Stability analysis of surrounding rock of high-pressure cavern tunnel under coupled stress-damage-seepage

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Abstract: The high-pressure cavern is located below the diversion tunnel, which will produce a large seepage force during the excavation process. Consider the effect of seepage field on the stress field with the seepage force, consider the effect of stress and damage on the seepage field through the improved Louis formula, and establish the stress-damage-permeability coefficient equation to consider the effect of stress and damage on the seepage field. The three-dimensional elastoplastic damage finite element analysis of rock mass structure has established a stress-damage-seepage calculation model for surrounding rock excavation of a diversion tunnel with high-pressure cavities. A sequential iteration method is proposed to summarize the above factors and then iteratively solve them in a certain order. Based on a water diversion project, the relevant calculation examples are appropriately simplified. The results show that the seepage effect has a greater impact on the stability of the surrounding rock of the diversion tunnel, and it can be seen that the coupling effect cannot be ignored in the analysis of the stability of the surrounding rock of the excavation of the diversion tunnel.

1. Introduction

With the continued advancement of my country's western development, deep-buried long tunnels will inevitably appear in highway projects, railway projects, and water diversion projects. Due to the complex terrain and special geological conditions in the western region, the tunnel project will inevitably encounter faults, high-pressure caverns and other bad geological conditions. The high ground stress and high water head encountered during the excavation process will seriously affect the safety of the project which often brings severe challenges to engineering construction. This paper takes the diversion tunnel as the research object to study the stability of surrounding rock under the coupling of stress-damage-seepage during tunnel excavation.

For deep-buried diversion tunnel projects, the interaction between groundwater and rock mass is an important influencing factor. Many scholars have done a lot of research on the coupling analysis of seepage-stress: Zhang Wei [5] studied the surrounding rock stability of underground caverns under the...
action of stress-damage-seepage coupling analysis; Chen Weizhong [6-7] conducted related studies on the influence of the interaction between hydraulics and the dynamic evolution of the permeability coefficient on the stability of the surrounding rock and lining of the diversion tunnel; Based on the Biot consolidation theory, Ma Rongfu [8] established the functional relationship between permeability coefficient and deformation, and performed numerical simulation analysis on the hydraulic coupling of fractures during tunnel excavation; Zhang Jixun [9] used ABAQUS finite element secondary development for a deep-buried tunnel project in a water-rich area to realize the coupling of seepage field and stress field, and talked about the necessity of coupling analysis in deep-buried underground engineering; In terms of the seepage volume force, Zhang Guoxin [10] analyzed and compared various finite element seepage load calculation methods with the seepage force and the pore pressure as the initial stress;

This paper proposes a sequential iteration method to summarize the stress, damage, seepage and other factors and then iteratively solve them in a certain order. The stability of the surrounding rock of the diversion tunnel through the high-pressure cavern under the coupling of stress-damage-seepage is comprehensively considered.

2. Stress-damage-seepage coupling analysis model

2.1 Three-dimensional elastoplastic damage finite element calculation model [11]

The expression of stress differential increment under the damage state is as follows:

$$
\Delta \sigma_{ij} = (1 - D) \left[ H \right]_{eq} \Delta e_{ij} + \frac{D}{3} \delta_{ij} \left[ H \right]_{eq} \Delta e_{kk} - s_{ij} dD
$$

(1)

In the formula: D is the internal variable of the damage; \( \left[ H \right]_{eq} \) is the elastoplastic matrix.

For unloading conditions, since the damage is irreversible, the value of the damage internal variable at this time is a constant, and its value is the value of the damage internal variable of the unloading money. If the influence of hydrostatic pressure and volumetric strain on the damage is not considered, the internal variables of the damage can be expressed as a function of the elastic-plastic strain tensor. According to the damage and failure test of rock material, after the material has micro crack failure, the damage and failure develop rapidly, and the damage evolution equation can be described by an exponential function:

$$
D = D_n \left( 1 - \exp \left( -K \zeta^a \right) \right)
$$

(2)

In the formula: \( D_n, K, a \) is the damage constant of the material; \( \zeta \) is calculated from the plastic strain deflection tensor as follows: \( \zeta = \left( e_{ij} e_{ij} \right)^{1/2} \). The rock damage and failure are mainly manifested as brittle tension failure, plastic shear failure and crush failure in the macroscopic view. It is considered that when the stress yield function satisfies \( F = 0 \), the material structure enters into plastic shear failure. This paper uses the Z-P hyperbolic yield function:

$$
F = \left( \alpha \right)^{1/2} \left( \sigma_e + \beta/2 \alpha \right) + \left( \sigma_0 + \gamma \beta \right) \left( \sigma_0 + \gamma \beta \right)
$$

