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MECHANICAL CHARACTERISTICS AND DEFORMATION LAW OF TUNNEL IN DIATOMITE CONSIDERING VARIOUS SOFTENING CONDITIONS

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ABSTRACT

At present, the research considering multi-factor softening conditions is rarely performed, and the research on the deformation law and mechanical properties of the tunnel in diatomite is even rarer. Diatomite is easy to soften in water, and its physical and mechanical properties change greatly after softening. Therefore, take the high-speed railway tunnel that passes through the diatomite stratum in East China as an example, considering various softening conditions (including softening degree and softening position), the deformation law and mechanical characteristics of the tunnel are obtained, and corresponding suggestions are also put forward according to different softening conditions. The results show that the deformation law and mechanical characteristics of the tunnel are greatly affected by the symmetry of softening part. The deformation of the inverted arch caused by the lower surrounding rock softening of the tunnel is the largest, and the maximum stress occurs at the arch foot when the upper surrounding rock of the tunnel softens. Different softening degrees and positions have a great influence on the mechanical characteristics and deformation law of the tunnel. The results obtained in this paper may provide some important references for similar projects in the future.

KEYWORDS

High-speed railway tunnel, Diatomite layer, Softening degree, Deformation law, Mechanical characteristic

INTRODUCTION

Diatomite stratum is mainly located in Jilin province and Zhejiang Province of China, due to the properties of poor stability and weak bearing capacity, diatomite is prone to collapse when exposed to water [1-2], which is different from other kinds of soil (like sand, silt, etc) [3-6]. Tran and Nguyen [7] used numerical methods to predict the damage area of tunnel lining under blast loads, and the blast peaks on the tunnel construction face was also determined. Guo et al [8] considered the adverse effect of karst seepage effect on the water-resistant rock mass of the karst tunnel and obtained a calculation method for the critical safety thickness of the water-resistant rock mass.

Through various tests on the physical and mechanical properties of diatomite microstructure, it was found that diatomite has a unique porous microstructure and high compressibility, which is closely related to its multiple pores [9-11]. Wang et al [12] analyzed the fractal characteristics and pore structure characteristics of natural diatomite under different consolidation pressures using the principle of image segmentation and optimal threshold method, then the relationship between the consolidation pressures fractal dimension of diatomite and isotropic isobars was obtained. The distribution characteristics and formation mechanism of diatomite landslides were studied based on an actual engineering project, and it was found that the mechanical strength of the soil on the slope was reduced due to the strong stratification and increased expansion, which led to the failure of the lining structure [13,14]. Zhang et al [15] analyzed the genesis, species, soil structure, and chemical composition of diatomite in different regions, and found that the diatomite lithology was not universal.

Water would accelerate the softening and reduce the matrix suction and strength of the soil, and pose a certain threat to the safety of the tunnel in severe cases [16, 17]. Softening degree of the surrounding rock was mainly reflected by water content, and some scholars had carried out some research on it. Wang [18] analyzed the deformation law of tunnels in loess area with moisture content through the test and suggested construction methods with different water contents. The deformation characteristics of tunnels in full-weathered red sandstone and Sigda area under different water contents were studied, and intensified precipitation measures and optimization schemes of tunnel lining parameters were put forward [19, 20]. Ye et al [21] analyzed the influence of water contents on the deformation of tunnels in expansive red clay area and lining structures, and the reserved deformation value for the tunnel was also proposed. The existing research mainly focused on the mechanical properties and engineering properties of slopes in diatomite area [22], while the research on the characteristics of tunnel engineering in diatomite area is rare. The deformation characteristics of tunnel in other soils (such as loess and expansive soil, etc.) had been studied considering softening degree of the surrounding rock, and previous studies mostly focused on the condition of a single variable of water content. However, the research on the deformation law and mechanical properties of tunnels under multiple softening conditions (including the softening degrees and positions) was rarely involved, and the research on the mechanical properties of tunnel in diatomite area was even rarer.

Therefore, in this paper, take the Feifengshan tunnel that passes through the diatomite area in East China as the engineering background, using the numerical simulation method, the influence of softening conditions on the mechanical properties and deformation law of the tunnel is further revealed by considering various softening conditions (including the softening degrees and positions), which may provide a design basis and reference for the related tunnel engineering in diatomite area in the future.

