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Interaction between weak surrounding rock and supporting structure of shallow buried tunnel based on numerical simulation

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Abstract. In order to design a better surrounding rock and supporting structure, the interaction between these of shallow buried tunnel based on numerical simulation is proposed. The stability of surrounding rock and support structure is tested by numerical simulation. During the construction of shallow tunnel, the stress and deformation characteristics of the supporting structure of the surrounding rock are the key to the stability of the tunnel, especially in the weak surrounding rock. The stability evaluation of the surrounding rock support structure is closely related to the design and construction of the tunnel. The selection of reasonable parameters of support structure is the guarantee of tunnel safety construction and operation. Therefore, it is necessary to study the interaction between soft rock and support structure of shallow tunnel. The mechanical and deformation characteristics of soft surrounding rock and supporting structures in shallow tunnels are studied by combining the measured data at the construction site with the finite element numerical simulation. The experimental results show the surrounding rock pressure of tunnel is not uniformly distributed over the supporting structure, and the pressure of surrounding rock in different parts is quite different. Based on the above finding, it is concluded that the difference between measured and calculated values of the stress of supporting structure is larger than that of surrounding rock stress. Therefore, the numerical simulation is suitable for calculating the degree of weakness of shallow separation tunnel.

Key words. Retaining structure, shallow buried tunnel, surrounding rock, finite element method, numerical simulation.

1. Introduction

With the rapid development of traffic in our country, the application of tunnel engineering in highway engineering is more and more (especially in mountain highway). Tunnels often encounter shallow buried strata, loose, weak and fractured surrounding rock belts and other unfavorable geological segments. Shallow buried tunnel has a shallow buried depth, and many surrounding rocks are weathered and

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broken, and the bias is obvious. The stress distribution and deformation condition of surrounding rock and support structure are complex. Especially in the hilly areas where the depth and topography are large, the stress distribution of surrounding rock and the stress and deformation of lining are more complicated. There are many difficulties in the design of the tunnel construction. If the effective measures are not adopted, the accidents such as collapse of surrounding rock, deformation of supporting structure and lining cracking can easily occur. After years of engineering practice, the construction technology of shallow and weak surrounding rock tunnel has been greatly improved, but the design and construction are different in complex environment such as topography, geomorphology, engineering geology and hydrological conditions.

The main problems existing in shallow buried weak surrounding rock tunnel are [1]: In tunnel construction, the integrity of overlying soil in shallow and weak surrounding rock tunnel is seriously damaged. The stress characteristics, bearing mechanism and failure modes are complex. In order to ensure the reliability and safety of tunnel design and construction, it is necessary to study deeply. The construction of shallow weak surrounding rock tunnel is affected by the site. How to adjust the construction technology and support measures in time according to the site conditions will lay the foundation for the quality of the tunnel project, and the economic benefits are remarkable. Proper selection of test section and appropriate test scheme and test method have great influence on the accuracy and authenticity of data collected at the test site. There is a bias phenomenon in shallow soft rock tunnel, and how to select model parameters and mechanical model in numerical analysis is the key technology of numerical analysis.

The above problems are difficult to be solved in the design and construction of shallow and weak surrounding rock tunnel, which needs further study. Combined with Lantau Peak tunnel construction project, based on numerical simulation analysis and field test, the interaction between shallow buried weak surrounding rock and support structure is studied.

2. Literature review

In the late twentieth century, the method of combining engineering practice and finite element analysis was applied to the tunnel construction of weak surrounding rock. In the twenty-first century, a large number of special finite element software was applied in engineering practice, which made the design more scientific and reasonable. Combined with theoretical calculation, construction monitoring and practical experience, the construction design method which is consistent with geological exploration, design and construction is formed.

2.1. Status of foreign research

Through numerical simulation of the interaction mechanism of surrounding rock and support, Ozsan A analyzed the ground support interaction analysis (GSIA), the empirical method based on the rock mass rating (RMR) and the rock quality index Q classification, and analyzed the reasonable supporting force of the tunnel [2]. Choi analyzed the stability of tunnel with weak surrounding rock by FLAG-3D, and optimized the relevant parameters of support structure [3]. Jeon compared the tunnel with weak interlayer by model test and numerical simulation. The influence of weak interlayer on the stability of tunnel is analyzed. Atkinson and other researchers have carried out the upper and lower limit method of limit analysis for the support reaction of unstable circular tunnel with cohesionless soil layer in the critical state. The calculation results are compared with the existing centrifuge test results, and the stress state of surrounding rock of shallow buried tunnel in cohesionless soil layer is described.

