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Research on Optimization of Pipe Roof Pre-Support Parameters in Closely Spaced Large Section Tunnels

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Abstract. In order to research the influence of the pre-support parameters of the pipe roof on the tunnel support effect of the large section and small spacing tunnels, the numerical analysis software MIDAS / GTS NX was used to model and analyze a new double-track tunnel. By changing the parameters such as pipe diameter, pipe spacing, arrangement angle and grouting thickness, the numerical simulation of various working conditions was carried out, and the influence of pipe roof parameters on the stability control effect of surrounding rock of large section and small spacing tunnels was analyzed. The results show that increasing the diameter and reducing the spacing of the pipe roof can reduce the settlement of the crown. The optimal diameter of the pipe roof is 108 mm and the pipe spacing is 0.4 m. Increasing the arrangement angle of the pipe roof has a good control effect on the deformation and failure of the middle rock pillar. Without other supporting measures, 180 ° can be selected as the optimal arrangement angle of the pipe roof. The optimized grouting thickness of the pipe roof is 1.0 m. When it is greater than this value, the control effect of increasing the grouting thickness on the stability of the surrounding rock is not obvious.

Keywords: Closely spaced large section tunnels; Surrounding rock stability; Numerical simulation; Pipe roof pre-support; Parameters optimization.

1 Introduction

With the acceleration of China 's urbanization process and the rapid growth of traffic volume, the structural form of large-section small-clearance tunnels has been more and more widely used in tunnel construction. The portal section of large section and small spacing tunnels often face the problems of shallow buried depth, poor surrounding rock conditions and insufficient self-stabilization ability. In the project, the method of advanced pipe roof pre-support is often used to ensure the stability of surrounding rock in the portal section.

In recent years, scholars at home and abroad have carried out some research on the mechanism and control effect of pipe roof pre-support. Based on Winkle 's elastic foundation model, Song et al. [1] established a stress analysis model of pipe roof considering the overall influence of pipe roof grouting reinforcement area, then deduced the

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calculation formula of pipe roof deflection and internal force and revealed the supporting mechanism. Hisatake M et al. [2] showed that the maximum settlement of full-face excavation with pipe roof pre-support was 1/4 of that without pipe roof pre-support through model experiments. Ali Morovatdar. [3] conducted a numerical simulation of the construction process of tunnel excavation and obtained the distribution of stratum deformation caused by tunnel excavation. The results show that the settlement of tunnel crown and ground surface is reduced by 76 % and 42 % respectively after using pipe roof pre-support. By analyzing the measured data of a loess highway tunnel, Zhu et al. [4] pointed out that the pipe roof can effectively reduce the ground settlement and reduce the stress of the supporting structure. However, most of the studies are only for single-hole tunnels, and only the effect of pipe roofs on controlling vertical deformation is studied. And there are few studies on the control effect and parameters influence of pipe roofs on the overall structure of large-section small-clearance tunnels, especially the middle rock pillar, so it is necessary to carry out relevant research.

Based on a practical project, this paper uses numerical simulation method to research the influence of pipe roof parameters on the overall stability control of large-section small-clearance tunnels, so as to provide reference for the design of pipe roof parameters in similar projects.

2 Project Overview

The excavation span of a new double-line highway tunnel reaches 16.7 m, the excavation height is 10.48 m, and the nearest distance of the excavation contour line is 10.85 m. It is a typical large-section small-spacing tunnel. The surrounding rock grade of the double-line tunnel is grade V, and the initial support is equivalent to shotcrete. The specific parameters are shown in Table 1. In addition, in order to ensure the stability of the tunnel portal construction, the arch of the tunnel portal is supported by advanced grouting pipe roof, the sketch of pipe roof pre-support is shown in Figure 1.

