Research on the Law of Stress and Strain Response of Surrounding Rock of Underground Powerhouse Cavity Excavated by Layered Cutting

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Abstract. As an important part of the construction of hydropower stations, underground powerhouses are increasingly perfected and synchronized with their construction methods. Layered cutting and excavation methods have emerged at the historic moment. This article takes Wendeng Pumped Storage Power Station as an example, using theoretical analysis, numerical simulation and other methods to study the influence of the layered cutting method on the change of stress and strain of surrounding rock, and draws the following conclusions: (1) The cave is from the first floor to the first during the eight-layer excavation, the tensile stress of the side walls on both sides is symmetrically distributed and there is a maximum on the same layer, and the compressive stress reaches the maximum at the bottom plate; with the increase in the number of excavation layers, the tensile stress on the side walls on both sides increases first and then decrease, the surrounding rock compression stress of the vault and floor continue to decrease. (2) During the excavation of the cavern, the strain of the vault on the same floor reaches the maximum value, and the strain continues to increase with the increase of the number of excavation layers. The excavation of the eighth floor has increased to 4.94mm; The strain changes less with the increase of the
number of excavation layers, and is always maintained at 2.50~2.75mm; the floor strain decreases layer by layer. (3) By comparing the on-site monitoring and numerical calculation data, analyze the changing trend of the on-site measured arch strain and the side wall stress around 2.50mm up and down, and calculate the difference ratio between the numerical simulation and the measured data. The excavation time difference ratio reaches the maximum value of 29.1%, which verifies the correctness of the simulation experiment and provides a supporting scheme for the underground powerhouse in harmony with the deformation law.

1. Introduction

As an important part of the construction of hydropower stations, underground powerhouses are gradually improving their construction methods while maintaining synchronous innovation. The layered cutting and excavation method is the product of innovation in recent years. Because the stress and strain of the surrounding rock of the underground powerhouse are monitored separately according to the specification during the construction process, it is extremely necessary to study the stress-strain response law of the surrounding rock of the underground powerhouse cavity excavated by layers.

Yanyan He, Xiaohui Tang, Zheming Hong, etc. [1, 2] studied the blade deformation, cutting quality and noise reduction of the diamond cutting tool for underground workshops. Jin-Ho Lee et al. [3] established a wire saw cutting model to study the relationship between the cutting depth of the rock and the shape of the saw blade. Li, Hai Dong, Hongtao Zhang et al. [4, 5] studied the relationship between cutting parameters and the effect of cutting speed on rock stress and cutting performance. Yong Sun, Song Yueqing et al. [6, 7] studied the manufacturing theory of diamond cutting tools through examples and found the best balance point for cutting tools in underground tunnels. Jung-Gyu Kim et al. [8] studied the grooving method and the disk cutting method. The experiments show that the disk cutting method can effectively suppress ground vibration caused by blasting. Xiang Wang et al. [9] studied the fracture mechanism of conical pick cutting rock and established a specific energy model.

Ang et al. [10] studied the stability and damage mechanism of the layered rock mass around the underground cavern through field survey, experiment and numerical simulation. Baofu, Yingren Zheng, Huhua Zhu et al. [11, 12] studied the stability and design theory of surrounding rock in underground engineering, and analyzed the stability characteristics of roadway bolts, lining and surrounding rock. Hu, Dongqiao Liu, Zuo Wang et al. [13, 14] studied the failure and instability of surrounding rock, analyzed the strain softening characteristics of the rock and established a damage constitutive model. K Ma et al. [15] proposed a method of stability analysis of underground caverns combining numerical simulation and microseismic monitoring, and developed the theory of underground cavern stability monitoring. Chen R, P Yang Liu, Gang Yang, etc. [16, 17] analyzed the principal stress implicit return mapping algorithm for the surrounding rock of underground powerhouses based on model tests, introduced the most appropriate damage variables to derive the stress-strain calculation formula, and improved the stress-strain response theory.

