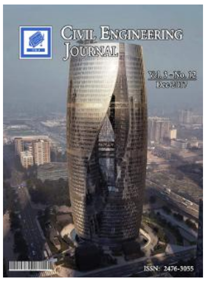
Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 3, No. 12, December, 2017



Numerical Simulation on the Stability of Surrounding Rock of Horizontal Rock Strata in the Tunnel

Nian Zhang [a*], Weihong Wang [b], Zhuoqiang Yang [c], Jianian Zhang [b]

[a] *Associate Professor, School of Transportation and Logistics, Taiyuan University of Science and Technology, Taiyuan city, China.*

[b] *Graduate student of Transportation Engineering, Taiyuan University of Science and Technology, Taiyuan city, China.*

[c] *Lecturer,School of transportation and logistics,Taiyuan University of Science and Technology, Taiyuan city, China.*

Received 30 October 2017; Accepted 23 December 2017

Abstract

Horizontal rock strata is a geological condition of rock which is often encountered in the tunnel construction, and it has an important influence on the tunnel construction, it is necessary to analyze and study the stability of horizontal rock strata in tunnel construction to ensure the tunnel construction's safety and efficiency. By taking "Xishan Highway Tunnel" as the research object, and using the numerical simulation method, the numerical model of the tunnel has been established in the Midas/GTS to simulate the tunnel excavation under the horizontal rock strata condition， and the deformation and failure mechanism of surrounding rock and the influence factors of surrounding rock stability after are studied and analyzed. The research focused on the displacement of surrounding rock horizontal and vertical deformation, the results show that the vertical displacement of the surrounding rock is obviously greater than that of other parts during the excavation of the horizontal rock tunnel. According to the calculation results, the optimization measures of horizontal stratum tunnel construction method are put forward, which has important reference value for ensuring the construction safety and construction quality.

Keywords: Highway Tunnel; Horizontal Rock Strata; Stability of Surrounding Rock; Numerical Simulation.

1. Introduction

The stability of tunnel surrounding rock refers to the self-stability of the surrounding rock without any supports, mainly reflected in two aspects, which are surrounding rock deformation and failure [1-4]. The essences of the stability analysis of surrounding rock are the analysis and evaluation of rock mass medium, the relationship between stress and strain. A large number of engineering practices shows that [5-9], the stability of tunnel surrounding rock is not only associated with the quality of geological structure and groundwater, but also with the excavation and supporting of the tunnel of time and form.

Man-chao, et al.(2009) [10] proposed a new approach of Physically Finite Elemental Slab Assemblage (PFESA), in order to construct a large-scale physical model simulating the geologically horizontal strata to capture the mechanism of roadway instability in deep mines. Wang, Yonggang, et al.(2014) [11] considered the mechanical properties of the structural plane and bedrock, and established the anisotropic mechanical model of layered rock mass. The model can be applied to the calculation and analysis of layered rock mass underground engineering. Chen, Wang (2014) [12] based on the study of the surrounding rock of the 2# inclined shaft of the tunnel in the South Lvliang mountain, the main construction methods and technical measures are put forward for the horizontal rock stratum construction of the single track railway tunnel. Peng Yanyan, et al. (2015) [13] according to the mechanical behavior of deformation and failure

* Corresponding author: zhangnian1984@126.com

http://dx.doi.org/10.28991/cej-030948

of deep rock engineering complex, with horizontal layered sedimentary rock mass as the research object of physical simulation, the soft rock roadway deformation simulation test of physical damage, crack of horizontal strata of soft rock roadway expansion and deformation and failure characteristics. Li, Shu-cai, et al. (2016) [14] to study the water inrush mechanism in the faults, both physical model test and numerical analysis were carried out, the results of crown displacement and hydraulic pressure of the monitoring sections in the physical model and numerical model were analyzed. Chen, Jiajia, et al. (2017) [15] analyzed the surface structure of the foams by Raman spectroscopy. The adsorption experiments showed that when the mass ratio of Chitosan (CS) to rectorite (REC) was 10:1 and nanotubes (CNTs) content was 20%, the composite foam performed best in adsorbing low concentration methyl orange, and the largest adsorption capacity was $41.65\ mg/g$. Liu, K, et al. (2017) [16] presented a finite element implementation of a strain-hardening Drucker-Prager model. The model was constructed based on the return mapping scheme, in which an elastic trial step was first executed, followed by plastic correction involving the Newton-Raphson method to return the predicted state of stresses to the supposed yield surface. By combining the plastic shear hardening rule and stress correction equations, the loading index for the strain-hardening Drucker-Prager model was solved. Then give an example to support the solution, and applied it to tunnel excavation.

