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Research Article

Influence of Support Parameter and Excavation Methods on Statistical Distribution Characteristics of Surrounding Rock Pressure in Shallow-Buried Metro Tunnel

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For large-spanshallow-buried tunnels in composite strata of urban metro, the study on the distribution characteristics of surrounding rock pressure is a necessary prerequisite for the reliability analysis of tunnel structure. In this paper, through numerical simulation, the random joint file generated by MATLAB is combined with the discrete element software to establish the corresponding random network model. According to the network model calculation, the influence of surrounding rock pressure on the support structure system is discussed, and the reasonable support parameter types are given. Comparing the whole section excavation with the subsectional excavation, the subsectional excavation can effectively control the internal stress self-adjustment of the surrounding rock and effectively restrain the plastic zone. It provides some theoretical guidance and reference for tunnel reliability design.

1. Introduction

With the acceleration of urbanization, the development and utilization of urban subway and its underground space are more and more favored by people, and especially, the shallow-buried underground spatial structure with large section has been paid more and more attention. In the process of urban construction, there are many special strata such as soft ground and hard ground. When a large-span tunnel or underground space is excavated, it inevitably disturbs the in situ stress field which causes ground movements leading to surface settlement, which may cause serious damage to adjacent structures. The ground surface settlement induced by tunnelling varies according to different construction approaches used for different tunnel cross sections [1]. The study of underground space tunnel cannot be separated from the determination of surrounding rock pressure, and the calculation of surrounding rock pressure is also a hot issue in tunnel design. Because tunnels exist in complex geological bodies, there will be many uncertainties, such as the uncertainty of surrounding rock pressure load and the uncertainty of physical and mechanical parameters of geological bodies [2, 3]. The size, property, and distribution of these uncertain factors directly affect the selection and design of tunnel support system and the determination of construction methods. Therefore, focusing on the distribution characteristics of surrounding rock pressure and the impact of construction schemes has become a hot topic to be solved urgently [4, 5].

Many scholars have done a lot of research on construction method and support parameter selection. Ding and Wang [6] studied the influence of shallow excavation method conversion on surface settlement. Zhang et al. [7] optimized the excavation methods of large-span flat highway tunnels and loess tunnels. Li et al. [8] analyzed the equivalent thickness of shotcrete by applying the lame solution formula. Yan [9] gave a theoretical explanation for the optimum spraying layer thickness of shotcrete. Bjureland et al. [10] studied the probability distribution of shotcrete parameters in the reliability analysis of rock roadway support. Chandra et al. [11] predicted the tunnel excavation method and rock support method in the Himalayas of India. Luo et al. [12] studied the deformation law and mechanical characteristics of temporary support of tunnel by the construction method of partial excavation. Wang et al. [13] studied the adaptability of the primary support arch covering method in the large-span tunnel. Sharifzadeh et al. [1] studied the sequential excavation design of large-span urban tunnels in soft soil area. Sadaghiani and Dadizadeh [14] proposed a new method of construction which is used in the construction of large-span metro stations. In terms of railway tunnels, Song et al. [15] studied the statistical characteristics of the lining effect of tunnels by the stochastic finite element method. Zhang et al. [16] made a similar model test on the surrounding rock pressure distribution of an unequal span multiarch tunnel. Zheng et al. [17] studied a new sequential excavation method for large-section tunnel construction in soft ground to limit ground settlement. Luo et al. [18] studied the rule of deformation of temporary tunnel support caused by continuous excavation. Li et al. [19] optimized the influence of the multistep excavation method on the deformation performance of large-section underground tunnels. At present, there are few reports on the statistical distribution characteristics of surrounding rock pressure of shallow and long-span tunnels in the urban subway, especially on the influence of excavation methods and support parameters on the distribution characteristics of surrounding rock pressure.

In view of this, this paper uses the discrete element program UDEC to integrate with the random joint network generated in MATLAB, establishes the corresponding calculation model, according to the distribution characteristics of joint fissures to study the distribution pattern of loose surrounding rock pressure, further discusses the influence of excavation method and support parameter on the distribution characteristics of surrounding rock pressure, and provides the theoretical basis for the reliability design of support structure in the future.

