Comprehensive Evaluation of Sensitivity of Surrounding Rock Parameters for Underground Powerhouse Experience Support

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Abstract. At present, the design and construction of underground powerhouse support are still in the experimental stage. Moreover, before the construction of the underground cavern group, the mechanical parameters of the surrounding rock mass cannot be accurately obtained. During the implementation process, these reasons may cause adjustments to the construction and design plans. To comprehensively evaluate the sensitivity of surrounding rock parameters, we used the multi-indicators, which have certain guiding significance for the accurate acquisition of surrounding rock parameters and the adjustment of empirical support schemes. This study combines the initial geological conditions of the underground powerhouse caverns of the hydropower station and the support scheme. We selected the key position deformation of the lining and the cable stress as the evaluation indicators. The elastic modulus, Poisson’s ratio, friction angle, and cohesion are the influencing factors for the comprehensive evaluation of sensitivity. The results show that the elastic modulus is a highly sensitive parameter for the empirical support scheme, the friction angle is a middling sensitive parameter, and the Poisson’s ratio is a low-sensitivity parameter. Moreover, it is reported that sensitivity is related to the selection of indicators.

1. Introduction
With its vibrant economic development, China’s energy structure is undergoing rapid changes. As one type of clean energy, hydropower is an important part of China’s energy structure. Consequently, research on the support of underground power plants during construction has gained prominence. In the 1960s, the support theory applicable to underground hydropower plants was formulated. The common support methods used at the time included shotcrete, anchor rods, and pre-stressed anchor cables. Using the underground powerhouse system of the hydropower station in Jinping, China, Zhihong et al. [1] investigated the long-term stress characteristics and temporal and spatial evolution law during and after the excavation of the system anchor by analyzing the long-term monitoring results of the anchor cable. Moreover, this study explored the factors influencing the force of the anchor cable structure and the long-term bearing risk under high stress. The long-term safety of the anchoring system is normally evaluated using numerical calculations. Jinxiu et al. [2] conducted an inductive study on the supporting parameters of 20 large-span underground powerhouses in China and postulated empirical formulas for the ratio of the supporting strength of the bolts and prestressed anchors to the surrounding rock strength stress and the span of the powerhouse. Moreover, they proposed the concept of supporting index and corresponding calculation formula, and suggested that...
the supporting index can be used to evaluate the surrounding rock supporting strength. Kun et al. [3] established a 3D geological model of the underground powerhouse of a large hydropower station through finite element software and simulated the excavation and support process using a self-editing program. This culminated in the evolution law of the surrounding rock displacement, calculation of stress, and determination of the plastic zone and supporting force during the excavation and support process, thus guiding on-site design and construction. On the basis of the analysis of support optimization of block theory, Yumin et al. [4] completely considered the relative position of surrounding rock faults, veins, and joints. Using UnWedge, they comprehensively evaluated the positioning, semi-positioning, geometric characteristics, sliding mechanism, and stability of random blocks. In Huachun's study [5], which is based on the underground powerhouse of Taolai River Sandaowan Hydropower Station in Gansu Province, the stress state of surrounding rock and the deformation of the cavern with or without the system anchor cable support were analyzed. Moreover, the necessity for anchor cable support was demonstrated, and the design of the anchor length was optimized. However, Zhu et al. [6] analyzed the calculation results of the underground powerhouse of the Xiaolangdi Water Control Project under different lateral pressure coefficients and with or without supporting structures. The results show that the lining structure has little effect on the surrounding rock displacement and plastic zone and that the excavation process has minimal effect on the stress of pre-stressed anchor cable.

Because of the complexity of the surrounding rock of an underground cavern, the relevant theory of surrounding rock support is still evolving, and the design and construction are still in the empirical stage. Therefore, additional research is required to understand the problems related to underground cavern support.

