Numerical Simulation of Separated Tunnel Under Vertical Dislocation of Fault

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Abstract: Taking the fault surface of Tao River separated tunnel as the research background, the mechanical response of separated tunnel and the displacement law of deep rock mass under the action of vertical dislocation of fault are explored. The three-dimensional model of tunnel is established by using finite difference software FLAC, and the simulation analysis of separated tunnel crossing fault is completed. The sudden drop of shear stress and the settlement law of deep rock mass are obtained. FLAC analysis shows that: (1) When the distance between the tunnel faces is less than 20m, the right line tunnel crossing the fault plane induces the second sudden drop of the left line tunnel, which increases the possibility of instability slip, and the distance between the tunnel faces is inversely proportional to the sudden drop of shear stress; (2) The closer the distance between the working faces, the greater the peak value of the ratio of shear stress to positive pressure, and the more prone to activation instability at the fault; (3) The distance between the tunnel face is inversely proportional to the secondary settlement. Considering the construction period and economic effect, it is recommended that the distance between the tunnel face is 25m.

Keywords: Separated tunnel; fault; shear stress mutation; rock mass displacement

1 INTRODUCTION

The fault is dominated by weak and broken, loose structure and high clay water content, forming a weak structural layer between hard rocks on both sides. The phenomenon of stress concentration and stress mutation occurs when the tunnel passes through the fault, which is easy to induce the instability and failure of rock mass such as earthquake and blasting. Therefore, the construction of tunnels should avoid crossing faults. However, with the continuous development of domestic infrastructure, high-speed rail, highway and other traffic tunnels inevitably cross the fault fracture zone. Scholars at home and abroad have done a lot of research on this. Min Zeng et al[1] used numerical simulation to study the mechanical response law of fault vertical displacement, dislocation rate and fault friction to tunnel under fault dislocation, and put forward that fault displacement and width are the main influencing factors of fault dislocation range. KIANI

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et al[2] revealed the failure mechanism of tunnels across normal faults by means of centrifuge model tests, and clarified the relationship between the thickness of overlying soil and the stability of tunnels. Based on the composite shear beam theory of fault zone, Daoyuan Wang et al[3] derived the expressions of critical damage load and ultimate displacement, and carried out the sensitivity analysis of the main parameters of tunnel stability. The fault width is the main sensitive parameter. Xuezeng Liu et al[4] established a finite element model based on the Qipanshi tunnel in Mianzhu, Sichuan, and studied the stress and deformation law of the tunnel near the active fault zone under the action of reverse fault dislocation displacement. Under the action of fault movement and ground fissures, the tunnel structure is seriously damaged. Rodríguez-Ochoa R et al[5] to study the influence mechanism of weak seabed strata on seabed mining and hydrocarbons.

In summary, at present, it has important guiding significance for the structural design and construction of fault tunnels. It mainly focuses on the study of single tunnel crossing faults, and does not consider the influence of the distance effect between the working faces of the separated double tunnels crossing faults on the surrounding rock. Under the action of fault fracture zone and high stress, the distance effect of the working face of the separated tunnel excavation has a more significant influence on the surrounding rock. Therefore, based on the background of the separated Tao River Tunnel of Anlan Expressway, the tunnel is orthogonal to the ridge and crosses two fracture zones. $FLAC^{3D}$ is used to simulate the structural failure mode and instability mechanism of separated tunnel face across faults at different distances. Furthermore, a better scheme for the construction of separated tunnels across faults is proposed in order to improve the construction speed and save money in the feasible scheme.

2 PROJECT OVERVIEW AND CONSTRUCTION SCHEME

2.1 Project Overview

Anlan Expressway is an important part of the national Yinbai Line and a key section to break through the Bashan barrier and connect the Chengdu-Chongqing Economic Zone. It is of great significance for the in-depth implementation of the western development and the " Belt and Road " development, the improvement of regional traffic conditions, the acceleration of poverty alleviation in the poverty-stricken areas of Qinba Mountain, and the promotion of resource development and coordinated economic and social development along the route. The whole process of the separated Tao River Tunnel of the Anlan Expressway is 645m, with an average buried depth of 130m. It crosses two fracture zones, and the proportion of grade V surrounding rock is as high as 58%. The strata of the Tao River Tunnel are mainly Quaternary Holocene slope residual, slide, alluvial and proluvial, and Cambrian Upper Series Heishui River Formation limestone. The thickness of the surface overburden is thin, the weathering is serious, and the rock joint development is very obvious.

