Study on Mechanical Properties of Transformation Construction Method of Loess Tunnel with Extra-Large Section

Shilei Zhang[1,2,*], Tianli Huang[1], Wanyun Yin[2], Lanmin Xie[2]

[1]School of Civil Engineering, Central South University, Changsha City ,410075, China
[2]China MCC17 Group Co., Ltd., Maanshan City, 243000, China

*Corresponding author's e-mail:840456184@qq.com

Abstract. The Loess Tunnel with extra large section is more and more popular in the construction of expressway in the northwest of our country, therefore, it is necessary to adjust the construction method in time according to the actual geological conditions. In this paper, the settlement deformation, horizontal convergence deformation and initial support stress state of the tunnel are analyzed when the excavation method of double-side-wall pilot pit is converted into the excavation method of single-side-wall pilot shichuan Tunnel. The results show that the stress concentration area is at the intersection of the internal braces in the initial support, and the local concrete cracks may occur in the initial support, but the initial support is a reinforced concrete structure, when local steel bars are cracked, the steel bars will further provide tensile stress; whether it is double or single side wall, the initial support has a high compressive safety reserve; The settlement and horizontal convergence will go through three stages, i. e. , short-time sharp increase, micro-adjustment and stabilization, and the final settlement is far less than the designed deformation.

Keywords: Super large cross-section tunnel, Double sidewall drift, Single side-wall drift, Vault settlement analysis, Horizontal convergence analysis,Initial support stress analysis.

1 Introduction

With the development of China's economy, Gansu region plays an increasingly important role in connecting inland China and Northwest China. Therefore, the need for highway construction becomes more and more urgent. Gansu Province is in the key part of the Northwest highway network construction, resulting in a huge daily traffic flow of expressways, which requires the construction of one-way three-lane or even one-way four-lane expressways. Due to the collapsible loess hilly terrain in Gansu, the number of large section loess tunnels serving expressway has increased. The research on the construction mechanical properties of large section loess tunnel has become more valuable. There have been some researches on the construction of large section

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tunnel at home and abroad. For example, taking the Lanhai high-speed Malin Tunnel as the research object, Wan Fei, Zhao Heng and Wang Qizhe et al studied the construction optimization scheme of large-section highway tunnel crossing the contact zone, pointing out that a reasonable tunnel excavation sequence is the main method to reduce the deformation of surrounding rock [1]. Liu Kui conducted a tunnel construction safety evaluation based on fuzzy hierarchical analysis for the tunnel section 2 of the new Nanning to Chongzuo Railway project [2]. Gong Dahui studied the mechanical effects of the combination of four construction methods, including full section excavation, step method and ring excavation with reserved core soil, on the surrounding rock of Haicang Undersea tunnel under the condition of crossing Grade III and IV surrounding rock [3]. Ji Xiaoye, Zhi Yanfeng and Wang Yufu et al. expounded the theoretical differences between the novelty method and the New AUF method, analyzed the stress and deformation of Qikeng tunnel in Zhejiang province under different levels of surrounding rock environment by using finite element method, and pointed out that the novelty method has more advantages in the tunnel construction of weak surrounding rock [4]. Taking Fengan Tunnel of Zihui Expressway in Guangdong as an example, PI Liang analyzed the transition time of step method under 60 different working conditions [5]. Chi Zuoqiang, Liu Ruihui, Chen Yao et al. studied the transition scheme of tunnel construction method from double-sidewall heading method to cross-center partition method [6]. Yin Minglun, Zhang Jinxun and Jiang Yusheng et al analyzed the reasonable length of conversion from CD method to step method [7]. Jiang Hui and Zhang Zhiqiang analyzed the surrounding rock stress, displacement and safety factor of Hengshan tunnel when the double-sidewall heading method is changed to the three-step and seven-step excavation method [8]. Taking Chengzai Mountain Tunnel as the research object, Yang Di, Qian Kun and Tong Jianjun et al. used FLAC3D software to analyze the tunnel arch roof settlement and arch foot deformation when the double-sidewall diversion method was converted to the step method [9]. Most of the above studies are carried out based on the transition from Grade IV to Grade III surrounding rock, and there is no detailed study on the mechanical properties of large-section loess tunnel construction method transformation[10-12]. However, the domestic and foreign norms and standards have not been perfect for the transformation of large-section loess tunnel construction methods, which leads to the difficulty of construction control. Therefore, this paper takes a V-class large section eolian loess tunnel in Gansu province as the research object, and analyzes the construction mechanics characteristics in the transition from the double-side diversion method of V-class surrounding rock to the single-side diversion method of IV-class surrounding rock during the transition from the entrance section to the tunnel body. In this paper, the conversion steps of double-wall heading method to single-side wall heading method and the mechanical laws of the transformation of V-type fan loess tunnel construction method are revealed, so as to provide reference for similar projects.

