Design of the dome shape of complicated huge cylindrical surge chamber in Baihetan hydropower station

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Abstract. Baihetan hydropower station located at lower reaches of Jinsha River in China, the hydropower station is characterized by its large scale and complicated layout. Four cylindrical throttled surge chambers sit in each bank with their heights about 100 m, and the diameters 43 to 48 m. The surrounding rock of the dome is affected by high in-situ stress, interlayer dislocation zone and columnar joints. The geological conditions are extremely complex and the stability of the surrounding rock is prominent. The numerical simulation method is used to build the calculation model of the dome with different shapes, and the excavation response characteristics of the domes are compared to determine the optimal shape. Research results: (1) The domes of the 1#~3#, 5#, 6# surge chamber are mainly affected by the initial in-situ stress and surrounding rock lithology. The semi-circular shape is beneficial to improve the smooth transition of surrounding rock stress at the crown and spandrel. (2) The interlayer dislocation zone C4 and C5 jointly affect the dome of the 7# surge chamber. The semi-circular scheme can be used to control the relaxation deformation of the surrounding rock. (3) The streamlined scheme of the 8# surge chamber can reduce the exposure range of columnar joints, reduce the risk of the impact of columnar joints, and improve the conditions of the dome.

1. Introduction
The surge chamber of Baihetan Hydropower Station adopts a cylindrical design scheme, which can significantly improve the stress condition of the top arch and the deformation state of the side wall. However, the surrounding rock of the cylindrical top arch still affected by high in-situ stress, interlayer dislocation zone and columnar joints, coupled with the large-scale excavation of the dome, the stability of the surge chamber dome has become one of the major challenges faced by the construction of Baihetan underground engineering.

In the classical arch structure theory, it is considered that the stability of arch structure is mainly guaranteed by the shape of the rigid block. The arch design is the most basic requirement to ensure that the excavation of the cavern is arched. For the stability of the dome of the huge cylindrical cavern in underground engineering, there are some basic characteristics that are different from the traditional arch structure theory. For example: (1) The arch of the traditional corridor-shaped cavern can be equivalent to a two-dimensional analysis, while the dome of the cylindrical cavern has the characteristic of "two-direction" arching[1]. (2) The distribution of the initial in-situ stress has a prominent influence on the stability of the dome. The horizontal principal stress dominated by the tectonic stress is favourable for arching. However, when the stress level is too high, the stress type failure of the surrounding rock may also occur[2]. (3) The joints may destroy the shape integrity of the cavern, so it is necessary to control the stress relaxation to ensure the integrity of the cavern contour. Generally speaking, the stability of the dome of the huge underground cavern is always obviously restricted by the shape. It is necessary to
optimize the shape scheme of the dome and to improve the stress distribution and stability of the surrounding rock by continuously adjusting the geometry of the cavern section\(^3\).

For this reason, this paper mainly studies the shape design and optimization of the huge cylindrical surge chamber dome under different geological environments. The calculation models of different shape schemes are constructed by numerical simulation, and the distribution characteristics of the surrounding rock stress, deformation and plastic zone are compared. The optimal design shape of the giant dome under a specific geological environment is determined.

2. General situation of engineering geology

2.1. Project overview
Baihetan Hydropower Station is located in Ningnan County of Sichuan Province and Qiaojia county of Yunnan Province. It has an installed capacity of 16000MW and a large number of underground caverns. Eight cylindrical throttled tailwater surge chambers are arranged on the left and right banks respectively. The excavation diameter of 1\(^{\#}\)~4\(^{\#}\) surge chambers on the left bank is 48m, 47.5m, 46m and 44.5m respectively. The excavation diameter of 5\(^{\#}\)~8\(^{\#}\) surge chambers on the right bank is 43m, 45.5m, 47m and 48m respectively. The excavation height of vertical wall is 57.92m~74.95m. The diameter and number of surge chambers rank the first in the world for hydropower projects built or under construction.

2.2. Engineering geological conditions and evaluation
The geological conditions of Baihetan Hydropower Station area are very complex. The surrounding rock is mainly composed of cryptocrystalline basalt and amygdaloid basalt. The rock has high strength and brittleness, and a large number of unfavourable structures such as subtle micro-cracks and joints of different scales are developed inside\(^4\). The surrounding rock of the surge chamber on the left bank is mainly of type II and III1, and the interlayer dislocation zone C\(_2\) obliquely penetrates the side wall of the surge chamber. The four interlayer dislocation zones on the right bank intersect the top arch and side wall of the surge chamber. According to the results of in-situ stress testing, the maximum principal stress on the left bank is 15.4-22.0 MPa, and the maximum principal stress on the right bank is 15.0-24.0 MPa.

