Construction mechanical characteristics of shallow buried large span tunnel

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Abstract

To study the construction mechanical characteristics of shallow buried large span subway station tunnel, the Shangxinjie subway station in Chongqing is selected to establish three-dimensional numerical model using Midas-GTS. The deformation and stress distribution of surrounding rock mass are highlighted. Besides, the monitoring date of the preliminary lining deformation was analyzed and compared to the numerical results to validate the correctness of numerical simulation. The simulation results show that the maximum settlement located at the crown of tunnel with the value of 5.37 mm, and the maximum lateral displacement located at arc springing of tunnel with the value of 4.39 mm. The pre-settlement takes up to 25% of the final settlement, and has great implication when evaluating monitored data to gain reliable information about ground behavior. Tunnel crown settlement develops rapidly when the core soil (part 7, 8, and 9) are excavated. Totally, displacements caused by the excavation of core soil takes 55 percent of the final displacement, thus the soil core is the key to control the tunnel deformation. The maximum principle stress concentrates at the arch foot at both sides with the value of 1.87 MPa. The maximum tensile stress is 0.05 MPa which is approximate to tensile strength of rock and mainly distribute in the upper left region of tunnel. In practice, tensile cracks of ground appeared in this region, and underground water pipe of this region was damaged leading to water gush. The curves of monitoring date with construction steps are similar with that of numerical results, but the monitored settlement is 2.02 mm that is less than numerical results, for the reason that only the residual displacement after completing the preliminary lining can be monitored based on the conventional measurements.
Keywords: Mechanical characteristics, Shallow buried depth, Large span tunnel, Numerical simulation, Field monitoring.

1. Introduction

In response to rapid growth in urban development there has been a pressing need for construction of new tunnels for transportation systems and underground utilities. Subway is construction in more and more cities in China to solve the increasingly serious traffic congestion problem. Based on existing research results, when a tunnel or underground space is excavated, it inevitably disturbs the in situ stress field which causes ground movements leading to surface settlement. Generally, the section of subway tunnel is quite large to meets the request for utilization. The sectional area of the subway station is approximate to 400 m^2 that is much larger than that of highway tunnel. In addition, the buried depth of subway station always ranges from 10m to 30m which is nearly one times of tunnel diameter. Thus, many subway station tunnels have the characteristics of shallow buried and large span. The construction mechanical characteristic is more complex than highway tunnel. Thus construction mechanical characteristics of shallow buried large span tunnel should be studied to acknowledge the stress and deformation distribution during tunneling to ensure the stability of tunnel and to reduce project cost.

Some researchers have studied the mechanical characteristics of tunnel during excavation. Kazuhiko Haruyama et al. (2005) described the outline of Ome tunnel and the auxiliary construction method adopted based on monitoring and analyzing ground behavior during construction. Mohammad

H. Sadaghiani and Saleh Dadizadeh (2010) introduced a method for construction of large underground spaces based on a new pre-supporting system and simulated all the construction stages and analyzed the ground behavior. Zhou et al. (2010) describes the technique and method of the support stress monitoring, and monitor and analyze the tunnel stress during different construction procedures. A. Valizadeh Kivi et al. (2012) introduced a method of underground construction by increasing the rigidity of the supporting system using Central Beam Column (CBC) structure, and investigated the settlement control of large span underground station in Tehran Metro using a full three-dimensional (3-D) finite element analysis. Li et al. (2011) carried the monitoring of ground settlement deformation characteristic on the shallow large-span tunnel in the construction process, and analyzed the three-lane seven-step parallel tunnel excavation and tunnel ground settlement deformation characteristic under the three-level seven-step parallel tunnel excavation.

Although there are some researchers concerned the shallow depth, large span tunnel, any mechanical characteristic have not been developed to detect the appropriate construction yet. In the current study, the construction mechanical characteristic of shallow buried large span tunnel is investigated using a comprehensive three-dimensional numerical model. The tunnel crown settlement and surface settlement, stress distribution after tunnel excavation was highlighted. And the field monitoring data was analyzed to validate the effectiveness of numerical simulation results.