PROJECT OVERVIEW

The Feifengshan Tunnel passes through the diatomite area in East China. Before this, there is no systematic experience in the construction of railway tunnels in diatomite. Also, diatomite shows obvious differences in the origin, species, soil structure, and chemical composition in different regions. The local diatomite properties are not universal and can only be used as a reference. The construction standards for high-speed railway tunnel engineering are high, and because the tunnel is usually buried in the stratum, all mechanical behaviors are closely related to the stratum characteristics. However, at present, there is little construction experience for railway tunnels crossing the diatom area, and diatomite has not been included in the special geotechnical and unfavourable geology in the design specification of railway, its survey methods, treatment principles and empirical parameters are still unclear. Moreover, the engineering properties of tunnel in diatomite area under different softening conditions are unknown. For tunnel engineering in diatomite stratum, how determining the mechanical properties and deformation law of tunnel is the key to ensuring the safety of construction and long-term operation stability of tunnel.

In this paper, based on the Feifengshan tunnel, the mechanical characteristics and deformation law of tunnel in diatomite area under various softening conditions are studied furtherly. The size of the tunnel is: length×clear span×clear height = 115×7.8×7.2 m, and the specific section size of the tunnel lining is shown in Figure 1. The preliminary lining is C25 shotcrete (thickness is

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230 mm) and steel arch, and the secondary lining is mainly C30 reinforced concrete (thickness is 400 mm). The specific lining parameters are shown in Table 1.

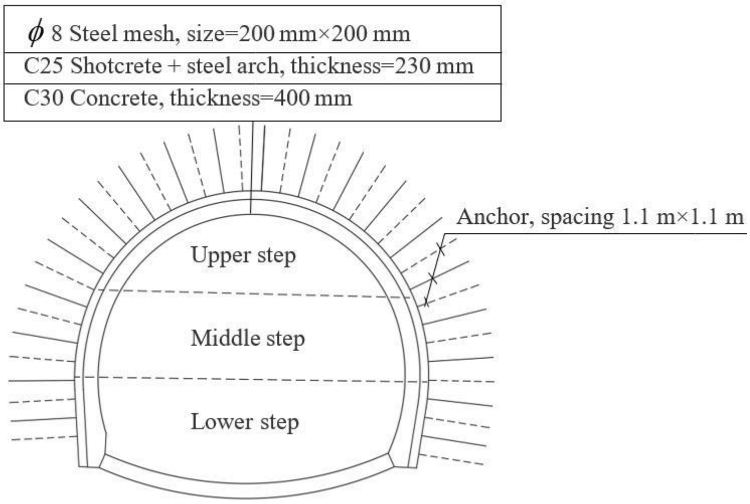

Fig. 1 - Schematic diagram of the tunnel section

Tab. 1: Lining parameters of the tunnel

Preliminary lining										Secondary lining	
C25 shotcrete		Wire mesh (φ8)		Anchor (φ22)			Steel arch			C30 concrete	
Position	Thick	Position	Spacing	Position	Length	Spacing	Position	Size	Spacing	Position	Thickness
Arch wall	230 mm	Arch wall	200×200 mm	Arch wall	3.0 m	1.1×1.1m	Arch wall	I-16	1.0 m	Full ring	400 mm

CALCULATION INSTRUCTIONS OF THE NUMERICAL SIMULATION

Calculation model

Flac3D software is used in this paper, and the typical section of the V-level surrounding rock of the tunnel is selected as the research object. To reduce the boundary effect of the calculation model [23-24], the longitudinal length of the model is selected as 98m, the calculation range is 120 m in the horizontal direction; the buried depth of the tunnel gradually increases from 11.96 m to 32.44 m along the longitudinal direction according to the actual project, and the distance between the tunnel invert and model bottom is 30 m. The excavation method of the tunnel adopts the three-step method, and the specific numerical calculation model as shown in Figures 2~3. Normal constraints are imposed on the sides of the model (namely, the direction of the front, back, left, and right), the bottom boundary of the model is fixed, and the upper boundary is set to free [25]. For the convenience of description, a schematic diagram of the key position of tunnel is drawn, as shown in Figure 4.