2.2. Status of domestic research

Fu Xinbin adopts the theory of elasticity and the theory of finite element analysis, and studies the mechanical behavior of tunnel construction and the whole stability of tunnel surrounding rock in shallow and weak surrounding rock. It is proposed that the settlement of vault caused by three steps parallel excavation method is less than that of CD method. In shallow buried weak rock, it is beneficial to keep the whole stability of surrounding rock. The reasonable construction method and construction organization of the tunnel that relies on the mountain are studied.

Taking the olecranon tunnel as the research background, the stability criterion of the surrounding rock supported structure is analyzed by Zhu Renjing. The elasto-plastic finite element method (FEM) is used to simulate the dynamic behavior of soft surrounding rock of tunnel. By analyzing the displacement and stress variation of surrounding rock support structure during construction, the stability and safety of surrounding rock support structure during tunnel construction are evaluated.

Liu Qinqin simulated the construction process of weak surrounding rock tunnel with ABAQUS software, and obtained the change law of displacement and stress during the excavation of surrounding rock and initial support structure. The mechanical properties of the contact face between surrounding rock and initial support structure are deeply studied, and a series of conclusions are obtained. For example, it is unreasonable to increase the support effect of surrounding rock by increasing the length of bolt or increasing the thickness of shotcrete layer, so the design parameter of shotcrete bolt support should be taken into consideration [4].

In view of the buried depth of the Foling tunnel and the poor stability of the surrounding rock, Li Chunsheng uses ANSYS analysis software to simulate the soft surrounding rock of tunnel based on three-dimensional numerical. The analysis software includes the reserved core soil method, CD method, CRD method, double side wall guide method. The deformation of surrounding rock, the distribution shape and development law of plastic zone, the stress characteristics of surrounding rock and the variation law of initial support stress are analyzed. The influence mechanism of tunnel construction on the stability of weak surrounding rock is studied.

Xu Daihong uses finite element method to simulate the pre-reinforcement and initial support structure of shallow buried bias tunnel by step method. The surrounding rock stability and construction mechanics characteristic of shallow bias tunnel are analyzed, and the technical scheme of the reasonable construction of sharp slope of tunnel engineering is proposed.

Yang Feng, Yang Junsheng and Zhao Lianheng have adopted rigid upper bound method and upper bound finite element method to calculate and analyze the stability of surrounding rock of shallow tunnel under different conditions. The calculation chart of stability coefficient of tunnel surrounding rock under undrained condition and the calculation chart of reaction coefficient of tunnel support under drainage condition are obtained, which can be referred to for practical reference [5]. At the same time, in the light of the large deformation and collapse of tunnel surrounding rock and support structure during the excavation of the sub clay layer of Yunyang mountain tunnel, the stability analysis of tunnel surrounding rock is carried out by using the upper bound finite element method of limit analysis.

Based on the construction of the shallow surrounding tunnel in the coastal area, using the finite element analysis software (FLAG), the nonlinear numerical simulation of partial excavation is carried out by Jiao Cang, Zhu Jianglin and Fan Peng. The mechanism of large deformation of tunnel weak rock during excavation is studied.

3. Experimental design and numerical simulation

3.1. Field experiment

In order to study the interaction between soft rock and support structure of shallow tunnel, field test is based on Lantau Peak tunnel [6]. Through the selection of two test sections in the tunnel, the pressure box and the concrete strain gauge are embedded, and the deformation of surrounding rock is monitored, and the data of the test element are collected. Mechanical and deformation characteristics of surrounding rock and support structure in tunnel construction of shallow weak surrounding rock are analyzed to ensure safe construction and operation of tunnel.

Two sections of ZK82+008 and ZK82+311 of Lantau Peak tunnel are selected as test section. The two test sections are in the left line of the tunnel and are V grade surrounding rock. ZK82+008 is at the entrance of the left line of the tunnel, taking the A section. ZK82+311 is at the exit line of the left line of the tunnel, taking the B section. Two the rock mass of test section is more broken. The fracture development of surrounding rock and the basic information of test section are shown in Table 1.