The horizontal principal stress is dominant in Baihetan Hydropower Station area, which is favourable for the arch forming of surge chamber dome. However, some surge chamber domes are inevitably affected by large-scale weak interlayer dislocation zone and columnar joints (such as 8\(^{\#}\) surge chamber), which makes the stability of local surrounding rock become the focus consideration in the design of the dome shape. The influence of the interlayer dislocation zone on the surrounding rock of the dome is mainly reflected in the following two aspects. (1) When the dislocation zone is located above the dome, such as 5\(^{\#}\) and 6\(^{\#}\) surge chamber. The rock mass between the dislocation zone and the excavation surface of the dome will have stress concentration, which will increase the degree of stress damage in the surrounding rock and cause stress-type failure. Therefore, it is necessary to study the reasonable shape design of the dome under high stress. (2) When the dislocation zone penetrates the arch of the dome, such as 7\(^{\#}\) and 8\(^{\#}\) surge chamber. The surrounding rock at the side wings may form relatively obvious stress relaxation zones. If the integrity of the geometric shape of the top arch is destroyed due to block sliding or partial collapse, that is, the line of the dome arch is destroyed, which will be detrimental to the stability of the dome surrounding rock.

Therefore, the research work of this paper will focus on the influence of high stress and dislocation zone on the shape design of the dome. In addition, the top arch of the 8\(^{\#}\) surge chamber is located in the columnar jointed rock. As the columnar jointed rock mass develops micro-cracks, it is susceptible to excavation damage and rupture, making the stability of the large-span dome facing greater challenges. In particular, columnar joints can simultaneously aggravate the high stress problem of the dome, and combine with the interlayer zone to cause local relaxation of the side wings. Therefore, the shape design of the 8\(^{\#}\) surge chamber dome considering the influence of columnar joints has become the key issue discussed in this article.
2.3. Shape design and numerical model of the dome

In view of the engineering geological conditions of the surge chamber, the following four design schemes with different shapes have been preliminarily drawn up during the engineering feasibility study stage: (1) The arc-shaped scheme, with a span of 49m and a height of 15.65m; (2) The semi-circular scheme, with a span of 49m and a height of 24.5m; (3) The ellipse scheme, with a span of 49m and a height of 30m; (4) The streamlined scheme, with an overall span of 49m×40.5m in height, and a small dome at the top with a span of 39.2m×16.07m in height. Figure 1 shows the corresponding numerical calculation models of the above four schemes, and the Mohr Coulomb strain softening model is used for calculation.

![Figure 1. Four design schemes of dome shape](image)

3. Comparison and selection of dome shape schemes

3.1. Comparison of the basic shapes of the dome

For #1~3#, #5#, #6# surge chamber, the stability of dome is mainly affected by the initial in-situ stress and surrounding rock lithology, followed by the joints, and the shape comparison mainly considers arc, semicircle and ellipse. Figure 2 shows the distribution of the maximum principal stresses after excavation of three different shapes. According to the calculation results, the center of the dome is the stress concentration area, and the maximum stress concentration levels of arc, semicircle and ellipse are about 40.14 MPa, 41.91 MPa and 43.68 MPa, respectively. That is to say, with the increase of the curvature of the dome, the stress concentration level in the center of the dome will increase.

![Figure 2. Stress distribution characteristics of three basic domes after excavation](image)

The deformation value of each characteristic point of the three shapes is shown in Table 1. It can be seen that increasing the curvature of the dome can reduce the deformation of the center of the dome, but the displacement of the two wings will also increase, which means that the stability of the surrounding rock is poor, and the stability and deformation problems of the block are prominent. Therefore, it is not suitable to choose the elliptical shape with a larger curvature under the specific in-situ stress condition. In order to improve the smooth transition of stress in the surrounding rock and spandrel of the dome, it is recommended to adopt semi-circular dome shape for #1~3#, #5#, #6# surge chamber.

| Location  | Arc | Semicircle | Ellipse |
|-----------|-----|------------|---------|
| Center    | 7.8 | 6.2        | 4.9     |
| E/W wings | 14.6| 16.2       | 19.1    |
| N/S wings | 19.8| 22.4       | 26.0    |

Table 1. Excavation deformation characteristics of three basic domes
3.2. Comparison of dome shapes affected by interlayer dislocation zone