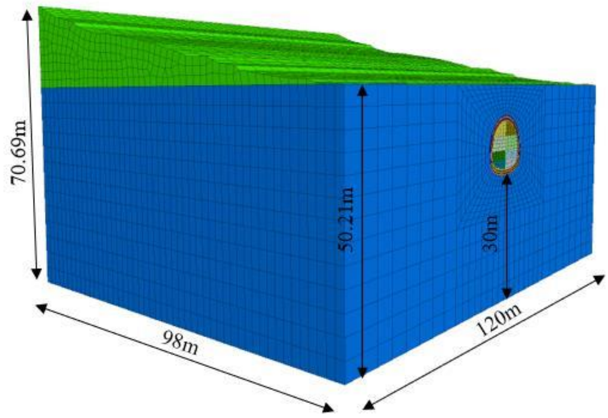

Fig. 2 - Numerical calculation model

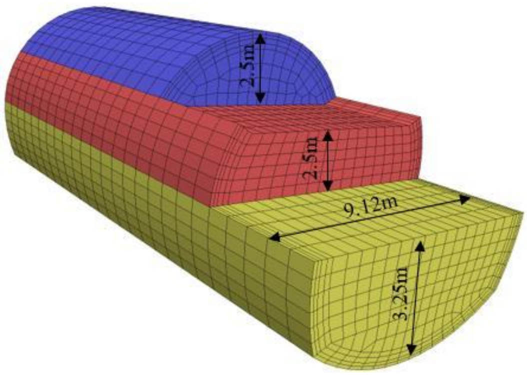

Fig. 3 - Schematic diagram of the construction method

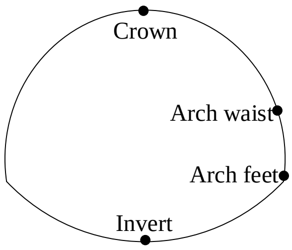

Fig. 4 - Key positions of the tunnel

The surrounding rock and secondary lining are simulated by solid elements, which obey the Mohr-Coulomb criterion and the linear elastic criterion [26], respectively. The effect of the self-weight stress field is considered. The anchor adopts the cable element, the shotcrete adopts the shell element, and the effect of the steel arch is converted to the shotcrete according to its elastic modulus [27]. The specific calculation method is as *Eq*. (1),

$$E = \frac{A_c \times E_c + A_s \times E_s}{E_c + E_s} \tag{1}$$

Where: E is the composite elastic modulus of the preliminary lining or secondary lining; A_c is the cross-sectional area of the concrete; E_c is the elastic modulus of concrete; A_s is the cross-sectional area of steel bar; E_s is the elastic modulus of the steel arch.

Calculation parameters and softening conditions

According to the geological data, diatomite is easy to soften by water, so several groups of conditions with different softening degrees are set up in this paper, namely softening conditions I~V (refer to the water content: 35%, 40%, 45%, 50%, 55%, respectively). The specific calculation parameters of surrounding rock and lining are shown in Tables 2 ~ 3.

Tab. 2: Calculation parameters of the lining

Lining type	Density /(kg/m³)	Elastic Modulus /GPa	Poisson's ratio	Lining thickness /m
Preliminary lining	2500	25.5	0.30	0.23
Secondary lining	2500	32.0	0.30	0.40

Tab. 3: Calculation parameters of surrounding rock with different softening conditions

Softening condition	Density /(kg/m³)	Elastic Modulus /MPa	Poisson's ratio	Cohesion /kPa	Internal friction angle /°
I	1900	28.37	0.35	42.23	19.45
II	1900	26.65	0.35	38.74	18.23
III	1900	24.93	0.35	35.25	17.00
IV	1900	23.21	0.35	31.76	15.78
V	1900	21.49	0.35	28.27	14.55

When the tunnel passes through the diatomite area, there are also some differences in the softening degree of surrounding rock in different positions, which will affect the stress and deformation of the tunnel. The present range of the softening conditions of surrounding rock is conditions 1~6, as shown in Figure 5. For different softening positions around the tunnel (the area marked in red in Figure 5) is the *II ~ V* parameter, while the white area is still kept as the *I* parameter in Figure 4. Considering the influence of different softening degrees (*I~V*) and softening positions (1~6) of the surrounding rock in diatomite
stratum, the deformation law and mechanical properties of the tunnel are comparatively analyzed.