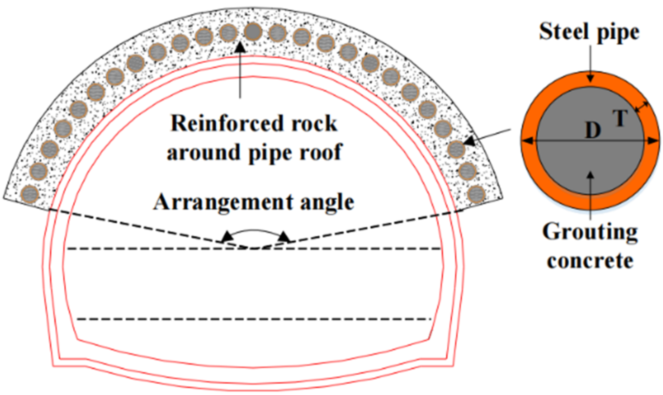


Fig. 1. Sketch of pipe roof pre-support.

Table 1. Surrounding rock and tunnel lining parameters.

Material	ρ(kg·m^{-3})	E(GPa)	v	c(kPa)	φ (°)	H(m)
Surrounding rock	2000	1.3	0.39	100	22	-
Tunnel lining	2400	26.2	0.2	-	-	0.3

3 Establishment of Numerical Model for Parameter Analysis of Pipe Roof

The following assumptions are taken in the numerical simulation.[5]:

(1) The stratum is homogeneous, continuous and isotropic ideal elastic-plastic medium;

(2) The influence of seepage and rock creep is not considered;

(3) When calculating the initial in-situ stress field, only the gravity stress is considered, and the influence of tectonic stress is not considered.

According to the Saint-Venant principle.[6], the influence range of stress redistribution is about 3-5 times of the excavation diameter. In order to reduce the influence of boundary effect, the geometric size of the overall model is taken as 200 m, 100 m and 100 m in the X, Y and Z directions respectively. The fixed end constraint is added to the bottom of the overall calculation model. The boundary of the top surface is set as a free surface, and no constraint is added. The left and right boundaries are subjected to the normal constraint in the X horizontal direction, and the front and rear boundaries are subjected to the normal constraint in the Y vertical direction.

In this simulation, the tunnel is excavated by CD method, the left tunnel is excavated first, and the right tunnel is excavated 30 m behind the left tunnel, the whole model sketch is shown in Figure 2. The Mohr-Coulomb elastoplastic material solid element is used to simulate the surrounding rock, the linear elastic material plate element is used to simulate the tunnel lining, and the beam element is used to simulate the pipe roof. The parameters of the grouting reinforcement area can be expressed by increasing the elastic modulus by 20%-30% and the cohesion by 2-3 times.[7].

In order to analyze the influence of pipe roof parameters on tunnel support effect, the main parameters such as pipe diameter, pipe spacing, arrangement angle and grouting thickness of pipe roof in large section small clear distance tunnels are optimized. Four groups of different pipe diameters (89 mm, 108 mm, 127 mm, 159 mm) are established respectively by controlling the principle of single variable and keeping the other parameters consistent. Four groups of different pipe spacing (0.6 m, 0.5 m, 0.4 m, 0.3 m); four groups of different arrangement angles (90 °, 120 °, 150 °, 180 °); four groups of different grouting thickness (0.8 m, 1.0 m, 1.2 m, 1.4 m), a total of 16 sets of numerical simulation models were analyzed. According to the stress deformation and failure characteristics of large section and small spacing tunnels, the tunnel crown settlement, horizontal convergence of arch waist and plastic failure ratio of middle rock pillar at the monitoring section (y = 20 m) after tunnel excavation are selected as the characterization parameters of surrounding rock stability control. [8], so as to evaluate the supporting effect of pipe roof under different parameters. The elastic modulus and density of the pipe roof are calculated according to equation 1 and equation 2, respectively. The cross-section parameters of different pipe roofs are shown in Table 2.

