3D Numerical Simulation of the Influence of Drilling-blasting Subway Construction on Subgrade Settlement

Yongyan Yu*, Jiliang Wang, Tianling Du, Ying Liu
Research Institute of Highway Ministry of Transport, Beijing 100088, China
*Corresponding author’s e-mail: 535165839@qq.com

Abstract. Based on the tunnel between Junfeng road-Xiliuzhuang of Qingdao metro, the tunnel excavation model is established by FLAC3D software. The established calculation model mainly includes:(1) Free field boundary conditions are adopted around and at the bottom of the model;(2) The blasting load is simulated by triangle pulse wave;(3) According to the peak value \( V \) of the surface velocity, the peak value \( P_{\text{max}} \) of the velocity in the triangular pulse wave is calculated by Sadovsky formula;(4) The calculation results show that the vertical settlement of subgrade is more significant when compared with horizontal settlement;(5) the calculation results are in good agreement with the field monitoring data. It shows that the method can simulate the dynamic characteristics of the model and reflect the dynamic response of subgrade settlement.

1. Introduction
The construction of subway tunnel causes the uneven settlement of the soil layer, which leads to the uneven deformation of the highway subgrade. Shield method or shallow buried and concealed excavations are often used in the urban tunnel construction in China. Therefore, the research on subgrade settlement in urban tunnel construction is mainly focused on these two methods. Some studies\(^1\)-\(^5\) release the displacement of pavement or highway subgrade settlement in which shield or shallow buried is used in tunnelling.

In recent years, with the construction of subway in Qingdao, Dalian, Chongqing and other cities, the drilling-blasting method has been widely used in these cities with the geological characteristics of "soil rock combination". At present, the research\(^6\)-\(^13\) on the influence of drilling and blasting method on the surrounding environment mainly focuses on the influence of construction on buildings or vibration reduction measures. But study of the influence of drilling-blasting tunnelling on subgrade settlement is not enough. And the study of parameters and method in dynamic simulation in drill-blasting tunnelling is few, which is crucial on accuracy of simulation results. The accuracy of parameters in drill-blasting simulation could lead to the correctness response of subgrade settlement.

In this paper, the tunnel construction of Junfeng road -Xiliuzhuang section (Jun-Xi area) of Qingdao Metro Line 3 is taken as the engineering background, and the drilling blasting method is simulated by FLAC3D software. This paper discusses the parameters in numerical simulation in drill-blasting tunnelling. And compare the subgrade settlement of monitoring and of simulation to evaluate the accuracy of parameter in simulation.

2. Modelling description

2.1. Calculation model
2.1.1. Model selection
K21 + 710 section between Jun-Xi district is selected for modelling and analysis. According to the actual situation of the section, a reasonable simplification method is considered. In the model, the size of the subway tunnel is simplified to a section with a width of 6.3m and a height of 6.6m. The size of the model is that the upper boundary is selected to the surface, the lower boundary is 3 times of the tunnel width from the tunnel edge, and the left and right boundary is 2.5 times of the tunnel width from the tunnel edge. That is to say, the distance between the tunnel crown and the ground surface is 11.4m, the distance between the left and right boundary and the tunnel is about 16m, and the distance between the lower boundary and the tunnel is 20m. The model size is 38m high and 38m wide, and the tunnel excavation direction is 18m.

The blasting load is needed in the model, so the free field boundary condition is used in the model. M-C constitutive relation is adopted for rock and soil around the tunnel.

2.1.2. Boundary conditions
The numerical simulation process is divided into static analysis and dynamic analysis. In the process of static analysis, the boundary conditions around the model are set as horizontal displacement constraints, the bottom boundary of the model is set as fixed end constraints, the upper surface of the model is set as free boundary conditions, and convergence calculation is carried out under the effect of gravity load. In the process of dynamic analysis, blasting load will be applied in the model. If the static field boundary is adopted, the large size of the model will affect the calculation speed. Therefore, the static boundary conditions are removed, and the free field boundary conditions are used around and at the bottom of the model.

2.1.3. Layout of monitoring points
FLAC3D software is used to monitor the displacement changes in X, y and Z directions of the subgrade during the excavation of the tunnel section. In the process of tunnel blasting excavation, the settlement range of subgrade above the excavation area changes greatly, and that far away from the excavation area changes little. Therefore, in the layout of subgrade settlement monitoring points, the tunnel centre line is taken as the axis, and the monitoring points are arranged symmetrically within 17m at the left and right ends. The monitoring points shall be set at the centre line of the tunnel and 1m at the left and right sides respectively, and one monitoring point shall be set every 2m in the following 3-17m range. The software monitoring data is compared with the field monitoring data to judge the correctness of parameter selection in numerical simulation.

2.2. Material parameters
The rock and soil layers in Jun-Xi area mainly include: fill, clay, coarse sand, strongly weathered granite, moderately weathered granite, etc. Table 1 shows physical and mechanical parameters of each layer of rock and soil mass obtained from geological investigation at the research section. C30 concrete is used for lining.
### Table 1  Physico-mechanical parameters of soil stratum in mode

| Thickness /m | Natural density / (g/cm³) | Cohesion/kPa | friction /° | E/MPa | Poisson's ratio |
|--------------|--------------------------|--------------|-------------|-------|----------------|
| fill         | 1.1                      | 1.8          | /           | /     | /              |
| clay         | 10.8                     | 1.94         | 30          | 14.1  | 15             | 0.33           |
| moderately weathered granite | 26.1 | 2.5       | 2000        | 35    | $15 \times 10^3$ | 0.22 |

2.3. **Application of blasting load**

2.3.1. **Input of blasting load**

In the study, the main application mode of blasting load is divided into two types: application monitoring and application model simplified wave. In this paper, the model simplified wave is used to apply blasting load.