Using the underground powerhouse of the Suki Kinari Hydropower Station as a case study, we establish a 3D geological finite element model is established through ABAQUS in this study. Taking elastic modulus, we selected the Poisson’s ratio, internal friction angle, and cohesive force as influencing factors; moreover, multiple indicators of lining convergence deformation and anchor cable stress increment are selected to establish an evaluation plan. A comprehensive evaluation of the sensitivity of empirical support to surrounding rock parameters is conducted. The results show that the elastic modulus, internal friction angle, and cohesion are highly sensitive parameters during the excavation of the underground powerhouse, whereas the Poisson's ratio has low sensitivity. Moreover, the comprehensive sensitivity of the surrounding rock parameters is related to the selection of evaluation indicators. On the basis of these results, the accurate values of surrounding rock parameters can be selectively obtained on-site by comparing the changes of surrounding rock parameters obtained before and after. The supporting scheme of surrounding rock is re-evaluated as per the comprehensive sensitivity of the surrounding rock parameters.

2. Comprehensive Evaluation Model of Sensitivity

Sensitivity analysis is extensively used in statistics to assess the degree of influence and sensitivity of factors in a program that are uncertain. Zhu et al. [7] introduced and popularized sensitivity analysis to the field of geotechnical engineering; however, the sensitivity of geotechnical parameters often cannot be determined by a single indicator such as deformation or change in stress. Therefore, to conduct a comprehensive sensitivity analysis in this study, multiple lining convergence deformations and anchor cable stress changes are selected as evaluation indicators.

2.1. Weights of different evaluation indicators

Because there are multiple evaluation indexes selected in this study, the weight of each evaluation index needs to be determined in the process of the comprehensive evaluation.

To analyze the sensitivity of the different parameters using the methods suggested by Zhu and He [7] and Wang and Chen [8], we can define the parameter sensitivity of the dimensionless form as follows:
where $s$ is the parameter sensitivity; $\alpha$ and $F$ represent the standard value of the parameter and the calculated value of the corresponding indicator under the standard parameter, respectively; and $\Delta \alpha$ and $\Delta F$ represent the change of the parameter and the change of the corresponding calculated value of the indicator, respectively.

Huang et al. [9] and Li [10] suggested that the weight between each index should be determined using the entropy method.

Assuming that the numbers of evaluation indicators and parameters are $m$ and $n$, respectively, then the corresponding sensitivity matrix can be written as follows:

$$
\begin{bmatrix}
s_{ij}
\end{bmatrix} = \left[ \begin{array}{ccc} s_{11} & s_{12} & L & s_{1j} \\
s_{21} & s_{22} & L & s_{2j} \\
M & M & O & M \\
s_{i1} & s_{i2} & L & s_{ij} \\
\end{array} \right]
$$

$$
s_{ij} = \left( \frac{\Delta F_{ij}}{F_{ij}} \right) / \left( \frac{\Delta \alpha_{ij}}{\alpha_{ij}} \right)
$$

Before the entropy method is used to calculate the weight of each index, it is necessary to normalize the above matrix. The standardization method is as follows:

$$
c_{ij} = \frac{s_{ij} - \min (s_{1j}, s_{2j}, \ldots, s_{nj})}{\max(s_{1j}, s_{2j}, \ldots, s_{nj}) - \min(s_{1j}, s_{2j}, \ldots, s_{nj})}
$$

where $c_{ij}$ is the parameter sensitivity after standardization. The matrix $C_{ij}$ formed by $c_{ij}$ is called the standardized matrix.

According to Equation (4), the sensitivity entropy value of each index is calculated as follows:

$$
e_i = \frac{-\sum_{j=1}^{n} (p_{ij} \cdot \ln(p_{ij}))}{\ln(n)}
$$

where $p_{ij}$ is the normalized matrix specific gravity value, i.e., under a certain parameter. The proportion of the sensitivity of different indicators to this parameter is solved as follows:

$$
p_{ij} = \frac{c_{ij}}{\sum_{i=1}^{m} c_{ij}}
$$
where \( p_{ij} \) in the logarithmic solution must be >0; hence, Equation (5) needs to be modified. Moreover, Equation (6) is adopted as follows [11]:

\[
p_{ij} = \frac{\left(1 + c_{ij}\right)}{\sum_{i=1}^{m} \left(1 + c_{ij}\right)}
\]

(6)

The weight of each index can then be calculated as follows:

\[
W_i = \frac{f_i}{\sum_{i=1}^{m} f_i}
\]

(7)

where \( f_i \) is the redundancy of the sensitivity entropy value \( f_i = 1 - e_i \).