The length of Xishan tunnel is $13.63\ km$, and it is the second longest highway tunnel in China. The main and auxiliary work of the tunnel is through the horizontal rocks. Because of its poor stability of tunnel surrounding rock, there is more likely to occur arch block off during the construction, it is one of the important factors affecting the tunnel construction safety. How to ensure the stability of surrounding rock of tunnel level plays a crucial role in tunnel construction and safety operation. By taking “Xishan Highway Tunnel” as the research object, and using the numerical simulation method, the numerical model of the tunnel has been established in the Midas/GTS to simulate the tunnel excavation under the horizontal rock strata condition, and the deformation and failure mechanism of surrounding rock and the influence factors of surrounding rock stability after are studied and analyzed. The research focused on the displacement of surrounding rock horizontal and vertical deformation, the results show that the vertical displacement of the surrounding rock is obviously greater than that of other parts during the excavation of the horizontal rock tunnel.

2. Analysis of Stability and Failure Characteristics of Surrounding Rock in Horizontal Rock Strata

The stability of surrounding rock is not only determined by the strength of the rock, but also depends on the integrity of the surrounding rock structure. The structure of rock mass is divided into five categories: the complete structure, block structure, catalectic structure, layered structure and granular structure, which are also the basic types of the tunnel surrounding rock structure in the horizontal rock area [8].

The rock mass of the horizontal layered structure is a simple sedimentary rock, which can be composed of a single lithology, and can also be formed by the combination of different lithological layers. The level is often the intercalated sliding between layers connecting level is weak, the damage mostly to the top curve subsidence and separation. When the subsidence is large, layers appear broken failure. Large span underground cavern excavation in layered rock is clearly layered, and the more prominent problem is the stability of surrounding rock.

The comprehensive effect of tunnel surrounding rock stability depends on many factors, the main factors are: physical and mechanical properties, structure and construction of rock mass, natural stress state of rock mass and geological structure influence, groundwater, rock under static and dynamic load, tunnel’s geometry and the construction scheme.

According to the factors affecting the stability of tunnel surrounding rock, influence factors of surrounding rock stability of tunnel in horizontal stratum area can be summarized into three types [4]: (1) the geological factors: rock stress, physical and mechanical properties of the rock, structure of the rock, rock composition and physical and chemical properties, etc.; (2) the engineering factors: the shape and size of the tunnel section and the high-span ratio; (3) the construction factors: tunnel construction methods, support time and support methods etc.. The geological factors are the main factors that influence the stability of surrounding rock.

The destruction of surrounding rock of the tunnel is mainly depended on the stability of surrounding rock [9]. The failure mode of surrounding rock is varied with its structural characteristics, and its failure mechanism is also different in different damage stages, and it is related to the shape of the tunnel. For horizontal strata, due to the rock level and surrounding rock itself of low strength and bad cementation, leading to deformation and failure in the process of excavation of the surrounding rock. It has its special characteristics and failure modes are: (1) fragmentation loose; (2) the expansion and drum inside; (3) crushing failure; (4) sliding failure; (5) underground water failure.

3. Research Methodology

With the development of science and technology, the numerical simulation theory and method to solve the problem of the tunnel have developed rapidly. Due to the successful application of various numerical methods [10-12], the understanding of the engineering geological phenomena of many tunnels has been deepened, and the quantitative process of the tunnel engineering disciplines has been greatly promoted. In this paper, by using the numerical simulation method, the numerical model of the tunnel has been established in the Midas/GTS to simulate the tunnel excavation under the horizontal rock strata condition.

3.1. MIDAS/GTS

MIDAS/GTS is a comprehensive finite element analysis software for geotechnical and tunnel engineering. MIDAS/GTS also has an advanced user friendly modelling platform that enables unmatched levels of precision and efficiency. It is specially used for analysis of tunnel and geotechnical engineering, and can be used for visual modelling of complex geometric models.

The MIDAS/GTS constitutive model is relatively complete, can not only elastic analysis, can also analyze elastoplastic and viscoelastic; also can analyze the nonlinear static analysis, construction stage, slope stability analysis, excavation and consolidation, seepage stability analysis, dynamic analysis, etc.

3.2. Geological Condition of Xishan Tunnel

The length of Xishan highway tunnel is 13.63km, the main tunnel and ancillary works across the horizontal rock tunnel is one of the important factors affecting the safety of the tunnel construction. The tunnel is through 17 fault fracture zones, faults in the entry section are relatively concentrated. In the 200m range, there are a total of eight faults, and some of the faults are more possibility to occur inrush. Karst development is in the tunnel site, and the geological condition is very complex. The geometric characteristics of the tunnel section as following Figure 1:

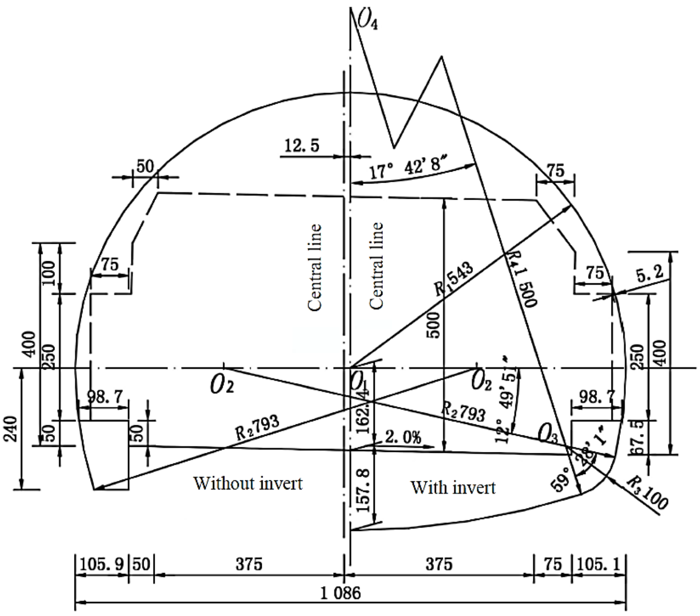


Figure 1. Standard cross-section of the tunnel (unit: cm)

