Analysis of large deformation mechanism of the underground powerhouse at the Baihetan hydropower station

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Abstract. Baihetan hydropower plant has the widest underground powerhouse and the largest scale of underground openings in the world. The surround rock mass of huge caverns is characterized by complex geological conditions and high in-situ stress of 30MPa. The monitoring deformation of the roof arch of the right bank powerhouse reached 165mm and the deformation of the side wall reaches 192mm, which had become the focus of the feedback analysis. In the paper, several field test methods, such as extensometer monitoring, grating fiber displacement monitoring, acoustic test and borehole image test, have been adopted to revealing the fracture expansion and time-dependent deformation of surrounding rock. Moreover, FLAC3D numerical simulation has been conducted integrated the monitoring results to analysis of large deformation mechanism. The results show that the combination of interlayer zone and high stress factors is the fundamental cause of large deformation caused by excavation. Finally, the reinforce measures and reinforcing range had been determined, and the stability of the powerhouse cavern has been evaluated according to the monitoring results for nearly 2 years after excavation. The studies, integrated the research approach of field geological survey, monitoring and numerical simulation, not only have shed light on the large deformation mechanism of excavation response of huge caverns, but also has provided a basis for dynamic optimization design and construction.

1. Introduction
The Baihetan dam and hydropower plant project includes the design and construction of a 289 m high, double curvature, concrete dam and of the world's largest underground powerhouse caverns, with a capacity of 16,000 MW in total. The project, currently under development, is located on the Jinsha River, in the southwest of China. Two large-scale powerhouse caverns as shown in Figure 1a with the span of 34m and the height of some 80m each have been excavated inside the both river banks.

The surround rock mass of huge caverns of Baihetan hydropower plant are characterized by complex geological conditions (Figure 1b) and high in-situ stress of 30MPa. Three types rock mechanical problems, the high stress inducing spalling of brittle basalt, the interlayer zone inducing deep deformation, and the unloading relaxation of columnar basalt have been found in the process of the excavation.

In particular, the monitoring deformation of the roof arch of the right bank powerhouse reached 165mm and the deformation of the side wall reaches 192mm, which had become the focus of the feedback analysis.
2. Response characteristics of surrounding rock

The response characteristics of surrounding rock excavation can be analyzed by combining numerical simulation based on FLAC3D with on-site extensometer monitoring, drilling acoustic wave velocity measurement, distributed grating optical fiber displacement monitoring and so on. The detailed FLAC3D model simulates the characteristics of cavern geometry, lithologic stratification and fault structures shown in figure 1, and the total number of elements is 150w, which can be used for fine simulation of caverns excavation under complex geological conditions.

2.1. Failure characteristics of surrounding rock

Figure 2 shows the maximum principal stress distribution calculated by FLAC3D:

- Because the large principal stress on the section of the powerhouse tends to be about 5-10° upstream, as shown in figure 2a, the upstream arch shoulder and the downstream sidewall are stress concentration areas, which is the basic pattern of stress distribution. Therefore, in the process of excavation, there is an obvious spalling failure phenomenon in the upstream side arch and downstream side wall, as shown in figure 3.

- The interlayer zone has an obvious influence on the stress distribution of the top arch, as shown in figure 2b, when the interlayer zone is a certain distance from the top arch, the interlayer zone blocks the stress redistribution of the surrounding rock, so that the stress concentration of the rock mass in the lower part of the interlayer zone is obviously enhanced. The local fracture is also intensified; on the other hand, when the interlayer zone cuts the excavation face, as shown in figure 2c, the local relaxation will be more obvious.

- The interlayer zone also has an obvious influence on the stress concentration of the downstream sidewall. As shown in figures 2b and 2c, C4 increases the stress concentration of the downstream wall corner of the powerhouse, resulting in obvious spalling failure in the downstream wall corner of each excavation steps. As shown in figure 3, the spalling in the range of 0-55 to 0+20 of the downstream side wall of the powerhouse is very extensive.
2.2. Displacement distribution characteristics
Figure 4 shows the displacement distribution calculated by FLAC3D. It can be seen that the influence of interlayer zones on the deformation distribution of surrounding rock is very prominent, which shows that the part where the deformation exceeds 100mm is related to the interlayer zone. First, the interlayer zone C3 and C3-1 cut the upstream sidewall, resulting in a large-scale deformation of the upstream sidewall of more than 100mm; second, the interlayer zone C4 cutting the south side arch, resulting in the local top arch and downstream side wall deformation is also larger than 100mm.

The actual displacement monitoring results (Figure 5) are consistent with the numerical simulation results (Figure 4), that is, the upstream side wall, the south side top arch and the south side downstream side wall appear areas where the local displacement is greater than 100mm. When the
powerhouse had been excavated to the layer \( V \), the maximum displacement of the 0-40 top arch is 132mm, and the monitoring displacement of the downstream side wall Myc0-056-6 is 173.6mm, which is the maximum monitoring displacement of the surrounding rock of the whole cavern.