Table 1. Basic information of test section

Test section	Pile No.	Buried depth	Surrounding rock grade	Initial support	Second support
A section	ZK82+008	40 m	V grade surrounding rock	26 cm thick C25 shotcrete $\varnothing 8$ steel mesh (spacing: 20×20 double deck) I18 I-beam	45 cm thick C30 reinforced concrete
B section	ZK82+311	15 m			

3.2. Numerical simulation

The buried depth of Lantau Peak tunnel is very shallow. The surrounding rock is broken and mixed with mudstone, and the strength is low [7]. Complicated engineering environment and geological condition bring huge safety hazard to the project construction. Combined with the engineering example of Lantau Peak tunnel, based on numerical simulation and analysis, the interaction between soft surrounding rock and support structure of shallow tunnel is studied, and the stability of tunnel surrounding rock and lining structure is evaluated.

The accuracy of finite element numerical calculation depends mainly on the rationality of the constitutive model and the accuracy of the calculated parameters. The plastic model and the elastic model of tunnel surrounding rock and lining structure are analyzed respectively. The ideal elastoplastic linear Mohr-Coulomb yield criterion is used to analyze the physical and mechanical characteristics of the interaction between the surrounding rock and the lining structure [8].

The tunnel is a slender structure, that is, the cross section of the tunnel is very small relative to the length of the longitudinal direction. It can be assumed that there is no displacement in the longitudinal direction under the action of the surrounding rock, and only lateral displacement occurs. Therefore, On the basis of the actual construction process and supporting measures, the tunnel model is simplified as an elastic-plastic plane strain model during the numerical simulation, and the plane model is extended along the longitudinal length in combination with the specific circumstances of the tunnel.

In view of the characteristics of shallow weak surrounding rock tunnel, based on numerical calculation, the stress distribution characteristics of surrounding rock and support structure, the law of surrounding rock settlement deformation and the law of convergence of characteristic points surrounding rock are analyzed. Detailed analysis is shown in Table 2.

Table 2. Analysis content

Construction method	Analysis content
Bench method	Stress of surrounding rock of tunnel Settlement of tunnel surrounding rock Support structure stress Feature point edge convergence

4. Results and analysis

As it can be seen from Figs. 1 and 2, during this period, the surrounding rock pressure change is relatively large. With the initial injection of concrete strength gradually increased to the design strength, the surrounding rock pressure is basically in a stable state, and increases little with time. Overall, the adjustment of A section surrounding rock pressure eventually tends to be stable and takes about two months.

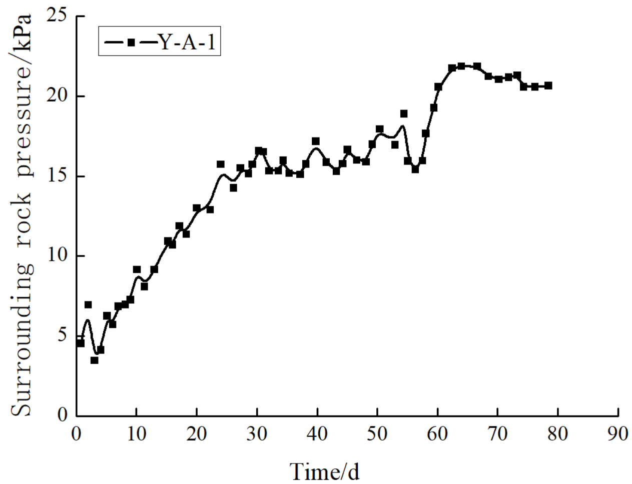

Fig. 1. Variation law of surrounding rock pressure with time at vault of A section

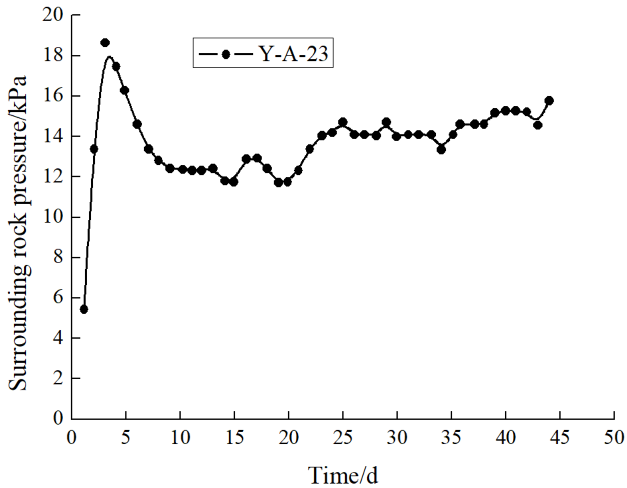

Fig. 2. Variation law of surrounding rock pressure with time under inverted arch of A section