2.2. Discrimination Matrix and Recognition Criteria for Sensitivity

In this study, the sensitivity discrimination matrix is established under the concepts of attribute set, attribute space and attribute measure proposed by Cheng et al. [12–14]. Assuming that \( D \) is the research object and \( X \) is one of the attributes, then \( D \) is called the attribute space and \( X \) is the attribute set. In this study, the sensitivity of the surrounding rock parameters studied is the attribute space, and the sensitivity of a certain parameter is the attribute set. The attribute measurement is used to describe the sensitivity of a parameter.

According to the above concept, the sensitivity discrimination matrix is established as follows:

\[
\begin{bmatrix}
C_1 & C_2 & C_3 \\
X_1 & d_{11} & d_{12} & d_{13} \\
X_2 & d_{21} & d_{22} & d_{23} \\
X_3 & d_{31} & d_{32} & d_{33} \\
X_4 & d_{41} & d_{42} & d_{43}
\end{bmatrix}
\]

(8)

The values in the formula are as follows:

\[
\begin{cases}
d_{11} = d_{21} = d_{31} = d_{41} = 1/3 \\
d_{12} = d_{22} = d_{32} = d_{42} = 2/3 \\
d_{13} = d_{23} = d_{33} = d_{43} = 1
\end{cases}
\]

(9)

There is no good standard for the relationship between sensitivity value and relative strength. In this study, we used the standardized sensitivity values, and the sensitivity of different parameters are categorized into the following: low sensitivity \( C_1 \), medium sensitivity \( C_2 \), and high sensitivity \( C_3 \). The sensitivity measurement coefficient is then calculated as follows.

When \( c_{ij} \leq d_{lj} \ (l = 1, 2, 3, 4) \), the measurement coefficient is considered as \( L_{ij1} = 1, L_{ij2} = 0 \), and \( L_{ij3} = 0 \).

When \( d_{ik-1} < c_{ij} \leq d_{ik} \ (l = 1, 2, 3, 4; k = 2, 3) \), it is considered as
The other value is zero.

Assuming the number of indicators is \( m \) and the importance of each indicator is different, we can obtain the weight of the measurement coefficient in Equation (7). Then, the comprehensive measurement coefficient [13] of the sensitivity of each surrounding rock parameter is as follows:

\[
L_{jk} = \sum_{i=1}^{m} W_i \cdot L_{ijk} \quad (k = 1, 2, 3)
\]  

(11)

We used different parameters of the surrounding rocks are calculated using the above formula. These relate to the comprehensive measurement coefficients of different degrees of sensitivity. The sensitivity level of a parameter can then be determined according to the confidence criterion. Generally, the confidence level is set to \( \zeta = 0.6 \sim 0.7 \). The specific judgment criteria are as follows [14]:

\[
z_j = \min \left\{ z : \sum_{k=1}^{K} L_{jk} \geq \xi, 1 \leq k \leq K \right\}
\]

(12)

The above confidence criteria can roughly determine the sensitivity of the surrounding rock parameters. According to Equation (13), the sensitivity of two parameters can be compared and scored as follows:

\[
g_j = \sum_{k=1}^{K} k \cdot L_{jk}
\]

(13)

3. Engineering Application and Three-Dimensional Model Establishment

3.1. Engineering situation

Located on the Kunhar River in Khyber Pakhtunkhwa Province, which is located in the northwest China–Pakistan border, the Suki Kinari Hydropower Station is a high-head, long tunnel diversion-type hydropower project. The main buildings of the power plant include the main machine room, the transformer room, the busbar tunnel, the cable and ventilation tunnel, the entrance access tunnel, the tailrace tunnel, and the switch station.

