Analysis of surrounding rock anchoring effect under the condition of squeezed mountain

MA Yujun, SU Chao, ZHANG Heng

College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China

Abstract: In the process of orogenesis, the geological conditions of vertical strata were formed due to the intense compressive tectonic movement, and lithologic stratification occurred in the rock mass of the plant along the horizontal plane and vertically upstream and downstream. The main powerhouse of a power station straddles two types of rock formations along the axis. Considering the lithological differences between the two ends, traditional support methods will inevitably fail to meet the requirements of safety and economy. In this paper, under the condition of systematic bolt support for the whole plant, prestressed anchor cables are added to the upstream and downstream side walls of the plant in the type III surrounding rock area to increase the stability, and the anchoring effect is analyzed and compared with the calculation of the burrow. The results show that the deformation around the cave in the surrounding rock areas of type II and III under unsupported conditions differs by 31.48%, and the depth of the plastic zone in the surrounding rock area of type III exceeds the anchoring depth of the bolt; After partition support, the horizontal displacements of typical cross-sections in the two types of surrounding rock areas have decreased by 8.66% and 17.11% respectively, the stress distribution is more uniform, the distribution range of the plastic zone in the downstream wall of the plant is significantly reduced, and the stability of the surrounding rock is guaranteed.

1. Introduction

The excavation of underground cavern makes the rock mass around the cave lose its original support, which leads to the breaking of the initial stress equilibrium state, and the surrounding rock will produce loose deformation towards the free face, thus causing the redistribution of internal stress in a certain range around the cave [1]. The stability of surrounding rock after excavation depends on the relationship between the redistributed stress and the bearing limit of rock mass. When the stress exceeds the bearing capacity of surrounding rock, instability will occur [2]. At present, the research on rock mass deformation and support control measures in the process of underground cavern excavation mainly includes numerical calculation, geomechanical model test and other methods [3]. Shao Bing [4] et al. used discrete element method to study the influence of gently inclined interlayer dislocation zone on the stability of roof arch surrounding rock and put forward the measures and scope of strengthening support; Su Chao [5] et al. studied the control factors of surrounding rock stability and the effectiveness of support measures in geological areas with weak structural planes; Shao Shuai [6] studied the failure mechanism of surrounding rock dominated by rock mass structure through the analysis of field survey data and finite element calculation, and gave the measures to improve the supporting strength of surrounding rock.

The research objects of the above-mentioned scholars are all underground power houses located in similar surrounding rock areas, and the supporting mode does not change along the axial direction of the power houses, and only local reinforcement is carried out at the places where faults and fissures...
develop. The research object of this paper is quite special. The workshop is located in the geological area of extruded vertical rock stratum, and it crosses Class II and Class III surrounding rocks along the axial direction. The proportion of the two surrounding rocks around the workshop cave is relatively close, so it is difficult to take the same supporting method along the axial direction of the main workshop to give consideration to safety and economy. At present, the research on the anchoring effect of surrounding rock in the geological area of extruded vertical rock stratum is scarce. In this paper, the prestressed anchor cable support is added to the upstream and downstream walls of the factory building in the third class surrounding rock area under the condition of systematic anchor bolt support, and the three-dimensional nonlinear finite element method is used to calculate, compare the excavation of hairy tunnel and analyze the anchoring effect.

2. Engineering survey

A pumped storage power station is located in the mountain upstream of the dam, which belongs to the second-class large (2) project. The surrounding rocks in the factory area are mainly Class II and III, and the surrounding rocks are Class IV when they encounter fault fracture zone or fissure dense zone locally. The proportion of all kinds of surrounding rocks is 55% in Class III, 30% ~ 35% in Class II and about 10% ~ 15% in Class IV. Affected by the intense compressive tectonic movement, the lithology of surrounding rock is distributed in layers along the axis direction of the main powerhouse, and the interface is located near the longitudinal section of No.2 bus tunnel. The rock mass on the side of the auxiliary powerhouse is Class II surrounding rock, and the rock mass on the side of the installation room is Class III surrounding rock. There are mainly four faults in the plant area, and the relative position with the plant is shown in Figure 1.

The excavation size of underground powerhouse is 172.5m×26.5m×55.0m (length × width × height), which is excavated in seven levels from top to bottom, and the support method of bolting and shotcreting followed by excavation is adopted. The main supporting measures are system anchors. For the sake of economic security, only the side walls of the main powerhouse and the high-end walls formed by excavation of the auxiliary powerhouse in Class III surrounding rock area are supported by prestressed anchor cables. The supporting parameters are shown in Table 1, and the schematic diagram of step-by-step excavation and supporting scheme is shown in Figure 2.

