa | Poisson's ratio |
|--------|------------------|---------------|---------------------------|-----------------------|------------------------|---------------------|-----------------|
| D1y1-3 | Weak weathered   | 2.82          | 0.92                      | 0.76                  | 0.55 0.86 0.82 0.60 | 5 8 0.28            |
| D1y1-2 | Slightly weathered | 2.82         | 0.94                      | 0.78                  | 0.57 0.88 0.85 0.62 | 8 12 0.26          |
| D1y1-1 | Slightly weathered | 2.79         | 0.90                      | 0.75                  | 0.55 0.85 0.80 0.60 | 5 8 0.28            |
| D1n12  | Slightly weathered | 2.77         | 0.87                      | 0.72                  | 0.53 0.81 0.79 0.58 | 3 4 0.32            |
| D1n13  | Slightly weathered | 2.75         | 0.91                      | 0.75                  | 0.55 0.85 0.82 0.60 | 3 4 0.28            |
| D1n14  | Slightly weathered | 2.79         | 0.97                      | 0.84                  | 0.58 0.94 0.97 0.63 | 5 8 0.26            |
3. Geomechanical model test

3.1 Test method and model similarity

Geomechanical model test belongs to nonlinear failure test. There are three methods of failure test, namely overload method, strength reserve method and comprehensive method. The three methods study the safety degree and stability of dam and its foundation from different angles: ① The overloading method takes into account the impact of possible flooding on the bearing capacity of the dam foundation. On the premise of keeping the mechanical parameters of the rock mass of the dam foundation unchanged, the upstream load is gradually increased until the whole failure and instability of the dam and the foundation. ② The strength reserve method takes into account the adverse effects of the gradual reduction of rock mass and soft structural surface parameters on the stability of the dam foundation during the long-term operation of the project. ③ The comprehensive synthesis method is the combination of the overload method and the strength reserve method, taking into account the advantages of the former two methods. The comprehensive method not only considers the influence of overloading factors, but also considers the mechanical behavior of weakening strength parameters, which is more in line with the engineering practice. Therefore, this paper adopts the comprehensive method to carry out geomechanical test analysis.

This test uses a comprehensive method of combining strength reduction and overloading. Under normal conditions, the shear strength of the six weak interlayers on the dam foundation is reduced by about 10%. On this basis, the upstream water load is classified into overload until the overall failure of the foundation occurs, and the deformation and failure modes of the foundation are observed under all levels of load. Before the overload factor is 4.0, the overload step size is increased by 0.2P₀ (P₀ is the water load under normal working conditions), and after 4.0P₀, the overload is carried out in steps of 0.3P₀~0.4P₀.

The geomechanical model test needs to meet the similar conditions of failure test: \( C_B = C_\gamma \times C_L \), \( C_\mu = 1 \), \( C_e = 1 \), \( C_f = 1 \), \( C_a = C_B = C_\gamma = C_L = C_\mu = C_e \), \( C_F = C_\gamma \times C_L^3 = C_B \times C_L^2 \). When \( C_\gamma = 1 \), there are \( C_B = C_L \), \( C_F = C_L^3 \), where \( C_B \), \( C_\gamma \), \( C_L \), \( C_a \), \( C_F \), \( C_\gamma \), \( C_\mu \), \( C_e \) and \( C_f \) are the similarity factors of Young's modulus, unit weight, geometry, stress or strength, force, cohesion, Poisson's ratio, strain and friction factor. According to the characteristics and test task requirements of typical dam section, combined with comprehensive analysis of test site scale and test accuracy requirements, the geometric scale \( C_L = 100 \) of the model was determined. Other similar relationships are variable-modulus ratios: \( C_B = 100 \), \( C_\gamma = 1 \), \( C_F = 100^3 \), \( C_f = 1 \), \( C_\gamma = 100 \), \( C_\mu = 1 \), \( C_e = 1 \).

3.2 Simulation range

The simulation range of the three-dimensional model of the dam section is mainly based on the comprehensive analysis of the topographic characteristics of the typical dam section, the main geological structure characteristics of the dam foundation and the test task requirements. The model simulation range is determined to be 2.15m×0.303m×1.26m (vertical×horizontal×height), which is equivalent in the prototype project 215m×30.3m×126m range.

4. Analysis of foundation deformation and failure characteristics

4.1 Dam foundation displacement

Under normal working conditions, the displacement of each measurement point of the dam foundation along the river: the foundation displacement close to the section of the dam toe is the largest, and the foundation displacement to the upstream and downstream decreases gradually. This law is mainly determined by the force characteristics of the dam and the dam. Under the action of the upstream water load and the dead weight load, the section of the dam toe bears the greatest pressure, and the load on the upstream and downstream is gradually reduced. Vertical displacement: The displacement values of the weak interlayers R9 and R14 with relatively deep buried depth are small, and the
displacement values are only 1mm~2mm under normal working conditions, while the weak interlayers R17, R18, R17, R18. The displacement values of R19 and R20 are relatively large, especially the maximum displacement value of R17 and R18 near the exposed part of the dam toe reaches -12mm. It can be seen that, under normal working conditions, the soft and gentle interlayer of the shallow surface layer has a certain influence on the working behavior of the dam and dam.