2. Implementation of 2-D Random Joints and Fissures Network Program and Its Integration with Discrete Element Software UDEC

In actual engineering rock mass, the development of structural planes has certain randomness. According to a large number of field measurements and research results of global scientific researchers, Wang et al. [20], on the basis of previous studies and on the basis of a large number of field measurements and statistical analysis, concluded that the geometric parameters of structural planes obey the following four distribution forms, that is, uniform distribution, negative exponential distribution, normal distribution, and lognormal distribution. In this paper, based on the probability theory, rock mass structure statistics, and previous research results, a simulation program for joint network generation is developed using the FISH language, and a visual interactive interface is developed by using the DUIDE function in MATLAB. Compared with the simulation programs developed by predecessors, the advantages of the simulation program in this study are as follows:

(1) The program integrates all of the functions of the predecessor programs, which will not be described here [21]
(2) The program can generate multiple sets of joints with different densities simultaneously
(3) The program can solve the problem of different numbers of joints in any combination of strata at the same time

The following is a simulation flowchart of the program, as shown in Figure 1.

The following is a simulation example of formation combination (Figure 2), see Table 1 for specific assumed parameters:

3. Numerical Calculation and Analysis

In this paper, based on the engineering background of the Dalian metro, according to the field geological survey test report and the national standard of China for rock mass classification [22], assuming that various physical parameters are as follows (Tables 2 and 3), according to the schematic diagram of subway tunnel section in Figure 3, the corresponding model (Figure 4) is established. The boundary on both sides of the model is 3–5 times of the tunnel diameter span, and the lower boundary is 1–3 times of the tunnel diameter span. All the block materials and structural surfaces in the model adopt the ideal elastic-plasticMohr-Coulomb strength criterion. The geological body studied in this paper is composed of upper soft and lower hard strata. The influence of support parameters and excavation methods on the change of surrounding rock pressure is discussed when the buried depth is 6 m and the soft rock is 5 m.

The specific modeling steps are as follows: (1) the first step is to establish the corresponding model according to the geometric dimensions of the model. (2) The second step is to assign corresponding physical parameters to different strata according to different strata attributes. (3) The third step is to implant corresponding fracture joints according to the different distributions of joints and assign corresponding physical parameters to the joints. (4) The fourth step is to endow the model with certain boundary conditions. The left and right boundaries of the model and the lower boundary are subject to displacement boundary constraints. The upper boundary is a free boundary. (5) The fifth step is to excavate the tunnel to redistribute its stress.