3.3. Establishment of Calculation Model of the Tunnel

The calculation model of tunnel is shown in Figure 2.

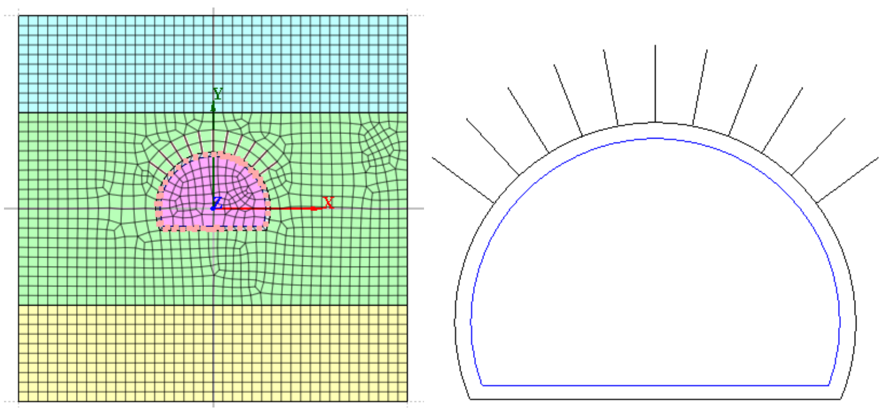


Figure 2. (a) Calculation model of the tunnel under Grade-III surrounding rock condition

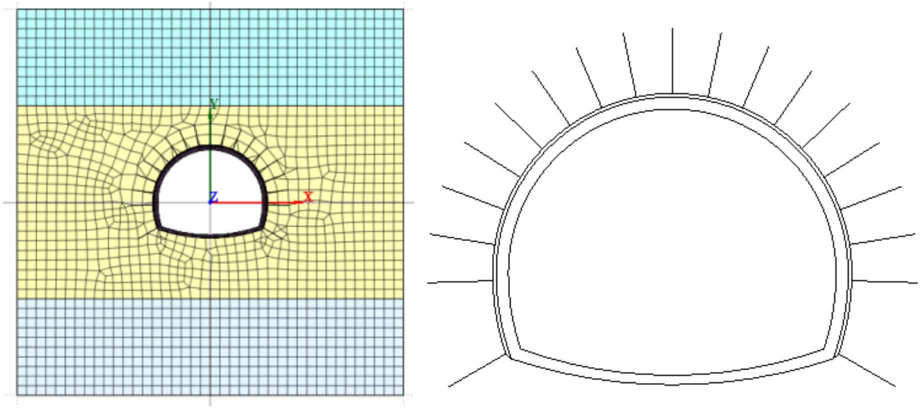


Figure 2. (b) Calculation model of the tunnel under Grade-IV surrounding rock condition

The Setting of the model is shown in Table 1.

Table 1. Setting of the model

Direction	The horizontal is the X direction, the vertical direction is Z, and the Y direction is along the tunnel axis.
Dimension of the model	The left and right away to the tunnel are 3 times of the tunnel span, the upper boundary is taken to the surface, and the lower boundary is to the 3 times the height of the tunnel.
Boundary conditions imposed displacement constraints	The left and right sides apply X to the constraints, the front and back surfaces (vertical axis of the two sides) apply Y to the constraints, the bottom surface applies Z to the constraints, the upper surface is set to be the free surface.
Mesh	In accordance with the "tunnel structure near the subdivision of the grid, away from the loose" principle, automatic division of the finite element mesh, the entire model has nearly 30 thousand nodes and more than 140 thousand units. The Minimum size of the mesh is $0.1 \times 0.1\ m$, and the max size of the mesh is $0.3 \times 0.3\ m$.
Excavation and support	The passivation and activation of the grid units.
The excavation surface of a single element	Extracted from the rock solid to simulate the initial shotcrete support structure

3.4. Parameter Settings in the Calculation Model

In the calculation of model, according to the characteristics of the horizontal strata in Xishan tunnel, the rock is assumed as ideal elastic-plastic body. The rock has been wreathing seriously, so the parameters obtained from the experiments should be cut to get closer to the true state of the surrounding rock. According to the geological survey data, the surrounding rock grade of Xishan tunnel is mainly based on the III and IV grade rocks. The physical and mechanical parameters of the materials in the model are set as Table 2.