(3)
In the formula:

\[\alpha = -\sin^2 \varphi \quad ; \quad \gamma = a^2 \sin^2 \varphi - c^2 \cos^2 \varphi \quad ; \quad \beta = 2c \sin \varphi \cos \varphi\]

\[\sigma_s = (\sigma_1 + \sigma_2 + \sigma_3) / 3 \quad ; \quad \sigma_0 = J^{1/2}/g(\theta) \quad ; \quad \sin 3\theta = -3\cdot J^{1/2}/2\left(J_2\right)^{3/2} \]

where \(J_2\) and \(J_3\) are the deviator stress 2nd and 3rd invariants; \(c\) is the cohesion of the material; \(\varphi\) is the internal friction angle of the material; \(a\) is an undetermined coefficient; With the decrease of \(a\), the hyperbola on the meridian surface can reach any degree of closeness to the Moore Coulomb envelope. \(g(\theta)\) represents the law of the change of the yield curve with the Lode angle \(\theta\) on the \(\pi\) plane.

According to the different mechanisms of rock damage and failure, the following rock stress damage states can be derived: EA means that the rock is in an elastic stage; RE means that the rock is unloaded from the plastic state; PA means that the rock has shear failure and enters plasticity; TD means that the rock is out of The ultimate tensile strain causes tensile loss; FD is the compressive loss of the rock beyond its compressive strength.

2.2 Basic differential equation of seepage field

It is assumed that the groundwater seepage flow obeys Darcy’s law on the micro-section pressure gradient. The calculation of the stable seepage field with free surface (without internal source) comes down to solving the quasi-harmonic equation that satisfies the boundary conditions:

\[\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial H}{\partial z}\right) = 0 \quad (4)\]

\[H|_{\Gamma_1} = \phi(x, y, z) \quad (5)\]

\[k \frac{\partial H}{\partial n}|_{\Gamma_2} = q(x, y, z) \quad (6)\]

\[H|_{\Gamma_3} = Z(x, y), k \frac{\partial H}{\partial n}|_{\Gamma_3} = 0 \quad (7)\]

\[H|_{\Gamma_4} = Z(x, y), k \frac{\partial H}{\partial n}|_{\Gamma_4} \leq 0 \quad (8)\]

Where: \(H\) is the head; \(k_x, k_y, k_z\) are the permeability coefficients in the three main directions of \(x, y, z\) respectively; \(\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4\) are the head boundary, discharge boundary, free surface boundary and overflow boundary.

2.3 Mechanical effect of seepage field
In the process of water seepage, the seepage volume force is generated due to the gradient of water pressure, and its change also causes the change of seepage volume force. The seepage volume force is calculated as follows:

\[
\begin{align*}
 f_x' &= \left[-\frac{\partial p}{\partial x}\right] \\
 f_y' &= \left[-\frac{\partial p}{\partial y}\right] \\
 f_z' &= \left[-\frac{\partial p}{\partial z}\right]
\end{align*}
\]

\[
\begin{bmatrix}
 f_x' \\
 f_y' \\
 f_z'
\end{bmatrix} = \begin{bmatrix}
 \frac{\partial H}{\partial x} \\
 \frac{\partial H}{\partial y} \\
 \frac{\partial H}{\partial z} - 1
\end{bmatrix} = -\gamma_w
\]

Where: \( f_x', f_y', f_z' \) are the components of the permeating volume force in the x, y, and z directions.

### 2.4 Influence of stress and damage on seepage field

In the empirical relationship between rock permeability coefficient and positive stress established by Louis in 1974 through experiments, it is theoretically explained and pointed out that the permeability coefficient decreases with the increase of positive stress, and the relationship between the two is negative exponential:[12]

\[
K = K_0 e^{-\beta \sigma}
\]

Formula (10) is used to reflect the characteristic that the permeability coefficient of rock decreases with the increase of normal stress. For different failure stages, different sudden jump coefficients are introduced to reflect the sudden change of permeability during the damage process, and a convenient method can be obtained. The relationship between the numerical calculation of the permeability coefficient and the change of stress and damage:

\[
K = \begin{cases}
     K_0 e^{-\beta \sigma} & \{\sigma\} \in EA \\
     \xi_1 K_0 e^{-\beta \sigma} & \{\sigma\} \in RE \cup PA \\
     \xi_2 K_0 e^{-\beta \sigma} & \{\sigma\} \in TD \\
     \xi_3 K_0 e^{-\beta \sigma} & \{\sigma\} \in FD
\end{cases}
\]

The parameters in formula (11) can be obtained through regression analysis of laboratory test results. In the three-dimensional stress state, the normal stress in the direction of the main permeability coefficient can be used to substitute \( \sigma \).