2. Geological and geotechnical engineering

Shangxiejie subway station project is a part of the metro line 6 which is under construction in Chongqing, China. The subway station has the characteristics of large span and shallow buried depth, and was excavated using subsurface excavation method. The width and height of the tunnel are 18.2 m and 23 m, respectively, with the net excavation area of 370 m^2. The buried depth above tunnel ranges from 6 m to 35 m. Through calculation, the tunnel cover depth (C) to tunnel diameter (D) ratio ranges from 0.26D to 1.5D. According to the tunnel section division standard of international tunnel association the tunnel belongs to large span shallow buried tunnel. To reduce the influence of tunneling on surface displacement and buildings, double sidewalls drift method was adopted as the construction method.

According to geological survey report (Chongqing Survey Institute, 2010), the ground condition encountered in Shangxiejie subway station project includes a 2 m thick Miscellaneous fill material consist of gravel, silty clay, and construction waste. Underlying the fill layer is a 3m thick silty clay. The silty clay is followed by the sandy mudstone with the thickness of 5 m, and the sandy mudstone is medium weathered have a high quality of integrity. According to the compressive strength of saturated rock sample, weathering degree, rock mass integrity coefficient, and groundwater, the sandy mudstone is classified into Ⅳ. The sandstone is located below the tunnel invert and is classified into Ⅲ. The engineering site is in the neighbor of the Yangtze river, and the height difference is approximate to 80m, which is beneficial to drainage. Generally, the hydrogeological condition is simple, there is no uniform groundwater level, and the groundwater in engineering site is poor. Thus the influence of groundwater on tunnel excavation was ignored in the following analysis.

3. Finite element analysis

Based on existing research results, the mechanical characteristics of tunnel can be calculated using theoretical method. But theoretical method can only consider the tunnel with regular shapes and con not take the construction steps into consideration. However, the consideration steps have a great influence on the deformation and mechanical characteristics of tunnel. Many researchers have studied the influence of construction steps on tunnel deformation. For example, the effect of different sequential excavation method for large span urban tunnel in soft ground has been studied by Mostafa Sharifzadeh et al. (2013) and Chungsik Yoo (2009) using finite element method. In this paper, to detail study the construction deformation and mechanical characteristic, a commercial finite element package Midas-GTS was used for analysis. The construction steps of double sidewalls method adopted in practice was simulated using a comprehensively three-dimensional numerical model.

3.1 Finite element model

The Shangxinejie subway station between the mileage of YDK12+522.4 to YDK12+570.4 was selected as study area. Fig. 1 shows a typical finite element model, with relevant dimensions, adopted in the analysis, including 51085 isoparametric tetrahedron units and 9369 grid-points. Outer boundaries of numerical model were built far from the tunnel so that they will not influence the accuracy of simulation results. The length and width of the numerical model are 161 m (8.0 Tunnel Diameter) and 48 m, respectively. The surface of the model was established according to the topographic map of engineering site. The boundary constraints are as follows. The horizontal displacement of the model boundary was fixed, and the vertical displacement in the bottom of model was pinned. The top surface of the model was free in both directions.