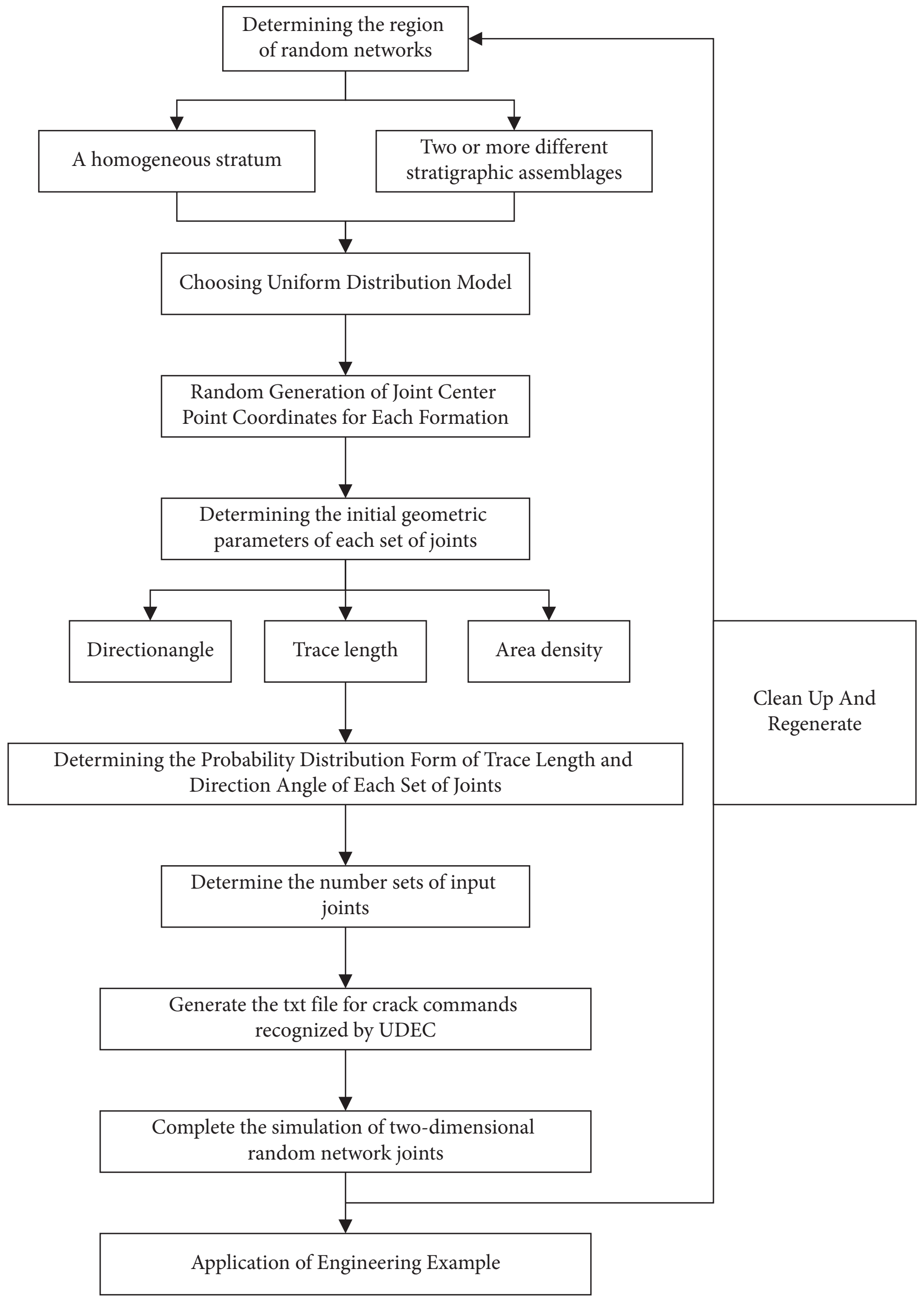


Figure 1: The road map of 2-D random joint network generation technology.

3.1. Influence of Surrounding Rock Pressure on Lining Action. Through the excavation simulation of the tunnel, the support with different thicknesses is adopted, and the shotcrete support with the thickness of 10, 20, 30, 40, 50, 60, and 70 cm is, respectively, carried out after excavation. The mechanical effect of surrounding rock pressure on the shotcrete lining with different thicknesses is discussed, respectively. Figure 5 shows the different states of lining structures with different thicknesses under the surrounding rock pressure. It can be seen from the figure that when the lining thickness is 10 cm, 85% of the lining has reached yield, and even some degree of damage has occurred. With the increase in lining thickness, the yield degree of the lining is decreasing. In this case, it can be selected that the thickness of the lining is 30 cm as the critical thickness value, which can guarantee the later tunnel construction and the safe operation of the railway.

3.2. Influence of Excavation Mode on Distribution Characteristics of Surrounding Rock Pressure. Figure 6 shows the excavation process chart of the CRD method for the shallow-buriedlarge-span metro tunnel. For large cross-section excavation, the CRD method has a good effect in controlling the subsidence range of the stratum. A certain temporary support is set up between each excavation part, and finally, the whole cross-section support system is closed. The

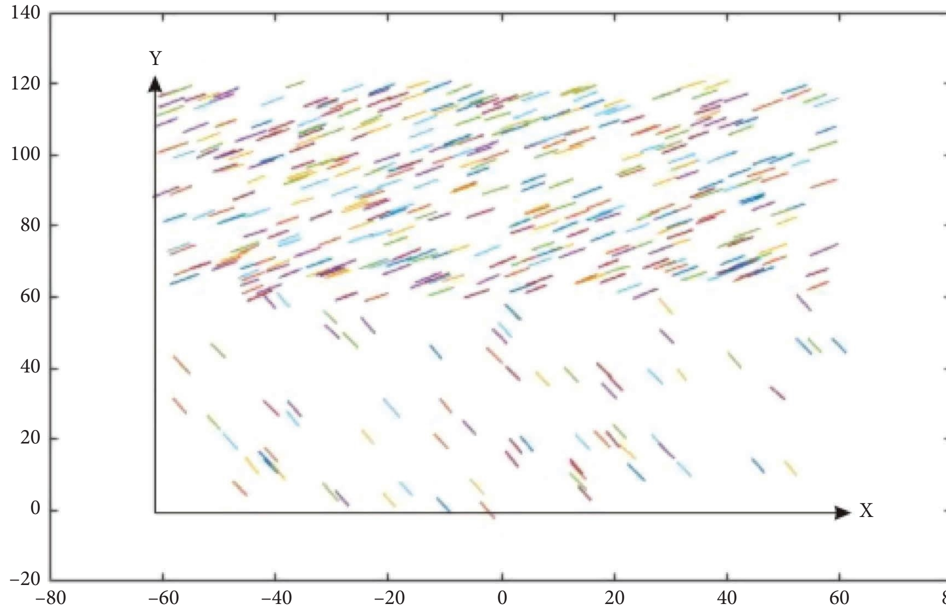


Figure 2: Schematic diagram of the joint network of two stratigraphic combinations.

Table 1: Characteristics of joint distribution parameters.

