Study on the Reinforcement Mechanism of the Deep Replacement Caverns for the Giant Slope Block Combined by Structural Planes

Daoping Lai 1*, Jianrong Xu1, Guanye Wu1 and Yuan Chen2

1 Powerchina Huadong Engineering Corporation Limited, Hangzhou, Zhejiang, 311122, China
2 Sichuan University, Chengdu, Sichuan, 610065, China
*Corresponding author’s e-mail: lai_dp@ecidi.com

Abstract. The left bank of the cushion pond of Baihetan hydropower station is a slant and dip slope. The gently inclined intra-layer fault zones, the steep-dip faults and the unloading fissures cutting the slope to form several potentially unstable blocks. The computational results show that the stabilities of the blocks are controlled by inclined intra-layer fault zones. A method of treatment applying deep replacement caverns and load-reduction excavation was proposed to reinforce the unstable blocks. In order to study the reinforcement mechanism of the deep replacement caverns for the giant slope blocks controlled by inclined intra-layer fault zones, the 3D simulation analysis of the slope treatment construction was carried out by use of FLAC3D software, and a 3D geo-mechanical model was developed to carry out experimental research. The results of the calculation and experiment show that the deep concrete replacement caverns effectively control the shear and sliding deformation of the bottom slide surface and improve the stability of the blocks combined by structural surfaces. In the process of slope strength reduction and overloading, the slope deformation and cracking are gradually extended from the surface to the inner part, and shear stresses of the front deep replacement cavern are the largest of all the caverns. Therefore, it is more beneficial to control the deformation of the slope and improve the stability of the giant blocks by increasing the size of the front deep replacement cavern. The research results have important guiding significance for the reinforcement treatment of the giant blocks in the left bank of Baihetan cushion pond and similar projects.

1. Introduction

The gently inclined structural plane is often controlling the stability of high rock slope. The left bank of the cushion pond of Baihetan hydropower station is a slant and dip slope. Due to the construction of basalt eruption cycle and the reconstruction of river valley in the later stage, many gently inclined interlayer dislocation zones developed in the slope, which are cut and combined with steep dip faults and long unloading fractures, forming a huge potential unstable block system. The stability and treatment of structural plane combination block is one of the main technical problems of Baihetan hydropower station. Due to the large scale of the block, it is difficult to make the stability of the slope block meet the design requirements by excavation load reduction and prestressed anchor cable anchorage. By studies using the three-dimensional rigid body limit method [1], it is found that the stability of the slope block can be significantly improved by increasing the shear strength of the gently inclined structural plane. However, the rigid limit equilibrium method can only simulate the equivalent
reinforcement effect of the replacement holes. In recent years, some scholars have paid attention to and carried out the research on the deep reinforcement measures and their effects of some slopes [2-5]. However, there is no work published on the mechanism of deep replacement caverns for giant blocks combined with structural surfaces.

In order to study the reinforcement mechanism of the deep replacement caverns and guide the design of the project, the numerical analysis method and geo-mechanical model method are applied to carry out the research.

The research and application of finite element method, discrete element method, block element method and numerical manifold method in slope deformation and stability have been developed deeply, which can simulate the initial stress condition and construction process of slope. Among them, FLAC3D program based on finite difference method can be used to solve large deformation problems. The comparative studies by applying strength reduction methods of various software to calculate slope stability show that the analysis results of FLAC3D program are reasonable [6]. Therefore, this method is selected to study the reinforcement mechanism of the deep replacement caverns.

Geo-mechanical model test method has been an important means to study the stability and deformation failure mechanism of complex high slopes because it can accurately simulate complex geological structures and structural planes, and effectively reflect the engineering characteristics of rock mass such as multi-element structure, non-elasticity and discontinuity [7-11]. A three-dimensional geo-mechanical model is developed to study the stability of the slope and the mechanism of the deep replacement caverns.

2. Characteristics and treatment scheme of left bank slope of Baihetan

Baihetan Hydropower Station is located in the lower reaches of Jinsha River, with an installed capacity of 16000 MW, which is one of the backbone power supply points for the West-East power transmission. The power station is composed of barrage, flood discharge and energy dissipation facilities, water-draining power generation system and other main structures. The dam is a concrete double curvature arch dam with a crest elevation of 834m and a maximum dam height of 289m.