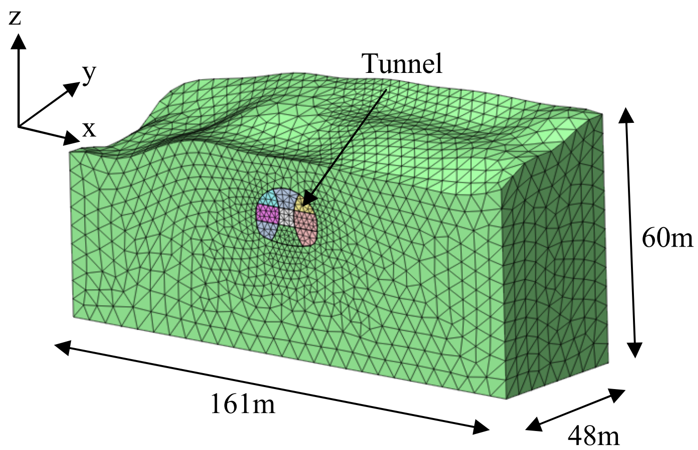


Fig.1. Three-dimensional numerical model

3.2 Physical and mechanical parameters for rock mass

The soil and rock layer were modelled using tetrahedron soil element. Considering the properties of local material and engineering experience, the soil and rock layer were both assumed to be an elasto-plastic material that conforms to Mohr-Coulomb yield criterion. While the shotcrete lining and rock bolt were modelled using plate element and implantable truss, respectively, and were assumed to behave in a liner elastic manner. During the construction of side drifts, not only shotcrete lining but steel ribs were both installed in the core soil to control ground deformation and improve the carrying capacity of core soil. In numerical simulation, the steel ribs were not simulated, but the effect of steel bars was converted to shotcrete lining using Eq. (1). The material properties of materials used in the analysis is listed in Table 1. Note that these values were taken from the geological survey report. The properties of shotcrete lining and rock bolt which were used in modelling are shown in Table 2.

$$E = E_0 + \frac{S_g \cdot E_g}{S_c} \tag{1}$$

Where, E is the elastic modulus of shotcrete lining after converting, E_0 is the elastic modulus of C30concrete, S_g is the transversal area of steel bar, E_g is the elastic modulus of steel with the grade of HRB400, and S_c is the transversal area of shotcrete lining.

Table 1 Geotechnical properties of soil and rock mass

Stratum	Density, γ (kN/m^3)	Elastic modulus, E (MPa)	Poisson's ratio, υ	Cohesion, c (kPa)	Internal friction angle, φ (^{o})
Miscellaneous fill	20.0	20	0.40	25	12
Silty clay	19.0	40	0.38	35	15
Medium weathered sandy mudstone	25.8	1442	0.35	603	32.7
Medium weathered sandstone	24.8	1533	0.28	1770	375

Table 2 Material properties of shotcrete lining and rock bolt

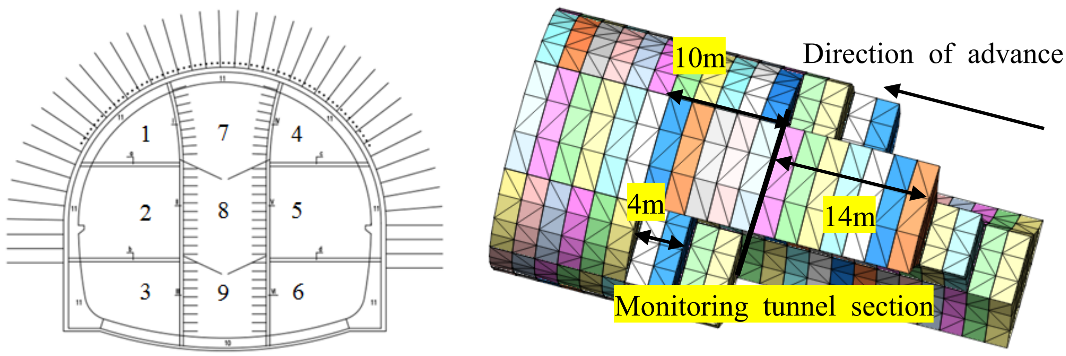
Material	Density, γ (kN/m^3)	Elastic modulus, E (GPa)	Poisson's ratio, υ	Thickness (m)	Length (m)	Diameter (mm)
Shotcrete lining	25.0	31.25	0.25	0.3	-	-
Rock bolt	78.5	200	0.2	-	4.0	22

3.3 Construction method

Due to the large span and shallow buried depth of subway station tunnel, many difficulties such as face unstability, big deformation, and cracks occurred in the buildings were often encountered. The phenomenon mentioned above may extend the construction period, improve the engineering cost, and even the complaints of nearby residents. Nowadays, the New Austrian Tunnelling Method (NATM) is widely used in tunnel design and construction. This method is a well suited for controlling the ground deformation and reducing the influence of tunneling on buildings above.

Considering the shallow buried depth and the large span of the Shangxinjie subway station, combined with the local engineering experiences, double sidewalls drift method was adopted for this project. Fig. 2(a) shows the design excavation method, it can be seen that the big cross section is divided into three drifts with nine parts. The left drift was excavated according to the number marked. After the excavation of each segment, shotcrete lining, steel ribs, and rock bolts were then installed as early as required to keep the stability of tunnel. The right drift was excavated when the left drift was several meters in front of the right one. When the right drift was far enough, the soil core can be excavated, the temporary support was also excavated, and the secondary lining was installed. These steps were repeated until the tunnel is fully advanced through the entire domain. The excavation of tunnel in numerical analysis was divided into 40 construction steps.