In summary, the current research on the stability and stress-strain law of the layered rock mass around the underground cavern is relatively complete. The research results on the analysis of the stability of the surrounding rock and the law of failure and instability are mature, but on the cutting of the underground cavern there are few studies, and the domestic and foreign scholars' research on surrounding rock cutting is more focused on the research of cutting tools. There are more researches on cutting speed, cutting quality, and cutting parameters, but less on the stress-strain response law of cutting surrounding rock. Therefore, it is very important to study the law of stress-strain response of surrounding rock of underground powerhouse excavation by layered cutting.

This paper studies the stress-strain response law of surrounding rock of underground powerhouse excavation by layered cutting, closely surrounding the layered cutting construction of Wendeng Pumped Storage Power Station, through literature research, numerical simulation and other technical means, based on elastic mechanics related theory, combined On-site construction monitoring data,
analysis of the changing law of the surrounding rock stress on the site of cutting and excavation, comparative analysis of numerical simulation and monitoring data on the surrounding rock stress and strain changes of the vault, side wall, bottom plate and other places to verify the correctness of the simulation test. Summarizes and analyzes the stress-strain response law of the layered cutting and excavation of the underground powerhouse to ensure the safe construction of the tunnel and provide a reference for similar projects.

2. Project Overview
Wendeng Pumped-storage Power Station is located in Jieshi Town, Wendeng District, Weihai City, Shandong Province. The underground plant includes a main room, main and auxiliary plants and an installation site. As shown. The total size of the underground plant excavation is 214.5×25.0×53.5m (length×width×height), the elevation range of the main underground plant is EL.75.50m~EL.22.00m, the total height is 53.5m, and the excavation span above the rock anchor beam 26.5m, the following is 25.0m.

![Figure 1. Three-dimensional perspective view of Wendeng Pumped Storage Power Station.](image)

This article mainly studies the excavation and support construction of the second floor of the main underground powerhouse. The elevation range is EL.66.00m~EL.55.00m, with a total height of 11m. 016, the design elevation of the rock platform is EL.59.320~EL.61.850, the slope length is 1.5m, and the angle between the slope and the vertical plane is 30°. The underground powerhouse is excavated in layers I, II and III, of which the second layer is constructed with layered cutting technology and cut in 8 layers, as shown in Figure 2 for the cross-section of the main and auxiliary powerhouses.

![Figure 2. Cross-sectional view of the main and auxiliary plant.](image)

3. Numerical simulation analysis of layered cutting excavation

3.1. Model building
In this paper, the FLAC3D numerical simulation software is used to simulate the layered excavation of the main powerhouse, and the stress analysis of the surrounding rock in various parts of the cave at
different excavation stages is carried out, so as to obtain the stress-strain law of the surrounding rock of the large-scale underground cavern excavation, such as shown in Figure 3.

![Numerical model of cutting and excavation of underground powerhouse.](image)

**Figure 3.** Numerical model of cutting and excavation of underground powerhouse.

### 3.2. Surrounding rock parameters

According to the exploration data, the surrounding rock of the underground powerhouse is dominated by Type I~II surrounding rocks. The specific values are shown in Table 1. The rock mass in the workshop area is dominated by the overall block structure, the lithology is monzonite granite, quartz monzonite, and the surrounding rock has good integrity.

| Physical Mechanics Index | Type I surrounding rock | Type II surrounding rock | Unit |
|--------------------------|-------------------------|--------------------------|------|
| Dry density              | 2.63                    | 2.63                     | g/cm³ |
| Saturation density       | 2.65                    | 2.65                     | g/cm³ |
| Permeability coefficient | 0.02                    | 0.03                     | m/d  |
| Dry compressive strength | 130                     | 120                      | MPa  |
| Saturated compressive strength | 110               | 100                      | MPa  |
| Elastic Modulus          | 40                      | 30                       | GPa  |
| Deformation modulus      | 20–25                   | 15–20                    | GPa  |
| Poisson's ratio μ        | 0.17–0.22               | 0.22–0.25                |      |
| Shear modulus            | 10                      | 8                        | GPa  |