Rock mass type	Group number	Trace length (m)		Dip angle (°)		Density (strip/m^2)
		Mean	Variance	Mean	Variance	
Soft rock	1	5	0.25	30	4	0.05
Hard rock	1	5	0.25	120	4	0.01

Table 2: Physical and mechanical parameters of the rock mass.

Jointed rock mass	Modulus of elasticity E (GPa)	Poisson's ratio υ	Weight γ (kN/m^3)	Cohesive c (MPa)	Internal friction ψ (°)	Normal stiffness Kn (GPa)	Shear stiffness Ks (GPa)	Tensile strength T (MPa)
Soft rock	0.8	0.42	18.50	0.7	15			1
Hard rock	1.3	0.38	22.00	1.1	30			1.3
Structural surface of soft rock				0.004	2	8	3	0.02
Structural surface of hard rock				0.025	6	9	5.5	0.17

Table 3: Distribution characteristics of multiple joint parameters.

Rock mass type	Group number	Trace length (m)		Direction angle (°)		Depth (m)	Thickness of weathered layer (m)	Density
		Mean	Mean square deviation	Mean	Mean square deviation			
Soft rock	1	6	0.7	0	5.5	6	5	0.15
	2	6	0.7	90	5.5			
Hard rock	1	10	0.7	30	2.2			0.09
	2	10	0.7	150	2.2			
Distribution form		Normal		Normal				

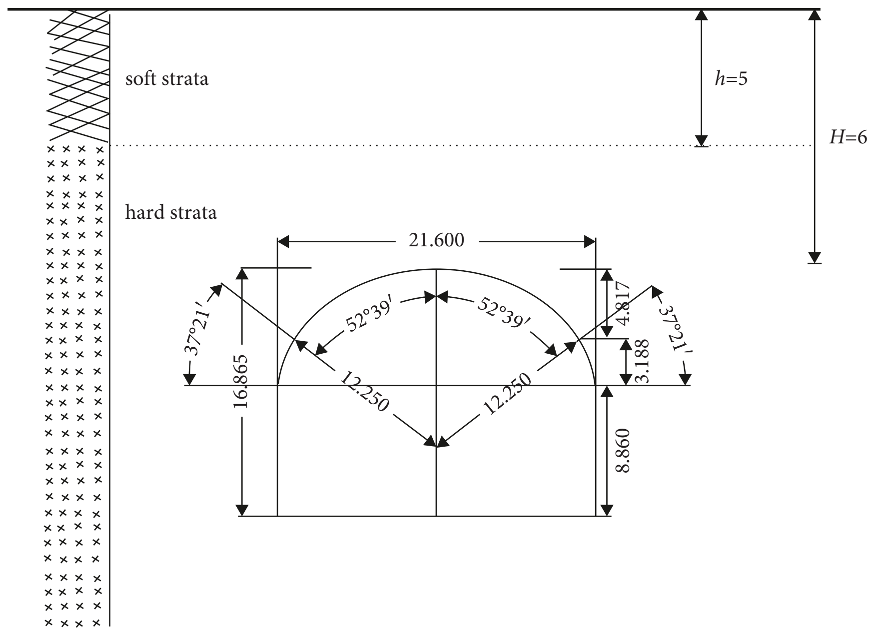


Figure 3: Cross section of the metro tunnel.

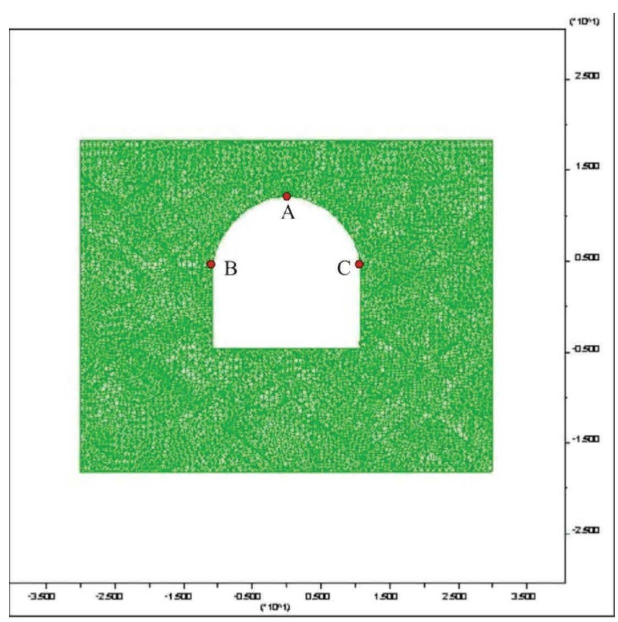
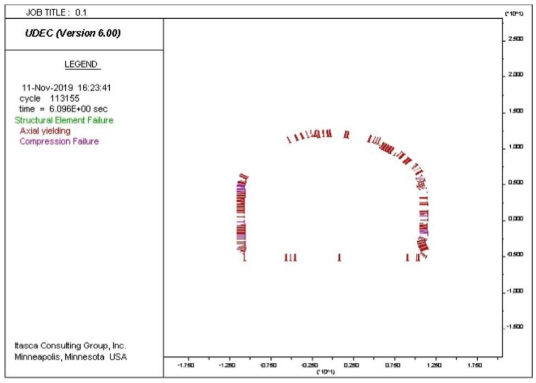


