Numerical Simulation Analysis of Surrounding Rock Deformation of Expansive Rock Roadway under Humidity Field

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Abstract: Based on the measured distribution law of humidity field, according to the humidity stress field theory, the coupling of the humidity field and the ground stress field is realized, and the humidity field is systematically analyzed. Under the conditions, the influence of the expansion of surrounding rock, lining, buried depth, height-span ratio and horizontal pressure coefficient on the deformation of the surrounding rock of the roadway, the general law of the surrounding rock deformation of the swelling rock roadway is obtained. The results show that the five factors have a certain impact on the approaching amount of the two sides of the surrounding rock and the approaching amount of the roof and floor of the swelling rock roadway, but the degree of influence is different. The order of factors affecting the approach of two sides is lining > expansibility > buried depth > horizontal pressure coefficient > height-span ratio; The order of factors affecting the approach of roof and floor is lining > expansibility > height-span ratio > horizontal pressure coefficient > buried depth. The research results provide valuable suggestions and references for the selection of reasonable support schemes and related design and construction of swelling rock roadways.

Keywords. Swelling rock, humidity field, failure law, orthogonal experimental design, numerical simulation analysis.

1. Introduction

Expansive rock refers to a kind of special soft rock, which is prone to volume expansion, strength softening and fragmentation and decomposition under the physical and chemical action of water [1]. The surrounding rock of swelling rock increases in deformation speed and ductility under high humidity environment [2]. Therefore, when roadways and chambers are being excavated in a rock mass expansion easily, the engineering accident of surrounding rock is often caused by water absorption and expansion [3]. In addition to the internal factors of the expansion rock, such as expansion and contraction, softening and disintegration caused by the water content changes. The inaccurate calculation of surrounding rock pressure and deformation, and the insufficient reliability of the supporting structure design are the external main causes of engineering accidents. In this paper, based on the practical problems, in a roadway with expansive rock mass and high-humidity environment, orthogonal method design is used as the calculation and analysis plan, and numerical simulation methods are used to study the influence of several factors on deformation of surrounding rock of roadway, such as the expansibility of surrounding rock, buried depth, lining, height-span ratio, and horizontal pressure coefficient.
2. Orthogonal Numerical Simulation Experiment

2.1. Calculation Scheme Selection

The orthogonal experiment method is adopted in numerical simulation [4]. Combining with previous research [5] in the actual situation, the main influencing factors are: (1) excavation method; (2) expansibility; (3) lining; (4) roadway section shape; (5) height-span ratio; (6) buried depth; (7) horizontal pressure coefficient. Based on various factors, the table of numerical simulation factor is drawn in table 1, and the cross-section shape of the roadway is shown in figure 1.

![Figure 1. Cross-sectional drawing of the tunnel (Unit: meter).](image)

| level | Combination of influencing factors | Height-span ratio | Buried depth(m) | σh/σv |
|-------|-----------------------------------|------------------|----------------|-------|
| 1     | Positive-Step, none, none         | 1:4 (three centered arch-wal) | 250            | 0.5   |
| 2     | \, yes, Bolting and shotcreting without invert | 1:3 (three centered arch-wal) | 275            | 1.0   |
| 3     | \, \, \, \ | 2:5 (three centered arch-wal) | 300            | 1.5   |
| 4     | \, \, \, \ | 1:2 (three centered arch-wal) | 325            | \     |
| 5     | \, \, \, \ | \ | 350            | \     |
On the basis of the factors considered in the calculation needs and the level of each factor, 240 calculation schemes are determined according to the mixed level orthogonal test table. According to the degree of agreement of relevant conditions and the purpose of the research, several representative schemes are selected for numerical simulation calculation analysis, as shown in table 2. By calculating and analyzing each scheme in table 2, the influence of the above factors on the deformation of the surrounding rock of the swelling rock roadway can be studied systematically.