During simulation, it was simulated by activing and passivating corresponding elements at designed steps. Fig .2(b) shows the tunneling condition at the 26th construction steps in numerical analysis. It can be seen that the advance length of each excavation round is 4 m, the lagged distance between the two drifts is 10 m. And the lagged distance between the right drift and core soil is 14 m.



(a) Design excavation sequences (b) Construction condition in the 26th construction steps

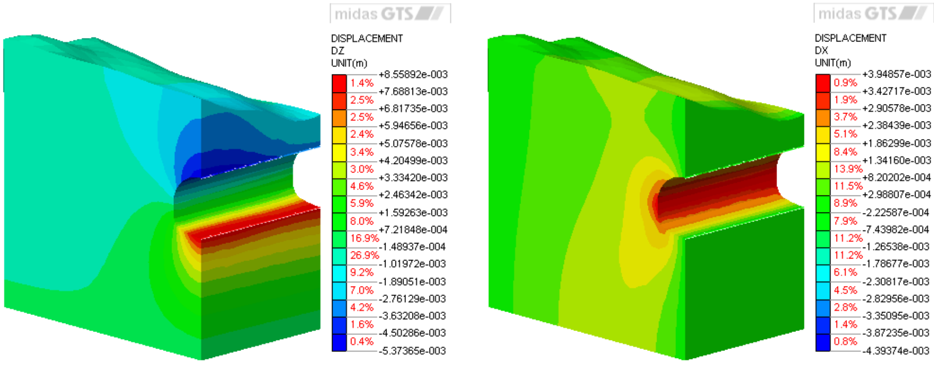
Fig.2. Schematic diagram of double sidewalls drift

4. Results and discussion

In this particular study, the deformation of surrounding rock mass, progressive development of tunnel crown and surface settlement with construction steps, the development of the principle stress with constructions, and plastic zone distribution were highlighted. The monitored tunnel section is depicted in Fig. 2(b).

4.1 Deformation of surrounding rock mass

The vertical and horizontal displacements of surrounding rock mass are shown in Fig. 3. It can be seen that tunnel settlement varies with the buried depth of tunnel, for the in-suit stress increases with the increase of buried depth. Thus the tunnel in the deep part caused great stress release, which leads to big displacement. The maximum tunnel settlement is 5.37 mm that is in within the allowable displacement 30 mm that is regulated by *code for monitoring measurement of urban rail transit* *engineering* (MOHURD, 2013). The upheave of the tunnel invert is larger than tunnel settlement in the same section, for the reason that after excavation of core soil the secondary lining was installed without primary support, which increases the exposure duration of soil in tunnel invert. The buried depth of tunnel is small, and there is no tectonic stress in engineering site, thus the lateral pressure coefficient is approximate to 0.5. The maximum horizontal displacement locates in the tunnel springing line with the maximum of 4.39 mm that is less than tunnel settlement.



(a) The vertical displacment (b) The horizontal displacment

Fig.3. Deformation of surrounding rock mass

4.2 Progressive development of tunnel crown and surface settlement

Generally speaking, due to the ground movement caused by stress release, tunnel crown and surface settlement occurred before the tunnel heading arrival. However, this part of deformation is not included in field monitoring for the field monitoring work was usually conducted after the completion of primary support. In numerical analysis, the deformation curves with construction steps can be monitored to analyze the progressive development. Fig. 4 shows the progressive development of tunnel crown and surface settlements at the monitoring section (as shown in Fig. 2(b)). As shown in Fig. 4, tunnel crown settlement and surface settlement starts to develop when the construction step is 18, and the tunnel face is about 20 m away from the monitoring section. Upon arrival of the part 7 at the monitoring section, tunnel crown settlement reaches 1mm which is almost 25% of its final value 4.04 mm, suggesting the pre-settlement, defined as the settlement that occurs at the time of part 7 arrival, is 25% of the final settlement. Based on the conventional measurement techniques, only the remaining 75% of the final settlement can be measured. The pre-settlement in fact has great implication when evaluating monitored data to gain reliable information about ground behavior (Sellner, 2000). A further inspection of Fig. 4 indicates the excavation of part 7 in the monitoring section cause approximate 1mm tunnel crown settlement. After excavation of part 9, tunnel crown settlements changes with a slow speed and the settlement curve tends to stable. The tendency of tunnel crown settlement suggests that any measures for controlling the crown settlement should be directed towards reducing tunnel crown settlement during the excavation of core soil including part 7, 8 and 9. Similarly, the surface settlement curve is can be discovered but with a gentler slope and slower settlement stabilization as expected.