Table 2. Physical and mechanical parameters of materials in the model

Names	$\gamma\ (KN/m^3)$	ϕ (°)	C (MPa)	E (Gpa)	μ
III grade surrounding rock	21	44	1.1	11	0.25
IV grade surrounding rock	20	30	0.4	3	0.30

4. Results and Analysis of Numerical Simulation

4.1. Results and Analysis of the Calculation Under Grade-III Surrounding Rock Condition

(1) The maximum shear, horizontal convergence and vertical displacement after excavation of the tunnel under Grade-III surrounding rock condition are shown in Figure 3.

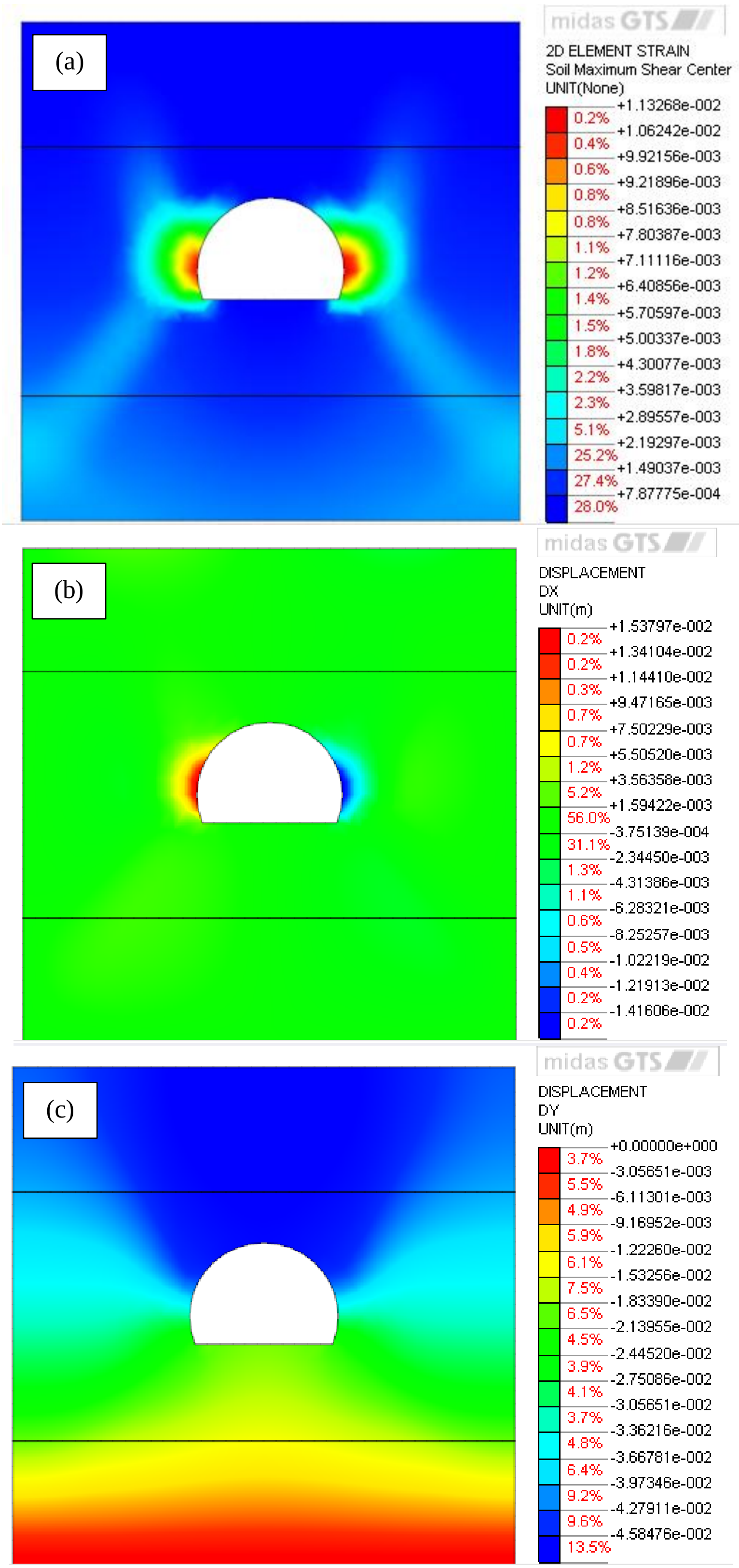


Figure 3. Schematic diagram of maximum shear, wall convergence and vertical displacement after excavation of the tunnel under Grade-III surrounding rock condition (a) Maximum Shear strain; (b) Horizontal convergence; (c) Vertical displacement

(2) The maximum shear, wall convergence and vertical displacement after support of the tunnel under Grade-III surrounding rock condition are shown in Figure 4.

