Deformation analysis of underground powerhouse of a large hydropower station based on FLAC3D

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Abstract. Aiming at the deformation characteristics of surrounding rocks in underground powerhouse area of a hydropower station in Western China, the finite difference method is used for numerical calculation, and an assistant modeling software is used to realize the refined modeling of complex surface, which effectively improves the simulation accuracy. The results show that the stress level of surrounding rocks is low, the deformation of surrounding rocks is small, and the surrounding rocks is basically stable. However, the plastic zone of surrounding rocks has the trend of transfixion, so it is necessary to adjust the spacing of powerhouse.

1. Introduction
The main characteristics of underground powerhouse design of large hydropower projects are large section size, large depth, large number and complicated arrangements of cavern. After excavation, with the release and transfer of energy in rock mass, the stress field of surrounding rocks will be redistributed. According to the stress-strain relationship, the surrounding rocks will produce corresponding displacement or various forms of damage to adapt to the change of stress state [1]. In the process of hydropower engineering design, the stability analysis of surrounding rocks of underground powerhouse is a key problem in prefeasibility study and scientific research stage [2].

In this paper, FLAC3D, a numerical simulation platform based on finite difference method (FDM), is used to analyze the stability of a large underground hydropower station in Western China. An external software is used for modeling, which has strong surface modeling ability and high-quality structure generation function. It has built-in NURBS modeling method, which can generate complex surface that is easy to control and modulate by using terrain elevation map, and can better ensure the authenticity of the model[3,4], so as to improve the simulation accuracy. The calculation results have certain research significance in the stability analysis and design readjustment of the underground powerhouse area in hydropower projects.
2. Materials and Methods

2.1. Overview of the project area

The project area is located in the western plateau area of China, and the macro geomorphic morphology is characterized by large surface elevation difference and complex landform morphology. The powerhouse area has abundant mountains and complete terrain. Small faults and fractures are developed in the project area, the extension length of faults and fractures is generally less than 100m, and the width of fracture zone is generally 5cm-30cm. The scale of faults and fractures is so small that they are negligible compared with abundant mountains.

According to the survey data, the stratum in the powerhouse area is relatively single, and the main exposed strata are Quaternary (Q3, Q4) and Jurassic lagongtang formation (J2-3l). The Quaternary (Q3, Q4) deposits are mainly distributed in the lame and gentle slope areas of the mountain, and the accumulation thickness is thin. Lagongtang formation (J2-3l) is mainly composed of gray black sandy slate, locally mixed with metamorphic sandstone band, and the sandy slate is in thin layer structure.

2.2. Calculation Model

The measured contour lines of the area are imported into the modeling software, and the high-precision surface model is constructed by breaking the line as the point and covering the curtain, (Fig. 1a). Based on the surface model, the solid extrusion tool is used to generate the stratum (Fig. 1b). The X direction of the model is 840 m, the Y direction of the model is 874 m, the Z direction of the model is affected by the topographic relief and changes greatly, ranging from 155 to 606 m. The excavation model of underground powerhouse area is constructed according to the design location, section shape and size, which is mainly composed of main powerhouse (referred to as MP), main transformer room (referred to as MT) and surge tank (referred to as ST) (Fig. 2a). In the software, the model is constructed by the method of “surface generated from lines, body extruded from surfaces”. The number of grids in the entire calculation model is 1462857 and the number of nodes is 24892 (Fig. 2b).

According to the rock mass test and investigation data, the lithology of the rocks stratum in the powerhouse area is single, mainly sandy slate, with low weathering degree, no obvious difference in mechanical properties of rock mass, and the thickness of loose deposits on the surface is less than 2m. Therefore, the whole model can be equivalent to the continuous medium model of sandy slate.

2.3. Calculation parameters

Mohr-Coulomb strength criterion, which is generally applicable to rock mass, is used for calculation. The specific calculation parameters are shown in Table 1. During calculation, the boundary around the model is constrained by normal displacement, the bottom boundary is fixed boundary, and the top boundary is free boundary.

| rock                  | density ρ (kg/m³) | Poisson's ratio μ | Elastic modulus E (GPa) | Cohesion c (MPa) | internal friction angle φ (°) | tensile strength T (MPa) |
|-----------------------|-------------------|-------------------|-------------------------|------------------|-----------------------------|-------------------------|
| Sandy slate           | 2600              | 0.27              | 7.83                    | 0.91             | 51.15                       | 0.72                    |
3. Results

3.1. Stress

![Surface model](image1)
![Computational grid model](image2)

**Figure 1.** Surface stratigraphic model

![Cross section of main caverns in Powerhouse area](image3)
![Excavation model of Powerhouse area](image4)

**Figure 2.** Plant area model

The calculation results from Table 2 (in Table 2, the division of left and right wall of cavern is shown in Fig. 2 a) show that the maximum principal stress $\sigma_1$ of the surrounding rocks after excavation of the powerhouse area reaches 13.7 MPa, and the stress concentration at the corner of the powerhouse is obvious; The location of inflection point $\sigma_1$ at the bottom of the main powerhouse increases with the depth of the cavern; On the whole, after the excavation of the powerhouse area, the stress concentration in the local area of the cavern, such as the corner point, is to a certain extent, but the stress level of surrounding rocks is generally in a low state [5].