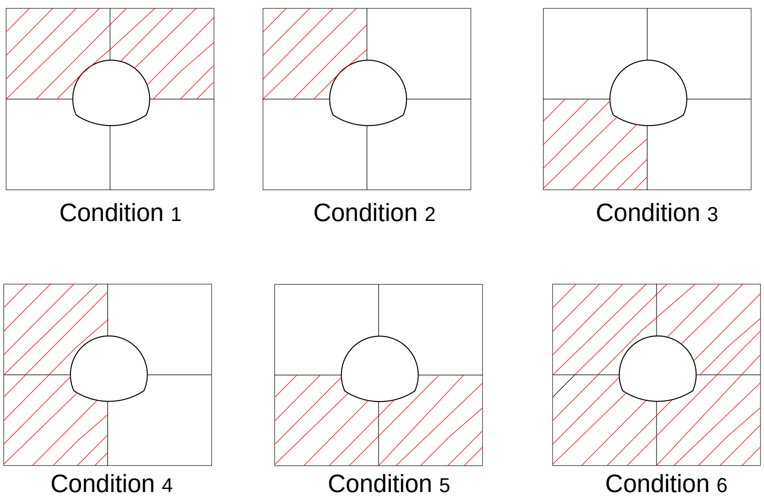

Fig. 5 - Schematic diagram of the calculation conditions for different softening positions of the surrounding rock

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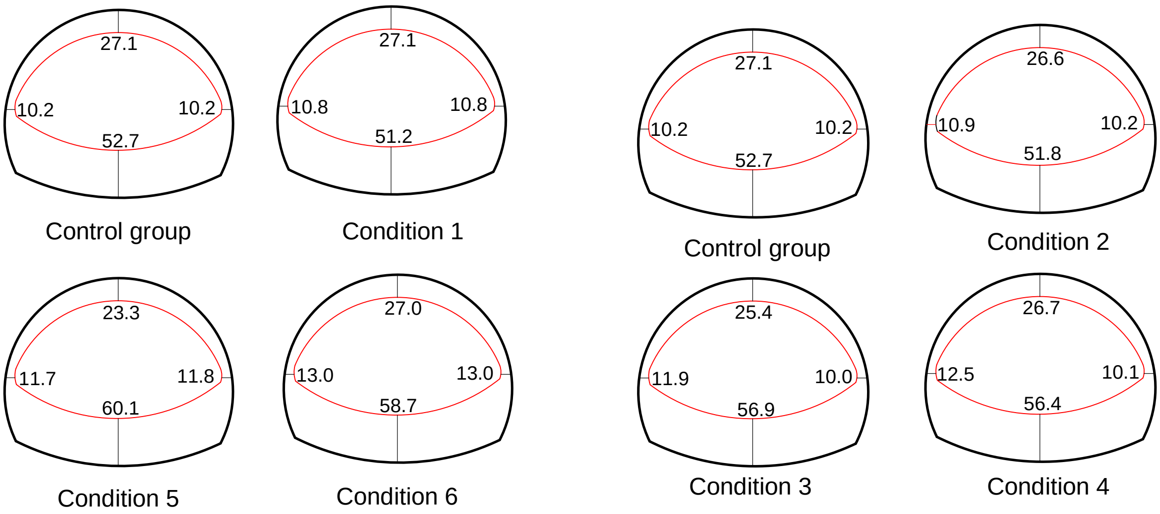
Considering that the spatial effect and boundary conditions of tunnel excavation may have a certain influence on the calculation results, the 50 m section of the middle part of the model is selected as the monitoring section, the deformation law and mechanical properties of the tunnel under different softening degrees and positions of the surrounding rock are studied in detail.

Deformation law of the tunnel

The overall deformation of the tunnel is analyzed when the softening positions of the surrounding rock are distributed symmetrically and asymmetrically (here, only the case when the largest softening degree of the surrounding rock is considered, that is, the parameter of condition V), the control group is the case when all positions of the tunnel surrounding rock adopting the parameter of condition I, as shown in Figure 6.