2 Project profile

The G30 Qingshuiyi to Zhonghe section of the Lianyungang to Khorgos Expressway project is an important part of the highway network in Gansu province and also an important part of the ring expressway in Lanzhou, it is connected with lianhuo national highway in the east and beijing-tibet National Highway and airport highway in the west.

Fig. 1. Xiaheping tunnel.

Xiaheping Tunnel is the control project of G30 project. The tunnel is a double-tunnel long tunnel with left-right separation,as shown in Fig. 1. YK26 + 530 ~ YK30 + 475, length 3945m, maximum buried depth 185m in the right lane, ZK26 + 542 ~ ZK30 + 487, length 3945m, maximum buried depth 180m in the left lane. Tunnel design speed at 100 km/h. NET width of tunnel: 0.75.0.75 + 3 × 3.75 + 1.0 + 1.0 = 14.75 m, net height: 5.0 m; net width of vehicle crossing hole: 0.25 + 4.0 + 0.25 = 4.5 m, net height: 5.0 m; net width of pedestrian crossing hole: 2 m, 2.5 m. The arched part adopts the single-center arc of R = 840cm, the side wall adopts the arc of R = 500cm radius, the radius of the overarched part is 2200cm, and the connection between the overarched part and the side wall adopts the arc of small radius of r = 180cm.

3 Mechanical characteristics of rock and soil

The Xiaheping Tunnel project area is mostly located in the loess hilly gully and the low Zhongshan District, Taipei River. The Loess Tunnel section is located in the eolian and alluvial loess of the upper Pleistocene of the tertiary, with the surrounding rock grade v. the lithology of the stone tunnel is dominated by granite and Cambrian biotite amphibolite schist, and the surrounding rock grade is dominated by III and IV, the broken segments and shallow buried segments of rock mass affected by local structure are grade V, of which the unstructured passage segment of the Granite Tunnel body is grade III, and the amphibolite biotite schist tunnel body segment and the granite fault affected range are grade IV, the entrance and exit section of the tunnel is grade IV-V. Cretaceous glutenite and Neogene unconsolidated sandstone belong to soft rock-extremely soft rock. According to the site data and investigation results, the starting stop number of the transition zone from the entrance section of Xiaheping Tunnel to the tunnel body section is YK27 + 350-YK27 + 770(ZK27 + 240-ZK27 + 660) , and the surrounding rock is buried at a depth of 50-100m, the upper part is upper Pleistocene aeolian loess, which is gray-yellow and light-yellow, loose, well-developed with large pores, homogeneous soil with collapsibility, and the grade of soil-rock is Class III hard soil, while the lower part is biotite hornblende schist, which is black-brown, the main minerals are biotite, hornblende, quartz, feldspar and so on. The rock mass is weak and broken. The design elevation of the tunnel is located near the boundary between rock and soil, the fluctuation of the bedrock surface is great, the surrounding rock of the tunnel is the transition zone between Aeolian loess and biotite schist, the engineering geological conditions are complex, the self-stability of the surrounding rock and the tunnel-forming conditions are poor, excavation is easy to collapse, drop block, the overall lack of groundwater, Wall Rock Grade V. During the construction of this section, the over-excavation should be strictly controlled, the stability observation of surrounding rock and geological prediction should be strengthened, and the supporting measures should be adjusted in time.

4 Method conversion mode

According to the geological investigation, the V-grade wall rocks are 200 m long in the range of YK27 + 350-YK27 + 550, and the IV-grade wall rocks are 220 m long in the range of YK27 + 550-YK27 + 770. The surrounding rock interface is at YK27 + 550, where the construction scheme is planned to carry out the transformation of construction method, that is, from the excavation of double-side-wall pilot pit to the excavation of single-side-wall pilot pit.