![Fig.1 Relative position map of cavern group and fault](image-url)
Table 1  Supporting parameter table of underground cavern

| Position                        | Support parameters                                      | Anchor rod                  | Sprayed concrete | Hanging steel mesh                       |
|--------------------------------|--------------------------------------------------------|-----------------------------|------------------|------------------------------------------|
| Top arch of underground powerhouse Class II surrounding rock | C28@1.5×1.5m, L = 6m/9m is arranged at intervals, and anchor bolts are padded | 20cm                       |                  | Ø8@20×20cm, Set keel reinforcement: diameter 12@ bolt spacing |
| Class III surrounding rock     | C28@1.5×1.5m, L = 6m/9m is arranged at intervals, and anchor bolts are padded | 20cm                       |                  | Ø8@20×20cm                               |
| Class II surrounding rock      | C28@1.5×1.5m, L = 6m/9m is arranged at intervals, and anchor bolts are padded | 15cm                       | Ø8@20×20cm       |                                          |
| Side wall of underground powerhouse Class III surrounding rock | C28@1.5×1.5m, L = 6m/9m is arranged at intervals, and anchor bolts are padded. Set system anchor cable, and the anchor cable layout is shown in Figure 2. L=18.5m/20m/40m, Spacing is 6m, and design prestress is 1600KN. | 15cm                       | Ø8@20×20cm       |                                          |

3. Research method

3.1 Computational model

Considering the distribution, relative position, topographic characteristics of the plant area, lithology of surrounding rock and rock stratum distribution of the underground caverns of pumped storage power station, a three-dimensional finite element calculation model including the main caverns is established (as shown in Figure 3). X-axis is positive along the factory axis pointing to the auxiliary building, Y-axis is positive along the upstream and downstream and horizontally pointing to the downstream, and Z-axis is positive vertically. Calculation scope: extend the front and rear end walls of the underground powerhouse to both sides for 150m as the front and rear boundaries of the model in X axis direction; The upstream and downstream boundaries along the Y-axis direction are respectively taken 200m away from the upstream wall of the main power house and 200m away from the downstream wall of the main transformer tunnel. The model range along the z axis is taken from the elevation of -50m to the ground surface. The model has 126934 nodes and 730789 cells. Non-linear finite element method is adopted for calculation, Mohr-coulomb yield criterion is adopted for materials, and rock physical and mechanical
parameters and design support parameters are shown in Tables 2 and 3.

![Three-dimensional finite element calculation model](image)

**Fig. 3 Three-dimensional finite element calculation model**

| Category       | $\rho (kg/m^3)$ | $E (GPa)$ | $v$  | $c (MPa)$ | $\varphi(\circ)$ |
|----------------|-----------------|-----------|------|-----------|------------------|
| Surrounding rock II | 2650            | 15        | 0.2  | 1.7       | 52.4             |
| Surrounding rock III | 2600            | 8         | 0.25 | 0.95      | 45               |
| Fault zone      | 2200            | 3         | 0.3  | 0.55      | 35               |

| Support category | Features                                      | $\rho (kg/m^3)$ | $E (GPa)$ | $v$  |
|------------------|-----------------------------------------------|-----------------|-----------|------|
| Lining           | Steel fiber reinforced concrete CF30          | 2500            | 30        | 0.2  |
|                  | Full-length bonded cement mortar bolt, grade HRB400, yield strength 400MPa | 7850            | 200       | 0.27 |
| Prestressed anchor cable | Eleven 7φ5 steel strands | 7850            | 200       | 0.27 |

**3.2 Geostress inversion**

In this paper, the gravity stress of rock mass and the influence of geological tectonic movement on in-situ stress field are considered, and the gravity stress, compression stress in two horizontal directions (X and Y directions) and shear stress in XY plane are taken as the four influencing factors of in-situ stress regression analysis. According to the stress data of measuring points obtained by hydraulic fracturing method, the in-situ stress in the factory area is calculated by multiple linear regression method, and the regression value is well fitted with the measured value by least square method, and the complex correlation coefficient is $R=0.995$. The in-situ stress inversion results are reasonable and reliable, which can provide a basis for the subsequent research on stability, support and excavation methods. The
regression coefficients of four stress influencing factors are as follows: $L_1 = 1.14$, $L_2 = 2.66$, $L_3 = 2.10$, $L_4 = 0.45$. The regression equation of initial geostress field is as follows:

$$
\sigma = 1.14\sigma + 2.66\sigma_X + 2.10\sigma_Y + 0.45\sigma_{XY}
$$

(1)