The underground plant adopts a tail-type layout scheme. The embedded depth of the main plant is vertically at \( \sim 450 \text{ m} \) and horizontally at \( \sim 750 \text{ m} \). The room section of the main plant is a straight-walled round arch with a net span of 24.0 m, a total height of 53 m, and a length of 134.6 m. Moreover, the main transformer room has a net span of 17.8 m, a height of 33.35 m, and a length of 126.85 m. Four busbar tunnels connect the main room and main transformer room. The cross-section of a busbar tunnel is a straight-walled round arch with a height of 6.70 m and a length of 45.0 m. An access tunnel is provided at the left and right ends of the main transformer room to connect with the main plant building. The cross-sectional dimensions are \( 7.15 \times 7.80 \text{ m} \) and \( 2.2 \times 3.0 \text{ m} \); the net size of the tailrace tunnel is \( 5.0 \times 5.5 \text{ m} \).

According to the preliminary geological survey data, it is inferred that the surrounding rock type in the plant area is mainly Q2. The middle and lower parts of the downstream sidewall are affected by the busbar and tailrace tunnels, and the surrounding rock type is mainly Q2a.
As shown in Fig. 1, the shotcrete and prestressed anchor cables are mainly used for underground powerhouse support.

![Figure 1 Support structure of underground powerhouse](image)

3.2. The three-dimensional model of the underground powerhouse

According to experience, the finite element model of underground engineering is generally five to eight times the underground engineering size, so the finite element model size is five times the underground powerhouse size, which is 1,000 m × 600 m × 300 m. The average embedded depth of the model top is 300 m. The solid elements C3D4 and C3D8 are used for the surrounding rock, whereas the shell element S3R is used for the lining. The rod element T3D2 is used for the anchor cable, which consists of a total of 802,551 units and 1,054,057 nodes. The finite element model of the lining support and anchor cable support of the underground powerhouse is shown in Fig. 2.

![Figure 2 Finite element model of the supporting structure of the underground powerhouse](image)

(a) (b)

Figure 2 Finite element model of the supporting structure of the underground powerhouse: (a) lining structure and (b) anchor cable

The settings of the initial ground stress of boundary conditions and simulations are as follows. The normal constraints are imposed on the bottom and sides of the model, whereas a node on the bottom is fixed to prevent rigid body displacement during the model calculation. For the top surface of
the model, the gravity of the overlying soil layer can be calculated through the burial depth, and the soil weight and tectonic stress are applied. The Drucker–Prager model was used in the analysis.

Because the dimension of the underground powerhouse is large, its construction will be a long-term continuous process. Figure 3 shows the excavation plan used for this construction.

![Figure 3 Schematic diagram of underground powerhouse excavation](image)

The surrounding rock parameters were obtained from on-site geological survey data and construction data, as shown in Table 1.

| Elastic modulus (GPa) | Poisson's ratio | Internal friction angle (°) | Cohesion (MPa) |
|-----------------------|----------------|---------------------------|----------------|
| Size                  | 10.69          | 0.3                       | 41.5           | 1.99           |

4. Comprehensive evaluation of parameter sensitivity of surrounding rock
Because of the complex shape of the underground powerhouse, 44 key locations were selected as evaluation indicators. The data of these indicators are from the test results. Out of these, 22 were selected for lining, that is, 11 powerhouses (C1–C11) and 11 main transformer rooms (Z1–Z11) (Fig. 4). At the same time, the nearest anchor cable was selected as the other 22 indicators. The anchor cables in the powerhouse area and the main transformer were named CS1–CS11 and ZS1–ZS11, respectively.
The sensitivity of the surrounding rock parameters to the above 44 indicators is shown in Table 2. It can be seen from Table 2 that the sensitivity of the surrounding rock parameters depends on the indexes selected for evaluation. For example, the sensitivity of elastic modulus is significantly higher than that of the other three parameters when C3 is selected as the evaluation index. However, when...
CS4 is selected as the evaluation index, the sensitivity of elastic modulus is the lowest, and the sensitivity of cohesive force and internal friction angle is high. Therefore, during the construction of large underground caverns, a single index cannot be selected for the sensitivity evaluation of the surrounding rock parameters. Instead, multiple indexes should be selected for a comprehensive evaluation.