4.1 V-class wall rock double side wall guide pit construction method

For the V-class surrounding rock of the entrance section of the tunnel, the double side-wall pilot pit construction is adopted, and the specific excavation method is as follows:

(1) The construction steps are:

- Excavation of the upper half section 1 of the guide pit on the left side wall and construction of initial support and temporary support I.
- Excavation of the lower half section 2 of the guide pit of the left side wall and construction of the initial support and temporary support II.
- Excavation of Upper Half Section 3 of guide pit on right side wall and construction of initial support and temporary support III.
- Excavation of the lower half section 4 of the guide pit of the right side wall and construction of initial support and temporary support IV.

- The circular excavation of the retaining core soil on the steps of the middle rock column 5 and the initial support V.
- Excavation of rock column under the step 6 and construction of the pilot pit inverted arch initial support VI.
- Construction of full-section inverted arch secondary lining VII.
- Construction of full-section inverted arch filling VIII.
- Construction of full-section arch wall secondary lining IX.

(2)The short-step method is adopted in excavation, and the circular footage is controlled in the range of 0.5-0.75 m. the initial support and temporary support follow the excavation face closely The distance between the initial supporting ring section and the excavation face of the pilot pit is 40-50 m, and the distance between the inverted arch and filling and the secondary lining of the initial supporting ring section and the initial supporting ring section should be less than 30 m, the distance control of each cycle construction procedure should be fully considered in construction organization to meet the above requirements.

(3)During the excavation of the steps under the side pilot pit, the side wall side and the middle bulkhead side stagger in longitudinal direction to avoid hanging in the air at the same time. The Arc Arch of the guide pit is excavated artificially under the protection of the advance support after the front face of the step on the back guide pit is 15 ~ 20m ahead.

(4)In order to ensure the safety of construction and supporting structure, the length control of each guiding pit step should be based on the safety and stability of the heading face and supporting structure, and the distance between the heading face of the leading pit and the secondary lining working face should not be more than 70m, it can be optimized according to the monitoring and measurement.

4.2 Construction method of guide pit of single side wall of grade IV surrounding rock

For the IV-class surrounding rock of the tunnel body section, the construction method of the single side wall pilot pit is as follows:

(1)The construction steps are:

- Excavation of the upper half section 1 of the guide pit on the left side wall and construction of initial support and temporary support I.
- Excavation of the lower half section 2 of the guide pit of the left side wall and construction of the initial support and temporary support II.
- Excavation of Upper Half Section 3 of guide pit on right side wall and construction of initial support and temporary support III.
- Excavation of the lower half section 4 of the guide pit of the right side wall and construction of initial support and temporary support IV.
- Construction of full-section inverted arch lining V.
- Construction of full-section inverted arch filling VI.
- Construction of secondary lining of full-section arch wall VII.

(2)The short-step method is adopted in excavation, and the circular footage is controlled in the range of 0.5 ~ 0.75 m. the initial support and temporary support follow the excavation face closely The distance between the initial support and the excavation face is 30 ~ 40m, and the temporary invert is added when the surrounding rock is poor. The distance between the secondary lining and the initial support should be less than 30m, and the distance between the secondary lining and the initial support should be controlled to meet the above requirements.

(3)The construction quality control of lock-foot support should be strengthened during the excavation of steps under the side pilot pit. After the front face of the step is about 20m ahead, the excavation of the step is carried out.

(4)In order to ensure the safety of construction and supporting structure, the length control of each guiding pit step should be based on the safety and stability of the heading face and supporting structure, and the distance between the heading face of the leading pit and the secondary lining working face should not be more than 60 m, it can be optimized according to the monitoring and measurement.

(5)First Guide pit support: according to the surrounding rock condition and design requirement, adopt anchor, shotcrete, steel arch support, i-shaped steel arch support in the initial shotcrete 4cm thick, the protective layer is not less than 2cm.

(6)Back Arch Construction: after the lower part is excavated to the design elevation, the bottom is cleared and one side of back arch is made, the other side of back arch is made after the middle wall arch frame is removed.

(7)Demolition of Middle Wall: when the arch frame of the tunnel is closed to form a ring, the settlement of the arch crown is measured, and the deformation of the initial support system of the tunnel is observed after the ring is closed, and when the deformation is confirmed to be within the normal range, before the temporary steel frame can be removed. When the middle wall is removed, large vibration and disturbance to the initial support system should be prevented.