Figure 4: Model diagram.

support system uses the structural beam unit in UDEC to simulate shotcrete. Table 4 gives the physical and mechanical parameters of the initial support material.

Figure 7 shows the statistical distribution characteristics of the surrounding rock pressure on the support structure after the full-face excavation of the tunnel. By fitting the statistical data, the surrounding rock pressure obeys a certain normal distribution. According to the statistical results in Table 5, with the increase of the thickness of the support structure, the surrounding rock pressure acting on the support system will increase accordingly. The analysis shows that this is because when the support structure is thin, the deformation of the rock mass after excavation is large, and the ability of the support system to resist deformation is weak. With the increase of the thickness of the supporting structure, the ability to resist the deformation and loosening of the rock mass increases, so the surrounding rock pressure acting on the supporting structure increases. Figure 8 shows the statistical distribution characteristics of surrounding rock pressure acting on the support system after excavation by sections, which has a certain normal distribution. According to Table 6, the mean value of surrounding rock pressure distribution characteristics on the support system increases with the increase of support thickness.



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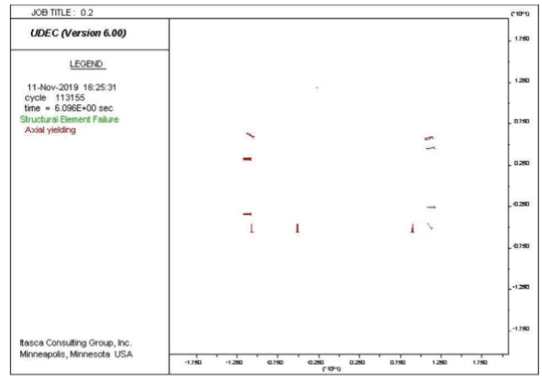

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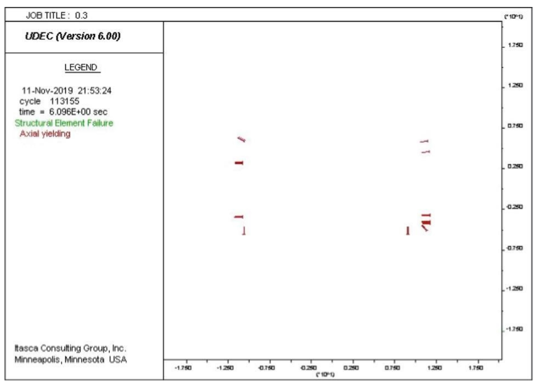

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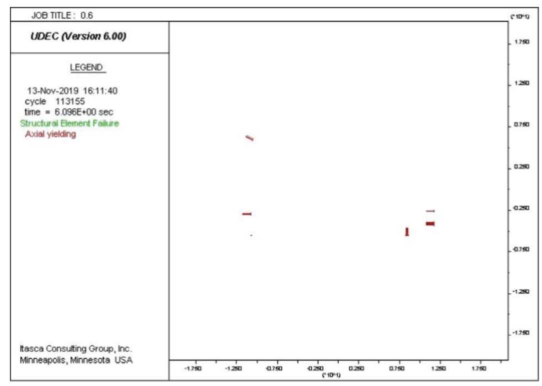
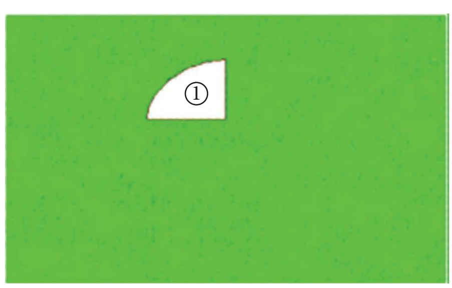


(d)

FIGURE 5: Stress state of shotcrete lining structure: (a) shotcrete 10 cm, (b) shotcrete 20 cm, (c) shotcrete 30 cm, and (d) shotcrete 60 cm.