The measured in-situ stress components $\sigma_x$ and $\sigma_y$ near the main powerhouse are similar in value, ranging from 6.48 MPa to 12.46 MPa, $\sigma_z$ ranging from 6.28 MPa to 11.73 MPa, and the shear stress component is very small. The distribution of in-situ stress field in numerical simulation is shown in Figure 4. It can be seen that the in-situ stress value is affected by topography and increases with the increase of overburden thickness. The initial ground stress at the same elevation is stratified in the direction of the factory axis with the boundary between Class II and III surrounding rocks, and the ground stress in Class II surrounding rocks is higher. The value of in-situ stress at fault has changed suddenly, especially at fp15 fault, which is obviously smaller than the surrounding rocks, and the in-situ stress at the part far away from the fault area is basically distributed in layers according to elevation.

![Fig.4 Ground stress distribution maps](image)

4. Calculation result

In order to analyze the calculation results intuitively, the key points shown in Figure 2 are selected around the tunnel, and the middle section of Unit 2 located in Class II surrounding rock area and the middle section of Unit 3 located in Class III surrounding rock area are taken as typical sections for analysis.

4.1 Stability analysis of surrounding rock without support

4.1.1 Displacement distribution of key points around the cave

During the excavation process, the top arch of the main powerhouse is deformed downward, and the deformation of the side wall is mainly horizontal contraction. Due to the influence of lithology, the displacement values of the middle section of Unit 1 and Unit 2 in Class II surrounding rock area are relatively close, while the displacement values of the middle section of Unit 3 and Unit 4 in Class III surrounding rock area are larger than those of Unit 1 and Unit 2. The deformation distribution curve of key points around the tunnel when excavation is completed is shown in fig. 5. The subsidence
displacement of NO1 key point of unit 2 is 13.04mm, while that of NO1 key point of unit 3 is 16.11mm, which is 23.5% higher than that of unit 2. The maximum shrinkage displacements of key points of upstream and downstream walls of Unit 2 are 28.27mm and 29.61mm respectively, while those of Unit 3 are 34.10mm and 38.93mm respectively, which are 20.62% and 31.48% higher than those of Unit 2 respectively. If Class II and Class III surrounding rocks adopt the same support method, it is obvious that Class III surrounding rocks will become short support plates, which will lead to excessive support of Class II surrounding rocks.

Fig.5 Displacement distribution map after excavation (the top arch displacement upward is positive, and the side wall displacement pointing downstream is positive)

4.1.2 Stress distribution of typical section
According to the physical and mechanical properties of surrounding rocks revealed by the exploration data, the saturated tensile strength of class ii and class iii surrounding rocks in the plant area is 3.5MPa and 2MPa respectively, and the saturated compressive strength is 80MPa and 120MPa respectively. After excavation, the main tensile stress distribution maps of the two typical sections are shown in Figure 6. It can be seen that obvious stress mutation occurs at the cutting parts of fp15 and fp19 faults, but it has little influence on the overall stress distribution law. The main tensile stress distribution laws of the two typical sections are similar, and they are distributed in the upstream and downstream side walls of the main powerhouse and the main transformer tunnel and the corners of the cavern without obvious stress concentration. From the numerical point of view, the maximum tensile stress of the two sections is 0.67MPa. Generally speaking, the tensile stress of Unit 3 section is slightly larger than that of Unit 2 section, but the main tensile stress never exceeds the saturated tensile strength of rock during the whole excavation process.

![Fig.6 Principal tensile stress distribution diagrams of typical sections(unit: KPa)](a)Section of unit 2 (b)Section of unit 3

The principal compressive stress has obvious stress concentration and is related to the construction process. With the increase of excavation series, the compressive stress generally shows an increasing trend. As shown in fig. 7, at the end of excavation, the compression stress concentration occurred at the bottom corner of the main powerhouse and the intersection of the upstream wall of the main transformer
room and the bottom plate, with the maximum value of 27.45MPa, and the circumferential stress at the key points around the tunnel was all compression stress. Compression stress concentration occurs at the intersection of the bus tunnel and the upstream side wall of the main transformer tunnel in the section of Unit 3, with a maximum value of 15.87MPa. The circumferential stress at key points around the tunnel is compressive stress, and the principal compressive stress does not exceed the saturated compressive strength of rock during the whole excavation process.