As shown in Figs. 3 and 4, the deformation time of the surrounding rock of the vault is longer than that of the side wall and the inverted arch [9]. The stress of surrounding rock gradually stabilized after 13 days' excavation. However, the stress of surrounding rock gradually stabilized after 15 days' excavation of the side wall and the inverted arch. The adjustment of the surrounding rock pressure of the B section eventually tends to be stable and takes about 2 months.

Through the selection of two typical sections in tunnel, the interaction between soft rock and support structure of shallow tunnel is studied, and the following con-

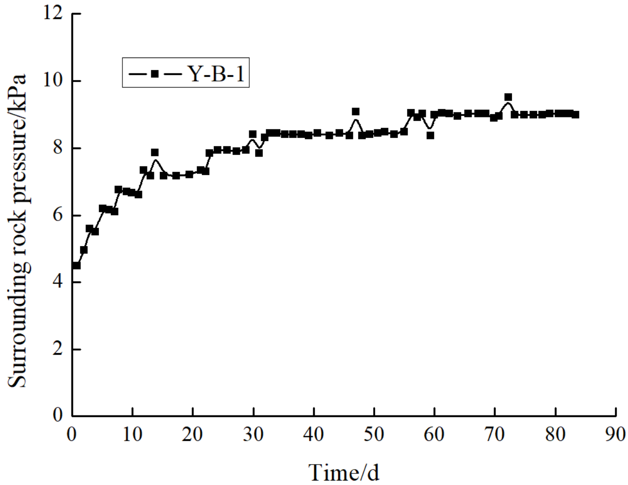

Fig. 3. Variation law of surrounding rock pressure with time at vault of B section

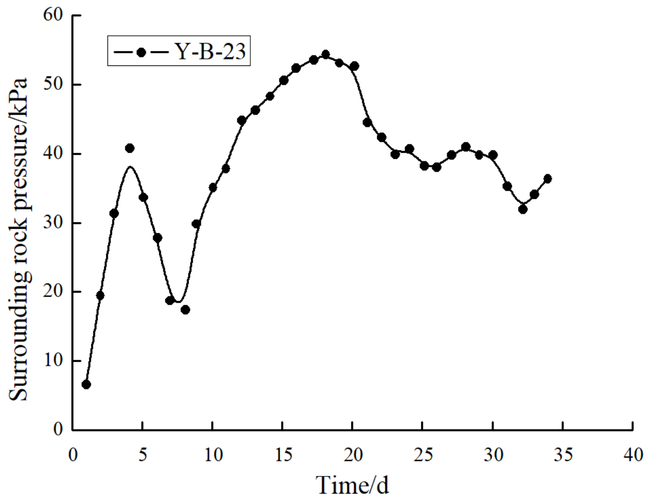

Fig. 4. Variation law of surrounding rock pressure with time under inverted arch of B section

clusions are obtained [10]. According to the monitoring data, the surrounding rock pressure of tunnel is not uniformly distributed over the supporting structure, and the pressure of surrounding rock in different parts is quite different. The pressure concentration of surrounding rock will appear in some areas, and the surrounding rock pressure of invert arch and arch waist is larger. The surrounding rock pressure, the initial lining, the two lining, the two-layer support, the pressure and the concrete stress in the two lining are smaller. It is much smaller than the compressive strength and the tensile strength of the original shotcrete and the two-lined reinforced concrete. It shows that the tunnel structure is safe and stable.

4.1. Numerical calculation results

As shown in Figs. 5 and 6, through numerical simulation, the curves of the stress of the tunnel vault surrounding rock with the overlying rock thickness and the vertical displacement of vault with the overlying rock thickness are obtained.

