Research on the Mechanical Response of Tunnel Structure under Water Softening Surrounding Rock

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Abstract. The state of water content is an important factor affecting the mechanical properties of rock. After the tunnel excavation, due to the formation of the loosening circle and the increase of the seepage path, the state of water content of the surrounding rock changes, making the mechanical properties of the surrounding rock soften with water. In this paper, the types and principles of water rock interaction are described. Taking a tunnel in Southwest China as the research object, through numerical simulation, the results of lining and surrounding rock before and after the softening are compared, and the mechanical response law of the lining and surrounding rock during tunnel excavation is discussed.

1. Introduction

There are more and more large mountain tunnels built in Southwest China. Water inrush and mud gushing have become the common geological disasters in the process of mountain tunnel construction. The groundwater in rock mass will have physical, chemical and mechanical effects on rock, which in turn will change the composition and flow state of groundwater. Lu Y.L. and others systematically elaborated the mechanism of water rock coupling and established water rock coupling calculation models.\textsuperscript{[1-2]} Xia D. et al. discussed the mechanism of different rocks softened by water, as well as the changes of physical and mechanical parameters with water immersion time and water content through laboratory tests.\textsuperscript{[3-7]}

Many experiments have been carried out to study the softening effect of various rocks when encountering water. However, there is little introduction about how to apply the experimental research to the practical engineering.

2. Mechanism of water rock interaction

Groundwater is an important geological construction force. The interaction between groundwater and rock, on the one hand, changes the physical, chemical and mechanical properties of rock mass, on the other hand, changes the chemical composition of the groundwater.
2.1. Physical process
The physical process of groundwater on rock mainly include lubrication, softening and freeze-thaw.

Lubrication, as the name implies, refers to the lubrication of the groundwater in the loose circle after the excavation on the discontinuous boundary of the rock mass, which reduces the friction resistance on the discontinuous surface and the connection force between the minerals.

The softening process of groundwater on rock mass is mainly manifested in the change of physical properties of fillings and particles in rock mass structural. With the change of water content, the fillings in the rock structural weaken from solid state to plastic state. Rock can be divided into softened rock and non softened rock according to the softening coefficient \( K_R \). When the softening coefficient \( K_R \) is less than or equal to 0.75, it is softened rock; when the softening coefficient \( K_R \) is greater than 0.75, it is not softened rock.

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K_R = \frac{\sigma_{cw}}{\sigma_{c0}}
\]

\( K_R \) —— softening coefficient;
\( \sigma_{cw} \) —— saturated compressive strength of rock;
\( \sigma_{c0} \) —— dry compressive strength of rock

When rock has special mineral composition or special structure, it will have different effect when softened by water, and can be divided into expansive rock, karst rock, disintegrated rock, salinized rock and so on.

2.2. Chemical process
Groundwater will react with rocks in dissolution, hydrolysis, hydration, ion exchange, oxidation-reduction and so on, which will destroy its original structure and produce new minerals. The type and speed of chemical process vary from different rock and water. When the ground water dissolved with \( O_2 \), \( CO_2 \), \( NH_3 \), \( H_2S \) and other gases contacts with soluble rocks such as limestone and dolomite, it will produce dissolution, increase the porosity and permeability of the rock mass, and reduce the rock strength. When water penetrates into the mineral crystal lattice of rock mass, it changes the rock structure in micro and macro. The nature of rock weathering is the hydration of groundwater to rock.

2.3. Mechanical process
The mechanical effect of groundwater on rock mass is mainly reflected by pore water pressure and seepage. The former reduces the effective stress of the rock mass to reduce the strength of the rock mass, while the latter has impact on the rock mass to reduce the shear strength of the rock mass.

3. Project introduction
The relying project is located in Yunnan Province, China. The top of the surrounding rock is red clay and breccia, followed by strongly weathered dolomitic limestone and moderately weathered dolomitic limestone. The entrance and exit of the tunnel are both walled portal, and mechanical ventilation is used. According to geological survey, the karst in the tunnel site area is generally well developed. During the construction process, serious water inrush occurred in many sections. The tunnel face is excavated by retaining core soil method, which is shown in Fig.1.

![Excavation sketch of retaining core soil method](image-url)
4. Numerical simulation and analysis

4.1. Numerical model and parameter selection

The tunnel lining section is shown in Fig. 2. C25 shotcrete with thickness of 24 cm is selected for initial support. The second lining effect is not considered.

The tunnel profile is 12.6m wide and 10.0m high, which is shown in Fig. 2. The whole model is 180m wide and 200m high, while the tunnel buried depth 100m. The boundary distance between the boundary and the tunnel profile is about 7 times the wide of the tunnel, which can basically eliminate the influence of boundary effect on the calculation results.