(a) Symmetrical condition *(b) Asymmetric condition*

Fig. 6 - Distribution law of tunnel deformation under different arrangements of softening positions /mm

In Figure 6-(a), under the same conditions, when the softening positions of the surrounding rock are distributed symmetrically, the distribution of horizontal displacement of the arch waist on both sides of the tunnel section is basically symmetrical and the difference is less than 0.1 mm. Comparing the crown settlement of different conditions, it can be found that the settlement values of condition 1 and condition 6 are very close, and the minimum value of crown settlement occurs in condition 5. This is because compared to other conditions (1, 2, 4), the upper half of the tunnel in condition 5 is non-softened, and the softened part is far away from the crown. Compared with condition 3 (one-sided softening), the left and right side are symmetrically softened in condition 5, so the settlement of condition 5 is more uniform and shows the minimum value. As shown in Figure 6-(b), under the same conditions, when the softening positions are distributed asymmetrically, the tunnel deformation is asymmetric, the difference of horizontal displacement at the arch waist of surrounding rock can be up to 2.4 mm, and the value of horizontal position at the side with higher softening degree is larger. In addition, it can be found that the influence degree of different softening degree of surrounding rock on different positions of the tunnel decreases in turn from invert displacement, crown settlement and horizontal displacement of arch waist.

The variation low of the displacement at the key positions of the tunnel with different softening degrees and positions are shown in Figures 7~9.

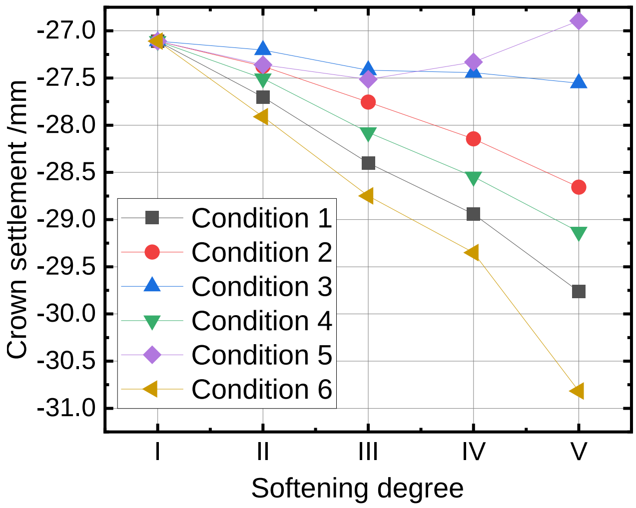


Fig. 7 - Crown settlement of the tunnel under different softening degrees and conditions

In Figure 7, the crown settlement of condition 5 increases first and then decreases with the increase of softening degree, but the change value is small (less than 1mm), and the crown settlement of the other conditions increases with the softening degree. The maximum variation value of condition 6 is 3.7 mm, which is 13.7% higher than the initial value of 27.1 mm. At the same time, it can be seen that the settlement curve changes approximately linearly when the softening degree is I~IV. But there is an inflection point at softening degree IV when the softening degree is I~V, which indicates that the settlement will increase sharply when the softening degree is large. Therefore, the monitoring should be strengthened to prevent excessive deformation of the tunnel for rock areas with severe softening.

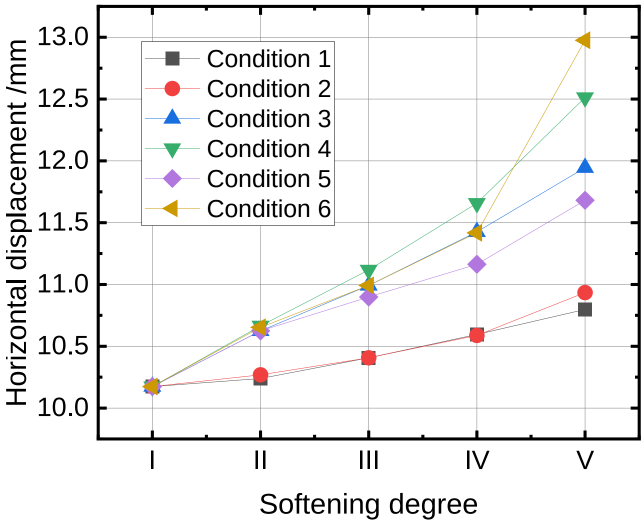


Fig. 8 – Horizontal displacement of arch waist of the tunnel under different softening degrees and conditions

In Figure 8, the horizontal displacement of the arch waist increases with the softening degree of the surrounding rock. Among them, the horizontal displacement of conditions 4 and 6 increased faster, followed by conditions 3 and 5, while the increasing trend of conditions 1 and 2 is the slowest and the difference between them is small. As the softening degree (conditions 4 and 6) increases, the horizontal displacement changes greatly. Compared with the initial value of 10.2 mm, the horizontal displacement of conditions 4 and 6 increases by 23% and 27.5%, respectively, which indicates that unilateral softening and overall softening have a great influence on the horizontal displacement of tunnel.