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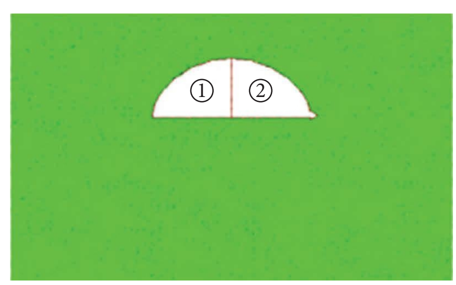

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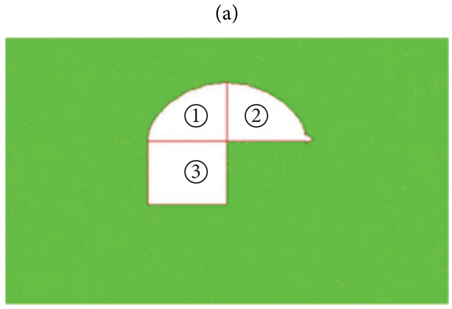

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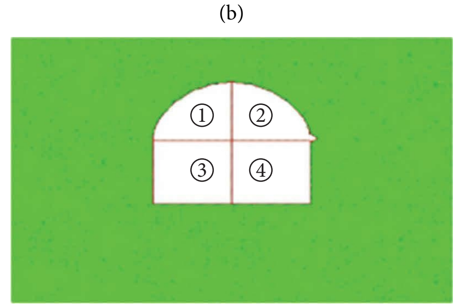

(d)

FIGURE 6: Continued.

(e)

Figure 6: Process of excavation by sections: (a) excavation step 1 and support, (b) excavation step 2 and support, (c) excavation step 3 and support, (d) excavation step 4 and support, and (e) remove temporary support.

Table 4: Physical and mechanical parameters of shotcrete.

Density (kg/m^3)	Modulus of elasticity E (GPa)	Poisson's ratio ν	Tensile yield strength (MPa)	Residual yield strength (MPa)	Compressive yield strength (MPa)
2500	23	0.2	2	1	25

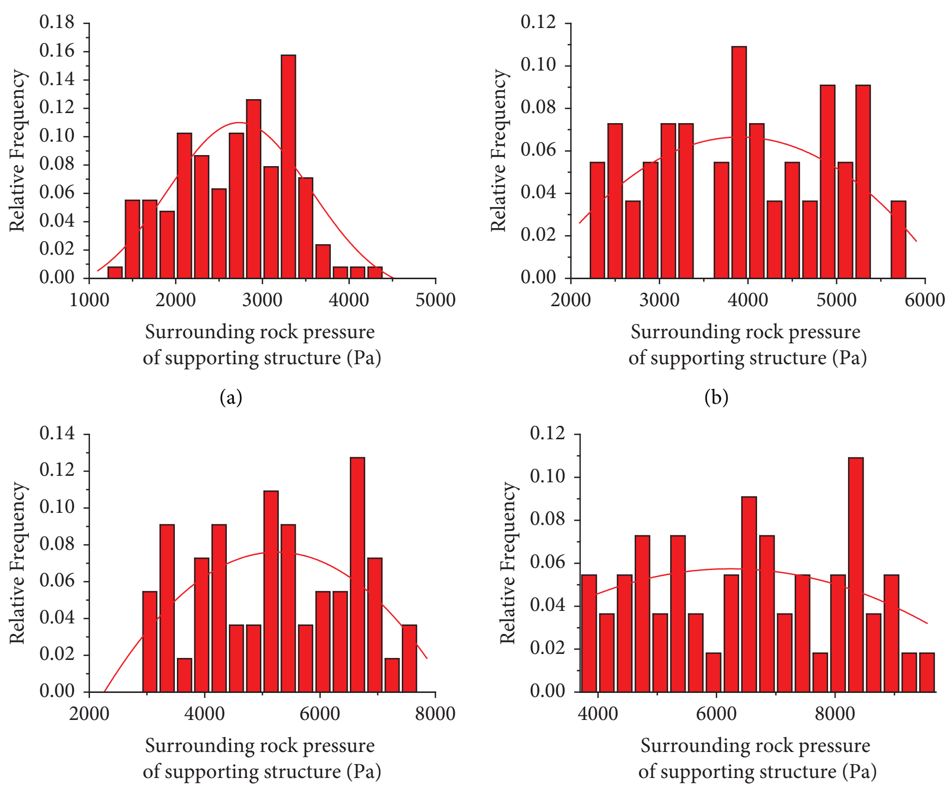

Figure 7: Continued.