### 3.3. Arrangement of monitoring points

The surrounding rock is disturbed after the excavation of the underground powerhouse cavern group. Due to the difference in lithology at different locations, the deformation is inconsistent. Therefore, to master the distribution and nature of the surrounding rock along the excavation process, it is reasonable to analyze its stability the supporting strategy is of great significance. In order to monitor the variation of the stress of the surrounding rock of the underground powerhouse vaults and side walls with the construction process of the project, a steel string frequency stress meter is installed in the underground powerhouse, as shown in Figure 4, 1.1, 1.3, 2.1, 3.1, 4.1, 5.1, 6.1, 7.1, 8.1, 9.1, 10.1; in order to monitor the changing law of the deformation of the surrounding roof of the underground powerhouse vaults and side walls with the construction process of the project, multi-point displacement meters are installed in the underground powerhouse, as shown in Figure 4, 1.2, 1.4, 2.2, 3.2, 4.2, 5.2, 6.2, 7.2, 8.2, 9.2, 10.2.
Figure 4. Schematic diagram of the layout of the monitoring points of the underground powerhouse.

4. Numerical analysis of surrounding rock stress by layered cutting

4.1. Analysis of stress numerical simulation effect

Figure 5. Stress cloud image of surrounding rock excavated from the first to the eighth floors.
According to the numerical simulation calculation results, as the number of excavation layers continues to increase, the surrounding rock stress changes significantly at the side walls on both sides, and the surrounding rock stress of the arch and floor continues to increase with the excavation of the cave:

During the first layer excavation, the tensile stress at the connection between the side walls and the bottom plate on both sides reached a maximum value of $5.52 \times 10^6$ MPa, and the compressive stress at the arch and bottom plate reached a maximum value of $4.51 \times 10^4$ MPa; during the second layer excavation, the side walls on both sides appeared. The two maximum tensile stresses are the connection between the side wall and the first floor and the connection between the side wall and the second floor. The maximum tensile stress is $4.83 \times 10^6$ MPa, and the maximum compressive stress is $4.24 \times 10^4$ MPa; During the third layer excavation, the maximum tensile stress at the connection between the side wall and the third floor bottom plate reached $4.50 \times 10^6$ MPa, and the maximum compressive stress at the vault was $3.98 \times 10^4$ MPa; during the fourth layer excavation, the maximum tensile stress was at the side wall and the connection point of the fourth floor is $4.89 \times 10^6$ MPa, and the maximum tensile stress reaches $3.77 \times 10^6$ MPa at the floor; when the fifth floor is excavated, the stress value is affected by the side wall excavation structure, and the maximum tensile stress appears on the fourth floor and the second floor. The maximum tensile stress reaches $3.69 \times 10^6$ MPa at the bottom floor; when the sixth floor is excavated, the side walls on both sides are connected to the bottom floor of the first floor due to the influence of the side wall excavation structure change the tensile stress at the location increased drastically, increasing to $3.50 \times 10^6$ MPa, and the increase of the tensile stress during the fifth layer excavation was maintained, the maximum value reached $4.01 \times 10^6$ MPa, and the maximum compressive stress at the floor reached $3.54 \times 10^4$ MPa; the seventh layer excavation at this time, the stress on the side walls on both sides gradually decreases, and the maximum value also decreases. The maximum tensile stress decreases to $3.75 \times 10^6$ MPa, and the maximum compressive stress decreases to $3.37 \times 10^4$ MPa. During the eighth layer excavation, the maximum compressive stress is on the side. The connection between the wall and the floor of the eighth floor caused flank damage. The farther away from the excavation surface, the smaller the tensile stress. The stress on the side walls on both sides is symmetrical distributed. The average tensile stress of the surrounding wall of the side wall reached a peak value of $3.75 \times 10^6$ MPa during the sixth layer excavation, and the farther away from the excavation surface, the smaller the tensile stress. The maintenance of the supporting structure is related to maintenance. The compressive stress of the surrounding rock vault is more obvious in the early stage of excavation. Overall, the compressive stress of the surrounding rock is kept decreasing, and the compressive stress above the vault is the smallest, and gradually increases toward both sides.

