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Study on Face stability analysis of the aeolian sand tunnel

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Abstract. In view of the particularity of the geological environment of the surrounding rock of the aeolian sand, the tunnel will be destabilized due to its poor self-stability during tunnel excavation, which is worthy of attention. In this paper, the three-dimensional discrete element method is used to establish the discrete element numerical model of the excavation surface of the aeolian sand tunnel. The macroscopic mechanical response of the face is obtained and analysed, and the process of instability of the excavation surface is revealed from the macroscopic and microscopic mechanics. Based on this, the reasonable and safe support force of the excavation face is determined. Compared with the existing research, this paper uses the discrete element method to influence the dynamic construction of aeolian sand stratum on the stability of the face, which is closer to the engineering practice. The research results can provide reference for ensuring the stability of the tunnel face in the aeolian sand stratum.

1. Introduction

Aeolian sand stratum is a special geological condition in the construction of tunnel engineering. It has great engineering properties with other genetic sands. It has uniform particles, fine particle size, low content of silt clay particles and cohesion. The water surface is low and the surface area is extremely difficult to self-stabilize and sensitive to external disturbances. In the case of excavation tunnels in such surrounding rock, if the support pressure is insufficient or not timely, the face surface collapses. The catastrophic problems such as sand blasting and even roofing have caused irreparable loss of manpower and material resources. Therefore, it is of great practical significance to carry out research on the stability of the face of the aeolian sand tunnel.

At present, domestic and foreign scholars have conducted a series of studies on the stability of the tunnel face. Broere [1] studied the shape of the instability zone as a wedge-shaped and logarithmic double helix by the limit equilibrium theory. Chambon et al [2] used a model test to obtain the limit support force of the face by gradually reducing the support pressure. With the continuous development of electronic computer technology, numerical simulation methods are widely used in their research. Qiu Yuliang et al [3] studied the change of surrounding rock pressure and the timing of the second lining of the aeolian sand road tunnel by using the finite element software FLAC3D. Wang Mingnian et al [4] used the discrete element software PFC to support the earth pressure of the face in the sand gravel stratum of Chengdu. The changes were studied to investigate the deformation and damage of the tunnel face.

Many studies mentioned above have yielded fruitful results from multiple methods and multiple angles, but there are still some shortcomings. For example, the constitutive law is simplified in theoretical analysis, but in practice, the geotechnical is extremely complex [5-6]. Many of the existing



studies have been simulated by finite element method. However, aeolian sand is a discrete medium, there is an error in the calculation results.

In view of this, according to the strong discrete characteristics of aeolian sand, the discrete element numerical model of the excavation surface of aeolian sand tunnel is established, and the macroscopic mechanical response of the face is obtained and analysed, including the change of the support force of the face. The process of instability of the excavation face is revealed from the macroscopic and meso-mechanical aspects, and the reasonable and safe support force of the excavation face is determined based on this.

2. Project Overview

2.1 Topographic features

The tunnel is located in the low-altitude mountain area. The ground elevation is 3146~3232m, and the relative height difference is 30~86m. The natural slope of the mountain where the tunnel is located is 30°~40°. The terrain of the tunnel entrance is relatively flat, the terrain of the exit is steep, and the terrain of the tunnel is undulating. The surface of the hillside of the tunnel exit and the surface of the shallow buried section of the tunnel cover the aeolian sand.

2.2 Stratigraphic lithology

The exposed lithology of the tunnel is mainly the Quaternary Holocene aeolian powder fine sand, alluvial fine sand, the Upper Pleistocene fine sand and fine breccia, and the lithology characteristics of the surrounding layers are as follows.

(1) Fine sand (Q₄): It is mainly distributed on the hillside near the exit of the tunnel and the surface of the mountain valley between the caves, with a layer thickness of 0.5~1m. Mainly yellow, uniform particles, pure sand, the main mineral components are feldspar, quartz, etc., loose - slightly dense, slightly wet, $\sigma_0 = 80 \sim 100\text{kPa}$, class II ordinary soil.

