Simulation and Measurement Analysis of NATM Tunnel Construction Method

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Key words: ABAQUS, NATM, footage size, lining, anchor

SUMMARY

In order to analyze the deformation law of surrounding rock and support in the process of NATM construction, through comparing with the measured values, the large finite element analytic software ABAQUS is adopted to build a 2D or 3D numerical simulation to simulate the first stage construction and measurement of 215-section of Dalian.

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ABSTRACT

In order to analyze the deformation law of the surface subsidence (uplift), dome subsidence (uplift) and the clearance convergence, through comparing with the measured values, the large finite element analytic software ABAQUS is adopted to build a 2D numerical simulation at the period of excavation and the initial support in three cross-sections located in the deeper, the shallower and the geological poorer area, based on the first stage construction of 215-section of Dalian Metro. 3D numerical simulation at different footage excavation's size of the same cross-section is selected to analyze comparatively the stratum total deformation, the surface deformation, the lining deformation, the lining stress and anchor stress and so on. It showed that the effect of footage is larger and there is a reasonable stage for the primary support of NATM construction.

Key words: ABAQUS, NATM, footage size, deformation law ,lining

1. INTRODUCTION

With the rapid progress of China's urbanization, the development and utilization of underground space has been improved to the strategic height of human process. The urban subway greatly relieves stress of the traffic congestion, air pollution and survival space and so on. The NATM, as a common construction method, based on Rock Mechanics Principle and utilized the self-stability of surrounding rock, holds bolt and shotcrete together as support, and therefore forms a trinity bearing structure composed of bolt, shotcrete and tunnel surrounding rock[1].

Currently, many domestic and foreign scholars have made a lot of further research about Tunnel engineering construction. Shi Zhilong[2] *et al.* got that the deformation of surrounding rock was larger when excavating the bottom bench. Shi Chenghua[3] *et al.* deduced longitudinal overlying strata movement and deformation formula caused by shallow tunnel excavation. Yang Lingde[4] *et al.* predicted the deformation of stratum around the cave. Sakurai Shunsuke[5] took the result of DBAP as reference and therefore judged the stability of surround rock. Hjiabdolmajid[6] took equivalent plastic strain as rock damage degree. But the calculation model does not exist, which can describe the condition of surround rock and the mutual relations accurately and all-sided [1].

2. THE CONSTITUTIVE MODEL OF ROCK MATERIALS AND SUPPORT[8]

The elastic-plastic constitutive model is usually selected to calculate rock materials, and the Mohr-Coufomb criteria is often used as failure criteria and yield criterion. In 3D stress space, the failure surface is an irregular hexagonal pyramid[9]. See Fig.1.

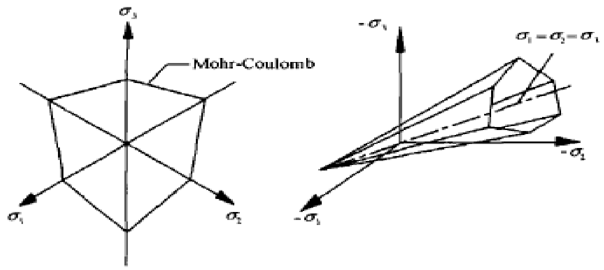


Fig.1. The constitutive model of rock materials and support

The function relationship of the failure surface using material factorsis

$$F(\sigma,\theta) = \frac{1}{3} I_1 \sin\varphi + \sqrt{J_2} \sin(\theta + \frac{\pi}{3}) + \frac{\sqrt{J_2}}{3} \cos(\theta + \frac{\pi}{3}) \sin\varphi - c\cos\varphi = 0 \quad (6)$$

I_1 represents the first invariant of strain tensor, $I_1 = \sigma_1 + \sigma_2 + \sigma_3$; J_2 represents the second invariant of deviatoric tensor of stress; θ represents stress lode angle, $0 < \theta < \frac{\pi}{3}$; c and φ represent the cohesion and friction angle. And in the polar coordinates, (6) can be expressed:

$$F(\xi,\rho,\theta) = \sqrt{2}\xi \sin\varphi + \sqrt{3}\rho \sin(\theta + \frac{\pi}{3}) + \rho\cos(\theta + \frac{\pi}{3}) \sin\varphi - \sqrt{6}c\cos\varphi = 0 \quad (7)$$