**Distribution law of compressive stress with excavation:**

During the first four layers of excavation, the compressive stress on the arch top and the bottom of the excavation continued to decrease, and the surrounding wall rock caused flank damage. After the excavation of the fourth wall of the underground powerhouse, the compressive stress change range decreased; During the excavation, the stress in the compressive stress concentration area of the arch and the bottom of the excavation began to decrease steadily.

**Distribution law of tensile stress with excavation:**

The tensile stress is concentrated on the side walls on both sides. The excavation of the first two layers greatly increases the tensile stress; the excavation of the third layer causes a sudden decrease in the tensile stress, and only a large tensile stress occurs at the connection between the side wall and the third floor bottom plate; The excavation of the fourth to sixth floors, the tensile stress began to increase gradually, reaching the peak at the sixth floor; the excavation of the seventh to eighth floors, the tensile stress of the side walls began to decrease significantly, tending to stabilize.

**Distribution law of shear stress with excavation:**

After the excavation of the underground powerhouse, the shear stress is concentrated on the bottom plate, and the surrounding rock in the whole bottom plate area is subjected to the shear stress in all
excavation stages. The maximum shear stress occurs when excavating the sixth floor. Due to the sudden change of the structural plane, the shear stress on the upstream side is greater than that on the downstream side. The stress value and change trend of the rock beams on both sides are basically the same. With the increase of the number of excavation layers on the upstream and downstream side walls, the shape of the cave is constantly changing, and the surrounding rock shear stress is continuously adjusted.

4.2. **Contrast analysis of surrounding rock stress monitoring data and numerical calculation**

Due to the influence of various factors such as stress and geological structure, the stress of surrounding rock in different parts of the side wall of the cave may be different. Calculate the stress growth rate in each period [18, 19] (stress growth rate = (Current stress - stress after initial support) / initial support stress × 100%), as of December 2019, this data can clearly reflect the change trend of stress. The steeper the curve, the faster the stress growth rate. It can be seen from Figure 6: a. The stress change trends at the same elevation are basically the same as those at the downstream, and they all experience the stages of relaxation, linear growth, slow growth, steep increase, and convergence; The stress loss rate of the wall is higher than that of the downstream side wall; in the tensioning stage, the stress growth rate of the upstream side wall is higher than that of the downstream side wall.

![Figure 6. Stress growth rate of the upstream and downstream side walls of underground powerhouse.](image)

Install a steel string frequency stress gauge on the side wall (monitoring points 2.1, 3.1, 4.1, 5.1, 6.1, 7.1, 8.1, 9.1, 10.1), and draw a graph 7 based on the monitoring data As of December 5, 2019, get:

![Figure 7. Comparison chart of actual measurement data and numerical calculation data of each monitoring point of the side wall.](image)

The overall trend of the surrounding rock stress obtained by numerical simulation is the law of increase first, then decrease, then increase, then decrease, and finally stability. The overall stress remains at $5.00 \times 10^6 \text{MPa}$~$6.00 \times 10^6 \text{MPa}$, which is consistent with the actual measurement basically agree. Analysis of on-site monitoring data reveals that the monitoring points at 5.1, 6.1 and 7.1
fluctuate greatly, which is caused by changes in the excavation structure. The change trend of the overall surrounding rock stress is consistent with the change trend of numerical calculation, which verifies the accuracy of the model.