2.1. Characteristics and stability evaluation of the complex giant block of slope

The left bank above the valley shoulder of Baihetan Hydropower Station is characterized by slope topography. The comprehensive terrain slope below the valley shoulder on the left bank is about 42 ° and the natural slope height below the valley shoulder on the left bank is 600 ~ 950 m. The left bank slope is mainly composed of basalt (P₂βδ, P₂β3, P₂β4) of the upper Permian Emeishan formation, which is monoclinic structure. The occurrence of the rock flow layer is N40 ~ 50 °E, SE ∠15 ~ 20 ° and inclines to the right bank upstream. The intersection angle of the rock stratum strike and the river flow direction is about 45° oblique, so the slope belongs to the oblique and consequent slope. The interlayer fault zones are formed by intermittent eruption of basalt. The interlayer fault zones C3,1 and C3 are developed in the middle and upper part of the left bank slope. At the same time, the intra-layer fault zones are developed, with unstable properties and poor continuity. The largest intra-layer fault zone is LS337, which has poor strength and wide distribution range. The dip angle of LS337 is up to 30 ° at some location and it plays an important role in controlling the stability of the left bank slope. Many fault structures developed in the left bank slope. Among them, the NW trending faults with large scale and controlling effect on the development of the bank slope include F₁₃, f₁₁₄, F₁₄, F₁₆, F₃₃, f₁₀₈.

The unloading cracks on the left bank slope are mainly tension cracks, and there are 15 unloading cracks with width greater than 10 cm. Strike direction of the long and large unloading fissures in the slope is mainly NS direction, which is basically parallel to the river flow direction. Among them, J₁₁₀ has the largest scale, 5~30cm in width, 165m in extension length, and 106m in maximum horizontal distance from the slope surface, which is connected by several en echelon tension cracks.

The structural planes of Baihetan left bank slope cut each other, forming the complex blocks, which are composed of interlayer and intralayer fault zones as the bottom sliding surface, steep dip faults or fissures as the side slip surface, and large and long unloading fissures as the posterior edge tension
fracture surface. The distribution of typical blocks combined by structural planes is shown in figure 1, and the boundaries of the blocks and their mechanical parameters are shown in Table 1.

| Slope block No. | Discontinuities boundaries | Discontinuity No. | E (GPa) | f′c (MPa) |
|----------------|----------------------------|-------------------|--------|----------|
| 1#             | Bottom Surface: LS337, Rear Fissure: J110, Side Surface: f114 | C3-1             | 0.20   | 0.35     | 0.04    |
| 1-1#           | Bottom Surface: LS337, Rear Fissure: J110, J139, Side Surface: f114 | LS337            | 0.20   | 0.38     | 0.07    |
| 2#             | Bottom Surface: LS337, Rear Fissure: F133, Side Fissure: J139 | f114             | 0.25   | 0.50     | 0.10    |
| 3#             | Bottom Surface: LS337 (LS3312), Rear Fissure: F33, Side Fissure: f120 | f320             | 0.15   | 0.45     | 0.10    |
| 4-1#           | Bottom Surface: C3-1, Rear Fissure: f101 (J101), Side Surface: f114 | f101             | 0.10   | 0.25     | 0       |
|                |                            | F33              | 0.25   | 0.45     | 0.10    |

The study results by applying the 3-D rigid body limit equilibrium method and numerical show that the bottom sliding surface LS337 plays a major role in controlling the stability of slope block, and the stability safety factors of block 1# (including 1-1#) and block 2# of natural slope are relatively low, and reinforcement measures should be taken.

2.2. Reinforcement scheme

Comprehensive treatment measures such as concrete replacement, excavation load reduction, anchoring, drainage and slope surface protection are adopted to improve the overall safety of the slope. The stability enhancement measures of the giant block are mainly the deep replacement treatment for the bottom sliding surface of the intra-layer sheared zone LS337 and the excavation load reduction combined with the construction layout, as shown in figure 2. Nine deep concrete replacement caverns with different elevation along LS337 are arranged for reinforcement treatment, which is implemented in two phases. In the first stage, there are 5 replacement caverns, No. 1-1~1-5, with section size of 3m × 3.5m (width × height) and length of 100m ~ 130m; in phase II, there are 4 replacement caverns, No. 2-1 ~ 2-4, with section sizes of 6m × 6m and 8m × 6m (width × height), with length of 60m ~ 130m. C30 concrete is used for replacement caverns. After the implementation of phase I replacement caverns, excavation and load reduction will be carried out, and finally phase II replacement caverns will be implemented.