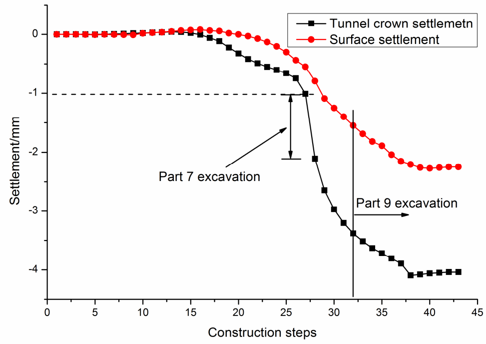
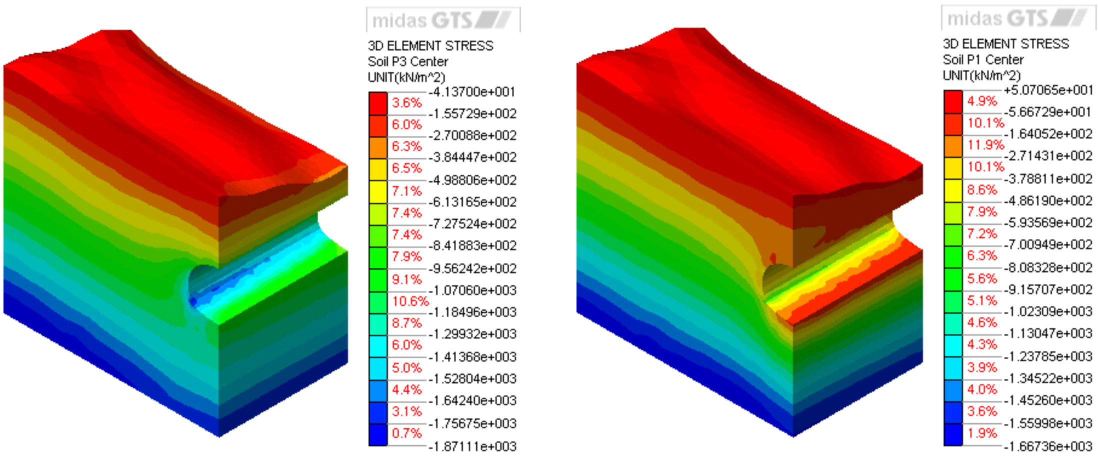


Fig.4. Settlements curves

4.3 Stress distribution of surrounding rock mass

Tunnel excavation causes stress deflects around tunnel boundary which will result in stress redistribution. Fig .5(a) shows the stress distribution of surrounding rock mass after tunnel excavation. It can be seen that the maximum concentrates in tunnel arch feet with the maximum value -1.87MPa. The maximum principle stress is still within the compressive strength of rock mass. But the thickness of shotcrete lining in this section should be increased to ensure tunnel stability during tunneling. The distribution of the minimum principle stress is shown in Fig. 5(b). The minimum principle stress locates in the surface and bottom of tunnel with the minimum value 50.71kPa. Due to the tensile strength of rock mass is only one tenth of the compressive strength. Thus special attention should be paid to the area that is tensioned. The area whose tensile stress is larger than 50 kPa is shown in Fig. 6. It can be seen that the tensioned area located in the left of tunnel. This part is vulnerable to tensile cracks and settlement. In engineering practice, tensile cracks indeed and vertical settlement indeed appeared in the part as described in Fig. (7). In addition, the underground water pipe was ripped, which leads to water inflow and then results in surface settlement. Tensile cracks appeared in engineering site is in accordance with that of numerical results.