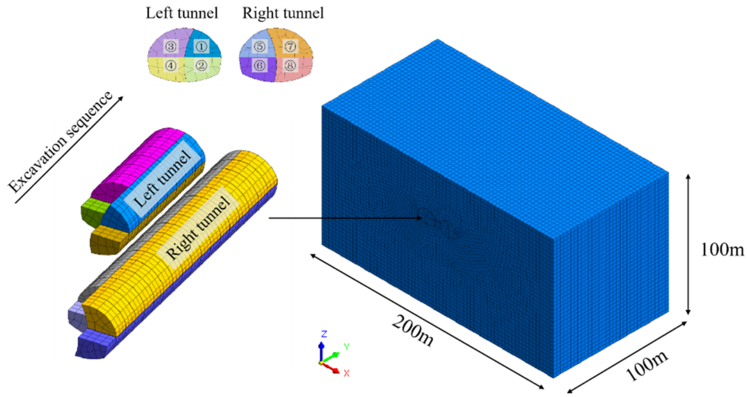
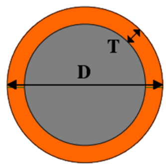


Fig. 2. Finite element analysis model.

Table 2. Cross-section parameters of pipe roof.

D(mm)	T(mm)	S(m^2)	I(m^4)	E(GPa)	ρ(kg/m^3)	Sketch
89	4	6.2×10^{-3}	3.1×10^{-6}	76.2	3252.9	
108	6	9.2×10^{-3}	6.7×10^{-6}	88.3	3464.8	
127	8	1.3×10^{-2}	1.3×10^{-5}	96.2	3610.3	
159	10	2.0×10^{-2}	3.1×10^{-5}	96.1	3608.4	

$$EI = E_1 I_1 + E_2 I_2 \tag{1}$$

$$\rho S = \rho_1 S_1 + \rho_2 S_2 \tag{2}$$

Where E, I, ρ, S are the equivalent elastic modulus, the moment of inertia, the equivalent density, and the area of the pipe roof; E1, I1, ρ1, S1 are the elastic modulus, the moment of inertia, the density, and the area of the grouting concrete; E2, I2, ρ2, S2 are the elastic modulus, the moment of inertia, the density, and the area of the steel pipe.

4 Effect Analysis of different Pipe Roof Pre-Support Parameters

4.1 Analysis of the Influence of Pipe Diameter

Four groups of numerical models with different pipe diameters (89 mm, 108 mm, 127 mm, 159 mm) support parameters are used to calculate the average crown settlement, the horizontal convergence of the arch waist and the plastic failure ratio of the middle rock pillar of the tunnel. The changes are shown in Figures 3, 4, 5. It can be seen from the figure that the control effect of increasing the diameter of the pipe roof on the settlement of the crown is obviously better than that of the horizontal convergence of the arch waist and the plastic failure of the middle rock pillar. This is because the arrangement range of the pipe roof is limited. Compared with the surrounding rock at the crown, the surrounding rock on both sides of the tunnel is not well protected. In addition, the diameter of the pipe roof is not the bigger the better. When the diameter of the pipe roof reaches 108 mm, the effect of increasing the diameter of the pipe roof on the lifting control is extremely limited, which will lead to the increase of construction cost and the difficulty of construction technology. Therefore, 108 mm can be selected as the optimal diameter of the pipe roof.

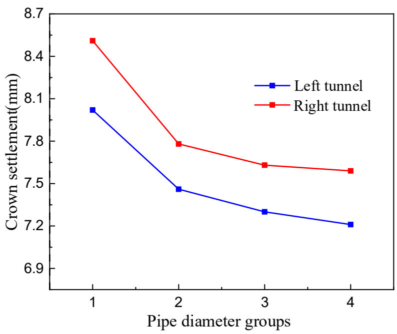


Fig. 3. Crown settlement of different pipe diameter.

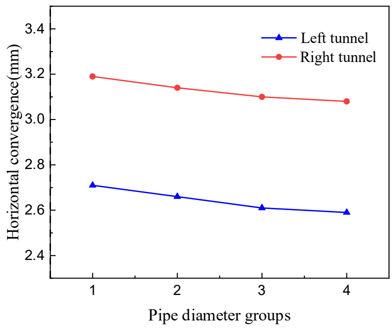


Fig. 4. Horizontal convergence of different pipe diameter.