3. THE NUMERICAL SIMULATION AND DEFORMATION ANALYSIS

3.1 Project overview

About the first stage construction of Dalian Metro 215-section, the NATM is adopted in the excavation section of concealed tunneling waterproofing. The Benching Tunneling Method is adopted in the excavation section of single-hole and single-line cross section. The surround rock grades are ~ . At the period of excavation and the initial support, the large finite element analytic software ABAQUS is adopted to find the deformation mechanism of surround rock, optimize support parameters and keep the construction safely.

3.2 Software simulation

The paper has a simulation of construction of excavation and primary support.

3.2.1 The construction simulation of up and down bench method of standard section

Based on Geological Survey Report and《Standard for Engineering Classification of Rock Masses》[10], three cross-sections located in the deeper, the shallower and the geological poorer area are selected to simulate, the parameters of surrounding rock as follows:

Table 1 Surrounding rock parameters

Hole NO.	Strata NO.	Cause time	Soil	Thickness（m）	E (Mpa)	γ (kN/m^3)	μ	φ(°)	C (kPa)
ZD-tt-44	①^1	Q_4^{ml}	Qml	0.8	9	17	0.35	9	10
	⑨^2	Z_{jxy}	Strongly weathered limestone	2	100	27	0.33	24	50
	⑨^3	Z_{jxy}	Moderately weathered limestone	34.4	1500	26.79	0.27	37.4	200
ZD-tt-23	①^1	Q_4^{ml}	Qml	2.8	9	17	0.35	9	10
	⑨^3	Z_{jxy}	Moderately weathered limestone	8.2	500	27.1	0.31	34.01	80
ZD-tt-109	①^1	Q_4^{ml}	Qml	1.7	9	17	0.35	9	10
	⑧^2	β_μ	Strong weathering diabase	15.9	100	28	0.34	24	55

Table 2 The material parameters of primary support

Material	E(Gpa)	γ(kN/m^3)	μ
Lining	25	25	0.2
Anchor	206	78.5	0.3

Note: The selection of anchor parameters is basis on《Code for design of steel structures》GB50017-2003 table 3.4.3

(1) The settlement cloud diagram analysis of excavation face

Fig.2. is the settlement cloud diagram of cross-section ZD-tt-109. And as an example, the suffering area of tunnel excavation is within the scope of the 45 degree angle of working face circle. The amount of movement along vertical strata is relevant to the distance to the tunnel working face. At the vault and soffit lining, the deformation of stratum reaches a maximum. With the distance to the tunnel working face increasing, the deformation decreases gradually, indicating having the distance weaken.