![Section of unit 2](image1)

![Section of unit 3](image2)

Fig. 7 Principal compressive stress distribution diagrams of typical sections (unit: KPa)

4.1.3 Distribution of plastic zone in typical section

The range of plastic zones in faults fp15, fp19, fp22 and fp28 is relatively large. The plastic zones in the main powerhouse and main transformer room mainly occur in the side walls and deep in the middle. The depth of plastic zones in the middle section of Unit 2 located in Class II surrounding rock area is relatively small. Within the supporting depth range of the system bolt, the large plastic zone occurs in Class III surrounding rock zone, and the plastic zone depth in the middle of the downstream wall of the main power house of Unit 3 reaches 10.5m, which has exceeded the maximum anchoring depth of the system bolt, and has a tendency to penetrate the plastic zone of the upstream wall of the main transformer tunnel, as shown in Figure 8.

![Section of unit 2](image3)

![Section of unit 3](image4)

Fig. 8 Distribution maps of plastic zone

4.2 Analysis of anchoring effect of surrounding rock

According to the analysis in the previous section, different support methods should be adopted for Class II and Class III surrounding rocks, that is, prestressed anchor cables should be adopted for the upstream and downstream side walls of the main powerhouse in Class III surrounding rock area on the basis of systematic anchor bolt support.

4.2.1 Displacement variation law of key points around the tunnel before and after supporting

The deformation distribution law of surrounding rock under the supporting scheme is basically similar to that under the unsupported working condition, and the overall displacement of surrounding rock of the cavern decreases after shotcrete and anchor support. The effect of shotcrete and anchor support at NO5, the key point at the intersection of downstream wall and busbar tunnel of the main powerhouse of Unit 2 section, is obvious. The displacement value is reduced from 27.70mm without support to
25.30mm with support, the horizontal displacement is reduced by 8.66%, and the vertical displacement of the top arch of the main powerhouse is reduced by 6.29%. The supporting effect of NO5, the key point at the intersection of the downstream wall of the main power house and the bus tunnel of Unit 3 section, is obvious. The displacement value is reduced from 38.93mm without supporting to 32.27mm with supporting, the horizontal displacement is reduced by 17.11%, and the vertical displacement of the top arch of the main power house is reduced by 9.12%. It can be seen that under the design support scheme, the deformation of Class II and Class III surrounding rock has been well controlled, especially the stability of the downstream wall of the main powerhouse in Class III surrounding rock area has been greatly improved under the support of system bolt and prestressed anchor cable.

Table 4  Displacement value of key points around the cave

| Working condition | Section of unit 2 | Section of unit 3 |
|-------------------|-------------------|-------------------|
|                   | NO1 | NO2 | NO4 | NO6 | NO8 | NO3 | NO5 | NO7 | NO9 | NO1 | NO2 | NO4 | NO6 | NO8 | NO3 | NO5 | NO7 | NO9 |
| Without support   | -13.04 | 17.23 | 27.34 | 28.27 | 21.01 | -8.91 | -27.70 | -29.61 | -26.35 | -16.11 | 19.74 | 32.72 | 34.10 | 23.71 | -13.27 | -38.93 | -37.49 | -32.52 |
| Support           | -12.22 | 16.63 | 26.91 | 27.72 | 20.74 | -8.60 | -25.30 | -28.12 | -24.81 | -14.64 | 18.62 | 31.52 | 31.88 | 23.17 | -11.75 | -32.27 | -33.90 | -28.74 |
| Without support   | -16.11 | 19.74 | 32.72 | 34.10 | 23.71 | -13.27 | -38.93 | -37.49 | -32.52 | -14.64 | 18.62 | 31.52 | 31.88 | 23.17 | -11.75 | -32.27 | -33.90 | -28.74 |
| Support           | -12.22 | 16.63 | 26.91 | 27.72 | 20.74 | -8.60 | -25.30 | -28.12 | -24.81 | -14.64 | 18.62 | 31.52 | 31.88 | 23.17 | -11.75 | -32.27 | -33.90 | -28.74 |

Note: the displacement of the top arch is positive upward, and the displacement of the side wall is positive downward (unit: mm)