(8)Full-section lining: after the back arch and backfilling are completed, the construction of side wall is started, waterproof layer and other drainage facilities are applied according to the design requirements, and all kinds of embedded pipes and holes are installed and checked to prevent wrong burying, leakage burial.

4.3 The method of transforming the guide pit from double side wall to single side wall

In order to speed up the construction, the construction unit decided to implement the construction method conversion at the interface of v-class and IV-class Wall Rocks. The steps are as follows:

- Excavate the interface of step 1-v and IV surrounding rock on the guide pit of left side wall, make initial support I and stop.
- Excavation of the lower step 2 of the left side wall pilot pit to the interface of the surrounding rock above, making the initial support II, stop.
- Excavate the step 3 under the guide pit of the right side wall to the interface of the surrounding rock, make the initial support III and stop.

- Excavate 4 steps under guide pit of right side wall to the interface of wall rock, make initial support IV, stop.
- In ring-shaped excavation, the core soil left on the steps 5 to the wall rock interface, the initial support V, stop.
- During excavation, 6 steps below the rock column reach the interface of the surrounding rock. During construction, the initial support VI of the inverted arch of the pilot pit stops.
- Construction of full-section inverted arch secondary lining VII to the wall rock interface, stop.
- Construction of full-section inverted arch filling VIII, stop.
- Construction of full-section arch wall secondary lining IX, stop.
- In accordance with the construction sequence of single-side wall pilot pit, construction began.

Through the above construction steps, the interface between V-grade and IV-grade surrounding rock is excavated for each soil body of the guide pit on both sides of the wall, and the construction is stopped uniformly, from the 11th step, the construction of single-side-wall pilot pit is carried out.

5 Numerical simulation analysis

5.1 Finite element model

According to the data of investigation and design and the code for design of highway tunnel in China, the stress-strain relationship of stratum is based on the Mohr-Coulomb constitutive model, and the basic calculation parameters are shown in Table 1. Equivalent modulus of elasticity of concrete:

$$E = E_C + A_S E_S / A_C \tag{1}$$

where *Ec* is the elastic modulus of the concrete; *Es* is elastic modulus of steel; *As* is section area of steel; *Ac* is Section area of concrete.

Table 1. Model parameters

	E (GPa)	μ	ρ (kN×m^{-3})	C (MPa)	φ
IV-class wall rock	3.0	0.3	27.3	0.27	27
V-class wall rock	1.0	0.4	13.9	0.23	24
Initial support	32	0.3	24	-	-
Anchor Rod	205	0.3	78.5	-	-

According to the design drawings and the interface between v-grade and IV-grade wall rocks, the length×width×height of the model is 60m×120m×144m. The influence of the model boundary is considered here. The width of the model is more than 3 times the tunnel diameter, and the height of the model is determined by the most unfavorable height at the fault location. One-dimensional rod element is used for advance small pipe and anchor, two-dimensional plate element is used for initial support and secondary lining, and three-dimensional solid element is used for soil. The interface of v-class and IV-class Wall Rocks is bonded together by operation, and the displacement of the boundary other than the free boundary of the top surface is restrained, as shown in Fig. 2.