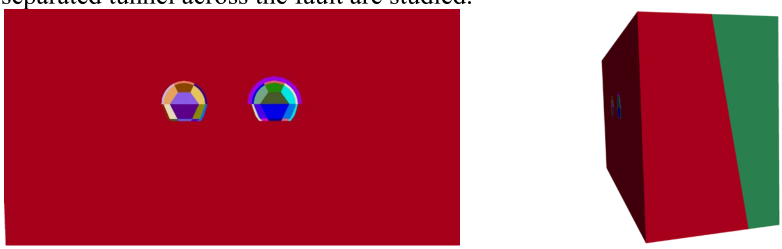
2.2 Construction Plan

The core soil method of circumferential excavation is adopted in the cross-fault area of the tunnel. The core soil is reserved on the platform, and the working face is excavated circularly. The initial support arch is constructed in time to enhance the support stability of the working face. The core soil and the lower step soil are excavated under the action of the initial support arch. The annular excavation footage is 0.8m, and the bolt shotcrete support is timely after excavation.

3 NUMERICAL SIMULATION ANALYSIS

3.1 Model Establishment

The section of Taohe tunnel is 8.9m high and 10m wide. The fault is thrust fault, and the dip angle of tunnel working face is about 55 ° ~ 85 °. Aiming at the weak surrounding rock of tunnel crossing fault, which is easy to collapse and impact damage during the excavation of working face, FLAC^{3D} software is used to establish a numerical model around tunnel excavation, structural support and tunnel crossing fault. FLAC^{3D} adopts Lagrangian algorithm and mixed-discrete partition technology, which can accurately simulate the three-dimensional structural stress characteristics and plastic flow of soil, rock and other materials. Fig.1 is a separated tunnel model. The calculated overall span is 100 m, which is about 5 times the span of the separated tunnel, and the height is 60 m. The overlying soil above is 25 m, and the height of the soil below is about 2 times that of the tunnel. The longitudinal length along the station is 50 m, which meets the requirement of ignoring the boundary effect. A vertical stress of 2 MPa is applied to the top, and the interface command is used to establish a fault plane of 80°. In this numerical simulation, it is assumed that each soil layer is uniform, using solid element, Mohr-coulomb simulation ; the material parameters of the rock mass are shown in Table 1. The normal stiffness of the fault is 20 GPa, the tangential stiffness is 10 GPa, the internal friction angle is 20 °, and the cohesion is 0.7 MPa. The Coulomb shear model is used for the fault, and the main parameters are given in [6]. The two sides of the model limit the horizontal displacement, the bottom limits its vertical displacement, and the upper surface is a free boundary. The working face of the tunnel is advancing along the y direction, and the failure law and instability mechanism of the surrounding rock of the separated tunnel across the fault are studied.



(a) Separated tunnel (b) Faults

Fig. 1. Separated tunnel model diagram

Table 1. Physical and mechanical parameters of soil

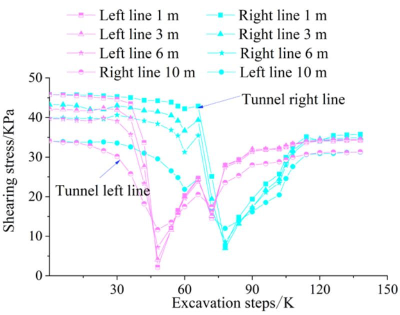
material type	poisson ratio	Gravity /(kg · m^{-3})	elastic modulus /MPa	cohesion /kPa	angle of internal friction /(°)
limestone	0.22	25	60	3.7	40
advance strengthening	0.28	22.0	60	60	0.35
Initial branch of pilot tunnel	0.2	23.0	20000	-	-