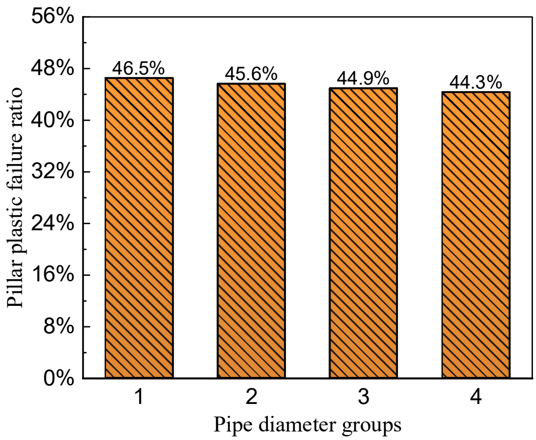


Fig. 5. Pillar plastic failure ratio of different pipe diameter.

4.2 Analysis of the Influence of Pipe Spacing

Four groups of numerical models with different pipe spacing (0.6m, 0.5m, 0.4m, 0.3m) support parameters are used to calculate the average crown settlement, the horizontal convergence of the arch waist and the plastic failure ratio of the middle rock pillar of the tunnel. The changes are shown in Figures 6,7,8. From the figures, it can be seen that the control effect of the reduction of the spacing of the pipe roof on the deformation of the crown is obviously better than that of the horizontal convergence of the arch waist and the plastic failure control effect of the middle rock pillar. When the spacing of the pipe roof increases gradually, the deformation of the surrounding rock and the decrease of the plastic ratio will gradually decrease. Especially when the spacing of the pipe roof is less than 0.4 m, the deformation is almost not reduced by continuing to reduce the spacing of the pipe roof. This shows that the effect of continuing to encrypt the spacing of the pipe roof is general and not economical when the arrangement of the pipe roof and the thickness of grouting are unchanged. On the whole, it is reasonable to choose the optimal spacing of the pipe roof to be 0.4 m.

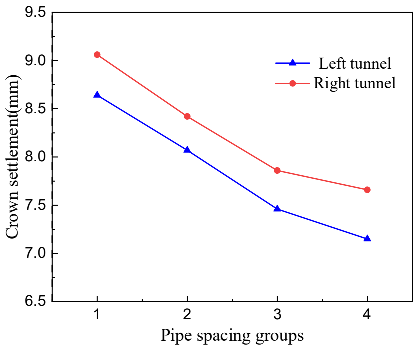


Fig. 6. Crown settlement of different pipe spacing.

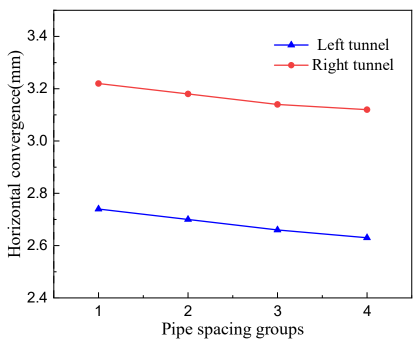


Fig. 7. Horizontal convergence of different pipe spacing.

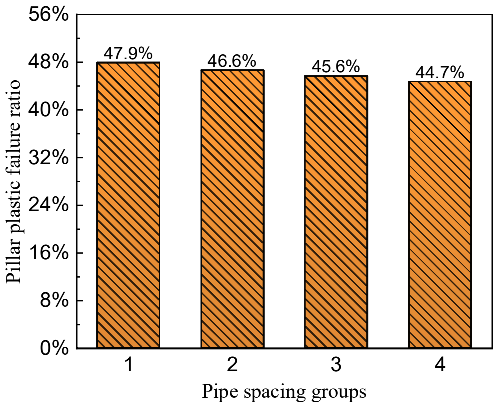


Fig. 8. Pillar plastic failure ratio of different pipe spacing.