(a) The maximum principle stress (b) The minimum principle stress

Fig.5. Stress distribution of surrounding rock mass

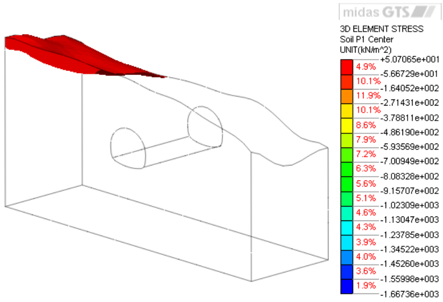


Fig.6. Tensile region diagram

Fig.7. Photos of surface tensile cracks

4.4 Analysis of field monitoring data

Field monitoring is very important for the safety construction of large span tunnel. The distance between monitoring sections varies from 10 m to 30 m based on the geological condition. The number of surface settlement points was dictated by surface conditions. The surface settlement was monitored using automatic level. The tunnel deformation was monitored using Leica total station cooperating with reflector. Fig. 8 shows the photos of field monitoring work. The monitoring data of section ZDK12+530 is shown in Fig. 9. The monitoring points were monitored once a day within the first week. Then the monitoring frequency was reduced to once every three days. The monitoring work lasts approximate to one month and a half. It can be seen that the maximum value of tunnel settlement and horizontal convergence are 2.20 mm and 1.90 mm, respectively. The field monitoring date is less than numerical results, for the reason that the monitoring points including reflectors and convergence monitoring point can only be installed after installing the primary support. In the future tunnel engineering, advanced monitoring instruments should be adopted in engineering site to obtain the full displacement curves with construction steps. But the tendency of the monitoring date is similar with that of numerical results after tunnel face passes the monitoring data and the tunnel deformation tends to be stable, which validate the correctness of numerical results.

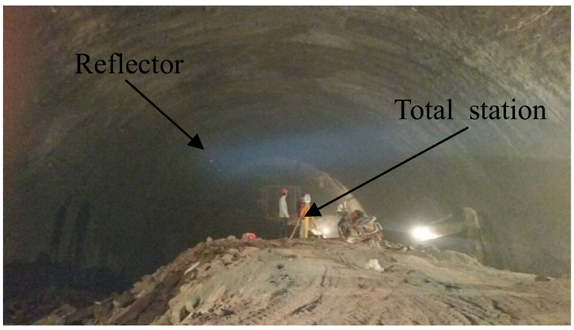


Fig.8. Photo of field monitoring work

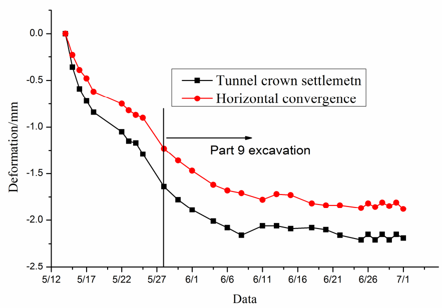


Fig.9. Field monitoring data

5. Conclusions

The main purpose of this study focuses on construction mechanical characteristics of shallow buried large span tunnel. For this purpose, a comprehensive 3D numerical model is developed. The numerical simulation is based on finite element method and Midas-GTS commercial software is used to simulate the progressive deformation of surround rock mass and stress distribution after tunnel excavation. The field monitoring date was analyzed and compared to numerical results to validate the effectiveness of the established numerical model. The following conclusions can be drawn for the tunneling conditions considered in this study.

(1) The final displacement of Shangxinjie subway station is 5.37 mm that is within the allowable displacement. The double sidewalls drift method is suitable for the large span tunnel.

(2) The pre-settlement of tunnel crown takes up to 25% of the final value, and the settlement is approximate to 25% of the final value upon the part 7 excavation in the monitoring section. Thus any measures should be taken to control tunnel settlement when the core soil (part 7, 8 and 9) is excavated.

(3) The maximum principle stress concentrates in tunnel arch foot, thus the thickness of the lining in this area should be increased. The maximum principle stress in the surface is tensile stress, special attention should be paid to avoid the rip of underground water pipe.

(4) Based on conventional monitoring measurements, the pre-settlement can not be monitored. Thus advanced monitoring instruments should be adopted in the future engineering to obtain the whole settlement curve with construction steps. The value and tendency of the monitored date is similar with numerical results. It can be concluded that the established numerical model and physical and mechanical parameters is correct.

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