The data in Table 2 are standardized by using Eq. (3), and the entropy value of the standardized data is calculated by using Eqs. (4) and (6). Finally, Eq (7) can be used to obtain the weight of each index, as shown in Table 3.

| Name | Weight | Name | Weight | Name | Weight | Name | Weight |
|------|--------|------|--------|------|--------|------|--------|
| C1   | 0.0228 | Z1   | 0.0227 | CS1  | 0.0226 | ZS1  | 0.0225 |
| C2   | 0.0227 | Z2   | 0.0228 | CS2  | 0.0228 | ZS2  | 0.0229 |
| C3   | 0.0227 | Z3   | 0.0227 | CS3  | 0.0226 | ZS3  | 0.0227 |
| C4   | 0.0228 | Z4   | 0.0226 | CS4  | 0.0228 | ZS4  | 0.0225 |
| C5   | 0.0228 | Z5   | 0.0228 | CS5  | 0.0227 | ZS5  | 0.0227 |
| C6   | 0.0227 | Z6   | 0.0228 | CS6  | 0.0229 | ZS6  | 0.0229 |
| C7   | 0.0228 | Z7   | 0.0226 | CS7  | 0.0227 | ZS7  | 0.0227 |
| C8   | 0.0227 | Z8   | 0.0228 | CS8  | 0.0227 | ZS8  | 0.0228 |
| C9   | 0.0227 | Z9   | 0.0227 | CS9  | 0.0229 | ZS9  | 0.0228 |
| C10  | 0.0228 | Z10  | 0.0226 | CS10 | 0.0226 | ZS10 | 0.0226 |
| C11  | 0.0228 | Z11  | 0.0226 | CS11 | 0.0227 | ZS11 | 0.0227 |

According to Eqs. (10) and (11), the attribute measure of the surrounding rock parameters can be obtained, as shown in Table 4.

| Low sensitivity | Elastic modulus | Poisson's ratio | Internal friction angle | Cohesion |
|-----------------|-----------------|-----------------|-------------------------|---------|
| 0.454           | 0.757           | 0.612           | 0.865                   |
| Moderate sensitivity | 0.045       | 0.015           | 0.121                   | 0.073   |
| High sensitivity | 0.501           | 0.228           | 0.267                   | 0.062   |

Assuming confidence of $\xi = 0.7$, we can see that the elastic modulus is a high-sensitivity parameter, the internal friction angle is a medium-sensitivity parameter, and the Poisson's ratio and cohesion are low-sensitivity parameters.

The comprehensive sensitivity of surrounding rock parameters is scored by using the evaluation criteria (Table 5).

| Score | 2.047 | 1.471 | 1.655 | 1.197 |

It can be seen from Table 5 that the sensitivity order is as follows: elastic modulus > internal friction angle > Poisson's ratio > cohesion.

The following conclusions can be drawn from the above analysis.
When the evaluation indexes are different, the sensitivity analysis results of surrounding rock parameters will be very different. Therefore, when the comprehensive evaluation of sensitivity is performed, important indexes such as the displacement of key nodes and the stress changes of key anchor cables should be selected.

When the surrounding rock parameters are acquired, the elastic modulus is the most important, followed by the internal friction angle. On the other hand, the Poisson's ratio and cohesion are of minimal importance.

For the surrounding rock parameters obtained when the elastic modulus is significantly different from the selected standard parameter, the excavation and support scheme of the underground cavern need to be re-evaluated.

5. Conclusions
In this paper, on the basis of the excavation of the underground powerhouse of the Suki Kinari Hydropower Station, the multiple lining convergence deformations and anchor cable stress increments are selected as the evaluation indicators to evaluate the sensitivity of surrounding rock parameters comprehensively. The evaluation results show that the elastic modulus, internal friction angle, and cohesion of surrounding rock are highly sensitive parameters, whereas the Poisson's ratio is a low-sensitivity parameter. By scoring the comprehensive sensitivity of surrounding rock parameters, we found that the internal friction angle is the most sensitive parameter, followed by the elastic modulus. The cohesion is slightly weaker than the other two parameters. The findings of this study provide important guidance for the next construction of underground caverns and the adjustment of the support scheme.

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