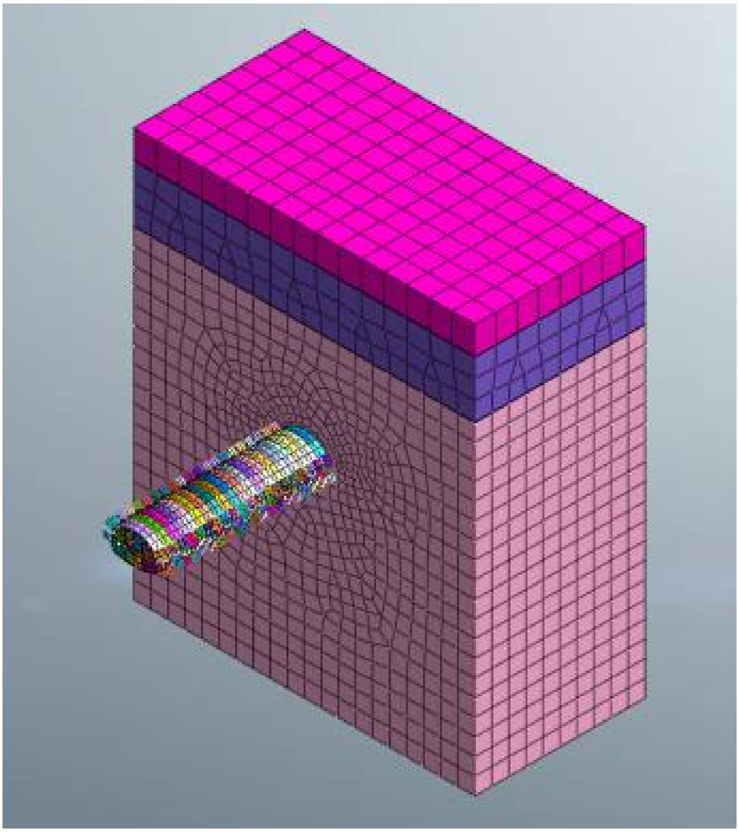
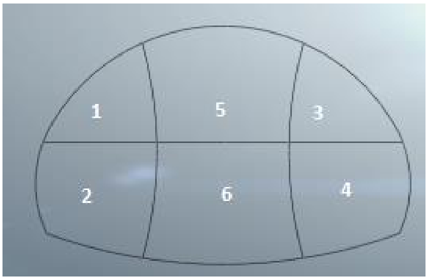


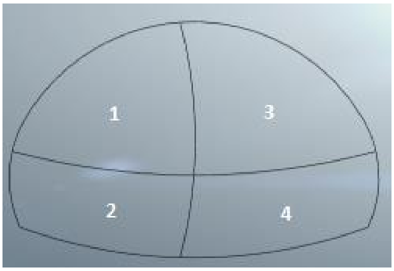
Fig. 2. Grid division of tunnel.

5.2 Two side wall guide pit to single side wall guide pit transformation

In order to keep the stress balance of the surrounding rock, the excavation of the guide pit on both sides and the excavation of the guide pit on one side are carried out in the order of first going up and then going down, first going left and then going right, the difference is that the retaining core soil links are increased by the retaining core soil, which reduces the cross-section span of a single excavation, and improves the supporting effect on the soil mass with the retaining core soil, this is more conducive to poor surrounding rock tunnel construction safety. Specifically, the two-sided pilot excavation follows a sequence of 1-2-3-4-5-6, whereas the single-sided pilot excavation consists of only 1-4 steps, as detailed in Fig. 3.



(a) Excavation sequence diagram of guide pit of double side wall



(b)Sequence diagram of excavation of guide pit of single side wall

Fig. 3. The schematic diagram of converting the construction sequence between the two methods.

5.3 Deformation analysis

In accordance with the above conversion steps, the tunnel excavation to 60 meters at the interface to start conversion method, that is, in accordance with the dual-wall pilot pit excavation to 60 meters after the suspension of excavation, after removing all the internal bracing of the double-sided walls and providing construction space, construction shall begin in accordance with the single-sided pilot pit method.

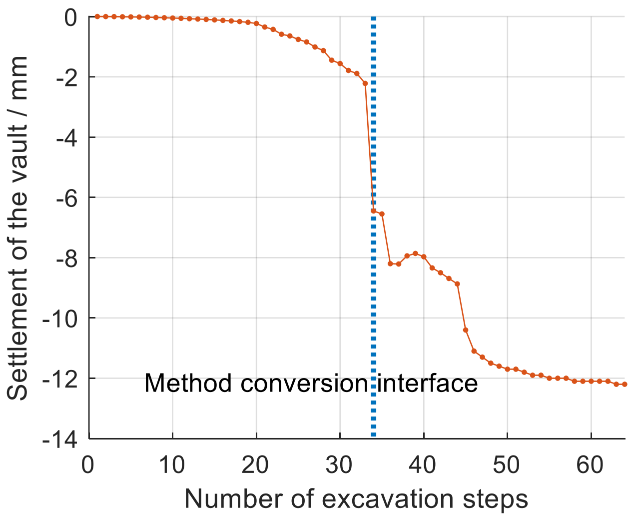


Fig. 4. Vertical deformation curve of tunnel vault.