4.2.2 Stress variation law before and after support

Compared with the unsupported condition, the stress value of surrounding rock has not changed greatly under the supported condition. From the numerical point of view, the maximum values of tensile and compressive stress calculated under the two conditions are far less than the tensile and compressive stress intensity index of surrounding rock. However, from the distribution point of view, the improvement of support measures on tensile stress is mainly reflected in reducing the influence range of tensile stress, as shown in Figure 9. Under the supporting condition, the compressive stress concentration at the corner and intersection of the cavern is alleviated, and the stress distribution of surrounding rock is more uniform. Especially after the anchor bolt and anchor cable support is adopted in Unit 3, the compressive stress concentration at the upstream wall of the main transformer tunnel near the bus tunnel has been significantly improved, as shown in Figure 10.

Fig.9 Distribution diagrams of main tensile stress in typical sections after support (unit: KPa)
4.2.3 Variation law of plastic zone before and after support

Compared with the unsupported condition, the distribution law of the plastic zone of surrounding rock under the supported condition is basically unchanged, but the depth of the plastic zone is obviously reduced, especially the supporting effect of the upstream and downstream side walls of the powerhouse of Unit 3 section is remarkable, the scope of the plastic zone is reduced and the penetration trend is restrained, as shown in Figure 11. Under the unsupported working condition, the plastic zone of the generator layer located at 84.5m elevation is relatively large, especially at the intersection of No.3 bus tunnel located in Class III surrounding rock area with the downstream wall of main power house, the upstream wall of main transformer room and fp19 fault. After supporting, the plastic zone and depth of the downstream wall of the main powerhouse are reduced, as shown in Figure 12. However, because the improvement of rock strength parameters by supporting measures is relatively small, the improvement of plastic zone of surrounding rock by supporting measures is limited on the whole.
5. Conclusion

In view of the particularity of geological conditions of vertical rock stratum, according to the distribution of displacement, stress and plastic zone after excavation of Maodong, on the basis of adopting systematic bolt support, anchor cable support is added to the side wall of powerhouse in Class III surrounding rock area. After the support, the anchoring effect is remarkable, and the deformation of surrounding rock is controlled, especially the horizontal displacement at the intersection of the downstream wall of the main powerhouse and the bus tunnel in Class III surrounding rock area is reduced by 17.11%; The influence range of tensile stress has been obviously reduced, and the upstream wall of main transformer tunnel near bus tunnel is supported by anchor cable, and the phenomenon of compressive stress concentration has been significantly improved. Anchor cable support inhibits the penetration trend of plastic zone. It can be seen that the design support scheme meets the economic and safety requirements.

Fund projects: Project of National Natural Science Foundation of China (51579089)

Author brief introduction: Ma Yujun (1995-), male, master's degree student, majoring in hydraulic structural engineering, E-mail: 944015067@qq.com

Correspondence author: Su Chao (1960-), male, Ph.D., professor and doctoral supervisor, his research interests are hydraulic structure engineering and simulation calculation research, E-mail: csu_hhu@126.com

References

[1] He shaohui. underground engineering [M]. Beijing: Tsinghua University press, 2006
[2] Xiang Tianbing, Feng Xiating, Jiang Quan, et al. Dynamic identification and control of failure modes of surrounding rock of large caverns [J]. Chinese Journal of Rock Mechanics and Engineering, 2011,30(5):871-883.
[3] Xu Qianwei, Cheng Panpan, Zhu Hehua, et al. Model test and numerical simulation of progressive failure of surrounding rock of cross-fault tunnel [J]. Chinese Journal of Rock Mechanics and Engineering, 2016,35(3):433-445.
[4] Shao Bing, Fang Dan, Wan Xiangbing, et al. Influence of gently inclined interlayer dislocation zone on stability of surrounding rock of roof arch of large-span underground cavern and supporting countermeasures [J]. Hydropower and Energy Science, 2019,37(12):53-57.
[5] Su Chao, Mao Xiaojing, Zhao Yebin, et al. Study on the stability of surrounding rock of large underground caverns under complex geological conditions [J]. Hydropower, 2018,44(3):19-22,28.
[6] Shao Shuai, Yang Xingguo, Huang Cheng, et al. Study on failure modes and control measures of surrounding rock in tunnel fracture zone [J]. Journal of Sichuan University (Engineering Science Edition), 2017,49(Z1):72-80.