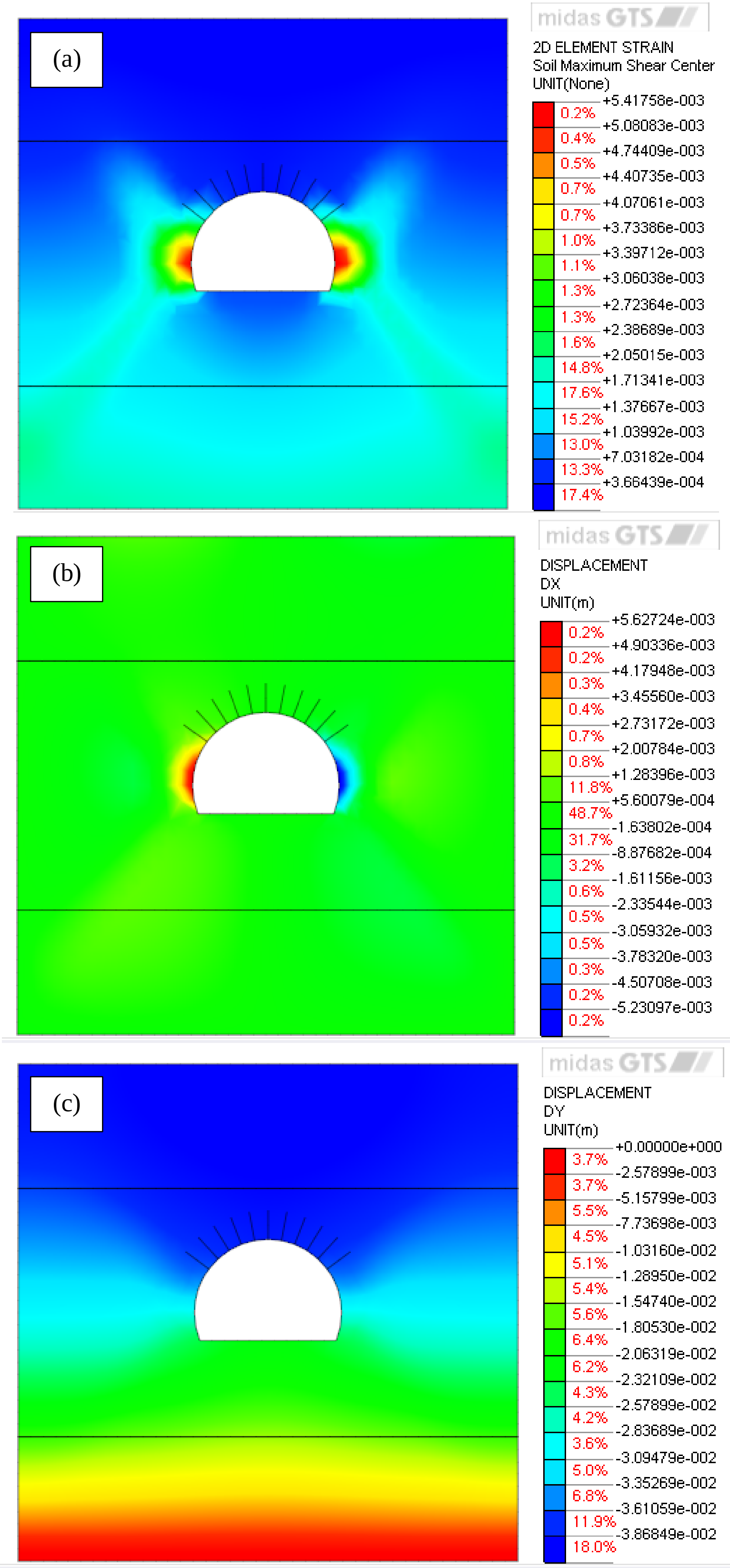


Figure 4. Schematic diagram of maximum shear, wall convergence and vertical displacement after support of the tunnel under Grade-III surrounding rock condition (a) Maximum Shear strain; (b) Horizontal convergence; (c) Vertical displacement

It can be seen from the Figure 3 and 4, under Grade-III surrounding rock condition, the maximum Shear strain is about 1.13×10^{-2}, the maximum wall convergence is about 15.3 mm, the maximum displacement of the tunnel vault is approximately 45.8 mm after the tunnel excavation. The maximum Shear is about 5.42×10^{-3}, the maximum wall convergence is about 5.6 mm, and the maximum displacement of the tunnel vault is approximately 3.86 mm after the tunnel support. After adding the support, the maximum Shear strain of tunnel surrounding rock decreased obviously, the horizontal convergence of the surrounding rock is obviously suppressed, and the vault displacement has also been controlled.

4.2. Results and Analysis of the Calculation Under Grade-IV Surrounding Rock Condition

(1) The lateral maximum shear, wall convergence and vertical displacement after excavation of the tunnel under Grade-IV surrounding rock condition are shown in Figure 5.