3.2 Shear Stress Analysis

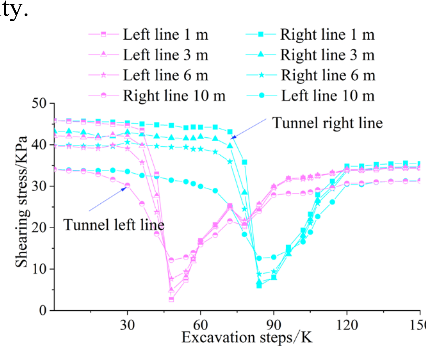
The tunnel face of the separated tunnel is close to the fault plane, the stress state of the fault plane changes, and the possibility of instability slip increases. Fig.2(a)~(d) shows the shear stress monitoring curve of the tunnel roof strata when the left and right tunnel faces of the separated tunnel pass through the fault surface at a distance of 15m, 20m, 25m and 30m. From figure 2, it can be seen that with the advance of the tunnel face, the shear stress of the fault plane decreases first and then increases slowly. In the early stage of tunnel excavation, the initial stress balance of rock strata is destroyed, but the tunnel face is far away from the fault, the tunnel excavation face is small, and the stress is redistributed under the support effect, and the shear stress of the fault surface fluctuates slightly up and down. When the tunnel face is 3m away from the fault plane, the shear stress drops sharply. After the tunnel face passes through the fault plane, the shear stress reaches the lowest point and then gradually rises. The farther the monitoring point is from the excavation section, the smaller the shear stress drop.

The tunnel face is 15m apart from each other, and excavated to the fault plane. The first sudden drop value of the monitoring point is 2.21KPa, 4.19KPa, 7.23KPa, 11.69KPa, and the second sudden drop value is 14.59KPa, 15.25KPa, 16.28KPa, 17.46KPa; the tunnel face is 20m apart from each other, and excavated to the fault plane. The first sudden drop value of the monitoring point is 2.67KPa, 4.85KPa, 7.65KPa, 12.16KPa, and the second sudden drop value is 20.27KPa, 21KPa, 20.69KPa, 20.5KPa; the tunnel face is 25m apart, excavated to the fault plane, and the first sudden drop value of the monitoring point is 2.55KPa, 4.85KPa, 7.52KPa, 12.22KPa; the tunnel face is 25m apart, excavated to the fault plane, and the first sudden drop value of the monitoring point is 3.58KPa, 4.68KPa, 7.45KPa, 12.22KPa; The tunnel face is 25m apart, excavated to the fault plane, and the first sudden drop value of the monitoring point is 3.58KPa, 4.68KPa, 7.45KPa, 12.22KPa; when the distance between the tunnel faces is less than 20 m, the shear stress of the right line tunnel passing through the left line tunnel of the fault plane will drop twice, which increases the possibility of instability slip, and the distance between the tunnel faces is inversely proportional to the shear stress drop interval. The larger the distance, the smaller the secondary drop interval of the monitoring section. When the distance between the tunnel face is greater than 25m, the shear stress of the fault surface of the left line tunnel only drops once. When the right line tunnel is excavated to the fault surface, the stress of the left line has been balanced, with only a small floating.

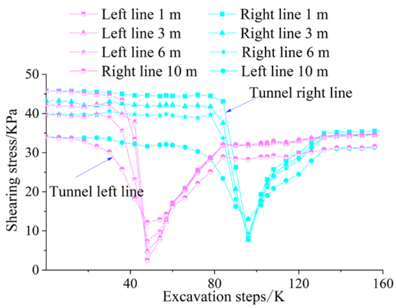
The working face is 15m and 20m apart. After the shear stress fluctuates slightly, it shows four stages of decline-rise-fall-rise. When the left line is excavated to the fault surface, the shear stress drops suddenly for the first time. With the advancement of the working face, the stress is redistributed under the action of support, and the shear stress begins to rise gradually. When the right line tunnel is excavated to the fault surface, the shear stress of the left line drops twice. Due to the close distance between the left and right lines, the stress of the rock mass does not reach equilibrium under the support effect, and it is subjected to secondary damage. The excavation face is 25m and 30m apart. After the monitoring shear stress of the left tunnel fault surface fluctuates slightly, it shows two stages of decline-rise. When the right tunnel is excavated to the fault surface, the stress has reached the equilibrium state under the support of the left tunnel, and the shear stress only decreases slightly. The failure of fault plane nodes leads to the sudden drop of shear stress, which induces the activation and instability failure of the fault. Therefore, the sudden drop of shear stress can be used as a sign to evaluate whether the fault has activation and instability.