Table 2. The test table of numerical simulation.

| No. | Expansibility | Lining | Height-span ratio | Buried depth (m) | σh/σv |
|-----|---------------|--------|------------------|-----------------|--------|
| I   | no/yes        | no     | 1:2              | 300             | 0.5    |
| II  | no/yes        | Bolting and shotcreting | 1:2          | 300             | 0.5    |
| III | no/yes        | Bolting and shotcreting | 1:4          | 300             | 0.5    |
| IV  | no/yes        | Bolting and shotcreting | 1:3          | 300             | 0.5    |
| V   | no/yes        | Bolting and shotcreting | 2:5          | 300             | 0.5    |
| VI  | no/yes        | Bolting and shotcreting | 1:2          | 250             | 0.5    |
| VII | no/yes        | Bolting and shotcreting | 1:2          | 275             | 0.5    |
| VIII| no/yes        | Bolting and shotcreting | 1:2          | 325             | 0.5    |
| IX  | no/yes        | Bolting and shotcreting | 1:2          | 350             | 0.5    |
| X   | no/yes        | Bolting and shotcreting | 1:2          | 300             | 1.0    |
| XI  | no/yes        | Bolting and shotcreting | 1:2          | 300             | 1.5    |

2.2. Calculation Models and Parameters
At present, the research on the constitutive model of expansive rock is still not perfect [6]. In this experiment, Drucker Prager elastic-plastic constitutive model suitable for geotechnical materials is adopted, which could better reflect the plastic deformation characteristics of expansive rock, and its model parameters are easy to obtain.

The main parameters of the material in the D-P elastoplastic constitutive of ABAQUS include yield stress, cohesion, internal friction angle, material density, elastic modulus, and Poisson’s ratio. The parameters involved in expansion and deformation mainly include thermal conductivity, specific heat capacity, and thermal expansion coefficient. Due to the very special lithological characteristics of swelling rock, its elastic modulus and Poisson’s ratio are greatly affected by water content. The rock mass mechanical parameters and structural unit parameters widely used in numerical simulation calculations are shown in tables 3-5. Among them, the rock mass strength-related parameters are comprehensively obtained according to the measured data and “Expansive Rock and Engineering” [7], and combined with numerical simulation calculation, the thermal conductivity and thermal expansion coefficient are determined according to the surface infiltration test and the expansion force test. According to the governing differential equation and basic principle of humidity stress field proposed by Miao Xiexing [8], the temperature field parameters β, T are transformed into corresponding humidity field parameters α, W. Calculated by

Table 3. Modulus of elasticity and Poisson’s ratio of the expansive rock.

| Water content | E (MPa) | μ    |
|---------------|---------|------|
| 10%           | 570     | 0.24 |
| 15%           | 513     | 0.24 |
| 20%           | 439     | 0.25 |
| 25%           | 387     | 0.25 |
| 30%           | 316     | 0.26 |
| 35%           | 272     | 0.26 |
Table 4. Physical and mechanical parameters of the expansive rock.

| Parameter            | Unit | Value |
|----------------------|------|-------|
| Constitutive model   | —    | —     |
| Rigidity             | Y    | MPa   |
|                      | c'_{ref} | kPa   |
|                      | \phi' | °     |
|                      | \rho_s | t/m³ |
|                      | \alpha | 1/%  |
| Strength             | —    |       |
| Heat                 | \lambda_s | kW/m/K |
|                      | c_s   | kJ/t/K |
|                      | \beta  | 1/°C  |

Table 5. Mechanical parameters of anchor arms and concrete.

| Parameter | Unit | Shotcrete (C25, thickness 20 cm) | Bolt (25MnSiA5, 2.2 m) |
|-----------|------|---------------------------------|------------------------|
| \rho      | t/m³ | 2.4                             | 7.8                    |
| E         | GPa  | 5(before hardening) 25.5(after hardening) | 200                   |

ABAQUS finite element software to calculate, take \(\alpha/\beta=100\), that is, when the temperature is set to 0°C \((t=0°C)\), correspond to the water content is 0 \((\theta=0)\) (representing a completely dry state), when the temperature is set to 100°C \((t=100°C)\), corresponding the water content is 1 \((\theta=1)\) (representing the saturated water state). As the result, T and W correspond one by one, that is, a 1°C increase in temperature T corresponds to a 1% increase in humidity W.