3.2.1 The interlayer dislocation zone is exposed in the arch shoulder of surge chamber

According to the analysis in the previous section, 1st, 3rd, 5th, and 6th surge chamber domes are recommended to be semicircle. If 4th surge chamber chooses the semi-circular shape under general conditions, the dislocation zone C2 will obliquely cut the whole surge chamber spandrel, resulting in the rock mass under the dislocation zone to relax and overhang, and the surrounding rock stability conditions are poor, which is not conducive to the formation of the arching effect and the local stability of the dome surrounding rock. In contrast, the arch shoulder position of arc shape is relatively high, and the dislocation zone C2 is mainly exposed in the side wall of the surge chamber, and the stability condition of surrounding rock of dome is relatively good. Therefore, combined with the spatial relationship between the dome and the interlayer dislocation zone C2, the arc shape is recommended to improve the local stability condition of the surrounding rock for the 4th surge chamber.

![Figure 3. Relative position of the 4th surge chamber dome and the dislocation zone C2](image)

3.2.2 The interlayer dislocation zone is exposed in the wings of surge chamber

For the 7th surge chamber, the dislocation zones C4 and C5 jointly affect the position of the dome, which will reduce the overall stress concentration of the dome. At the same time, because C4 cuts the wings of the dome, it will directly lead to potential deformation and block stability problems in the relaxation area. For this reason, the following three design schemes of arc, semicircle and ellipse are compared and optimized. Table 2 shows the calculation results of the dome excavation response of the three shape schemes.

| Index                  | Location                        | Arc      | Semicircle | Ellipse |
|------------------------|---------------------------------|----------|------------|---------|
| Maximum deformation (mm)| Displacement of the crown       | 16–18    | 13–15      | 11–14   |
|                        | The upper part of C4            | 14–21    | 13–22      | 13–21   |
|                        | E/W wings                       | 25–30    | 16–28      | 15–28   |
|                        | N/S wings                       | 40–83    | 40–75      | 41–81   |
|                        | The low part of C4              | 33–76    | 34–121     | 37–159  |
|                        | E/W wings                       | 18.7     | 15.7       | 15.5    |
|                        | N/S wings                       | 15.8     | 12.6       | 10.3    |
| $\sigma_1$ (MPa)       | Stress of the low part of C4    | +0.17    | +0.19      | +0.26   |
| $\sigma_2$ (MPa)       | Depth of plastic zone (m)       | 5.6      | 6.2        | 9.2     |

According to the calculation results, the top arch, E/W wings and side walls are the stress concentration areas, the stress concentration degree of semicircle and elliptical arch is 2–3MPa higher than that of circular arch, while the N/S wings and side walls are the stress relaxation areas, as shown in Figure 4. Affected by the dislocation zones C4 and C5, the relaxation of the top arch of the arc-shaped scheme is relatively obvious, while the relaxation of the elliptical scheme under C4 is more significant. The deformation distribution characteristics of the dome are in good agreement with the stress distribution characteristics, that is, the greater the curvature of the dome, the smaller the deformation of the top arch, and the greater the deformation of the relaxation zone of the two wings, and there is significant discontinuous deformation in the cutting part of the dislocation zone C4. In summary, the relative advantages and disadvantages of the selected schemes according to the distribution conditions.
of the dome stress and deformation are: semicircle>circular arc>ellipse. Therefore, it is recommended to choose the semi-circular scheme for the 7th surge chamber.

![Figure 4. Maximum principal stress distribution of 7th surge chamber dome with different shapes](image)

3.3. Comparison of dome shapes affected by columnar joints
The 8th surge chamber dome is located in the first and second type of columnar jointed basalt in the P2β61 layer. The column is generally 0.5-2.0m long and 0.25-0.5m in diameter, with poor integrity. Because the columnar jointed rock mass has developed original micro-cracks and prominent anisotropic deformation, it is prone to rupture due to excavation damage. The failure modes include relaxation failure, disintegration failure and collapse, etc[5]. In other words, it is better to reduce the degree of stress concentration of the dome when comparing the shape schemes. This analysis only compares and selects the basic shape (semi-circular scheme) and streamlined scheme of the 8th surge chamber.

![Figure 5. Numerical calculation model of the 8th surge chamber](image)

Figure 6 shows the comparison of the deformation of two domes in columnar jointed rock. In the two design schemes, the near-horizontal maximum principal stress in the N/S direction makes the center of the dome, the E/W wings and the side walls present stress concentration, and the deformation magnitude is smaller, while the relaxation deformation of the N/S wings and side walls is more obvious. The statistical results of the specific deformation values of each part of the dome under the two shape schemes are shown in Table 3. The results show that the deformation at the center of the dome is generally small. The semi-circular scheme and the streamlined scheme are 7 mm and 5 mm, respectively. The maximum deformation of the dome of the streamlined scheme is reduced by about 30%. The deformation magnitude of the E/W wings columnar joint decreases by 15% in the streamlined scheme, and the depth of the relaxation deformation zone decreases by 45%.