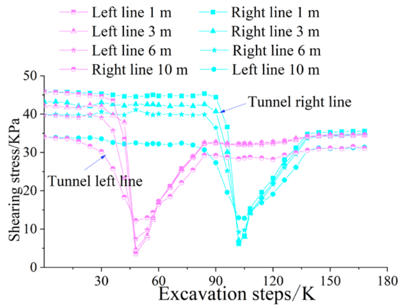
(a) The face of the tunnel is 15m apart



(b) The face of the tunnel is 20m apart



(c) The face of the tunnel is 25m apart

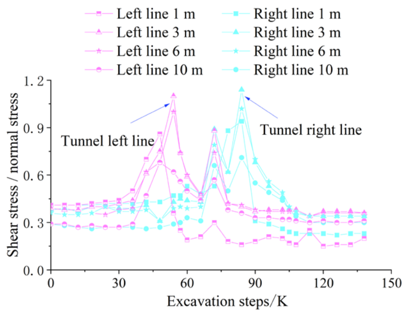


(d) The face of the tunnel is 30m apart

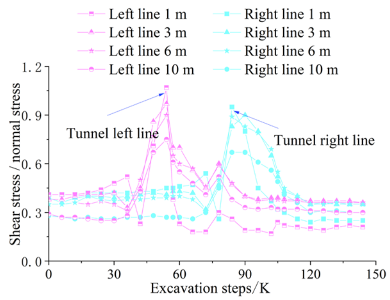
Fig. 2. Shear stress curve of separated tunnel roof strata

3.3 Analysis of the Ratio of Shear Stress to Normal Stress

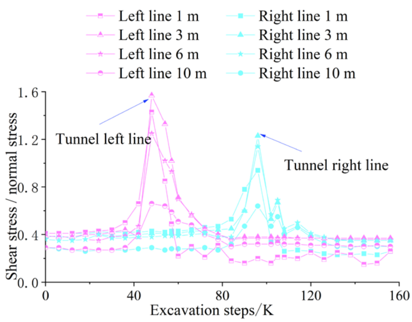
According to the law of friction, the ratio of shear stress to positive pressure determines the friction properties of the contact surface. Therefore, the ratio of shear stress to normal stress can be used to judge whether the fault plane is activated and unstable. Fig.3(a)~(b) is the ratio curve of shear stress and normal stress of the monitoring point, which is 15m, 20m, 25m and 30m away from the fault plane of the left and right lines of the separated tunnel. When the distance between the tunnel faces is less than 20m, the ratio curve of shear stress to normal stress of the left line tunnel fluctuates slightly and then shows four stages of rising-falling-rising-falling. When the distance is 15 m, the ratio of the fault vertex of the left line tunnel is 1.1 and 0.88, and the ratio of the fault vertex of the right line tunnel is 1.14; when the distance is 25m, the ratio of the fault vertex of the left line tunnel is 1.07 and 0.59 respectively, and the ratio of the fault vertex of the right line tunnel is 0.95. When the distance between the two faces is greater than 20m, the ratio of shear stress to normal stress increases first and then decreases. When the distance is 25m, the peak value of the ratio curve of shear stress to normal stress is 1.57 and 1.23. When the distance is 30m, the peak value of the ratio curve is 1.3 and 1.13. The closer the distance between the working faces, the greater the peak value, and the more prone to activation instability at the fault.