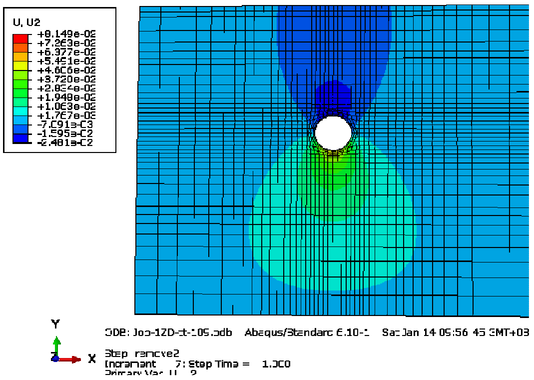


Fig.2. The settlement cloud diagram of tunnel excavation face

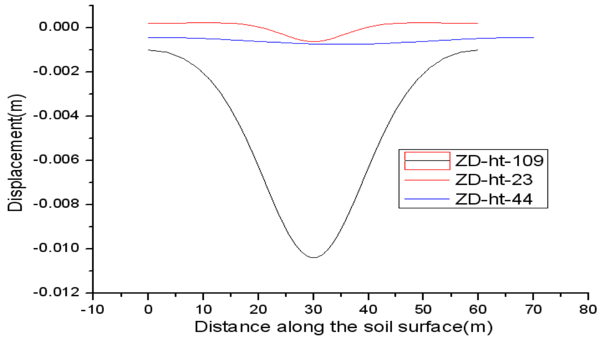


Fig.3. The surface displacement curve of tunnel excavation face

(2) Analysis of surface displacement

As Fig.3. shown, the surface deformation of the three working face all have settlement troughs. The vault embedded depth of cross-section ZD-ht-44 is 35.4m. Because of the declining of the ground deformation, the surface deformation value is smaller, about 0.74mm. The sinking maximum is 0.61mm directly over the vault in the cross-section ZD-ht-23, and slight uplift (the maximum is 0.2mm) emerged farther from vault due to the soil mass of vault sank. About the cross-section ZD-ht-109, its surrounding rock condition is worse, the sinking maximum is 12.67mm, the suffering area is 28m from the vault to left and right and spreads within the the scope of the 45 degree angle of working face circle. The deformation minimum is about 1mm.

(3) Comparative analysis of analogue values and measured values.

Compare the software analogue values with the measured values, the result just as table 2.3 shown. From that we can see, the measured values are smaller than the analogue values, mainly owing to the limitation of measuring technique: the displacement happened before measurement can not be obtained, but the analogue values include the displacement which happens throughout this process. However, the analogue results are in agreement with measured results on the whole.

Table 2.3 Comparison of analogue values and measured values

Location	Vault settlement (uplift) (mm)		Clearance convergence (mm)		Ground surface settlement (uplift) (mm)	
	Analogue values	Measured values	Analogue values	Measured values	Analogue values	Measured values
ZD-tt-44	-2.29	-1.49	0.33	0.54	-0.74	-
ZD-tt-23	-1.19	-1.94	0.28	0.57	-0.61	-
ZD-tt-109	-12.67	-9.91	3.64	2.57	-10.39	-9.43

3.2.2 3D FEM simulation under different footages

There are two footage sizes (1.5m and 2.0m) are adopted to simulate ten excavation steps. The model sizes are 50m×60m×15m (X×Y×Z)， 60m×60m×20m (X×Y×Z). The stress release is 60 percent,and 80 percent. Mechanical parameters of rock masses are as follows.

Table 2.4 Parameter of rock

Material	E(Mpa)	γ (kN/m^3)	μ	Φ(°)	C(kPa)	ξ
Qml	9	17	0.35	9	10	0.55
Rock mass	50	22	0.33	20	50	0.43

(1) Analysis of 1.5m footage size cloud diagram of settlement.

Take 1.5m footage size as an example, Fig.4. is the cloud diagram of vertical displacement. As shown, ground deformation is larger around the hole, and it declines far away from the hole, the same as 2D.

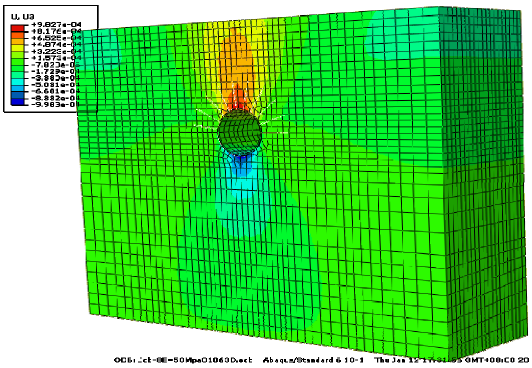
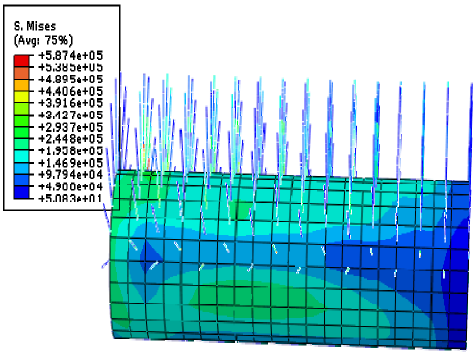


Fig.4. 1.5m footage size cloud diagram of settlement

(2) Analysis of Mises stress cloud diagram

Fig.5. and Fig.6. are the Mises stress cloud diagrams of anchor and lining of 1.5m and 2.0m footage size. The maximum(1.5m footage size) of Mises stress is 244.8kPa, and 2.0m is 8523kPa. Stress increases significantly.