(2) Fine sand (Q₄^{pl4}): mainly distributed in the tunnel entrance and the shallow buried gully section of the tunnel, with a thickness of 3 to 9 m. Gray-yellow, mineral composition is mainly feldspar, quartz, uneven particles, impure sand, high content of local gravel, slightly wet, slightly dense, $\sigma_0 = 120\text{kPa}$, grade I loose soil.

(3) Fine sand (Q₃^{pl4}): distributed in the lower part of shallow buried gully, thick 0~16m. Light yellow, the mineral composition is mainly feldspar, quartz, the sand is more uniform, contains a small amount of soil, slightly wet, dense, $\sigma_0 = 200\text{kPa}$, grade I loose soil.



Figure 1. Distribution of aeolian sand on the ground.

3. Model establishment and calculation parameter selection

3.1 Mesoscopic parameter calibration

In this study, the triaxial compression test was used to calibrate the mesoscopic parameters of the aeolian sand. Considering the buried depth of the tunnel as shown in the figure, the confining pressures were selected to be 50, 100, and 200 kPa, respectively. The mesoscopic parameters are analysed for the stress-strain curves obtained under the parameters of each group, so that the mesoscopic parameters of the model are consistent with the mechanical parameters of the material to calibrate the model mesoscopic parameters and the macroscopic physical and mechanical parameters of the soil. The comparison between the indoor triaxial test and the discrete element simulation results is shown in Fig. 2. The physical and mechanical parameters of aeolian sand are shown in Table 1.

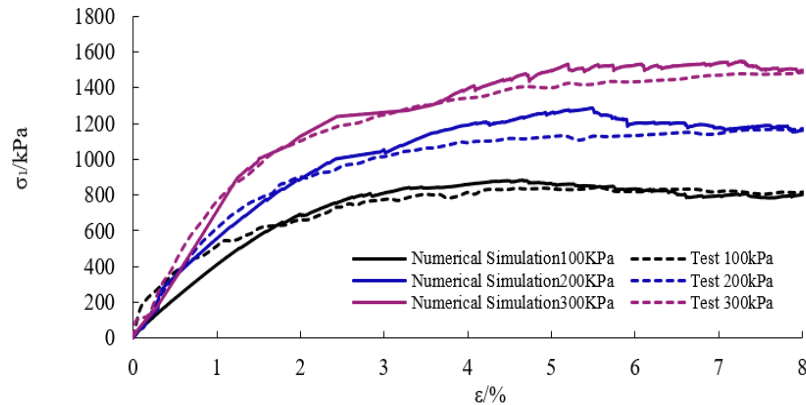


Figure 2. Comparison of indoor triaxial test and discrete element simulation results.

Table 1. Physical and mechanical parameters of aeolian sand.

material	($\text{kN}\cdot\text{m}^{-3}$)	μ	E/Gpa	C/kpa	φ ($^{\circ}$)
Aeolian sand	18.7	0.40	0.031	3.94	27

Taking the macroscopic physical and mechanical parameters in Table 2 as the goal, the three-axis numerical simulation test is adopted, and the corresponding deformation modulus, friction angle and cohesive force are obtained for the multiple sets of mesoscopic parameters under the confining pressure of 50, 100, and 200 kPa. The macroscopic physical and mechanical parameters of the sand are calculated and analysed, and the calculated results are compared with the mechanical parameters of the aeolian sand, so that the model mesoscopic parameters corresponding to the macroscopic mechanical parameters of the aeolian sand are determined [7], as shown in Table 2.

Table 2. Parameters used in discrete element calibration.

material	ρ (g/cm^3)	$R_{\max}/R_{\min}$	μ	k_n/Mpa	k_s/Mpa
Aeolian sand	1.91	1.2	0.8	$1\text{e}8$	$1\text{e}8$

3.2 Establishment of numerical model

The size of the numerical model is length $\times$ width = 60m $\times$ 30 m, and the tunnel diameter (D) is 6m. In this study, the distance between the bottom of the tunnel and the bottom boundary is 0.5D, 1D and 2D. The ground surface of the model is set as a free surface, and deformation constraints are adopted around the surface. After the particles are generated, the gravitational acceleration is applied to the model, and then the particles of different parts of the surface are deleted according to the working conditions to simulate different buried depth conditions of the tunnel. As shown in Figure 3

The tunnel face is placed at a position 2D from the boundary, which can effectively reduce the influence of the boundary effect on the face of the face. In addition, since this study focuses on the stability of the face, the PFC-specific monitoring circle is used to set 8 earth pressure measuring points (T1~T8 in Figure 4) on the wall unit of the model face. It is used to monitor the changes in the value and distribution of support forces during the unloading process of the face. As shown in Figure 4.