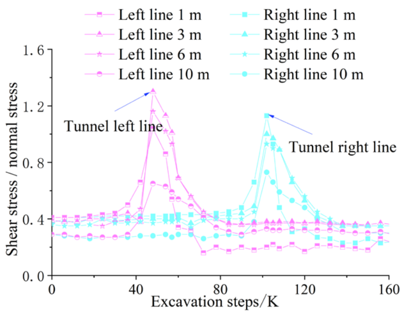
(a) The face of the tunnel is 15m apart



(b) The face of the tunnel is 20m apart



(c) The face of the tunnel is 25m apart



(d) The face of the tunnel is 30m apart

Fig. 3. Ratio curve of shear stress to positive pressure of separated tunnel

3.4 Displacement Analysis

Figure 4 is the vertical displacement cloud map of the deep rock mass at the fault of the separated tunnel. The cloud map is symmetrically distributed along the middle line of the separated tunnel. The settlement of the tunnel top is the largest, the settlement on both sides decreases gradually, and the tunnel floor appears obvious uplift. Figure 5 is the vertical displacement time history monitoring curve of the separated tunnel passing through the fault. When the tunnel face advances, the monitoring curve decreases slowly. After the tunnel face passes through the fault, the settlement increases sharply, and the support tends to be gentle and stable. The maximum vertical displacement of the left line at the faults of 15m, 20m, 25m and 30m between the working faces is 13.56mm, 12.25mm, 12.45mm and 12.30mm, and the maximum vertical displacement of the right line is basically the same as 10.866mm. The secondary settlement of the roof strata of the left line tunnel is induced by the right line tunnel passing through the fault surface. The secondary settlement induced by the tunnel face is 0.8mm when the distance between the tunnel faces is 15m, and the secondary settlement induced by the tunnel face is 0.25mm when the distance between the tunnel faces is 20m. The smaller the spacing of the tunnel face, the greater the secondary settlement induced, which is consistent with the conclusion of 3.2 shear stress analysis. Considering the construction period and economic effect, it is recommended that the tunnel face is 25 m apart.

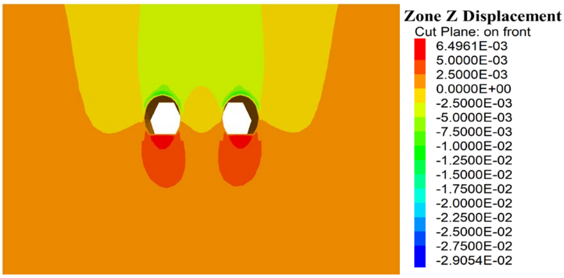


Fig. 4. Vertical displacement nephogram of deep rock mass in separated tunnel

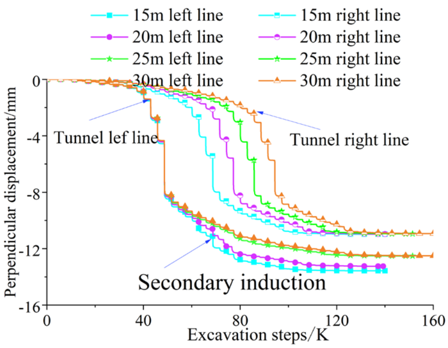


Fig. 5. Time-history curve of vertical displacement of separated tunnel

4 CONCLUSION

In this paper, taking the separated tunnel as an example, the tunnel model is established based on $FLAC^{3D,}$ and the rock material is assumed to be uniform. The sudden drop of shear stress and the vertical displacement of deep rock mass induced by tunnel excavation through fault surface are simulated and analyzed to guide the construction of tunnel site. The sudden change of shear stress and the law of rock subsidence are analyzed, and the following conclusions are drawn :

(1) When the distance between the separated tunnel faces is less than 20m, the second sudden drop of the left tunnel is induced by the right tunnel crossing the fault surface, which increases the possibility of instability slip. The distance between the tunnel faces is inversely proportional to the shear stress drop interval. The larger the distance is, the smaller the second sudden drop of the monitoring section is.

(2) The closer the distance between the separated tunnel faces, the greater the peak value of the ratio of shear stress to positive pressure, and the more prone to activation instability at the fault. The spacing of the tunnel face is inversely proportional to the induced secondary settlement. Considering the construction period and economic effects, it is recommended that the tunnel face of the separated tunnel is 20m apart.

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