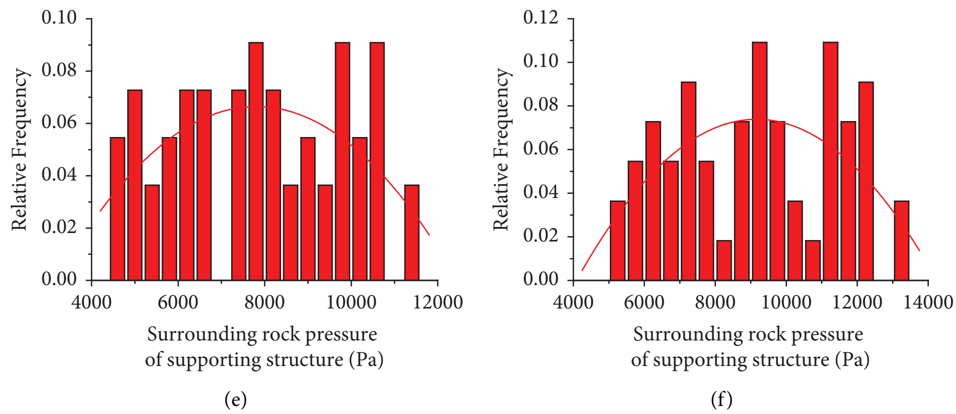

Figure 7: Distribution characteristics of surrounding rock pressure of support structure with different thicknesses after full-face excavation: (a) 20 cm, (b) 30 cm, (c) 40 cm, (d) 50 cm, (e) 60 cm, and (f) 70 cm.

Table 5: Statistical average value of surrounding rock pressure in full-face excavation.

Support thickness (cm)	20	30	40	50	60	70
Statistical average (kPa)	2.733	3.908	5.248	6.237	7.805	9.167

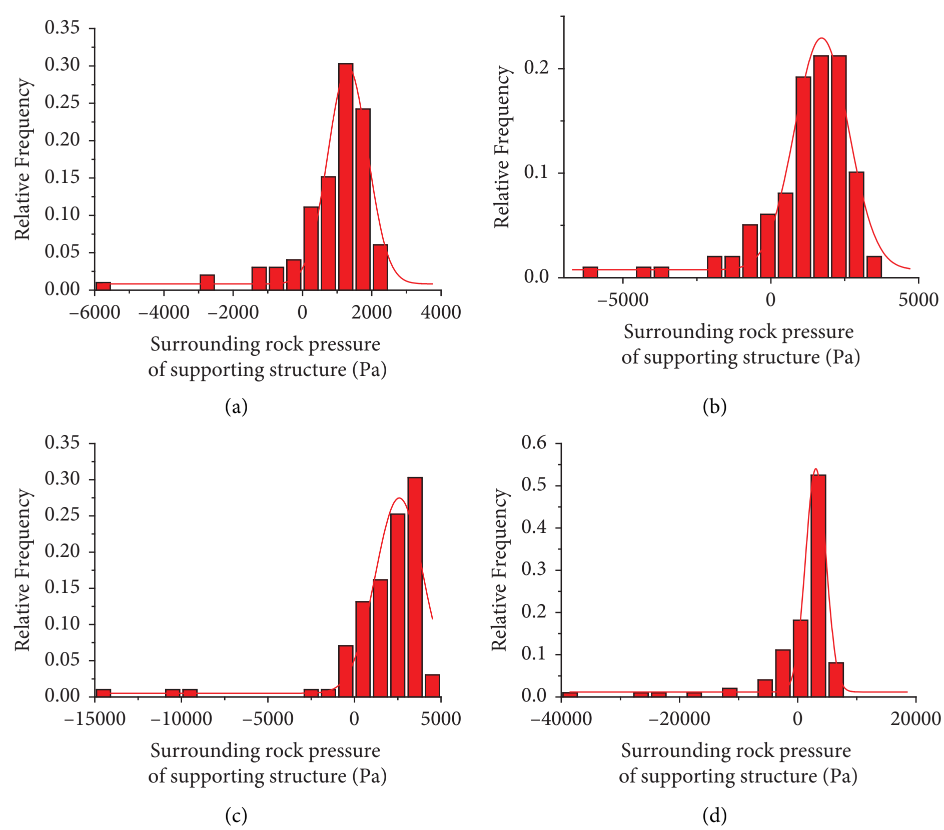

Figure 8: Continued.