### 3. A sequential iteration method for coupling model solving

For the stress-damage-seepage coupling analysis of the diversion tunnel, the solution of the calculation model is often a rather complicated nonlinear problem. The difficulty of the solution is mainly reflected in the elastoplastic damage of rock mass materials, seepage free surface, seepage overflow boundary, stress-damage-seepage interaction and so on. Based on so many non-linear factors, this paper proposes a sequential iteration method to summarize the above factors and then iteratively solve them in a certain order, and solve many non-linear problems at once to achieve the ultimate goal of solving the coupled model.

The sequential iteration method is mainly divided into three iterative modules: elastic-plastic damage
calculation module, seepage calculation module, and coupled iteration module.

3.1 Elastoplastic damage calculation
The calculation adopts the incremental load variable stiffness method. When the load increment is small enough, it can be approximated that the damage parameter D is a constant during the iteration process under this level of incremental load, then \( \frac{dD}{d} = 0 \). Equation (1) The constitutive relationship of elastoplastic damage stress can be written as:

\[
d \left( \sigma_{ij} \right)_p = \left( \left[ H \right]_e - \left[ H \right]_p \right) d \varepsilon_{ij}
\]

(12)

Where: \( \left[ H \right]_p = \left( D - D\delta_{ij}/3 \right) \left[ H \right]_e + \left( 1 - D + D\delta_{ij}/3 \right) \left[ H \right]_p \); \( \left[ H \right]_e, \left[ H \right]_p, \left[ H \right]_p \) are elastic matrix, plastic matrix and damage matrix.

In each iteration process, for the damaged element, calculate or modify the damage internal variables of the element according to formula (2), according to the final stress and strain state and damage parameters of each modification, and then modify the stiffness matrix according to formula (12). Each time the iteration is completed, the modified stress should be calculated for the element that enters the failure, and the modified stress should be transferred to the nodal load for the next iteration of the calculation.

3.2 Seepage calculation
The free surface iteration adopts the Gauss point method. This paper uses the following unit permeability coefficient correction function\(^{[13]}\) \( E \left( H - Z \right) \):

\[
E \left( H - Z \right) = \begin{cases} 
0.001 & H - Z \leq \varepsilon \\
1 + \left( H - Z \right) 0.999 / \varepsilon & \varepsilon < H - Z < 0 \\
1.0 & H - Z \geq 0
\end{cases}
\]

(13)

In the formula: H is the calculated head value; z is the position elevation.

In each iteration, the permeation matrix is modified according to equation (13) for each Gaussian integration point.

The overflow boundary is solved iteratively according to the definition. That is, for all possible overflow boundary nodes, judge whether they are overflow boundary nodes according to equations (4) to (8), and then transfer to the next iteration.

In this paper, the free surface iteration loop is nested in the overflow boundary iteration loop, that is, after each equation is solved, the element permeability matrix is corrected according to equation (13), and iterated repeatedly until the free surface iteration converges, and then press equations (4) to (8). After correcting the overflow boundary, enter the free surface iteration again, and repeat until convergence.

3.3 Coupled iteration
Under the initial stress state, the seepage field is solved by free surface iteration and overflow boundary iteration; on this basis, the seepage load is calculated according to equation (9), and the new stress field and damage field are obtained by substituting the elastic-plastic damage structure
calculation iteration. Under the new stress field and damage field, the seepage field is solved again after correcting the Gauss point permeability coefficient according to formula (11). This is repeated until the stress field, damage field and seepage field obtained by the previous and two solutions all satisfy the convergence criterion.