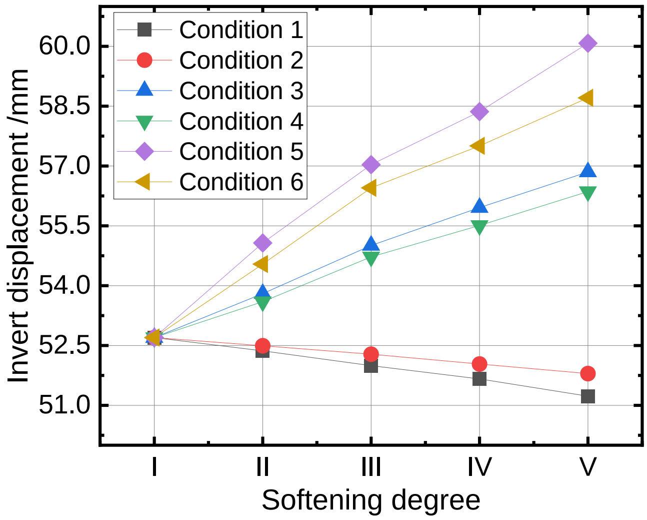


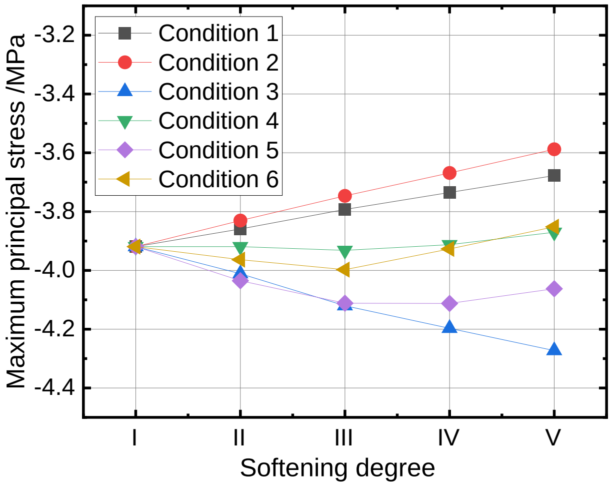
Fig. 9 – Invert displacement of the tunnel under different softening degrees and conditions

In Figure 9, the displacement of the invert under different softening conditions mainly shows three trends with the increase of softening degree: (1) conditions 1 and 2 show a decreasing trend, and the change value from the softening degree I to V is about 1.5 mm, which is 2.8% lower than the initial value. (2) Conditions 3 and 4 show a slow increase trend, and the change value from the softening degree I to V is about 4mm, which is 7.8% higher than the initial value. (3) Compared with other conditions, conditions 5 and 6 show the fastest growing trend, and the change value from the softening degree I to V is about 7 mm, which is 14% higher than the initial value. The line curve of "condition I and II", "condition III and IV", "condition V and VI" is very close, respectively. This is because the softening parts of conditions I and II, III and IV, V and VI are relatively similar, such as both softening in the top left and top right, in whole or part. In addition, since both V and VI are fully softened at the lower part of the tunnel, and the displacement of the invert is monitored, the displacement of the two is larger than that of other conditions.