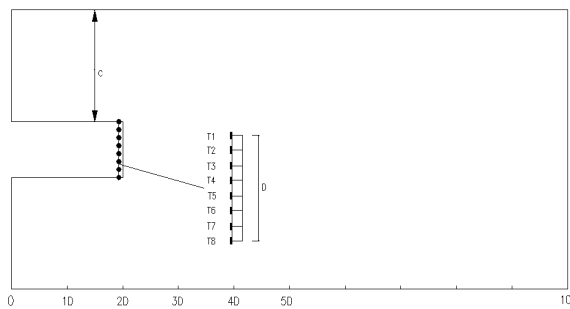


Figure 3. Model measuring point and layout position

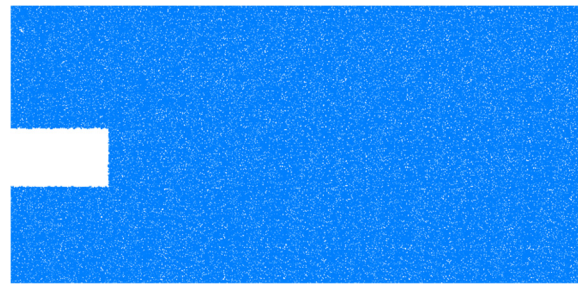


Figure 4. Discrete element calculation model for aeolian sand tunnel

4. Numerical analysis of the stability of the face of the aeolian sand tunnel

4.1 Calculation process

Under different working conditions, the change and influence of the support stress of the face is the focus of this paper. Therefore, in the simulation calculation, the tunnel face is excavated to a certain distance, and the process of unloading and extrusion is monitored by monitoring the face. To study the effects of stress changes on the face of the face. The specific simulation process is as follows:

1 Aeolian sand formation model was established and boundary conditions were set. Under different working conditions, after the initial balance of the calculation model is reached, the static earth pressure of the formation is calculated by monitoring the earth pressure measurement points on the face, as shown in Table 3.

2 The tunnel excavation model is established, and the support structure of the tunnel is set. When the tunnel face moves backward by 0.5% D, the change of the support force of the face will be recorded once by the monitoring system.

3 When the support pressure of the face reaches the limit minimum support pressure, the displacement of the face will increase rapidly until it is destroyed, and the back distance of the tunnel face reaches 15%D [8-11] as the condition for termination of calculation.

Table 3. Initial stress of aeolian sand formation under different conditions

buried depth	Vertical stress at the center of the tunnel face σ_H/kPa	Horizontal stress at the center of the tunnel face σ_V/kPa	Static earth pressure coefficient/ μ
2D	266.4	130.86	0.49
D	135.4	81.454	0.52
0.5D	99.9	57.864	0.58

4.2 Limit support pressure

With the unloading and backward movement of the face, the support force will gradually decrease, and when the minimum value is reached, it will be the limit support force. The variation curves of support pressure and displacement of the tunnel face under different buried depths are shown in Fig. 5. During the process of unloading and moving back, the development of support pressure is divided into three stages: 1 With the increase of the displacement of the face, the support pressure decreases rapidly and the reduction is large. The subsurface displacement continues to increase, and the support pressure reduction rate gradually decreases. After decreasing to a certain value, it remains unchanged. From 1-2, it can be seen that the palm surface is unstable at this time. The limit support pressure (P_f). 3 as the displacement of the face continues to increase, the support pressure starts to rise again from the minimum value to a certain stable value P_r (the definition of P_r is the residual support pressure). The residual support pressure values under different buried depth conditions are basically equal, about 12 kPa higher than the limit support pressure. The reason may be that the aeolian sand particles soften after reaching the peak strength, resulting in the residual branch of the face. The pressure is increased.