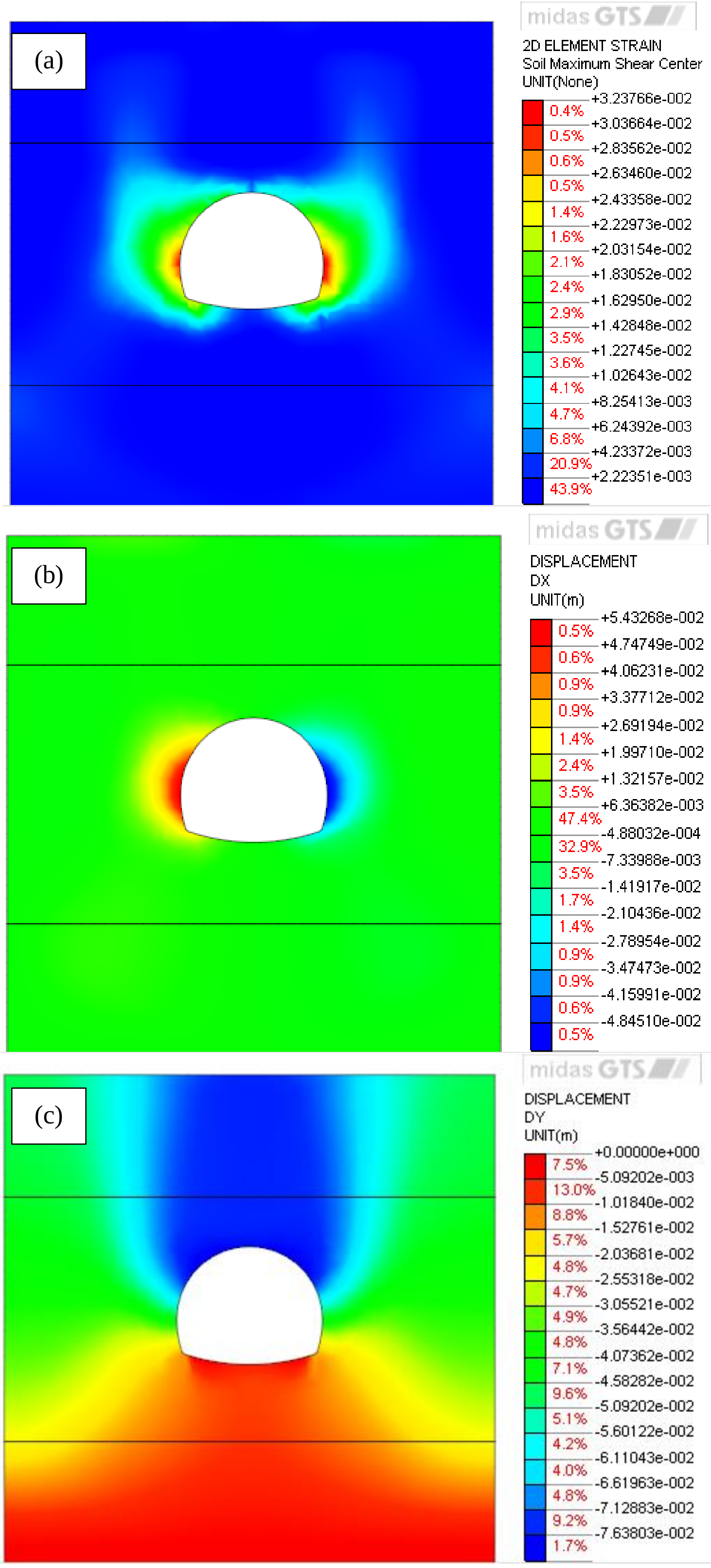


Figure 5. Schematic diagram of maximum shear, wall convergence and vertical displacement after excavation of the tunnel under Grade-IV surrounding rock condition (a) Maximum Shear strain; (b) Horizontal convergence; (c) Vertical displacement

(2) The lateral maximum Shear, horizontal convergence and vertical displacement after support of the tunnel under Grade-IV surrounding rock condition are shown in Figure 6.