4.3 Analysis of the Influence of Arrangement Angle

Four groups of numerical models with different pipe roof arrangement angles (90 °, 120 °, 150 °, 180 °) support parameters are used to calculate the average crown settlement, horizontal convergence of the arch waist and the plastic failure ratio of the middle rock pillar of the tunnel. The changes are shown in Figures 9,10,11. It can be seen from the figures that the control effect of the increase of the pipe roof arrangement angle on the horizontal convergence of the arch waist and the plastic failure of the middle rock pillar is better than that of the crown settlement. Especially when the arrangement angle is increased to 150 ° and 180 °, the horizontal convergence and the plastic failure ratio of the middle rock pillar are greatly reduced, and the control effect is very obvious. The reason is that the deformation and failure of the middle rock pillar during the excavation of the double-hole tunnel are mainly caused by the advance disturbance before the excavation of the tunnel and the unloading effect during the excavation, while the small spacing tunnel is too narrow due to the middle rock pillar. The impact of these two aspects is particularly obvious. The pipe roof joint grouting forms a shell-like structure with good mechanical properties, which can not only bear a part of the upper surrounding rock load, but also play a role in controlling the load transfer to control the deformation and failure of the surrounding rock. When the angle of the pipe roof is 150 °, half of the area of the middle rock pillar is within the protection range of the pipe roof shell. When the angle of the pipe roof is 180 °, the whole area of the middle rock pillar is almost within the protection range of the pipe roof. Therefore, the mutual disturbance between the small spacing tunnels can be greatly reduced, so that the arch waist convergence and the plastic failure of the middle rock pillar can be controlled. Based on the above analysis, in the absence of other supporting measures, from the point of view of controlling the stability of rock pillars, 180 ° is selected as the optimal arrangement angle of pipe roof.

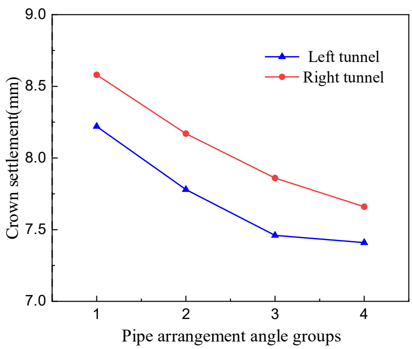


Fig. 9. Crown settlement of different pipe arrangement angle.

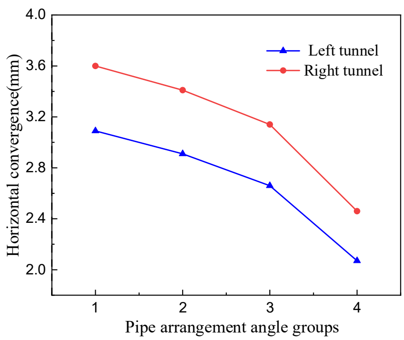


Fig. 10. Horizontal convergence of different pipe arrangement angle.

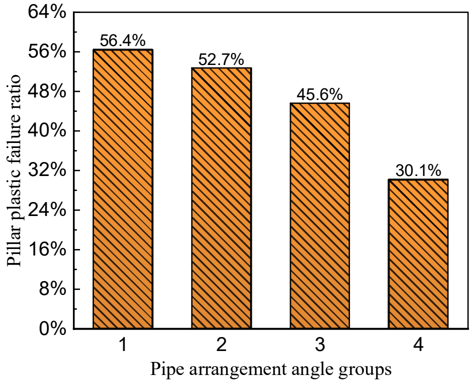


Fig. 11. Pillar plastic failure ratio of different pipe arrangement angle.

4.4 Analysis on the Influence of Grouting Thickness

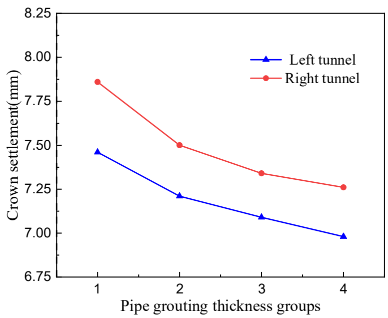


Fig. 12. Crown settlement of different pipe grouting thickness.