4. Examples

4.1 Overview of calculation examples
The lithology of part of the tunnel section of a water diversion project is shale and marl of the Qingbaikou System Nanfen Formation, and the surrounding rock category is the third type of surrounding rock. In the lower part of the excavated tunnel, there is a hidden high-pressure cavern. After proper simplification, the finite element model shown in Figure 1 and Figure 2 is obtained:

![Finite element model](image)

**Figure 1.** Finite element model
The physical and mechanical parameters and permeability coefficient of surrounding rock are shown in Table 1:

| category | Deformation modulus/GPa | Poisson's ratio | Cohesion/MPa | Internal friction angle (°) | Compressive strength/MPa | tensile strength/MPa | Permeability coefficient/cm/s |
|----------|-------------------------|-----------------|--------------|-----------------------------|--------------------------|---------------------|-------------------------------|
|          | 20                       | 0.30            | 0.266        | 40                          | 15                       | 0.1                 | 4.03e-6                       |

4.2 Initial stress field

When calculating the initial ground stress, generally only its own weight is considered. The model contains a high-pressure cavity, and the water pressure in the cavity is 0.5 MPa. As shown in Figures 3 and Figures 4, the initial seepage field of the model will produce a large seepage volume force. Therefore, the model not only considers its own weight when calculating the initial stress, but also considers the penetration resulted by the existence of high-pressure cavity.
4.3 Analysis of calculation results

The calculation condition is one-time excavation of the burr hole, which is divided into two conditions, considering the coupling effect and not considering the coupling effect. From the calculation results, it can be seen that the calculation results with and without coupling effects are basically the same, and the difference is mainly in numerical values. Due to space limitations, only the damage field and seepage field under the condition of considering the seepage volume force are listed, and the results are shown in Figures 5 and Figures 6. Some calculation results are shown in Table 2 and Table 3.

The comparative analysis shows that considering the coupling effect, the displacement around the cave is significantly increased due to the fact that the seepage volume force is directed into the cave; the first principal stress of the surrounding rock increases from -4.69 to 2.24 MPa to -14.08 to -8.41 MPa; The three principal stresses increased from -2.23 to -0.64 MPa to -6.76 to -2.36 MPa; considering the effect of the infiltration volume force, the volume of the failure zone and the dissipation energy increased significantly. This is because the permeability coefficient increases after the rock mass is damaged, which intensifies the adverse effect of seepage on the stability of the surrounding rock of the excavated tunnel. As the rock damage around the cave increases the permeability of the rock, the infiltration line decreases slightly.
Figure 5. Damage distribution of tunnel

Figure 6. Considering the coupling effect seepage contour map

Table 2. Calculation results for each working condition

| Position   | Consideration not with coupling | Consideration with coupling |
|------------|---------------------------------|-----------------------------|
|            | Displacement /mm                | $\sigma_1$/MPa $\sigma_2$/MPa | Displacement /mm | $\sigma_1$/MPa $\sigma_2$/MPa |
| Top        | 17.2                           | -4.69 -2.23                 | 23.3            | -14.08 -6.76           |
| Left wall  | 33.8                           | -2.24 -0.64                 | 46.1            | -8.41 -2.36            |
| Right wall | 33.7                           | -2.25 -0.64                 | 45.5            | -8.64 -2.43            |
| Bottom     | 17.2                           | -4.69 -1.94                 | 34.4            | -14.08 -6.64           |

Table 3. Damage characteristic index of each working condition

| Parameter               | Consideration without coupling | Consideration with coupling |
|-------------------------|--------------------------------|-----------------------------|
| Plastic volume /m³      | 1531.7                         | 2123.6                      |
| Strain volume /m³       | 4522.2                         | 3744.7                      |
| Pressure loss volume /m³| 1696.4                         | 3856.5                      |
| Total damage /m³        | 7750.2                         | 9724.8                      |
5. Conclusion

- Due to the elastoplasticity of the rock mass material, the stress damage state of the rock mass is relatively complicated. The existence of high-pressure caverns makes the seepage effect obvious, and there is a coupling effect of stress, seepage and damage. The surrounding rock stress-damage-seepage of underground caverns Coupling analysis is often more complicated. Based on the existing step-by-step iterative method, this paper proposes an improved calculation method of permeability to solve the problem, and has achieved good calculation results.

- Since the seepage load is directed into the cave, it will generally have an adverse effect on the stability of the surrounding rock of the underground cavern. Considering the coupling effect, the permeability coefficient after the damage of the rock mass increases, which intensifies the adverse effect of seepage on the stability of the surrounding rock of the underground cavern. It can be seen that the stress-damage-seepage coupling analysis is a non-negligible factor in the stability analysis of the surrounding rock of underground caverns, and it should attract enough attention.

- The innovation of this paper is to use the coupling method to obtain the initial ground stress of the model, and to penetrate the coupling idea in the whole calculation process.

- Due to the lack of detailed surrounding rock, geology and related data, and the lack of comparative calculations, the project cannot explain the contingency or inevitability of the results.

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