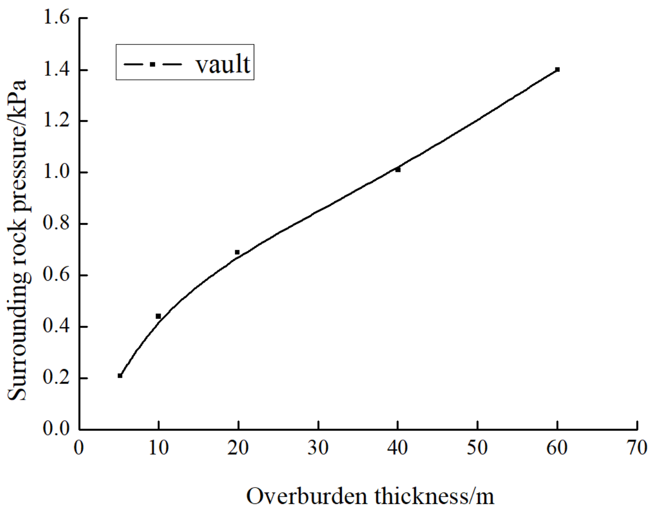

Fig. 5. Curves of stress of surrounding rock of tunnel vault with overlying rock thickness

Through the numerical calculation and analysis of the interaction between the shallow buried weak rock and the support structure, the following conclusions are obtained. When the thickness of the overlying rock on the tunnel is from 5 m to 20 m, the stress of the surrounding rock of the vault increases accordingly, and the stress increases from 0.2032 MPa to 0.6870 MPa. The deformation of the surrounding rock of vault decreases correspondingly, and the settlement of vault decreases from 0.4368 m to 0.0536 m. When the thickness of the overlying rock on the tunnel is from 20 m to 60 m, the deformation of surrounding rock increases, but the amplitude of the increase is small. The dome is increased from 0.0536 m to 0.0677 m, and it is concluded that the thickness of the overlying rock mass is 20 m, which is the limit thickness of arching effect.

5. Conclusion

By comparing and analyzing the results of field test and numerical simulation, it is shown that the difference between measured and calculated values of the stress of supporting structure is larger than that of surrounding rock stress, except for

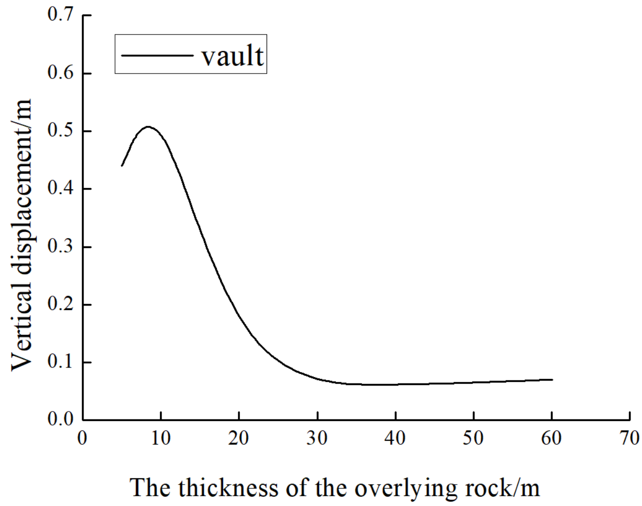

Fig. 6. Vertical displacement of vault with thickness of overlying rock

the abrupt change of 3 points of B section. In numerical calculation, the ideal is to close the surrounding rock with the initial lining, the initial lining and the two lining. But in fact, the tunnel is not smooth. There is no numerical calculation of the effect of the initial lining and the surrounding rock. The first lining and the two lining are actually attached to the waterproof board, and the gap between them leads to the deformation and coordination of the lining under the stress of the surrounding rock. The stress from the surrounding rock is reduced, so the numerical value of the stress of the supporting structure is larger than the measured value. In the B section vault, the measured stress is 0.006 MPa, while the numerical value is 0.025 MPa compressive stress. In the course of pouring concrete, the pressure box is inclined and offset by the impact of the concrete, resulting in the stress distortion of the supporting structure.

The measured data and numerical simulation values are compared from three aspects: deformation of surrounding rock, surrounding rock stress and stress of supporting structure. The two data are different in the same order. Through the finite element analysis, it can basically reflect the actual force and deformation characteristics of the tunnel, and put forward scientific guidance for design and construction.

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