The design requires that the deep treatment of replacement caverns play an important role in slope stability enhancement. Therefore, it is necessary to study the reinforcement mechanism of replacement treatment caverns to guide the design of the project.

Figure 1. Plan of slope blocks on Baihetan left bank  Figure 2. Typical section of the left slope
3. Numerical simulation of the replacement caverns

3.1. Numerical calculation model and simulation method

FLAC$^3$D program is used for numerical simulation. FLAC$^3$D program uses the fast Lagrangian method, based on the explicit difference method to solve the motion equation and dynamic equation. It transforms a static problem into a quasi-dynamic problem, which is suitable for solving nonlinear large deformation problems.

The calculation model includes the engineering slope between F14 and f320. The structural planes simulated in the calculation model include: interlayer fault zone C3-1, intra-layer sheared zone LS337, faults F14, f114, f101, f102, unloading fractures J110, J101, J130, J139, J106, J115, J136, and J134. Thin layer elements are used to simulate faults, inter- and intra-layer sheared zones and unloading fractures. The rock mass is mainly modelled of hexahedral elements, a few of degenerated hexahedron elements. A thin layer element is set up between the concrete and the rock mass to simulate the tension and shear yield state between the concrete and the rock mass. The main grid structure and model of the replacement caverns are shown in figure 3 and figure 4.

In order to evaluate the reinforcement mechanism of the replacement treatment caverns and simulate the construction process of the slope, the first step is to calculate the initial stress of the natural slope, the second step is to simulate the excavation and concrete backfill of the first stage replacement treatment caverns, the third step is to simulate the excavation and load reduction of the slope, and the fourth step is to simulate the excavation and concrete backfill of the second stage replacement caverns. Then, the strength reduction method is used to analyze the deformation of the slope blocks and the mechanical characteristics of the replacement caverns.

The strength grade of replacement caverns concrete is C30. The shear strength parameters of concrete are determined by two parameter yield criterion, and appropriate reduction is made. The strength of replacement concrete is determined as $c=2\text{MPa}$, $f=1.4$. The shear strength parameters of the interface between concrete and rock mass surrounding the tunnel are obtained by shear tests, which are $c=1.05\text{MPa}$, $f=1.05$.

The initial strength parameters of rock mass and structural plane are shown in Table 2.

3.2. Analysis of stress and deformation characteristics of the replacement caverns

3.2.1. Stress and deformation characteristics of the excavated slope and phase I replacement caverns

After excavation load-reduction, the $x$-direction displacement distribution of block 1-1# is shown in figure 5. The surface displacements are toward the river overall. The displacements are between $-0.32\text{cm} \sim 2.78\text{cm}$, and the maximum displacement toward the river occurs at the front-end of block 1-1#. The results show that the maximum principal compressive stresses and the maximum principal tensile stresses of the five phase I replacement caverns are $-18.586\text{MPa} \sim -3.622\text{MPa}$ and $1.471\text{MPa}$.
~ 1.520 MPa respectively; the unit area tangential stress of replacement cavern 1-1 is 2.612 MPa, and those of replacement caverns 1-2 ~ 1-5 are 0.609 MPa ~ 0.878 MPa.

3.2.2. Mechanical characteristics of the replacement caverns during slope strength reduction

The shear strength parameters of block structural planes, replacement cavern concrete and its surrounding interface are reduced. The strength reduction ratio $K$ is 1.00 ~ 2.00. When $k$ is 1.5, the change rate of slope displacement increases obviously, and the percentage of yield area of LS337 and replacement cavern concrete increases obviously, as shown in figure 7 and figure 8. The yield zone of LS337 is over 90%.