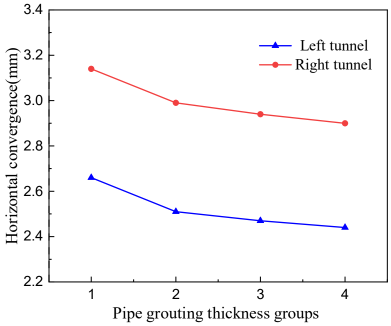


Fig. 13. Horizontal convergence of different pipe grouting thickness.

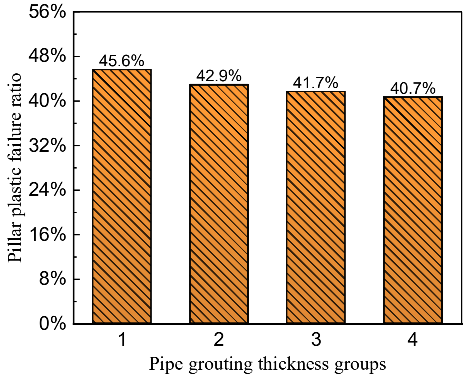


Fig. 14. Pillar plastic failure ratio of different pipe grouting thickness.

Four groups of numerical models with different grouting thickness (0.8m, 1.0m, 1.2m, 1.4m) support parameters are used to calculate the average crown settlement, horizontal convergence of the arch waist and the plastic failure ratio of the middle rock pillar of the tunnel. The changes are shown in Figures 12,13,14. It can be seen from the figures that the control effect of increasing the thickness of grouting on the crown settlement is better than the horizontal convergence of the arch waist and the plastic failure ratio of the middle rock pillar. When the thickness of the grouting area continues to increase, the decrease of the crown settlement displacement gradually decreases. After the thickness of the grouting area reaches 1.0m, the decrease of the tunnel crown settlement is basically small. This is because the grouting of the surrounding rock will also increase its weight and increase the settlement value to a certain extent. With the increase of grouting thickness, the horizontal convergence of the arch waist and the plastic failure ratio of the middle rock pillar decrease evenly. In this study, the pipe roof arrangement angle is 150 °, and about half of the middle rock pillar area is within the protection range of the pipe roof shell. Increasing the grouting thickness can not only make the middle rock pillar grouting area larger, but also make the left and right sides of the grouting body close to the joint, which can better bear the upper load of the middle rock pillar, which is conducive to the stability of the lower rock mass, thus playing a role in the horizontal convergence of the arch waist and the stability control of the plastic ratio of the middle rock pillar. Based on the above analysis, 1.0 m is selected as the optimal grouting thickness.

5 Conclusion

In this paper, a three-dimensional finite element analysis model is established to optimize the support parameters of the pipe roof in the large-section small-clearance tunnels, and the following conclusions are drawn:

- The control effect of increasing the diameter of the pipe roof and reducing the pipe spacing on the crown settlement of large-section and small-clearance tunnels is better than the control effect of the horizontal convergence of the arch waist and the plastic damage of the middle rock pillar. However, the diameter of the pipe roof is not the larger the better, and the spacing is not the denser the better. Considering the engineering economy, 108mm is selected as the optimal diameter of the pipe roof, and 0.4m is selected as the optimal spacing of the pipe roof.
- The shell structure formed by the pipe roof and the grouting body is helpful to control the load transfer, reduce the disturbance and damage of the surrounding rock within the arrangement range, and increase the arrangement angle of the pipe roof has a good control effect on the deformation and damage of the middle rock pillar. In the absence of other support measures, 180 ° is selected as the optimal arrangement angle of the pipe roof.
- Increasing the thickness of pipe roof grouting is helpful to control the settlement of the crown, and can bear a certain load on the upper part of the middle rock pillar. Considering the difficulty of construction, 1.0 m is selected as the optimal grouting thickness of the pipe roof.

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