Illustrations:
Y: Yield stress; \(c'_{ref}\): Cohesion; \(\phi'\): internal friction angle; \(\rho_s\): density; \(\alpha\): expansion-humidity coefficient.
\(\lambda_s\): Thermal conductivity; \(c_s\): Specific heat; \(\beta\): Coefficient of thermal expansion.

2.3. ABAQUS Modeling Process

In this paper, based on similar model tests, the moisture distribution characteristics are obtained, so as the water content contour map under the influence of factors such as construction water and drilling water in the swelling rock roadway under certain conditions [9-10]. The temperature unit of ABAQUS numerical simulation software was used to simulate the water distribution under this condition, and the temperature distribution cloud map could be obtained.

2.3.1. Element Type Selection and Grid Division. Take the height-span ratio of 1: 2 as an example, the temperature field of surrounding rock is modeled by ABAQUS. Firstly create the swelling rock surrounding rock components, and combine the density, thermal conductivity, thermal expansion coefficient and the specific heat capacity which input into the material properties of thermal analysis (see table 3), select “heat transfer” as the analysis step type, and the basic information is “steady-state thermal analysis”. The quadrilateral unit [DC2D4] is selected as the unit type, the heat transfer method is four-node linear heat transfer, and the roadway is divided evenly and incrementally on both sides of the roadway by using four-structured network division technology, and a more reasonable grid density is determined. The central roadway and surrounding rock are divided into grids by the neutral axis algorithm, which the total number of cells finally divided is 8452.

2.3.2. Boundary Conditions. In figure 1, the heat transfer model of surrounding rock of roadway with four cross-sections is established, and a pre-defined field is created, the input temperature of surrounding rock is selected as 15 °C to complete the initial temperature setting, and through the above conversion, the initial water content of surrounding rock is 15%. In the boundary conditions, 35 °C
heat source at 1 m below the roadway is selected as the water source to diffuse to the surrounding area, and the boundary conditions a dowre set at 2.5 m above the roadway to slow and block the continuous diffusion of temperature. According to the results published in the previous experimental research carried out by the fund project supported in this paper [11-13], the humidity field is applied as shown in figure 2.

![Figure 2. Water content contour map after tunnel excavation (unit: mm).](image)

2.4. Mechanical Analysis

The ABAQUS numerical analysis software is used to model and realize the thermal mechanical coupling analysis [14]. The model is established according to the scheme in table 2 in turn. Now take calculation scheme VI as an example for illustration. In the calculation scheme VI, the buried depth of the tunnel is 250 m, and the net section of the main body is 3.8 m high, 4.0 m wide, and the top is a semicircle with a diameter of 4 m. In order to reduce the influence of the boundary effect, according to the Saint-Venant principle, the height of the model is 30 m, the width is 40 m, the distance between the left and right sides of the roadway is 20 m, the top is 11.2 m, and the bottom is 15 m. The surrounding rock range meets the conditions of numerical calculation. The material parameters of surrounding rock are shown in tables 3-4.

The rock mass is regarded as a homogeneous elastoplastic body. The left and right sides of the model are horizontal constraints, the top is free constraints, and the bottom is fixed constraints. The self-weight stress is applied along the vertical direction, and the horizontal tectonic stress is realized by applying horizontal pressure coefficients. In this way, the horizontal pressure coefficient simulated by the calculation scheme is 0.5, and the vertical deadweight stress is greater than the horizontal tectonic stress. The Drucker Prager model is used to calculate the initial deadweight stress balance. Through the property settings in the ABAQUS software, the temperature in the properties is called to reduce the elastic modulus of the surrounding rock to 80% of the original, so as to simulate the stress release problem in the process of surrounding rock excavation and achieve the effect of releasing 20% stress.