5. **Numerical analysis of surrounding rock strain excavated by layered cutting**

5.1. *Strain numerical simulation effect analysis*

![Figure 8. Strain cloud diagram of surrounding rock excavated from the first to the eighth floors.](image)

According to the numerical simulation calculation results, as the number of excavation layers continues to increase, the surrounding rock strain changes significantly at the floor, and the vault continues to increase with the excavation of the cave:

- During the excavation of the first layer, the strain on the central axis of the vault (that is, at the monitoring point 1.2) reached a maximum value of 4.79mm, the maximum side wall strain was 2.75mm, and the maximum floor strain was 1.50mm; when the second layer was excavated, the arch top central axis strain reaches a maximum value of 4.82mm, the side wall strain maximum value...
is 2.75mm, and the bottom plate strain maximum value is 1.25mm; when the third layer is excavated, the arch top center axis strain reaches a maximum value 4.84mm, and the side wall strain maximum value Is 2.50mm, the maximum floor strain is 1.00mm; when excavating the fourth floor, the central axis strain of the vault reaches the maximum value 4.87mm, the maximum side wall strain is 2.50mm, the maximum floor strain is 1.25mm; the fifth floor During excavation, the central axis strain of the dome reaches a maximum of 4.88mm, the maximum side wall strain is 2.75mm, and the maximum floor strain is 1.25mm; during the sixth layer excavation, the central axis strain of the dome reaches a maximum value of 4.90mm, The maximum side wall strain is 2.75mm, and the maximum floor strain is 0.75mm; during the seventh floor excavation, the central axis strain of the vault reaches a maximum of 4.91mm, the maximum side wall strain is 2.50mm, and the maximum floor strain is 0.75 mm; when excavating the eighth floor, the central axis strain of the vault reaches a maximum of 4.94 mm, the maximum side wall strain is 2.50 mm, and the maximum floor strain is 0.50 mm.

In summary, with the increase of the number of excavation layers, the strain of the vault also keeps increasing, the strain of the central axis of the vault always maintains the maximum value, and gradually decreases to both sides; With the increase of the number of excavated layers, the floor strain decreases from 1.50mm of the first layer to 0.50mm layer by layer; The maintenance of the structure is related to maintenance.

5.2. Contrast Analysis of Strain Monitoring and Numerical Calculation Data of Surrounding Rock
Install multi-point displacement meters on the vault (monitoring points 1.2, 1.4) and side walls (monitoring points 2.2, 3.2, 4.2, 5.2, 6.2, 7.2, 8.2, 9.2, 10.2), and draw based on the monitoring data Figure 9, Figure 10 (data as of December 2019), get:

Figure 9. Displacement graph of monitoring data of the arch roof, upstream arch foot and downstream arch foot of the underground powerhouse.

Figure 10. Displacement diagram of monitoring data of the side wall of the underground powerhouse.

It can be seen from Figure 9 that the maximum displacement of the surrounding rock at the vault of the cave is 4.80mm and the minimum displacement is 4.11mm; the displacement of the surrounding rock at the vault is significantly higher than that at the arch foot, the reason for this difference and the
structure of the surrounding rock Inseparable; there is a misalignment zone in the gentle-inclined layer near the dome. Due to the misalignment zone, the surrounding rock is relatively broken, and the gentle-inclined structural plane parallel to the dome is densely developed. The maximum displacement of the surrounding rock at the arch foot of the cave is 3.80mm; the minimum displacement of the surrounding rock at the arch foot of the cave is 3.23mm; the same monitoring section: a. The displacement of the surrounding rock with the number of excavation layers The increase and change range is not large; b. The difference in displacement of the surrounding rock of the arch foot of the upstream and downstream is not large.

According to the deformation characteristics of the surrounding rock of the arch vault excavation, the deformation of the surrounding rock vault is divided into unstable and stable types. The characteristics of the unsteady deformation of the surrounding rock are: the amount of deformation is large, and the excavation increases stepwise; The characteristics of the stable deformation of the surrounding rock are: the amount of deformation is small or even slightly rebound, and the excavation has no obvious effect on it.

