Comparative Simulation Research on Stability of Layered and Homogeneous Surrounding Rocks

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Abstract—Layered surrounding rock mass is common in underground engineering, and it has obvious anisotropic mechanical properties. Therefore, the stability of the cavern excavation of layered surrounding rocks has always been a key issue in the engineering community. Based on an example of a hydraulic tunnel, the stability analysis of the excavation in cavern of the layered and homogeneous surrounding rocks are compared. The results show that the overall distribution of the stress field and displacement field of the layered and homogeneous surrounding rocks are basically the same. The stress field of the layered surrounding rocks has obvious discontinuous characteristics, and the deformation caused by excavation of the cavern is greater than the homogeneous surrounding rocks. The extent of the plastic zone along the joints of the layered surrounding rocks is also significantly larger than that of the homogeneous surrounding rocks.

1. INTRODUCTION

The terrain and geomorphological characteristics of mountain areas determine that a large number of tunnels and underground caves will inevitably appear in projects such as transportation and hydraulic engineering. However, the geological structure and lithology of mountainous areas are more complicated. Tunnels and caves often have to go through various unfavorable geological conditions [1]. Layered surrounding rock mass is a kind of rock mass often encountered in tunnel engineering. The deformation and failure of surrounding rocks are controlled by structural planes. Weak joints and cracks cut the surrounding rocks, making the surrounding rock materials have the different structural characteristics from the rock specimen, with its anisotropic mechanical properties [2]. Due to the
existence of inter-layer joints, the damage and deformation of the surrounding rocks are unevenly developed [3]. The stability of the surrounding rocks at different locations around the cavern is also different. Its deformation and strength characteristics are more complicated than homogeneous surrounding rocks. Affected by the bedding distribution, the damage and deformation development of surrounding rocks also differ at different locations [4]. Therefore, it is easy to cause the bias phenomenon of the surrounding rocks of the cavern.

In the process of traversing layered surrounding rocks, if there is insufficient understanding, improper construction or ineffective measures, it will often cause landslides. It may bring great difficulties to construction, delay the construction period, consume funds, and bring hidden dangers to construction and operation safety [5].

2. ENGINEERING SIMULATION AND CALCULATION CONDITION

The burial depth of a diversion tunnel of a certain hydropower station is about 25m. The excavation section is a gate-type tunnel, the central angle of the top arch arc is 180°, the radius is 4m, and the side wall height is 6m. The excavation scheme is a one-time excavation. According to the analysis of the provided geological data, the stratum surrounding rocks can simplify the striped fringe marble and the weakly weathered crystalline limestone. Marble has two sets of parallel joints, both of which have a certain degree of connectivity. The crystalline limestone has a set of conjugate joints.

Establish a numerical model based on engineering data, as shown in Figure 1. The upper boundary of the calculation area is taken to the surface. The left, right and lower boundaries are more than 5 times of the cavern diameter. Known boundary conditions are taken as displacement constraints. The upper boundary is a free boundary, the left and right are horizontal displacement constraint boundaries, and the lower is a vertical displacement constraint boundary. The yield criterion for the constitutive model of the surrounding rock mass is the ideal elastoplastic Mohr Coulomb criterion, that is, after the stress and strain pass through the elastic stage and reach the peak value, the ideal state enters the yield platform along the peak strength. The material parameters of layered surrounding rocks are shown in Table 1.

| Rock mass | Bulk density (kN/m³) | Deformation modulus (GPa) | Poisson ratio | Cohesion (MPa) | Friction factor |
|-----------|----------------------|---------------------------|--------------|----------------|----------------|
| Zone I    | 27                   | 10                        | 0.3          | 0.2            | 0.58           |
| Zone II   | 27                   | 20                        | 0.25         | 0.3            | 0.84           |

This calculation and analysis uses Mohr Coulomb slip constitutive model on shear strength criterion for structural planes. The shear strength follows Mohr Coulomb criterion. The material parameters for structural planes is shown in Table 2.

| Structural plane category | Peak internal friction angle (°) | Peak cohesion (MPa) | tensile strength | Normal stiffness (MPa/m) | Shear stiffness (MPa/m) |
|--------------------------|---------------------------------|---------------------|------------------|------------------------|------------------------|
| Joint 1                  | 20                              | 0                   | 0                | 100000                 | 10000                  |
| Joint 2                  | 25                              | 0                   | 0                | 250000                 | 10000                  |
| Joint 3                  | 27                              | 0                   | 0                | 250000                 | 10000                  |