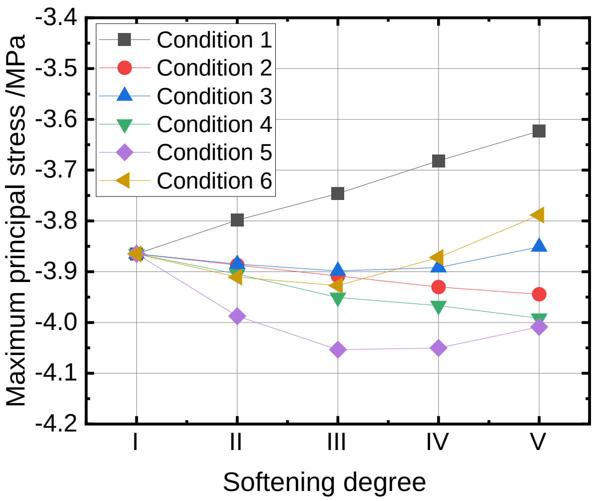
In conclusion, the softening on the left side or the overall upper part of the tunnel has little effect on the horizontal displacement of the tunnel waist. The settlement of crown and horizontal displacement of arch waist increase with the softening degree of surrounding rock. Comparing all softening conditions, it can find that softening above the tunnel has the least influence on the displacement of the inverted arch, while softening below the tunnel has the greatest influence. The invert displacement of the condition when the surrounding rock of tunnel is softening as a whole is smaller than that of only the lower part of the surrounding rock is softened.

Mechanical characteristics of the tunnel

The schematic diagram of the mechanical characteristics of the tunnel with different softening degrees and positions is shown in Figure 10.



(a) Left arch foot



(b) Right arch foot

Fig. 10 - Change law of the mechanical characteristics of the tunnel

In Figure 10, the changing trend of maximum principal stress of the left and right foot of the tunnel is basically the same in conditions 1, 5, and 6 (the softening positions of the surrounding rock are symmetrically distributed) with softening degree. However, the changing trend of the maximum principal stress of the left and right arch foot of tunnel with softening degree is completely different in conditions 2, 3, and 4 (namely, asymmetric distribution of softening positions). In condition 1, the maximum principal stress of the left and right foot of the tunnel gradually decreases with the increase in softening degree, and the maximum principal stress decreases by 6.17%. For condition 2, when the softening degree increases, the maximum principal stress of the left arch foot decreases, while that of the right arch foot increases, and the maximum principal stress increases by 2.06%.

For condition 3, the maximum principal stress of the left arch foot of the tunnel increases with softening degree, while that of the right arch foot of the tunnel increases first and then decreases, and the maximum principal stress increases by 9.02%. For condition 4, when the softening degree increases, the maximum principal stress of the left arch foot shows the trend of “first increases and then decreases”, while that of the right arch foot of the tunnel increases, and the maximum principal stress increases by 3.28%. In conditions 5 and 6, the maximum principal stress of the left and right arch foot increases first and then decreases with softening degree, reaching the maximum value in softening degree III, and the maximum principal stress is increased by 3.66% and 1.72%, respectively.

To sum up, it can be concluded that the softening of the surrounding rock at the lower left corner of the tunnel has a great influence on the mechanical properties of the left arch foot, while the overall softening has a great influence on the mechanical properties of the right arch foot of the tunnel and the maximum principal stress is the largest. At the same time, it can also be found that when the surrounding rock above the tunnel is softened as a whole, the stress at the arch foot of the tunnel is the smallest.

CONCLUSION

Based on the actual engineering, the deformation law and mechanical characteristics of the tunnel under different softening degrees and positions are further analyzed in this paper, and the main conclusions are as follows:

(1) When the softening positions are distributed symmetrically, the tunnel deformation is basically symmetrical, but when the softening positions of the surrounding rock are distributed asymmetrically, the horizontal displacement of the arch waist is larger on the side with higher softening degree. Under different softening conditions, the change value of the invert displacement (uplift) caused by the softening at the invert is the highest, which is higher than that when the surrounding rock is softened in a whole.

(2) The softening of the left side or the overall softening above the tunnel has little effect on the horizontal displacement of the tunnel waist. The greater the softening degree, the greater the crown settlement and the horizontal displacement of the arch waist. The softening of the surrounding rock above the tunnel has the least impact on the uplift value of the invert, while the softening below the tunnel has a greater impact on it. The uplift of the invert displacement in the condition when the surrounding rock softens in a whole is smaller than that of only the lower part of the tunnel is softened.

(3) When the softening positions are distributed symmetrically, the maximum principal stress at the left and right arch foot of the tunnel is consistent with softening degrees, while that of the asymmetric conditions is completely different. The softening at the lower left corner of the tunnel has a great influence on the mechanical properties of the left arch, while the overall softening has a great influence on the right arch foot, and the stress is the largest. On the other hand, when the surrounding rock above the tunnel is softened as a whole, the stress at the arch foot is the least.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY

All data, models, and code generated or used during the study appear in the submitted article.

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