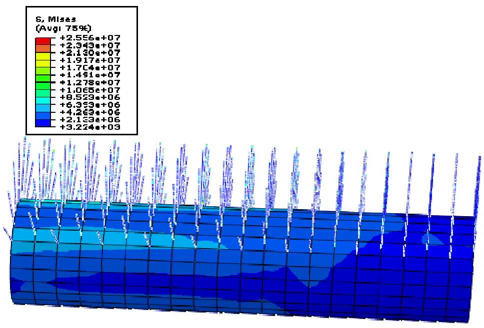


Fig.5. The Mises stress cloud diagrams of anchor and lining of 1.5m footage size

Fig.6. The Mises stress cloud diagrams of anchor and lining of 2.0m footage size

(3) Analysis of lining axial stress

Fig.7. and Fig.8. show lining axial stress. Tensile stress is positive, compressive stress is negative. As Fig.7.(1.5m footage size) shown, tensile stress appears at the soffit and vault of lining. As Fig.8.(2.0m footage size) shown, compressive stress appears soffit and vault of lining.

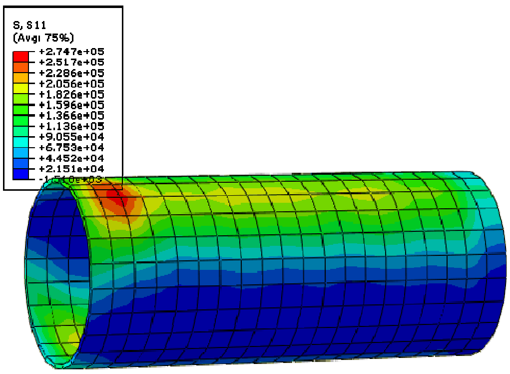


Fig.7. 1.5m footage size lining axial stress

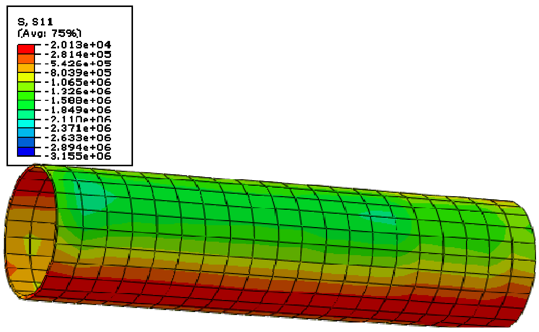


Fig.8. 2.0m footage size lining axial stress

(4) Analysis of feature points displacement with excavating going ahead

Fig.9. and Fig.10.are the vectographs of displacement along with the proceeding of excavating of the five sorts monitoring points, and the footage size are 1.5m and 2.0m respectively. The five sorts points on the initial tunnel working face are the surface points over the vault, the vault surrounding rock points, the vault lining points, the soffit lining points, the soffit surrounding rock points."+" means settlement, "-" means uplift. As Fig.9.shown, The variation of vault lining make up 63 percent of the total variation of stratum, which is in conformity with the stress release 60 percent in the excavation zone. As Fig.10.shown, the deformation of each monitoring point is lager when excavated by 2.0m footage size. From the data, the variation of lining and stratum increase obviously when the footage size increases.

The deformation excavated by 2.0m footage size is larger much more than 1.5m, as shown in Fig.9. and Fig.10. The deformation of each point tends to be stable under the two working condition when the excavation step was 30. In other words, the initial working face tends to be stable when pushed ahead five excavation steps, and the sharp deformation stage transforms to slow deformation stage[7]. Because of the self-ability of surrounding rock, initial support is not the earlier the better, but not the later the better. The support construction will be economic rationality after the surrounding rock has deformed in a certain extent.