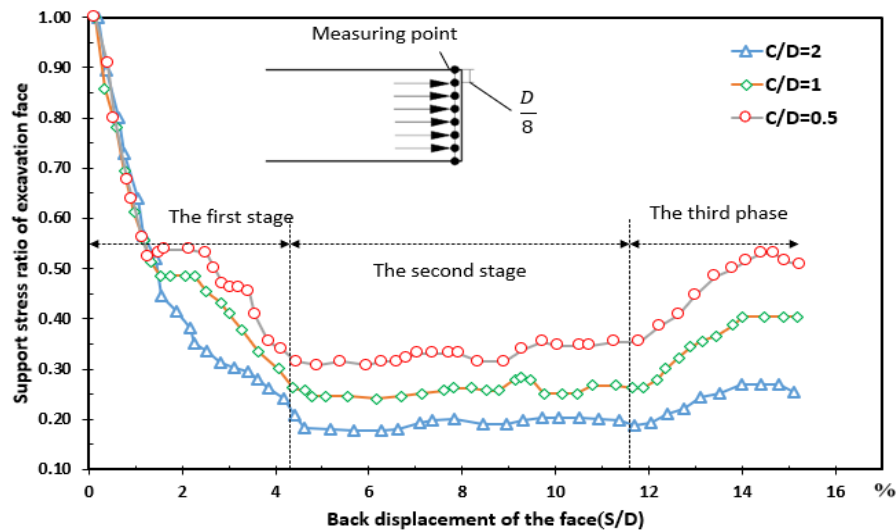


Figure 5. Relationship between support pressure and displacement of tunnel face.

It can also be seen from Figure 5 that different buried depths have a certain influence on the magnitude of the support pressure. When the extrusion displacement of the face is $4.2D\%$, the support pressure drops rapidly. The limit support pressure of the three buried depth conditions ($2D$, D and $0.5D$) occurs when the displacement of the face is $4.2D\%$, 23.15 kPa, 19.58 kPa, and 17.80 kPa, respectively. After that, the displacement of the face is gradually increased. When the extrusion displacement is about $11.6D\%$, the residual support pressures of the face of the three buried conditions are 35.15 kPa, 32.93 kPa and 29.82 kPa, respectively. The calculation results are shown in Table 4.

Table 4. Influence of buried depth on support pressure

Different indicators	C/D		
	0.5	1	2
Limit support pressure (kPa)	17.80	19.58	23.15
Residual support pressure (kPa)	29.82	32.93	35.15
Limit support stress ratio	0.18	0.24	0.31

It can be concluded from Table 4 that the ultimate support pressure increases linearly with the buried depth of the tunnel, and the corresponding limit support stress ratio ranges from 0.18 to 0.31. The calculation result is larger than that other strata. The main reason is that the aeolian sand stratum has low strength, and the static earth pressure coefficient is large and the dispersion is large and easy to deform.

5. Conclusion

The stability of the face of the tunnel in the aeolian sand formation is the focus of engineering attention, and the ultimate support force is the core of the research. In this paper, a three-dimensional discrete element method is used to establish a more sophisticated model to analyse the stability of the face of the tunnel during construction, and the ultimate support pressure of the face is obtained. The study has mainly achieved the following three conclusions.

(1) The process of the face support changing is divided into two stages. first, the support force will be directly reduced to the minimum value, that is, the ultimate support force of the excavation face. Then the support will gradually rise to a certain level of stability.

(2) Under different buried depth conditions, the ultimate support pressure occurs when the displacement of the excavation surface is $4.2\%D$, and the corresponding support ratio of the ultimate support force is 0.18~0.31.

(3) The micro mechanical parameters obtained through calibration in the indoor triaxial test can fully reflect the key mechanical properties of the sand samples. Finally, after calibration, the

micromechanical parameters corresponding to the 71 layers of silty sand in Shanghai are: $kn=ks=9e7$, m .

Acknowledgments

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