![Figure 6. Comparison of the deformation of two domes under the influence of columnar joints](image)

| Dome         | depth/m (deformation>10mm) | Maximum deformation/mm | Semicircle | streamline | percentage | Semicircle | streamline | percentage |
|--------------|-----------------------------|-------------------------|------------|------------|------------|------------|------------|------------|
| Dome center  | <1                          | <1                      | 6~7        | 4~5        | 69%        |
| The upper part E/W | 3~3.5                  | 1.5~2.1                 | 55%        | 16~18      | 13~16      | 85%        |
In summary, the streamlined design scheme proposed for the columnar jointed rock not only reduces the dome height by nearly 10m, but also reduces the dome span from 49m to 39.2m, which greatly reduces the exposure range of columnar jointed rock. Since the top arch curvature of the streamlined scheme is between the arc and the semicircle, there is no obvious stress concentration in the center of the top arch. Therefore, in terms of controlling the stress concentration area of the top arch and the stress disintegration of the columnar jointed rock mass, the streamlined shape is better than the semi-circular shape. For the deformation distribution characteristics of the dome, the deformation of the dome center and two wings in streamlined scheme is 15~30% less than that in semi-circular scheme, and the relaxation zone of the depth is also significantly reduced. Therefore, the 8\textsuperscript{th} surge chamber is recommended to adopt a streamlined design.

### 4. Conclusions

Aiming at the dome shape design of the tailwater surge chamber of Baihetan Hydropower Station under the complex geological environment, this paper uses numerical simulation to establish the calculation model of the surge chamber with different shape schemes. The shape design and optimization of the dome under the influence of high in-situ stress, interlayer dislocation zone and columnar joint are carried out in turn. The differences and advantages and disadvantages of different shapes of the dome are analyzed to determine the optimal shape of each surge chamber. The main research results are as follows:

1) For the dome affected by high ground stress (e.g., 1\textsuperscript{st}~3\textsuperscript{rd}, 5\textsuperscript{th}, 6\textsuperscript{th} surge chamber), it is recommended to adopt semi-circular shape from the aspects of properly improving the stress of surrounding rock and arch shoulder.

2) For the dome affected by the dislocation zones C\textsubscript{4} and C\textsubscript{5} at the same time (e.g., 7\textsuperscript{th} surge chamber), the circular arc scheme is not good for the deformation of the top arch, the ellipse scheme is not good for the discontinuous deformation control of the two wings. While the semi-circular scheme can balance these two problems well, which can be used as the recommended scheme.

3) For the dome affected by both the columnar joints and the interlayer dislocation zone (e.g., 8\textsuperscript{th} surge chamber), the streamlined scheme can reduce the exposure range of the columnar joint rock, significantly improve the relaxation of the top arch excavation, improve the cavern forming conditions of the dome, and reduce the impact risk of the columnar joint rock.

### 5. References

[1] Meng GT, Hou J, Chen JL, Wang HB, Chen H. Study on the prevention and control measures of high stress fracture in the brittle surrounding rock of the giant underground cavern. Chinese Journal of Underground Space and Engineering, 2019, 15(1):247-255 (in Chinese).

[2] Meng GT, Fan YL, Jiang YL, He W, Pan YB, Li Y. Key rock mechanical problems and measures for huge caverns of Baihetan hydropower plant. Chinese Journal of Rock Mechanics and Engineering, 2016, 35(12):2549-2560 (in Chinese).

[3] Yang YW. Study on the optimal design and the construction safety forewarning system of tailrace surge chamber. Wuhan University, 2014 (in Chinese).

[4] Zhang CQ, Liu ZJ, Zhang CS, Zhou H, Gao Y, Hou J. Experimental study on rupture evolution and failure characteristics of aphanitic basalt. Rock and Soil Mechanics, 2019, 40(7):2487-2496 (in Chinese).

[5] Zhou CY, Chen PZ, HE SH, Chen JL, Liu L, Zhu WJ. Key rock mechanics problems and countermeasures on huge diversion tunnel of Baihetan hydropower station. Tunnel Construction, 2018, 38(3):383-389 (in Chinese).

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