In general, the shear stresses of the phase I and II replacement caverns decrease gradually from upstream to downstream, as shown in figure 6. The tangential forces per unit area of the replacement caverns 1-1 ~ 1-5 are 4.851 MPa, 2.341 MPa, 2.214 MPa, 1.657 MPa and 1.628 MPa, respectively. The tangential forces per unit area of replacement caverns 2-1 and 2-2 are 1.287 MPa and 0.943 MPa respectively.

The mechanical characteristics of the replacement caverns show that they play a significant role in shear resistance and sliding resistance. The concrete of the replacement caverns is bonded with the rock mass of LS337 upper and lower wall, which does not affect the shear performance of the replacement cavern concrete.

3.3. Reinforcement mechanism of the replacement caverns and suggestions to improve their effects

The replacement treatment caverns for LS337 can significantly improve the stability of the slope. The stresses of the replacement caverns increase obviously during the excavation of cushion pond slope, especially the mean shear stress of replacement cavern 1-1 exceeds 2MPa. The strength reduction analysis of the design slope shows that except for the replacement cavern 1-1, the normal stress of the
replacement hole appears tensile stress, that is, the concrete is in the tensile-shear state. However, when the concrete of the replacement caverns yields in a large range, the yield ratio of the contact surface between the replacement caverns and the bedrock is small. It can be seen that the deep replacement cavern can improve the shear resistance of the bottom surface of the block.

According to the mechanical characteristics of the replacement caverns, it is suggested to increase the size of replacement cavern 1-1 appropriately. The shear stress of replacement cavern 1-1 is high, and it is in the compression shear state, and the stress condition is good. Increasing the section of replacement cavern 1-1 is more conducive to the reinforcement effect.

4. Geo-mechanical model study on reinforcement mechanism of the replacement caverns

A three-dimensional geo-mechanical model is developed to simulate the design slope with the main faults, inter- and intra-layer sheared zones, unloading fractures and other geological structures that affect the slope stability, as well as the reinforcement measures of deep concrete replacement caverns. The comprehensive method of strength reduction and overloading is applied to study the effect of deep treatment caverns on limiting deformation of the blocks combined by structural planes and improving their stability safety factors.

4.1. Geo-mechanical model design and test method

(1) Comprehensive method of geo-mechanical model test

The comprehensive method of geo-mechanical model test is adopted in this test, which is the combination of strength reduction method and overloading method. Firstly, the mechanical parameters of weak structural planes are reduced to a certain multiple. Under the condition of keeping the mechanical parameters unchanged, the steel frame is gradually lifted until the slope is overloaded to damage. The safety factor obtained is called the comprehensive safety factor. The comprehensive safety factor \( K_{SC} \) is the product of strength reduction coefficient \( K'_{S} \) and overloading coefficient \( K'_{P} \) when failure of the slope occurs.

(2) Model design and production

Geo-mechanical model test belongs to nonlinear failure test, which must meet the requirements of geometric similarity, stress-strain relationship similarity, shear strength similarity of structural planes and load similarity.

The main similarity coefficients used in this model test are as follows: geometric similarity coefficient \( C_{L}=200 \), deformation modulus similarity coefficient \( C_{E}=200 \), bulk density similarity coefficient \( C_{\gamma}=1 \), stress similarity coefficient \( C_{\sigma}=C_{\tau}=200 \), friction coefficient \( C_{f}=1 \), cohesion similarity coefficient \( C_{c}=200 \), Poisson's ratio similarity coefficient \( C_{\mu}=1 \), and strain similarity coefficient \( C_{\varepsilon}=1 \). The simulation scope of the 3D model is mainly based on the geography characteristics of the left bank slope, the structural characteristics of the weak structural planes and the requirements of the test task. The scope of the model is limited to meet the requirements that the sliding deformation of the slope rock mass will not be affected by the boundary constraint during the test. The 3D geo-mechanical model covers the slope area of the block systems on the left bank. The width is 540m from the toe of the bank slope to the inside of the mountain, and the length between fault F14 and fault F13 is 530m along the river. The bottom elevation of the model is 550.00 m, and the top elevation is 1050.00 m. The size of the test model is 2.7m×2.65m×2.5m (width×length ×height).