3.2. Displacement

The calculation results show that the total displacement volume of the middle section of the powerhouse area is large. According to the representative middle segment displacement nephogram (Fig. 3), the deformation of surrounding rocks after excavation of cavern group has the following basic characteristics.
Table 2. Maximum principal stress of surrounding rocks in Powerhouse Area

| Main cavern        | Bottom of left wall at entrance end | Roof of right wall at entrance end | Bottom of left wall in middle section | Middle right wall roof | Bottom of left wall at tail end | End right wall roof |
|--------------------|-------------------------------------|-------------------------------------|---------------------------------------|------------------------|---------------------------------|---------------------|
| Main workshop      | 10.0                                | 10.0                                | 13.0                                  | 9.3                    | 13.4                            | 9.1                 |
| Main transformer room | 13.5                                | 9.7                                 | 12.8                                  | 9.7                    | 13.7                            | 9.4                 |
| Surge tank         | 9.7                                 | 9.5                                 | 9.8                                   | 9.4                    | 10.0                            | 9.2                 |

The total displacement of surrounding rocks is small, and the distribution range of magnitude is 2-17cm. The top and bottom of the main powerhouse are the areas with the largest displacement, and the maximum value is about 17cm; The vertical displacement of the surrounding rocks in the powerhouse area is significantly greater than the horizontal displacement, which is most obvious in the main powerhouse. After excavation, considering that the vertical displacement of surrounding rocks is relatively large, the vertical displacement change of surrounding rocks at the top and bottom of each main cavern is monitored.

Figure 3. Cloud chart of middle section of plant area

According to the vertical displacement monitoring curve (Fig. 4), the distance between surrounding rocks and excavation free face has significant influence on surrounding rocks deformation. The displacement decreases more obviously at the top of the main powerhouse, the displacement of the main transformer chamber at the bottom of the main powerhouse is more than 15m away from the excavation face. It can be seen that after the excavation of the powerhouse area, there is an obvious displacement attenuation zone in the rock mass with a distance of about 15m away from the excavation face.

The displacement of rock mass around surge shaft and main transformer chamber is obviously small, with the value of 2-8cm; The displacement of the surrounding rocks on both sides of the main transformer chamber in the middle position is the smallest, and the distribution has a certain symmetry. Therefore, it can be seen that the spacing of the main caverns is reasonable without obvious interaction.

3.3. Plastic zone

After excavation, the tangential stress increases and the radial stress decreases due to stress redistribution(Or the maximum principal stress increases while the minimum principal stress decreases)
Because of the decrease of radial stress and the increase of tangential direction, the stress concentration degree is the largest at the intersection angle of arch wall at the top of tunnel, the intersection angle of wall foot at the bottom of tunnel, and the middle part of side wall, which has the potential risk of shear failure, the safety shear zone of surrounding rocks can be judged by the distribution of plastic zone [6,7].

![Figure 4. Variation Trend of surrounding rocks displacement in middle section of cavern](image)

The calculation results show that (Table 3), the thickness of the plastic circle around the surge shaft is the largest, followed by the main power house, and the smallest is the main transformer chamber. As can be seen in Fig. 5 (a), the distance between the main power house and the plastic zone around the main transformer chamber is relatively far, and the surrounding rocks with obvious thickness in the middle has high shear resistance and high stability. The plastic zone around the surge shaft and the main transformer chamber has the trend of connecting, and even the local plastic zone has been connected, so the rock mass has the risk of shear failure. The main transformer room was fixed and the design spacing between the surge tank and the main transformer chamber was continuously increased. When the distance was 29m, it was found that the plastic zone around the main transformer chamber and the surge shaft was obviously separated (Fig. 5 b).

| Cavern                  | Thickness of plastic circle (m) |
|-------------------------|--------------------------------|
|                         | Left side wall | Right side wall |
| Main workshop           | 7.1            | 7.0             |
| Main transformer room   | 5.0            | 6.1             |
| Surge tank              | 7.4            | 7.1             |
4. Conclusion

(1) By establishing a high-precision surface model and simulating the excavation of underground powerhouse, it can be seen that the stress level of the underground powerhouse area is generally low after excavation, and there is a certain stress concentration at the corner of the cavern bottom, with the maximum value of 14MPa. The displacement of the top and bottom of the cavern is large, and the maximum value is about 17cm. On the whole, the stress level of surrounding rocks is low, the deformation value is small, and the stability of surrounding rocks is high.

(2) The plastic zone of the main transformer room and surge shaft has the trend of transfixion. By gradually increasing the design spacing, it is found that when the distance between the main transformer chamber and surge shaft is 29m, the plastic zone of surrounding rocks of the cavern is obviously separated and the distribution is ideal. This point has a certain guiding significance for powerhouse design.

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