The roadway support plan [15] is as follows: the bolt and shotcrete support is adopted, the length of the bolt is 2.2 m, the distance between the anchor holes is 0.6×0.6 m, the 25MnSiA5 threaded steel bar is used, and the thickness of the concrete spray layer is 20 cm. Shell elements are selected for the lining, and the constitutive model is an elastic model. Beam element is selected for anchor rod, and the mechanical parameters of anchor rod and concrete are shown in table 5. Bolting and shotcrete support is an important support measure to control the deformation of the surrounding rock of the roadway. After the upper step bolt construction is completed, the concrete support is immediately sprayed, and then the lower step bolt is constructed in the same step and the concrete support is immediately sprayed to reduce the deformation of surrounding rock. Rock deformation provides flexible support for the release of residual stress in surrounding rock.
3. Analysis of Numerical Simulation Test Results

3.1. Analysis on the Influence of Expansion and Lining Deformation
By comparing the results of calculation schemes I and II, according to the distance $U_x$, roof settlement $U_r$ and floor bulge $U_f$, the paper analyzes (1) the influence of surrounding rock swelling on roadway deformation with and without support; (2) the influence of lining on surrounding rock deformation under the condition of surrounding rock swelling and no swelling. Due to the symmetry between the structure and the humidity field, only the deformation of the left side is given below. The comparison of the calculation results is shown in figures 3.

It can be seen from figure 3(a) that (1) under the condition that the roadway is unlined the horizontal displacement of the two sides above 1.2m height is particularly prominent, and the surrounding rock produces great deformation. In engineering practice, if there is no time to apply the lining under special circumstances, the preliminary protection measures can be taken above $2/3$ height of the two sides to ensure the engineering safety. (2) Under the condition that the roadway is lined, the surrounding rock at the height of 0.2 m to 1.5 m on the two sides gradually increases along the height, that is, the horizontal displacement values of the two sides change more sensitively at the height of 1/9 to 5/6 of the two sides, and the approach distance reaches the maximum at 1.5 m. Therefore, these parts should be reinforced during the construction of the second lining.

![Diagrams showing deformation](image)

Figure 3. Influence of expansion and lining on deformation.

It can be seen from figures 3(b)-3(c) that in (1) a roadway without expansive surrounding rock, the lining has a more obvious effect on limiting the subsidence of the roadway roof. (2) The amount of roof sinking and floor swelling before lining is 26.9 cm and 14.3 cm respectively. After lining is applied, the sinking amount of roof and bottom heaving are 12.0 cm and 11.5 cm respectively. In an expansive roadway, the effect of the sinking of the roof of the roadway is particularly obvious.

3.2. Analysis of the Influence of Buried Depth on Deformation
In order to study the influence of the burial depth on the deformation of the surrounding rock of the expansive rock roadway, the numerical simulation calculation of schemes VI, VII, II, VIII, IX is carried out, and the results are shown in figures 4.

From figures 4(a) and 4(b), it can be seen that (1) the deformation of the surrounding rock increases gradually along the height from 0.2 m to 1.5 m on both sides, and the maximum deformation is found at 1.5 m height, which verifies the viewpoint in Section 2.1. (2) In the roadway with this type of section and original rock stress field, with the increase of buried depth, the deformation of both sides gradually increases, and the increasing trend is gradually obvious with the increase of time. In general, for every 25 m increase in the buried depth, the displacement of both sides increases about 1 cm.

It can be seen from figures 4(c)–4(f) that the roof subsidence and floor heave increase with the increase of the buried depth of the roadway under this type of section and structural stress. In the non-expandable surrounding rock roadway, the roof subsidence increases by 0.8 cm and floor heave...
Settlement value

Deformation (m)
Height (m)

(a) Deformation of left side without expansion.

Deformation (m)
Height (m)

(b) Deformation of left side with expansion.

Deformation (m)
Height (m)

(c) No expansion bottom plate.

Deformation (m)
Height (m)

(d) Bulging with expansion bottom plate.

Deformation (m)
Height (m)

(e) No expansion of the roof sink.

Deformation (m)
Height (m)

(f) Sinking with expansion roof.

**Figure 4.** The influence of buried depth on deformation.

### 3.3. Analysis of the Influence of Height-Span Ratio on Deformation

In order to study the influence of the height-span ratio on the deformation of the surrounding rock of the swelling rock roadway, the numerical simulation of schemes II, III, IV and V is shown in figures 5.