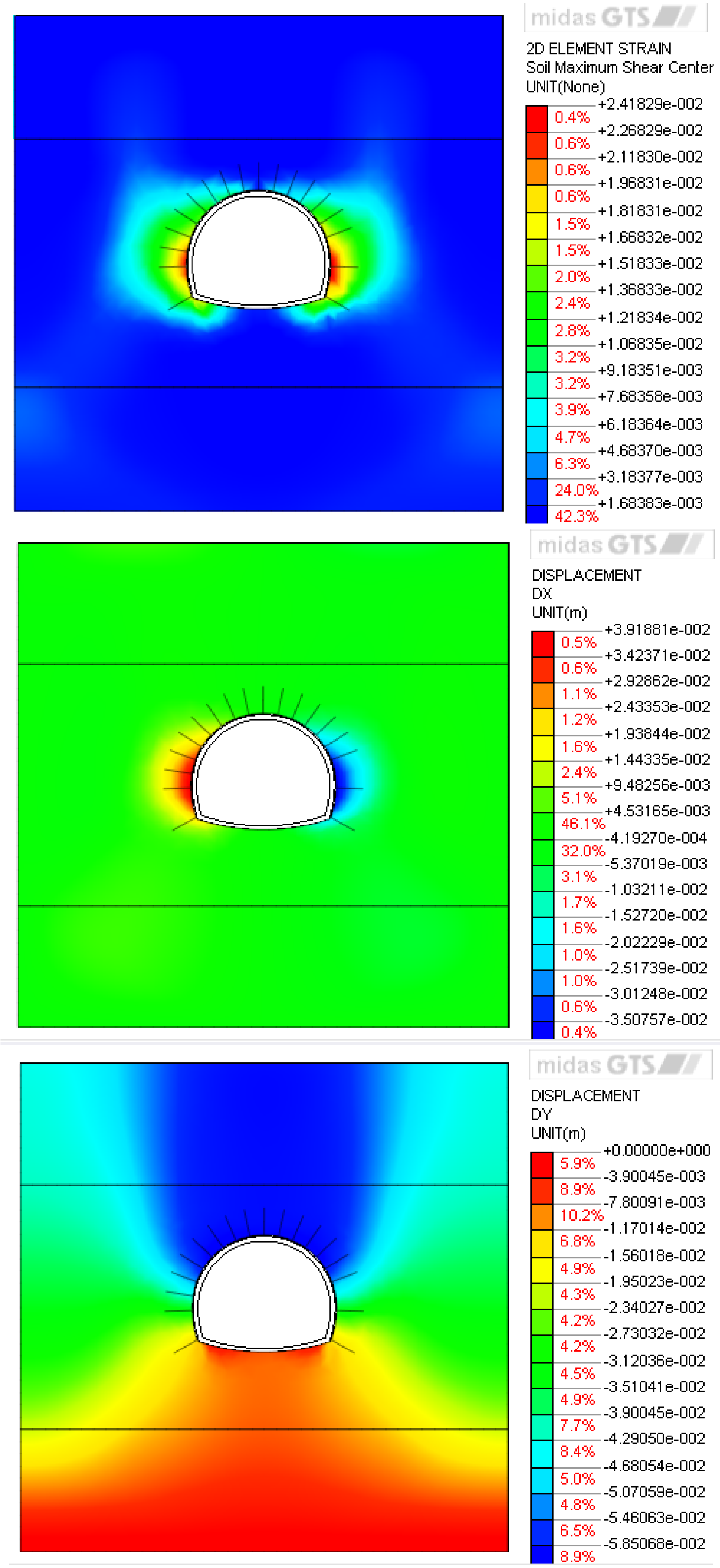


Figure 6. Schematic diagram of maximum shear, horizontal convergence and vertical displacement after support of the tunnel under Grade-IV surrounding rock condition (a) Maximum Shear strain; (b) Horizontal convergence; (c) Vertical displacement

It can be seen from the Figure 5 and 6, under Grade-III surrounding rock condition, the maximum Shear strain is about 3×10^{-2}, the maximum wall convergence is about 55 mm, the maximum displacement of the tunnel vault is approximately 80 mm after the tunnel excavation. The maximum Shear is about 2×10^{-2}, the maximum wall convergence is about 39 mm, and the maximum displacement of the tunnel vault is approximately 62 mm after the tunnel support. After adding the support, the maximum Shear strain of tunnel surrounding rock decreased obviously, the horizontal convergence of the surrounding rock is obviously suppressed, and the vault displacement has also been controlled.

It can be seen from the above simulation analysis:

(1) After the excavation of Grade-IV surrounding rock tunnel, all maximum Shear strain, the horizontal convergence and the vertical displacement of the vault is larger than that of the Grade-III surrounding rock tunnel.

(2) After the excavation of the horizontal rock tunnel, the tunnel wall of the surrounding rock has a convergence trend. The Convergence of the tunnel wall is essentially a lateral displacement of the tunnel section, which is counteracted by the convergence of both sides. This is due to the tendency of layered rock mass, resulting in the difference of resistance between the two sides of the surrounding rock, but relatively speaking, the overall section and structure of the tunnel will not have a great influence.

(3) The vertical displacement of the vault soil is obviously larger than that of the other parts after the excavation of the horizontal rock tunnel. In horizontal strata, after excavation of the tunnel, the bottom slab of the arch is hollowed out under the horizontal rock slab, which is equivalent to the horizontal beam plate supporting the two sides of the arch, and generally horizontal rock formation is difficult to form a pressure arch or stable, it makes the arch rock strata bear considerable pressure on the surrounding rock, and then leads to the larger vertical displacement.

According to the results obtained from the above calculation, the following measures are put forward for the construction of horizontal rock strata in Xishan tunnel:

(1) To avoid the tunnel vault crown displacement, the arch bolt should be strengthened to ensure that the arch is tightly connected with the undisturbed and micro disturbed rigid rock stratum, and the pressure arch is formed, and the anchor bolt is made of 22 cement mortar bolts.

(2) After the bolt is buried, after the anchor is buried, the steel mesh is hung on the arch and the side, and the shotcrete is sprayed in time. The flexible composite support is used to adjust the convergence deformation of the side wall of the tunnel, and the influence on the surrounding rock and structure of the tunnel is controlled in the minimum range. The steel mesh is paved with double layers, and steel bars are made with 6 round bars. The mesh size is 20cm×20cm. The shotcrete is made of C25, the front half circle of each circle is pressed, the single jet is 4-6cm, and the total injection thickness is 20cm.