Fig. 4 shows vertical deformation curve of the vault during tunnel excavation respectively. It can be seen that extreme arch deformation occurs after tunnel excavation to the interface of construction method conversion. From 2mm to 6.3 mm, and then further settlement to 8mm with the completion of the process conversion slightly recovered, and then further settlement, until about 12mm tend to smooth. According to the trend of vertical settlement, the change of construction method disturbed the deformation of tunnel in a short time. With the completion of the conversion of the method, the subsequent role of one-sided wall internal support, settlement slightly back, and then in accordance with the characteristics of one-sided wall method changes. It can be seen that: compared with the two-sidewall, the single-sidewall inner support is less, the disturbed area of soil is larger, and the settlement rate of vault is higher than that of the two-sidewall pilot pit method. However, the settlement difference of the accelerated settlement section is 6 mm, and the total settlement of 1.2 cm is less than the pre-designed deformation, so the transformation displacement of the method meets the requirements of the code.

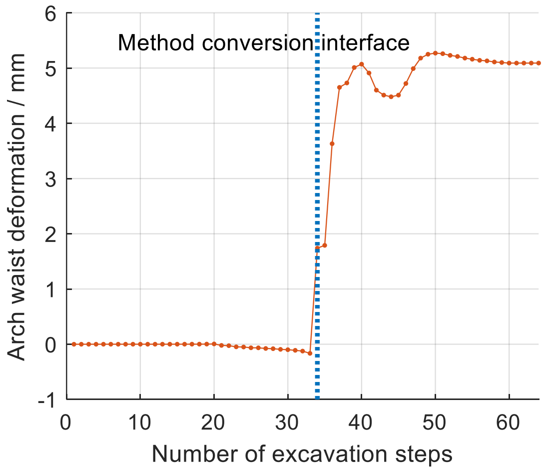


Fig. 5. Horizontal deformation curve of tunnel arch waist.

Fig. 5 is the curve of horizontal deformation of tunnel arch waist, respectively. Compared with the settlement of arch crown, the horizontal deformation of arch waist decreases by 58% . The arch waist has the tendency to extend to both sides. And the trend of the horizontal deformation of the arch waist is similar to that of the vault settlement, which experienced a sharp increase to a slight correction and finally tended to be stable. It shows that the deformation of the tunnel is controlled under the combined action of the whole surrounding rock pressure and the tunnel support structure.

6 Discussion

The overall stiffness and stability of the tunnel meet the construction requirements by deformation analysis, and the strength state of the tunnel should be obtained by force analysis. Fig. 6 shows the maximum and minimum principal stresses of the initial support of the tunnel before the conversion. According to the figure, the maximum principal tensile stress of initial support is 4.08 MPA, which is greater than the ultimate tensile strength of C30 Concrete 2.2 Mpa, and the maximum principal compressive stress of initial support is 8.17 MPA, which is less than the ultimate compressive strength of

C30 Concrete 22.5 Mpa. The main tensile stress and the main compressive stress are concentrated at the intersection of the internal supports, which indicates that the stress center area needs to be strengthened.

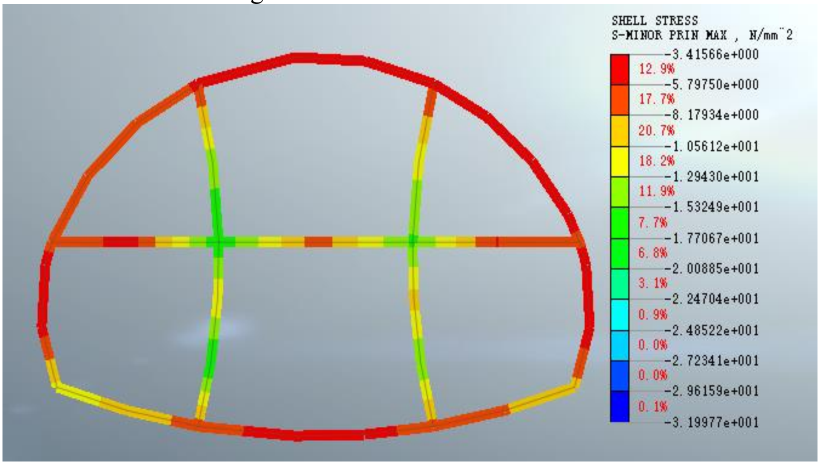


Fig. 6. Stress Cloud of initial support of tunnel before method conversion.