In the strength reduction stage, the displacement of the measuring points can be obtained: (1) During the process of heating and decreasing strength of the 6 weak interlayers of the dam foundation, the displacement value of the dam foundation increases to a certain extent, and the settlement displacement value increases more than changes along the river direction. The position is large (the maximum displacement of each weak interlayer along the river is 4mm, and the average settlement displacement is 6~12mm), indicating that the reduction of the shear strength of the weak interlayer of the dam foundation has a more obvious impact on the vertical displacement. This is because The decrease in shear strength reduces the anti-sliding stability, and it is easier to slide along the interlayer under the action of water load. (2) Compared with the normal working conditions, on the same weak interlayer, the settlement displacement of most of the measuring points shows that the displacement value of the measuring point on the hanging wall is greater than that of the measuring point on the bottom wall, that is, the slip ratio of the upper part of the weak interlayer. The lower layer is large, indicating that the foundation starts to slip to a certain extent along the weak interlayer. (3) Relatively speaking, the settlement displacement values of weak interlayers R17, R18, R19, R20 with shallow depth increase more obviously, indicating that the vertical displacement of the weak interlayers in the shallow surface is more likely to be affected by the strength of the dam foundation. Reduced impact. On the whole, the decrease in the strength of the weak interlayer of the dam foundation, especially the weak interlayer with a shallow depth of the dam foundation, has a significant impact on the deformation and stability of the dam and the foundation. This article lists the more representative R9 and R17 weak interlayer deformation curves at the strength reduction stage as shown in Figure 2 and 3(where R9 is at the heel of the upstream dam and R17 is at the toe of the downstream dam).

Figure 2(a) $K_s$-$\delta_v$ of the weak interlayer R9

Figure 2(b) $K_s$-$\delta_H$ of weak interlayer R9
In the overload stage, the relationship between the surface displacement of the weak interlayer of the dam foundation R9 and R17 and the overload coefficient $K_P$ is shown in Figure 4. It can be seen from the displacement curve that when the overload coefficient $K_P=1.8$, the displacement curve of most of the measuring points has a certain fluctuation phenomenon, especially the surface displacement measuring points in the shallow layer, the fluctuation phenomenon is more obvious, indicating that with the load The increase of the dam foundation has a certain displacement adjustment. For example, the vertical displacement measurement points 34# and 35# on the weak interlayer of R9 also have obvious fluctuations (Figure 4a); when $K_P=2.0\sim2.8$, most of the measurement points The displacement of the dam is increasing steadily, and the displacement of the part of the dam foundation near the dam heel appears to be reversed. For example, when $K_P=2.2$, the displacement of R9 measuring point 33# changes from the original downstream displacement to upstream displacement from the original downstream displacement at $K_P=2.2$. (Figure 4b), when $K_P=2.4$, the displacement of measuring points 34# and 35# reversed from the original vertical settlement displacement to the upward displacement (Figure 4a), indicating that as the load increases, the sluice dam Under the combined force of water load and dead weight, the dam toe is squeezed and displaced downstream, and the heel area is slightly uplifted and displaced upstream; when $K_P=3.0\sim3.6$, most of the dam foundation is measured. The displacement curve of the point has fluctuated again, and the displacement value of most of the measuring points in the dam toe area has been large, especially the vertical settlement displacement. For example, the settlement displacement of the 63# measuring point of R17 has reached -28mm--34mm (Figure 5a), indicating that most areas of the dam foundation have entered yield deformation, and then the displacement of most of the measurement points of the dam foundation increases rapidly; when $K_P>5.0$, the displacement of most of the measurement points of the dam foundation, especially the surface layer is weak The displacement of the interlayer fluctuates greatly, the displacement is unstable, and the displacement value is large. When $K_P=8.5$, the displacement of each weak interlayer is larger, and the dam foundation appear to slide along the shallow surface of the foundation and lose stability.
4.2 Model failure form