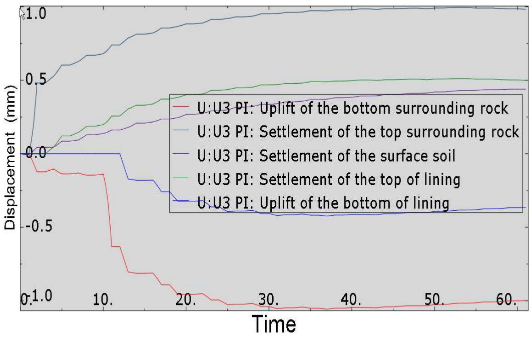


Fig.9. The feature points displacement with excavating going ahead---1.5m footage size

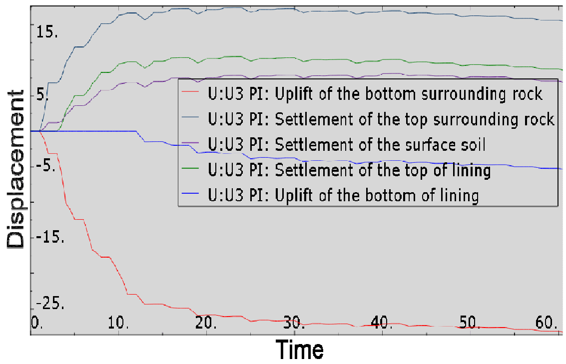


Fig.10. The feature points displacement with excavating going ahead---2.0m footage size

(5) Comparative analysis of vertical and horizontal displacement of working face

As Fig.11.shown, the settlement maximum are 0.8mm and 8mm corresponding to 1.5m footage size and 2.0m, large difference between them. Fig.12.is the settlement of each monitoring point that along the direction of tunnel excavating, which shows the situation at the end of excavating.

The settlement of each monitoring point is approximately equal to 1mm (1.5m footage size), in other words, the settlement of each point tends to a stable level. The settlement curve of 2.0m footage size is sawteeth shape.But the value is 6~7mm, coinciding with the measured value.

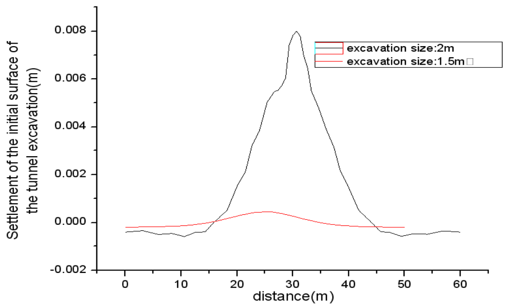


Fig.11. The surface subsidence of initial excavation face of two different excavated size

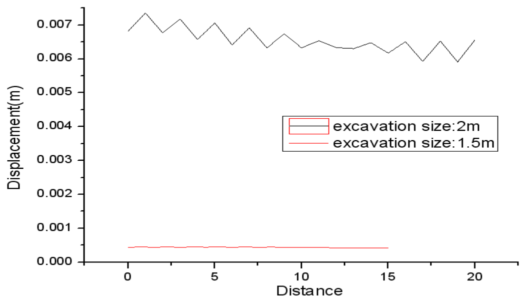


Fig.12. The surface subsidence along the direction of tunnel longitudinal of two different excavated size

4. CONCLUSIONS

(1) To the tunnel excavation surface as a starting point, the stratum moves up, forward and lean-forward, and the impact area expands from the tunnel bottom to top.

(2) The amount of movement of stratum deformation along the vertical relates to the distance to the working face. At the vault and soffit of lining,the stratum deformation reaches maximum, and it decreases along with the distance to the working face increasing and has the distance weaken.

(3) The subsider produced by the tunnel construction approximately obeys the gaussian distribution, and it extends forward in the form of contour with the construction proceeding.

(4) The deformation of initial working surface transforms from the sharp deformation stage to slow deformation stage when the excavation face extended forward five excavation steps.

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BIOGRAPHICAL NOTES

Yi Xiaodong, born in 1965 in China, works at School of Civil and Hydraul of Dalian University of Technology as associate professor, engages mainly at the use of photographic surveying, the GPS technology and deformation observation and analysis. Copy of mainly article or paper that the author has published as follows:

[1] Yi Xiaodong, Yi Tinghua, Li Hongnan, Wang Guoxin, (2007), Cycle Slip Detection and Correction of GPS Carrier Phase Based on Wavelet Transform and Neural Network, Vol. 20 No.4, pp.897-902, Chinese Journal of Sensors and Actuators,Nanjing.

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