It can be seen from figure 5 that (1) the horizontal displacement of the two sides is less affected by the different height-span ratio, and the displacement can be ignored. (2) When the stress ratio is 0.5, in the roadway with expansive surrounding rock, due to the influence of vertical stress on surrounding rock, and the roof deformation of the roadway with a height-span ratio of less than 1:3 is larger than that of other height-span ratio. Therefore, in order to prevent excessive roof deformation under the
condition of small horizontal stress, the section form with height-span ratio greater than 1:3 should be adopted for excavation and lining of expansive rock roadway Support.

![Graphs showing deformation and settlement values](image)

**Figure 5.** The influence of height-span ratio on deformation.

### 3.4 Analysis of the Influence of Horizontal Pressure Coefficient

The influence of the horizontal pressure coefficient on the deformation of the surrounding rock of the swelling rock roadway is analyzed. The results are shown in figures 6, through numerical simulation calculation of scheme II, X and XI.

It can be seen from figures 6(a)–6(f) that (1) with the increase of stress ratio, the impact of the vertical stress on the roadway decreases, and the impact of horizontal stress increases. For every 0.5 increase of the stress ratio, the displacement of the two sides increases by 3 cm. Horizontal stress extrusion has an obvious influence on floor deformation. When the stress ratio is 1.5 and 0.5, the bottom plate deformation will be as much as 4 times different. In the case of high stress ratio, the supporting structure of the two sides and the bottom plate should be strengthened. (2) Under the same stress ratio, the deformation of the roof and floor of the expansive surrounding rock increases by about
30%, and the deformation of the two sides increases by about 50% compared with the non-expandable surrounding rock. Therefore, in engineering practice, the influence of expansibility on surrounding rock deformation must be taken into account.

![Graphs showing deformation and uplift values](image)

**Figure 6.** The influence of horizontal pressure coefficient.

### 3.5. Comparative Analysis of the Two Limit Cases

By comparing the numerical simulation calculation results of schemes III and XI, two cases are analyzed, the stress is relatively large and the roadway height-span ratio is also large, and the stress is relatively small and the roadway height-span ratio is also small. The results are shown in the figures 7.
It can be seen from figures 7(a)-7(b) that (1) when the stress is relatively small and the height-span ratio of the roadway is also small, the vertical stress of the surrounding rock is more obvious, and the deformation of the floor is small and the deformation of the roof is large. If the surrounding rock has expansibility, the deformation of the roof will increase. Therefore, in this case, it is necessary to strengthen the roof support structure; (2) When the stress is relatively large and the roadway height-span ratio is also large, the vertical stress of the surrounding rock is more obvious, and the roadway is squeezed and the two sides of the pressure transmit to the bottom plate, which makes the bottom plate deformation become large and the top plate deformation become small. If the surrounding rock has expansibility, the bottom plate deformation increases by about 30%. Therefore, in this case, it is necessary to strengthen the bottom plate support structure.

4. Conclusion
Based on the existing distribution law of humidity field, the coupling of humidity field and in-situ stress field is realized in ABAQUS. Through ABAQUS simulation, deformation data and plastic deformation zone of surrounding rock of non-expansive surrounding rock roadway and expansive rock roadway under various working conditions are obtained. The influence of expansibility, lining, buried depth, height-span ratio and horizontal pressure coefficient on surrounding rock deformation of roadway is explored, and the general regularity of the deformation of the surrounding rock of the swelling rock roadway is obtained, which bring suggestions and references provided for the support plan and related design and construction for the swelling rock roadway. The results show that 5 factors have a certain impact on the approaching amount of the two sides of the surrounding rock and the approaching amount of the roof and floor of the swelling rock roadway, but the degree of influence is different. The order of the magnitude of the factors affecting the approaching amount of the two banks is: lining>expansibility>buried depth>horizontal pressure coefficient>height-span ratio; the order of the magnitude of the factors affecting the approaching amount of the roof and floor is: lining>expansibility>height-span ratio> horizontal pressure coefficient> buried depth.

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