Fig. 7 shows the maximum and minimum principal stresses of the initial support of the tunnel after conversion. According to the figure, the maximum principal tensile stress of initial support is 1.65 MPA, which is less than the ultimate tensile strength of C30 Concrete 2.2 Mpa, and the maximum principal compressive stress of initial support is 18.2 Mpa, the ultimate compressive strength of C30 concrete is 22.5 mpa. The main tensile stress and the main compressive stress are both concentrated at the intersection of the internal braces, which is the same as the excavation of the pilot pit on both sides.

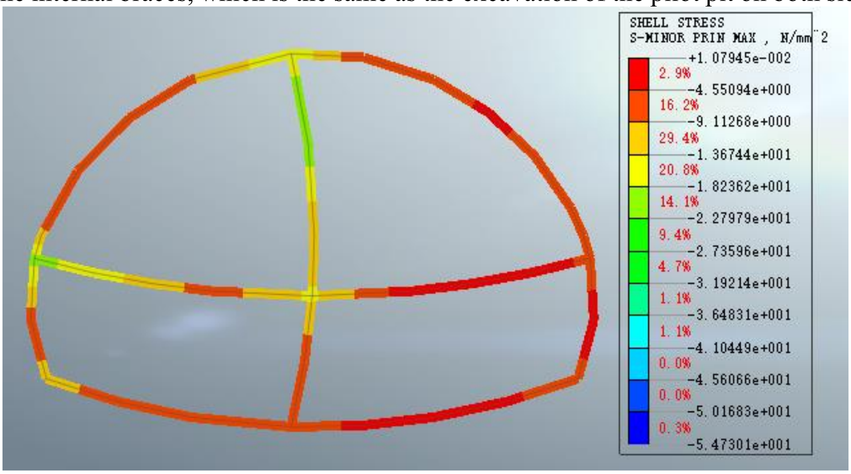


Fig. 7. Stress Cloud of initial support of tunnel before method conversion after method conversion.

According to the above calculation results, the structural stress under all working conditions is less than the ultimate stress state of concrete except that the main tensile stress of the excavation of the pilot pit of the double side wall is slightly greater than the ultimate tensile strength of concrete, the main compressive stress of the excavation method is only 36.3% of the ultimate compressive stress, which proves that the structure has more safety reserves. But the actual tunnel initial support is reinforced concrete structure, in the tunnel initial support local micro-cracks, the reinforcement still has enough safety reserve to ensure the strength of the structure, therefore, the local main tensile stress slightly larger than the ultimate tensile stress of concrete will not lead to the overall strength failure. However, it may lead to local concrete cracking, so it is necessary to strengthen the strength and density of concrete tensile stress concentration area, and appropriately increase the concrete grade and thickness. In addition, the maximum principal compressive stress of single-side-wall pilot excavation is 2.23 times of that of double-side-wall pilot excavation, but less than 80.9% of the ultimate compressive stress of concrete, it shows that the weakening of support and the enlargement of excavation section will increase the pressure of initial support greatly, but the support structure still has 19.1% safety reserve, indicating that the overall strength of the structure meets the construction requirements.

7 Conclusion

In this paper, the Heping Tunnel is taken as the research object, and the mechanical properties of the transition from the normal to the single side drift are analyzed, and the following conclusions are drawn:

(1)The increase of tunnel excavation section will have a great influence on the initial support. The maximum compressive stress of the initial support of the single-side drift excavation method is 2.23 times that of the double-side drift excavation method, but it is still less than the ultimate compressive strength of the concrete, the initial support has 19.1% safety reserve.

(2)Double side wall pilot pit method has tensile stress greater than the ultimate tensile strength of concrete, indicating the possibility of local concrete cracking, should increase the concrete label and thickness, but at this time the initial support is mostly in the state of compression, the maximum principal compressive stress is only 36.3% of the ultimate compressive strength of concrete, indicating that the initial support has a high safety reserve, and the initial support is a reinforced concrete structure, the steel bar will continue to provide safety after concrete cracks, so the structure as a whole is in a safe state.

(3)In the conversion project, the displacement and horizontal deformation of the vault river will go through three stages, which will increase dramatically, then adjust slightly, and finally become stable. The maximum settlement of vault is 1.2 cm, which is less than the designed deformation. The maximum settlement variation of the extreme settlement section is 6 mm, which will not affect the tunnel construction as a whole.

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