![Figure 2. Numerical model](image)

| Material           | Constitutive model | Cell type | Unit weight $\gamma$(kN/m$^3$) | Modulus of Elasticity $E$(GPa) | Poisson's ratio $\mu$ | Cohesion $c$(kPa) | Friction angle $\phi$ (°) |
|--------------------|--------------------|-----------|-------------------------------|-------------------------------|----------------------|-------------------|------------------------|
| Loose media        | Mohr-Coulomb Body  | 19.5      | 1.1                           | 0.42                          | 80                   | 21                |
| Surrounding rock   | Mohr-Coulomb Body  | 20.5      | 1.5                           | 0.37                          | 160                  | 24                |
| Initial support    | Elastoplasticity Beam | 25.0   | 26.0                          | 0.20                          | /                    | /                 |

![Figure 3. Softening curve of cohesion](image)

![Figure 4. Internal friction angle softening curve](image)

Based on field geological survey data and relevant code, the recommended values of main design parameters for each stratum in the field are presented in Table 1. According to the test results of rock
softening when encountering water, the cohesion and friction angle of the surrounding rock of the loosening circle change with time as shown in Fig. 3-4.

4.2. Analysis of numerical calculation results

4.2.1. Horizontal and vertical displacement

Before softening, due to the good integrity of the rock mass itself, relatively high cohesion and friction angle, there is a high side pressure coefficient. After excavation, the left and right surrounding rocks have a squeezing effect on the structure, so the lining structure has a horizontal convergence of about 4mm, and the horizontal displacement is mainly concentrated in the upper stage lining. However, after the surrounding rock is softened, the shear strength of the surrounding rock is greatly reduced and the structure is more loose, resulting in the increase of vertical pressure, the decrease of horizontal pressure, the decrease of the supporting effect of the surrounding rock on the structure on both sides, and the decrease of the horizontal convergence of the structure. The lining structure at the arch foot even deforms outwards. (As shown in Fig.5)

Figure 5. Horizontal displacement (before softening on the left, after softening on the right)

Before softening, the crown settlement is about 7.3mm, the invert uplift is about 10.7mm, and the vertical convergence is about 18.0mm. After 90 days of softening of surrounding rock, the settlement of arch crown is about 36.1mm, increasing by 28.8mm; the deformation of inverted arch is 13.9mm, increasing by 24.6mm. The vertical convergence is about 22.2mm. (As shown in Fig.6)

Therefore, it can be concluded that the settlement of the arch crown is caused by the superposition of two reasons: 1) due to the softening of the surrounding rock in the loosening circle and the parameter reduction, the stratum in this area has certain settlement, which makes the lining structure have settlement together; 2) due to the parameter reduction of the surrounding rock, the lining structure of the tunnel bears more loose loads, the internal force of the structure increases, which produces certain deformation.

Figure 6. Vertical displacement (before softening on the left, after softening on the right)

4.2.2. Lining internal force

Figure 7-9 show the internal force distribution of the lining structure before and after softening. Before softening, the maximum axial force of lining structure is at the arch foot, about 6634 kN, and the minimum axial force is at the invert, about 3520 kN. The force is relatively uniform. The maximum
moment is at the arch foot, about 783.1 kN·m, and the minimum moment is at the invert, about 397.0 kN·m. The maximum shear force is located at the arch foot, about 70.74 kN, and the shear force values at other positions are small.

After softening, the position of the maximum axial force of the lining structure moves up, which is located at the middle of the side wall and the arch foot, it becomes 8102 kN, increasing by about 22.1%. The minimum value is still at the inverted arch, about 3042 kN, decreasing by about 13.6%. The maximum bending moment is about 959.0 kN·m, which is located at the arch foot, increasing by about 22.5%. The maximum shear force is located at the arch foot, about 83.8 kN, increasing by about 18.5%.

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### Figure 7. Axial force (before softening on the left, after softening on the right)

![Axial force distribution](image)

### Figure 8. Bending moment (before softening on the left, after softening on the right)

![Bending moment distribution](image)

### Figure 9. Shear force (before softening on the left, after softening on the right)

![Shear force distribution](image)

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#### 4.2.3. Development of plastic zone

Figure 10 shows the distribution of plastic zone of surrounding rock. The plastic zone of surrounding rock is concentrated at the side wall and arch foot on the left and right sides. Due to the release of horizontal stress, the minimum principal stress becomes 0, and the shear stress increases rapidly, which is tangent to the Mohr Coulomb envelope line. Shear failure occurs in the surrounding rock and the rock mass deforms towards the free section. With the softening of the surrounding rock, the plastic zone extends to about 4m, which is about the thickness of the loose zone. The surrounding rock is finally unstable.
5. Conclusion
Water-rock interaction is a kind of complex coupling, but generally speaking, the rock will soften to a certain extent after encountering water. Based on a tunnel in Yunnan, China, the stress and deformation of lining and surrounding rock before and after softening of surrounding rock are compared by numerical simulation. The results show that the horizontal convergence of the tunnel decreases, while the vault settlement increases after the surrounding rock softening. The internal force of lining structure increases in different positions, and the maximum position increases by about 20%. Whether it is lining or surrounding rock, the softening of surrounding rock has the most obvious effect on the plastic development of both sides of the arch waist.

Acknowledgments
The authors would like to acknowledge assistance and encouragement from the programs: “Research on the Key Technology of Safety Construction of Highway Tunnel Under the Complex Conditions in Mountain Area of East Yunnan” (Science and Technology Project of Yunnan Provincial Department of Transportation, China) and “Research on Key Technology of Design and Construction of Fabricated Corrugated Steel Arched Shed” (Tongji University Scientific Project, China).

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