(3) Testing process

The program of the 3D model slope test is divided into two stages: strength reduction and overloading test. The shear strength of the main structural planes is reduced by 1.2 times (1 to 18 test steps) by heating up. In the overloading stage, the inclined overload was carried out under the condition of keeping the strength parameters of the structural planes reduced by 1.2 times. The steel frame of each overload step was inclined to 0.5° until the overall instability of the slope appeared. There were 16 test steps (19 to 34 test steps) in the overloading stage.
4.2. Analysis of test results on reinforcement mechanism of treatment caverns

The treatment measures of concrete replacement caverns have excellent effect on controlling slope deformation and improving slope stability, and the reinforcement effects are mainly manifested in the following aspects:

(1) They can enhance the shear resistance of the bottom sliding surface, delay the cracking and its propagation of the structural planes and reduce the damage degree of the rock mass. According to the failure development process of slope model, LS337 starts to crack in the unreinforced area of the front edge when the model cracks, and the failure range is smaller than that of C3-1. With the decrease of the shear strength of the structural planes, the cracks continue to extend along the structural planes. Because there are several concrete replacement caverns on the LS337 intra-layer, the crack propagation speed of LS337 is significantly slower than that of C3-1. At the end of the strength reduction test stage, C3-1, F33, f320, and J101 have a wide range of cracks along the structural planes, as shown in figure 9. Among them, C3-1 cracks have penetrated in the range of F14~f320, while LS337 only cracks at the front edge of block 1-1# and its intersection with f320, and the cracking range is obviously smaller than that of other structural planes. In the final failure stage (figure 10), in addition to cracking failure along the structural planes, the rock mass in the unreinforced area at the back edge of the slope and the downstream side has dense cracks on the surface and has a tendency to collapse for serious damage. There are less cracks on the surface of block 1-1# with 7 replacement caverns arranged at the front part of the slope. The rock mass of block 1-1# has only local cracking nearby LS337 and C3-1 structural planes, and the damage degree of rock mass is obviously reduced compared with other areas. The failure process and failure mode of the model show that the concrete replacement caverns can effectively improve the anti-sliding capacity of LS337, delay the crack propagation and reduce the damage degree of the key block 1-1#.

Figure 9. Damage morphology of model in strength decrease stage
Figure 10. Eventually damage morphology of model

(2) The deformation of rock mass in the reinforcement area is obviously limited, and the slope stability is effectively improved. According to the distribution characteristics of the surface displacement near the structural planes and the internal relative displacement of the structural planes, the displacements of the downstream rock mass and the unreinforced area are relatively large. The concrete replacement caverns on LS337 structural plane can effectively reduce the deformation of the rock mass, and the displacement of the measuring points in the reinforced area is obviously smaller than that in the unreinforced area. According to the internal relative displacement distribution of LS337 structural plane, as shown in figure 11, the measuring points 12# and 15# with large displacement are located at the front edge of block 1-1# and the rear edge of block 2#, while the displacements of 13# and 14# measuring points located between replacement caverns are smaller. In addition, according to the surface displacement curves of the exposed LS337 and C3-1 structural planes, as shown in figure 12 and figure 13, the surface displacement of the reinforced
LS$_{337}$ is significantly less than that of the C$_{3-1}$ in the strength reduction stage and overloading stage. Therefore, the concrete replacement caverns on LS$_{337}$ structural plane can effectively reduce the rock mass deformation in the reinforced area, reduce the sliding displacement of the key block 1-1# and other blocks at the rear edge, which effectively improves the overall stability of the slope.

![Figure 11. Translocation curve of internal monitoring points of LS$_{337}$](image)

![Figure 12. Translocation curve of outside monitoring points of LS$_{337}$](image)

![Figure 13. Translocation curve of outside monitoring points of C$_{3-1}$](image)

In summary, the treatment measures of concrete replacement caverns can enhance the resistance of the bottom sliding surface LS$_{337}$, effectively reduce the deformation of slope rock mass, improve the stability of key blocks in the front part. Therefore, they are good reinforcement measures to ensure the overall stability of the strong unloading slope on the left bank of Baihetan hydropower station.