Figure 5. Monitor displacement distribution

3. Mechanism of large deformation of surrounding rock
The 0-55 to 0+20 of the south section of the powerhouse on the right bank of Baihetan is prominently affected by C4, which is the area of maximum deformation of surrounding rock and the most concerned section of the whole feedback analysis.

3.1. Enhancement of local stress concentration caused by C4
Figures 6 and 7 show the characteristics of stress concentration of III layer and V layer after excavation respectively. As can be seen from the figure:

- The top arch stress concentration area ① of the C4 lower side continues to strengthen, so the surrounding rock fracture relaxation of the C4 lower side continues to develop, and the acoustic wave velocity of the rock mass of the C4 lower side continues to decrease; at the same time, the distributed grating fiber (figures 7c) has been detected to produce obvious local micro-strain.

- Due to the influence of C4 cutting, there is an obvious stress concentration area ② in the corner of the downstream sidewall at each excavation step, resulting in banded spalling failure of the downstream sidewall, as shown in figures 3 and 6c.

- The stress concentration zone ③ at the corner of the end wall also continues to strengthen, resulting in local shotcrete cracking, as shown in figure 6.

Figure 6. Effect of C4 on stress concentration.
3.2. Increase of local deformation caused by C4

Figure 8a shows the displacement distribution characteristics after excavation of III layer, V layer and VII layer, which shows that the overall large deformation of the surrounding rock in the lower wall of C4 is remarkable. With layered excavation, the unloading and relaxation deformation of the downstream sidewall is significant, as shown in the following figure of figure 7b, the local tension pressure area of the sidewall is produced, therefore, a large number of tension cracks are produced in the traffic tunnel which perpendicular to the sidewall (figure 8b), and the maximum width of the crack can reach 13cm.
Because the downstream side wall of the powerhouse has experienced the process from stress concentration fracture (figure 7a) to stress relaxation (figure 7b) in the process of layered excavation, the relaxation deformation of rock mass in the range of 5m in the shallow layer will be very prominent, and it is obviously disturbed by the coming excavation of the lower layer. As shown in figure 9, in January 2018, the monitoring displacement of the downstream sidewall Myc0-056-6 after excavation in the VI layer reached 173.6mm, and there was no obvious convergence trend.

![Figure 9. Myc0-056-6 monitoring displacement process line](image)

4. Dynamic feedback analysis and support design
In practical engineering, for the areas with large deformation, it is necessary to predict the deformation trend of subsequent excavation based on numerical analysis, optimize the excavation scheme and strengthen support to ensure the overall stability of surrounding rock.

4.1. Prediction of deformation increment caused by different subsequent excavation schemes
Because the stress rupture and relaxation of the side wall is relatively strong, it is easy to be affected by the follow-up excavation. The numerical simulation results show that although Myc0-056-6 is located in the auxiliary powerhouse, it is still affected by the excavation disturbance of adjacent units. During the excavation of layer VIII-X, the displacement increment of Myc0-056-6 is about 20mm, and the final cumulative displacement is about 194mm, while the excavation of the catchment well will also lead to the displacement increment of about 15mm (Figure 10a), and it is predicted that the final maximum displacement will reach 210mm. Therefore, moving the catchment well outward, as shown in Figure 10b, is helpful to reduce the disturbance to the surrounding rock caused by subsequent excavation.

![Figure 10. Comparison of displacement increment caused by different excavation schemes](image)
4.2. Strengthen support
At the same time, in view of the large deformation area shown in figure 11a, the site adopts the reinforcement measures of suspending excavation and increasing cable, which is beneficial to accelerate the convergence of deformation and reduce the deformation increment of excavation disturbance in the later stage, as shown in figure 12.

Figure 11. Partial use of cable to strengthen support

4.3. Stability characteristics of surrounding rock
The excavation of the layer X of the powerhouse was completed in March 2019. The field monitoring results show that the maximum displacement of Myc0-056-6 is 192 mm, which is basically consistent with the 194mm predicted by feedback analysis. Moreover, with the follow-up prestressed anchor cable and concrete pouring, the maximum displacement of the surface rock mass decreases, and the displacement of the 3.5m measuring point tends to be stable. By 2021, the deformation of surrounding rock has no obvious increment and is stable as a whole.

Figure 12. Myc0-056-6 monitoring displacement convergence characteristics

5. Conclusion
The geological conditions of the underground powerhouse on the right bank of Baihetan are complex and the cavern group is large, so the high ground stress can easily lead to the spalling and relaxation of brittle basalt. The large deformation mechanism of Baihetan underground powerhouse is analyzed by the combination of numerical simulation analysis and monitoring. The results show that the interlayer zone is the root cause of stress concentration enhancement and relaxation large deformation. Dynamic
optimization design and strengthening support measures reduce the final deformation increment and accelerate the deformation convergence.

In a word, based on the research methods of on-site geological survey, monitoring and numerical simulation, the large deformation mechanism of giant cavern excavation response is revealed, which assists the dynamic optimization design and construction scheme decision-making, and supports the long-term stability evaluation of surrounding rock.

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