Compare the on-site monitoring data and numerical calculation data of the side walls on both sides, and calculate the difference ratio. The difference ratio is the difference between the simulated calculation value of the index value and the actual monitoring value. The actual monitoring value is shown in Table 2. According to the calculation data, the difference between the numerical calculation data and the on-site monitoring data reached the maximum at the sixth layer of excavation, which was 29.1%, which was caused by the change of the excavation structure.

| Horizon | Elevation (m) | Excavation stage | Actual monitoring value (mm) | Numerically calculated value (mm) | Difference ratio |
|---------|--------------|-----------------|------------------------------|----------------------------------|-----------------|
| One     | 64.62~66.00  | The first layer is dug | 2.45                         | 2.75                             | 12.2%           |
| Two     | 63.23~64.62  | The second layer is dug | 2.47                         | 2.75                             | 11.3%           |
| Three   | 61.85~63.23  | The third layer is dug | 2.35                         | 2.50                             | 6.4%            |
| Four    | 60.59~61.85  | The fourth layer is dug | 2.37                         | 2.50                             | 5.5%            |
| Five    | 59.32~60.59  | The fifth layer is dug | 2.68                         | 2.75                             | 2.6%            |
| Six     | 58.24~59.32  | The sixth layer is dug | 2.13                         | 2.75                             | 29.1%           |
| Seven   | 57.16~58.24  | The seventh layer is dug | 2.39                         | 2.50                             | 4.6%            |

6. Conclusion
In this paper, combined with the measured geological data of Wendeng Pumped Storage Power Station, through the numerical simulation analysis of the layered cutting excavation of the second layer, comparing the monitoring data, the stress-strain response law formula of the layered cutting excavation of the underground powerhouse cavern is deduced, and the following results are obtained:

(1) According to the numerical simulation calculation, when the cave is excavated from the first floor to the eighth floor, the stress of the side walls on both sides is symmetrically distributed and there is a maximum on the same floor. The stress of the first floor to the eighth floor The maximum values are: $5.52\times10^6\text{MPa}$, $4.83\times10^6\text{MPa}$, $5.44\times10^6\text{MPa}$, $4.89\times10^6\text{MPa}$, $4.59\times10^6\text{MPa}$, $4.01\times10^6\text{MPa}$, $4.16\times10^6\text{MPa}$ and $4.52\times10^6\text{MPa}$, the surrounding rock stress of the arch and floor is small; with the
excavation. With the increase of the number of layers, the stress on the side walls on both sides increases first and then decreases, and the stress on the surrounding rock of the vault and floor continues to increase, but the strain shows a trend of increasing layer by layer. The maximum value always appears near the central axis of the vault, and the first the maximum strain values of the layer to the eighth layer are: 4.79mm, 4.82mm, 4.84mm, 4.44mm, 4.87mm, 4.73mm, 4.90mm, 4.94mm.

(2) According to the strain monitoring data, the maximum displacement of the surrounding rock at the vault of the cave is 4.80mm, and the maximum displacement of the surrounding rock at the arch foot of the upstream and downstream is 3.80mm. The difference ratio is obtained, and the difference ratios of the excavation from the first floor to the eighth floor are 12.2%, 11.3%, 6.4%, 5.5%, 2.6%, 29.1% and 4.6% respectively. According to the calculation results, the first The difference ratio of the six-layer cutting and excavation reached the maximum value, which was 29.1%, which was mainly due to the change of the surrounding rock structure during the excavation.

(3) By comparing the numerical simulation calculation data with the on-site monitoring data, it can be obtained that the stress of the surrounding rock of the underground powerhouse generally keeps increasing first, then decreasing, then increasing, then decreasing, and finally the stable change law, the numerical calculation data and the site The monitoring data shows that the overall stress of the surrounding rock is stable at 5.00×10^6 MPa~6.00×10^6 MPa, and the tensile stress of the side wall suddenly increases when the sixth layer is excavated, and the maximum value is reached in many places; the maximum strain is at the arch top, and the numerical calculation data the on-site monitoring data shows that the maximum strain of the vault is 4.98mm, and the overall remains at 4.50mm~5.00mm; the strain of the side wall is stable at 2.5mm~2.75mm, which verifies the correctness of the simulation test and provides coordination with the deformation law for the underground powerhouse The supporting scheme guarantees the safe construction of the tunnel and provides a reference for similar projects.

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