5. Conclusions and recommendations

(1) Many structural planes develop in Baihetan left bank slope, and they cut each other forming the complex block system, with the inter-layer or intra-layer sheared zones as the bottom slip surface, the steep dip faults or fissures as the side slip surface, and the large and long unloading fissures as the rear edge split surface. The stability safety factors of 1-1# and 2# blocks of the natural slope are insufficient. Based on the design research, comprehensive treatment measures such as concrete replacement, excavation load reduction, anchoring, drainage and slope protection are adopted to improve the overall safety of slope. The stability enhancement measures for the giant blocks are mainly the deep replacement treatment for the bottom sliding surface LS$_{337}$ and the excavation load reduction combined with the construction layout. Nine deep concrete replacement caverns were arranged along different elevations of LS$_{337}$ and implemented in two phases.

(2) The results from 3D numerical simulation show that the stresses of the replacement caverns increase obviously during the process of slope excavation and structural plane strength reduction. When the strength reduction coefficient is 1.5 times, the area of replacement caverns at LS$_{337}$ plane yield almost. However, yielding area of the replacement concrete and its contact surface with bedrock is very small. Therefore, the shear resistance of the block bottom surface is improved by the replacement...
caverns. According to the mechanical characteristics of the replacement hole, the shear stress of the replacement hole at the front edge is the largest. It is suggested that the size of the front replacement cavern should be appropriately increased to enhance its reinforcement effect.

(3) The comprehensive method of geo-mechanical model test also proves that the replacement measures play a good role to enhance the slope stability on the left bank of Baihetan hydropower station. The test shows that the concrete replacement caverns delay the cracking and its propagation of LS337. The final failure mode of slope model is that the cracks distribute along all of the structural surfaces and at some part of the slope surface, and all sliding blocks have been formed.

(4) Based on the results of numerical simulation and comprehensive geo-mechanical model test, the deep replacement can improve the slope stability effectively, and the stability safety factors of the giant blocks after reinforcement meet the requirements.

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References
[1] Chen C. Y., Mi H. L. (2001) A three-dimensional limit equilibrium method for slope stability analysis. Chinese Journal of Geotechnical Engineering, 23(5):525-529.
[2] Liu Quan-sheng, Lei Guang-feng, Peng Xing-xin (2016) Advance and review on the anchoring mechanism in deep fractured rock mass. Chinese Journal of Geotechnical Engineering, 35(2): 312-332.
[3] Liu Quan-sheng, Lei Guang-feng, Peng Xing-xin (2018) Deep reinforcement study on right dam shoulder slope of Dagangshan hydropower station. Yellow River, 40(1):138-144.
[4] Yan Zhi-xin, Long Zhe, Qu Wen-rui (2016) The effect of shear on the anchorage interface of rock slope with weak layers under earthquake. Rock and Soil Mechanics, 35(2): 312-332.
[5] Xiang Bo-yu, Jiang Qing-hui, Song Sheng-wu, et al. (2012) Reinforcement design method for deep embedded concrete shear resistance structure and its application to large-scale engineering slope. Chinese Journal of Geotechnical Engineering, 31(2): 289–302.
[6] Cheng Can-yu, Luo Fu-rong, Qi Cheng-zhi, et al. (2012) Comparative analysis of slope stability by strength reduction method. Rock and Soil Mechanics, 33(22): 3472–3478.
[7] Yang Baoquan, Chen Yuan, Zhang Lin, et al. (2015) Research on dam abutment reinforcement effect of Jinping arch dam based on geomechanical model test. Rock and Soil Mechanics, 36(3): 819–826.
[8] DONG Jianhua, ZHANG Lin, CHEN Jianye, et al. (2012) Techniques of geo-mechanical model test and engineering application. Journal of Yangtze River Scientific Research Institute, 29(12): 78–82.
[9] ZHANG Lin, CHEN Yuan, CHEN Jianye, et al. (2015) Application of model test of dam and foundation to engineering. Science Press, Beijing.
[10] YANG Jin-wang, CHEN Yuan, ZHANG Lin, et al. (2018) Stability of high bedding slope of rock based on comprehensive geo-mechanical model test. Chinese Journal of Rock Mechanics and Engineering, 37(1): 131－140.
[11] YANG Jin-wang, CHEN Yuan, ZHANG Lin, et al. (2018) Study on the anti-dip layered rock slope toppling failure based on centrifuge model test. Journal of Hydraulic Engineering, 49(2): 223-231.