(3) Close the invert timely to make the tunnel section closed as soon as possible, and to improve the stability of the tunnel. Strengthen the monitoring and measurement, especially the displacement of the vault.

5. Conclusion

The special bedding structure of the surrounding rock in the horizontal layer of Xishan tunnel makes the interlayer adhesion greatly reduced, and the tunnel construction period is tight, so there is a great risk in the tunnel construction. In this paper, through numerical simulation method, Xishan tunnel construction process of horizontal rock stability is studied and analyzed, and puts forward the targeted construction measures, in the tunnel construction, still need to optimize the construction method to ensure the construction safety and construction quality.

6. Acknowledgment

This work is sponsored by the Found of Shanxi Province (20150313014-2, 2016011013) and the Youth Fund of Taiyuan University of Science and Technology (20153014, 201733) which are gratefully acknowledged.

7. References

[1] Yang Xiaoyong. "Study on stability of surrounding rock of highway." Master's Degree Thesis of Chang'an University, 2004. doi:10.7666/d.W029446.

[2] Zhang Lezhong. "Study on stability of surrounding rock in the horizontal strata area -- taking the New Yao Ditch tunnel as an example." Master's Thesis of Chang'an University, 2006. doi:10.7666/d.Y977933.

[3] Shao Mingmin, Wang Zhongwei and Fu Jinyu. "Stability analysis and construction measures of horizontal rock strata in Huofeng Mountain tunnel ." Railway Engineering12 (2011): 69-71. doi:10.3969/j.issn.1003-1995.2011.12.022.

[4] Guan Baoshu. Key Points Set of Tunnel Engineering Construction." Beijing People's Communications Press, 2003. ISBN：9787114092428.

[5] Huang Guang, Chou Wenge, Zhang Huijian, Pan Jianping. "Study on failure mechanism and cconstruction ccountermeasures of horizontal rock tunnel." Pioneering With Science & Technology Monthly,10(2012): 188-190. doi:10.3969/j.issn.0254-

5357.2008.05.010.

[6] Feng Wenkai, Shi Yuchuan, WANG Xing-ping, He Chuan. "Support optimum on horizontal bedded surrounding rock of expressway tunnel" China Journal of Highway and Transport, 02 (2009): 65-70. doi:10.3321/j.issn:1001-7372.2009.02.012.

[7] Wen Wenzhao. "Stability analysis and construction measures of horizontal rock stratum of HengShan tunnel." Railway Standard Design, S1 (2009):133-135. doi: 10.13238/j.issn.1004-2954.2009.s1.049.

[8] Guo Qiliang, Wu Faquan, Qian Weiping, Zhang Yanshan. "Study on relationship between deformation of surrounding rock and in-suit stress in Wushaoling deep-buried railway tunnel." Chinese Journal of Rock Mechanics and Engineering, 11 (2006): 2194-2199. doi:10.3321/j.issn:1000-6915.2006.11.005.

[9] Hao Wenguang. "Deformation mechanism and finite element analysis of tunnel in horizontal layered rock mass." Railway Construction Technology,06 (2013):30-34. doi:10.3969/j.issn.1009-4539.2013.06.010.

[10] Man-chao, et al. "Physical modeling of failure process of the excavation in horizontal strata based on IR thermography." International Journal of Mining Science and Technology 19.6(2009):689-698. doi: 10.1016/S1674-5264(09)60128-9.

[11] Wang Yonggang. "Anisotropic model of layered rock mass considering characteristics of structural interface." highway traffic science and technology 3.1 10(2014): 86-92. doi: 10.3969/j.issn. 1002 -0268.2014.10.014.

[12] Chen Wang. "Construction technology of horizontal stratum in single track railway tunnel." International Journal of Modern Tunnelling Technology 51.6(2014):142-147. doi: 10.13807/j.cnki.mtt.2014.06.023.

[13] Peng Yanyan,et al."Physical simulation study on failure process of horizontal strata soft rock roadway in Qishan Mine. Coal science and technology. "0253 - 2336 (2015) 09 - 0024 - 06. doi: 10.13199/j.cnki.cst.2015.09.005.

[14] Shu-cai Li, et al. "Large scale three-dimensional seepage analysis model test and numerical simulation research on undersea tunnel." International Journal of Applied Ocean Research 59 (2016): 510-520. doi: 10.1016/j.apor.2016.07.013.

[15] Jiajia Chen, et al. Construction of horizontal stratum landform-like composite foams and their methyl orange adsorption capacity [J]. Applied Surface Science, 2017, 397:133-143. doi: 10.1016/j.apsusc.2016.10.211.

[16] K Liu,et al. Finite Element Implementation of Strain-Hardening Drucker-Prager Plasticity Model with Application to Tunnel Excavation [J]. Underground Space, 2017. doi: 10.1016/j.undsp.2017.08.003.