According to geological data, the joints in zone I are parallel joints. For one group of the joints, the angle is 45°, the spacing is 3m, the extension length is 4m, and the connectivity rate is 0.7. For the other group of the joints, the angle is -10 °, the spacing is 2m, and the extension length is 2m and the connectivity rate is 0.5. The structural surface type of those joints in zone I is joint 1. the joints in zone II joints are cross joints. For one group of the joints, the angle is -21°, the spacing is 2m, the structural surface type is joint 2. For the other group of the joints, the cross joint angle is 69°, the spacing is 5m, and the structural surface type is joint 3.
In order to study the difference between the layered and the homogeneous surrounding rocks under the excavation of the cavern, a numerical calculation model of the homogeneous surrounding rocks is established, as shown in Figure 2, without considering the joints of the layered surrounding rocks. The boundary conditions are consistent with the layered surrounding rock mass. The yield criterion for the constitutive model of the surrounding rocks is selected from the Hoek-Brown criterion. It can consider the influence of the structure surface on the discontinuities formed by the cutting of the rock mass. The material parameters of homogeneous surrounding rocks are shown in Table 3.

**TABLE 3 PARAMETERS OF HOMOGENEOUS SURROUNDING ROCKS**

| Rock mass | GSI | UCS (MPa) | modulus (GPa) | m | Poisson ratio | Bulk density (kN/m³) |
|-----------|-----|-----------|---------------|---|---------------|---------------------|
| Zone I    | 20  | 18        | 10            | 8 | 0.3           | 27                  |
| Zone II   | 30  | 25        | 20            | 10| 0.25          | 27                  |

3. RESEARCH ON THE CONVERGENCE CRITERION OF HOEK-BROWN FAILURE CRITERION

In this paper, based on the generalized Hoek-Brown failure criterion associated with geological data and the finite element energy convergence criterion, the Hoek-Brown failure criterion and energy convergence criterion are embedded in the finite element software. The maximum and minimum principal stress envelope formula of the Hoek-Brown failure criterion is as follows:

\[
\sigma_1' = \sigma_3' + \sigma_{c1}(m_b \sigma_{c1} + s)^\alpha
\]

Where, \(\sigma_1'\) and \(\sigma_3'\) are the maximum and minimum effective principal stresses at failure; \(\sigma_{c1}\) is uniaxial tensile strength of complete rock mass; \(m_b\), \(s\) and \(\alpha\) are the rock mass material constants which are related to the geological strength index GSI, holonomic rock parameter and complete rock
deformation modulus. According to the relationship between stress and strain, strain and displacement, and the finite element static analysis convergence criterion, the formula is as follows:

$$K\Delta U^{(i+1)} = P^{(n)} - F^{(i)}$$  \hspace{1cm} (2)

Where, $K$ is finite element stiffness matrix; $P$ is external loading; $F$ is internal response; $\Delta U$ is finite element mesh node displacement; $i$ is iteration steps; $n$ is number of external loading. Iterative analysis is continuously performed in the calculation, and finally the defined energy convergence tolerance is satisfied as the stable convergence criterion of the Hoek-Brown criterion. the formula is as follows:

$$\left\|{\frac{\Delta U^{(i)}(P(n)-F(0))}{\Delta U^{(0)}(P(n)-F(0))}}\right\| < \text{Defined energy tolerance}$$  \hspace{1cm} (3)

In this paper, the energy tolerance is defined as 0.001, which is used as the criterion for the stability and convergence of the surrounding rock calculated and analyzed by the Hoek-Brown failure criterion.

4. COMPARATIVE ANALYSIS OF SURROUNDING ROCKS STABILITY SIMULATION

First, the initial stress field of the surrounding rock under its own weight is calculated. The initial vertical stresses of the layered and homogeneous surrounding rocks are shown in Figure 3 and Figures 4. The vertical stress field of the homogeneous surrounding rock is controlled by its own weight, and it is basically distributed in layers along the depth, and the position of the boundary of the rock layer is offset. The vertical stress field of layered surrounding rock shows obvious discontinuous stress contours due to the cutting of various joint groups, but the overall distribution law is basically consistent with the homogeneous surrounding rock.