The weak interlayers R9 and R14 located in the upstream dam heel area are the first to crack. This is because the shallow surface of R14 and R9 is located in the tension area, and stress concentration is prone to occur here under the action of upstream water load; and after passing the front The strength reduction treatment reduces the shear strength of weak structural surfaces by 10%; at the same time, due to the limitation of model tests, there is no simulation of the vertical water pressure of the upstream cover and the reservoir water on the bedrock, and the upstream dam lacks the constraints of both the first crack in the heel is in line with reality. With the increase of the overload multiple, compressive shear failure occurs in the downstream dam toe, and then the cracks in the dam heel and dam toe area continue to develop into joint cracks with weaker shear strength. Eventually, a failure zone is formed in the upstream, step failure in the downstream, and cracks in the upstream and downstream areas. They are not connected to each other. Although the contact surface between the dam chamber and the dam foundation at the heel of the dam was damaged to a certain extent during the overload process, it did not completely shear failure with the increase of the overload multiple, so the danger of sliding along the dam foundation did not appear. At the same time, the upstream and downstream damage zones are not connected, so there will be no deep damage. In the process of failure, the displacement of the measuring point in the shallow surface of the weak structural surface is much larger than that of the measuring point with a larger buried depth, and the cracks mainly appear in the weakened areas of the joints and cracks in the shallow surface. This shows that the stress redistribution of the shallow dam foundation under the action of water load, it can be considered that the shallow part of the weak interlayer such as R9, R14, R17, R19 plays a controlling role in the stability of the dam foundation.
4.3 Evaluation of stability safety

Comprehensive stability safety factor $K_{SC}$, namely:

$$K_{SC} = K'_{S} \times K'_{P}$$

According to the analysis of the failure process, it is obtained that the strength reserve factor of this test $K'_{S} = 1.1$ and the overload factor $K'_{P} = 3.0 \sim 3.6$, then the comprehensive stability safety factor:

$$K_{SC} = K'_{S} \times K'_{P} = 1.1 \times (3.0 \sim 3.6) = 3.3 \sim 4.0$$

That is, the overall comprehensive stability and safety $K_{SC}$ value of the dam section is 3.3 to 4.0. Generally speaking, since the upstream dam heel area is easier to damage, a triangular damage area will be formed when the overload multiple is large. It is recommended that the actual project should be combined with the existing engineering measures to properly deal with the serious upstream dam heel cracking damage area and the weak interlayer R14, R9. Reinforcement treatment. The downstream dam toe area and the apron are severely cracked and damaged, and sufficient attention should be paid to it. It is recommended that the severely damaged area and the weak interlayer R17 and R18 of the $D_{1n13-3}$ rock formation, and the weak interlayer R19 of the $D_{1Y1-1}$ rock formation be reinforced. The treatment method can adopt reinforcement measures such as excavation and backfilling, consolidation grouting, and anchor rods.

5. Conclusions

(1) In this paper, a comprehensive method of combining strength reduction and overloading is used to conduct a destructive test study on the overall stability of the dam foundation under the weakened structural surface. Under normal conditions, the shear strength parameters of the 6 weak interlayers that affect the overall stability of the dam foundation are reduced by about 10%, and then the upstream water load is gradually overloaded until it fails and becomes unstable. The test shows that the composite method test strength reduction coefficient of the dam dam and the foundation of the dam section $K'_{S} = 1.1$, and the overload factor during large deformation $K'_{P} = 3.0 \sim 3.6$, then the comprehensive method test safety factor is $K_{SC} = K'_{S} \times K'_{P} = 1.1 \times (3.0 \sim 3.6)$, namely $K_{SC} = 3.3 \sim 4.0$, the overall stability of the dam and the foundation is good.

(2) Under normal working conditions, the displacement value of the dam base is small; in the phase of strength reduction, due to the weakening of the strength parameter, the displacement value of the foundation increases, but the increase is not large; in the overload phase, it varies with the overload multiple. The increase in dam foundation is affected by the weak interlayer, and the vertical displacement is slightly larger than that along the river, and the settlement displacement is the main one. The weak interlayer R9 and R14 at the upstream dam toe first appeared micro-cracks, and finally the rock mass fissures between the upper part of the weak interlayer R9 and the boundary line of $D_{1n13-2}$ and $D_{1n13-3}$ basically penetrated, forming a triangular failure zone; downstream dam toe area Compression-shear failure occurs along the weak interlayer R17, and finally penetrates R19 to form a step failure. It can be considered that the shallow part of the weak interlayers R9, R14, R17, R19 and other weak interlayers control the stability of the dam foundation, and the cracks do not penetrate each other between the upstream and downstream, so the failure mode of the dam foundation of the sluice dam is shallow cracking.

(3) Evaluation of dam foundation safety and suggestions: Due to the dense cracks in the upstream dam heel area, triangular-shaped area damage is likely to form under high overload multiples, it is recommended that the upstream dam heel cracking and damage serious areas and weak interlayers R14 and R9 should be treated in actual projects. Carry out appropriate reinforcement treatment. However, the weak interlayers R17, R18, and R19 in the downstream dam toe area are severely cracked and penetrated to the apron, forming a step-shaped failure, which should be paid enough attention. It is recommended that the weak interlayers R17, R18, and $D_{1Y1-1}$ in the severely damaged area and the $D_{1n13-3}$ rock formation should be taken seriously. The weak interlayer R19 of the rock
formation is reinforced. The treatment method can adopt reinforcement measures such as excavation and backfilling, consolidation grouting, and anchor rods.

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