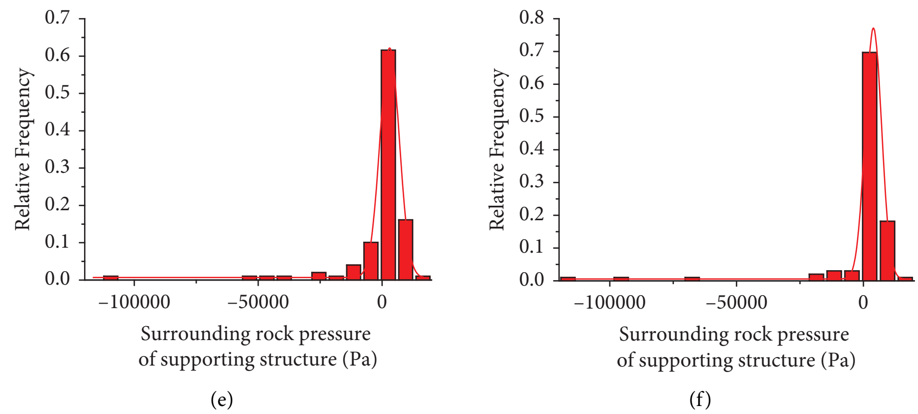

Figure 8: Distribution characteristics of surrounding rock pressure of support structure with different thicknesses of subexcavation: (a) 20 cm, (b) 30 cm, (c) 40 cm, (d) 50 cm, (e) 60 cm, and (f) 70 cm.

Table 6: Statistical average value of surrounding rock pressure of subexcavation.

Support thickness (cm)	20	30	40	50	60	70
Statistical average (kPa)	1.312	1.718	2.585	3.065	3.032	3.959

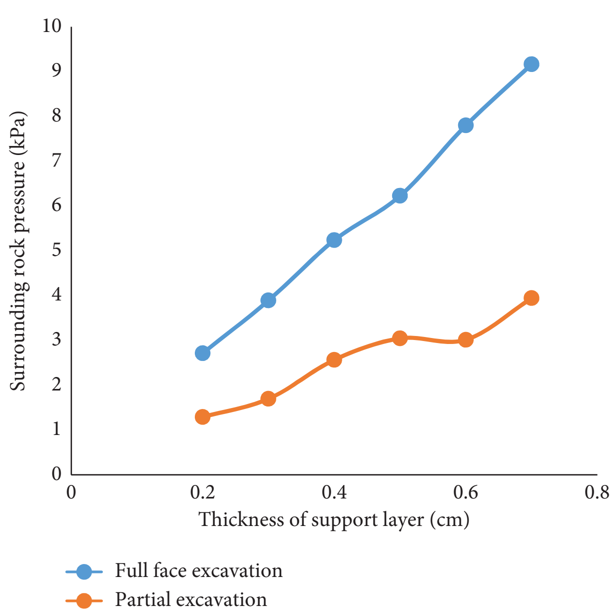

Figure 9: Comparison of surrounding rock pressure of different excavation methods.

Figure 9 shows the statistical distribution of surrounding rock pressure with the thickness of support structure under different excavation conditions. It can be seen from the figure that the variation rule of surrounding rock pressure with the thickness of support structure under different excavation methods is consistent. According to the results of the two excavation methods, when the thickness of the support layer is certain, the surrounding rock pressure value of the support system generated by the partial excavation method is small, and the surrounding rock pressure value generated by the full-face excavation is large. According to the analysis, the deformation of the rock mass release after the one-timefull-section excavation can be relatively large, and the surrounding rock pressure acting on the supporting system is large. The partial excavation is intermittent, and then the part is excavated, and then the supporting part is supported, so that the deformation energy of the rock mass is released in part. The internal structure form of the surrounding rock is self-adjusted, resulting in the final action on the support system pressure value becoming smaller.

4. Conclusion

Through the above research on the influence of the surrounding rock support parameters and the excavation method on the pressure statistical distribution of the surrounding rock on the surrounding rock support structure, the following conclusions can be drawn:

(1) Through the observation of the yield degree of the support system, the parameters of the thickness of the support layer can be reasonably and effectively selected, which has certain guiding significance for the selection of the support parameters after the tunnel excavation

(2) The statistical distribution value of the surrounding rock pressure on the lining increases with the increase of the thickness of the supporting layer after the tunnel excavation, and the statistical distribution value of the surrounding rock pressure on the supporting system after the full-section excavation is greater than the statistical distribution value of the surrounding rock pressure after the partial excavation

(3) Through the comparison of the distribution characteristics of surrounding rock pressure between the two excavation methods, it is found that the distribution characteristics of surrounding rock

pressure are generally normal distribution, and the normal distribution characteristics of surrounding rock pressure produced by partial excavation are more obvious, which indicates that the excavation mode has little influence on the distribution characteristics of surrounding rock pressure

Data Availability

The data used to support the findings of the study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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