Under the conditions of the initial stress field of the surrounding rocks, the stability calculation of the excavation of the cavern is performed. The displacement contour maps of the layered and homogeneous surrounding rock, the plastic area and displacement vector around the cavern are shown in Figure 5 to Figure 10. It can be seen from the figures:
(1) After excavation of the cavern, the surrounding rock is deformed towards the hollow surface under the initial ground stress, that is, the deformation is concentrated in the surrounding rock of the cavern. The deformation of the right side walls is the largest.

(2) After excavation of layered and homogeneous surrounding rocks, the overall law of surrounding rocks deformation is consistent.

(3) Due to the cutting of the joint group in the plastic zone of the layered surrounding rocks, a large plastic zone will appear along the joint direction. It shows obvious layered regularity. The position with the largest extension of the plastic zone appears at the top of the left wall.

(4) From the displacement vector of the layered surrounding rocks, the starting points of the vectors are where the joints are. It indicates that the joints have the tendency and possibility of spreading, shifting, slipping and instability when there is an hollow surface.

(5) For the excavation of the layered surrounding rocks, the left side wall is prone to slip and damage along the side layer. The right side wall may be subject to tensile damage at the bottom corner, and the rock blocks may be peeled off, then dumping failure happened. These two failure mechanisms should be paid enough attention in practical engineering.

Figure 5. Vertical displacement contour map of layered surrounding rocks (m)

Figure 6. Vertical displacement contour map of homogeneous surrounding rocks (m)

Figure 7. Plastic zone of layered surrounding rocks

Figure 8. Plastic zone of homogeneous surrounding rocks
Figure 9. Displacement vector of layered surrounding rocks

Figure 10. Displacement vector of homogeneous surrounding rocks

According to the calculation results, a comparison table of the excavation influences of layered and homogeneous surrounding rocks cavern is compiled, as shown in Table 4. It can be seen from the table that the horizontal and vertical deformation of the layered surrounding rocks is greater than that of the homogeneous surrounding rocks around the excavation of the cavern. It indicates that the cutting of layered surrounding rocks joints has destroyed the integrity of the rock mass to a certain extent, and the surrounding rocks are greatly affected by excavation disturbance. For horizontal displacement, the layered surrounding rocks at bottom is relatively larger than that of homogeneous surrounding rocks. The main reason is that the deformation develops along the bedding tendency toward the hollow surface.

The inversion analysis of the parameters in the equivalent simulation Hoek-Brown method is mainly based on the GSI and mi indicators. After the inversion calculation, the comparison of the displacement of the monitoring points is shown in Table 5. The average error is within 5%, which meets the engineering accuracy requirements. Combining the stress field and displacement field laws, it shows that the equivalent method is also more suitable for simulating the excavation and deformation of layered surrounding rocks. At this time, it is especially suitable for the surrounding rocks with very well-developed joints and cannot simulate the binary medium.

### Table 4. Comparison of the Impacts of Layered and Homogeneous Surrounding Rocks

| Surrounding rocks category | Direction of displacement | Displacement increased ratio relative to homogeneous surrounding rocks (%) |
|----------------------------|---------------------------|---------------------------------------------------------------------|
|                            |                           | Top    | Right | Bottom | Left  |
| Layered surrounding rocks   | Horizontal                | 31.6   | 4.8   | 69.0   | 7.1   |
|                            | Vertical                  | 31.7   | 27.6  | 23.6   | 63.2  |

### Table 5. Comparison of Layered and Homogeneous Surrounding Rocks After Parameter Inversion

| Surrounding rocks category | Direction of displacement | Displacement increased ratio relative to homogeneous surrounding rocks (%) |
|----------------------------|---------------------------|---------------------------------------------------------------------|
|                            |                           | Top    | Right | Bottom | Left  |
| Layered surrounding rocks   | Horizontal                | 4.9    | 0.8   | 6.1    | 2.1   |
|                            | Vertical                  | 3.7    | 3.6   | 3.3    | 5.2   |

### 5. Conclusion

In the case of excavation of the cavern, the deformation of the surrounding rocks is mainly concentrated around the cavern, and it is deformed towards the hollow surface of the excavation. The deformation of the layered surrounding rocks at the periphery of the cavern is greater than that of the homogeneous surrounding rocks. The layered surrounding rocks are deformed along the bedding direction toward the
air surface at the position of the floor, and the displacement of the floor and the right wall is large, which may lead to damage first, and then cause the right surrounding rocks to collapse and fail.

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