In this paper, the triangle pulse wave is used to apply the blasting load in the model. The main parameters of triangle pulse wave include action time $t_r$, $t_s$ and peak value $P_{max}$. In the model, through the calculation of formula (1) - (5), the main parameters of triangular pulse wave are determined. The function of triangular pulse wave is input into the model by fish language, and the blasting load is applied to the excavation surface in the form of stress in the model.

![Figure 2. Triangular pulse wave](image)

The rise time $t_r$ / s and total action time $t_s$ / s of triangular pulse wave load are calculated as follows$^{[14]}$:  

$$t_r = 12\sqrt{r^{-\mu}Q^{0.65}/K}$$  

$$t_s = 84\sqrt{r^{-\mu}Q^{0.2}/K}$$  

(1)  

(2)

Where: K is the bulk modulus of rock mass, $10^5$Pa; $\mu$ is the Poisson’s ratio of rock mass

The existing research based on the application of blasting load in Qingdao area shows that the load rise time of 8-12ms and the total load action time of 0.08-0.12s can be used in the triangular pulse wave$^{[15]}$.

In the construction of Qingdao metro tunnel, the safety of blasting construction is guaranteed based on the control of surface vibration velocity. Therefore, in the determination of the peak value of triangle pulse wave, the peak value of pulse wave will be calculated by the maximum value of surface vibration velocity.

According to Sadovsky formula (3), proportional distance formula (4) and peak load formula$^{[16]}$(5), combined with the engineering geological conditions and peak vibration velocity in Qingdao area, the peak load $P_{max}$ / MPa in the triangular pulse wave formula can be obtained.

$$V = K\sqrt[3]{Q/R}$$  

$$Z = R/Q^{0.3}$$  

(3)  

(4)
In the formula, \( V \) is the peak value of particle vibration velocity / (cm/s); \( K \) is the attenuation index related to blasting site conditions; \( Q \) is the total charge quantity when blasting with explosive quantity, and the maximum section charge quantity /kg when blasting in sections; \( R \) is the distance from the blast hole to the loading surface, and the distance from the blasting application surface to the ground surface /m; \( \alpha \) is the attenuation index related to geological conditions; \( Z \) is the proportional distance.

The attenuation index \( K \) related to blasting site conditions and the attenuation index \( \alpha \) related to geological conditions are shown in Table 2.

| Lithology           | \( K \)     | \( \alpha \) |
|---------------------|-------------|-------------|
| Hard rock           | 50~150      | 1.3~1.5     |
| Medium hard rock    | 150~250     | 1.5~1.8     |
| Soft rock           | 250~350     | 1.8~2.0     |

2.3.2. Damping ratio parameters

The damping mainly comes from the internal friction of the material and the possible sliding of the contact surface. FLAC3D provides three damping forms in dynamic calculation: Rayleigh damping, hysteresis damping and local damping.

In the form of damping, Rayleigh damping is used by many researchers because its theory is similar to the conventional dynamic analysis method. Rayleigh damping can reduce the amplitude of natural vibration mode of the system when used in dynamic calculation. The relevant practice proves that the corresponding law of acceleration obtained by Rayleigh damping calculation is more practical. However, the disadvantage of Rayleigh damping is that the calculation time step is smaller, so the dynamic calculation time is longer.

The modulus attenuation coefficient \( M_\delta \) is used to describe the nonlinear characteristics of the soil in hysteresis damping. Compared with Rayleigh damping, it does not affect the time step of dynamic calculation. It can be applied to any material model. However, at present, there are few references, and when the model is more complex, it is not easy to get satisfactory analysis results. Therefore, this study does not consider the use of hysteresis damping.

In the vibration cycle, the local damping achieves convergence by increasing or decreasing the mass on the nodes or structural element nodes. Because the increasing element mass is equal to the decreasing element mass, the system maintains the mass conservation as a whole. The formula of local damping coefficient is shown in formula (6)

\[ \alpha_L = \pi D \] (6)

Where: \( D \) is the critical damping ratio, which can be taken as the minimum critical damping ratio \( \zeta_{\min} \) in Rayleigh damping. For geotechnical materials, the range of critical damping ratio \( \zeta_{\min} \) is generally 2-5%, and the range of structural system \( \zeta_{\min} \) is generally 2-10%. In this study, critical damping ratio \( \zeta_{\min} = 5\% \) is selected for model calculation.

2.3.3. Cell size control

The size of the grid unit shall not be greater than 1/8 ~ 1/10 of the wavelength corresponding to the highest frequency of the waveform. In the calculation, the highest frequency of the input wave will be controlled to prevent the distortion of the wave form.

\[ \Delta l = (1/8 ~ 1/10) \lambda \] (7)

\[ f = \frac{c}{\lambda} \] (8)
Where: $\Delta l$ is the maximum length (m) of the differential triangular grid element along the wave propagation direction; $\lambda$ is the shortest wavelength, i.e. the wavelength corresponding to the highest frequency (m); $c$ is the small value of the P-wave velocity $C_p$ and S-wave velocity $C_s$.

When there is no field measured wave velocity, the determination of $C_p, C_s$ method are as follows:

\[
C_p = \sqrt{\frac{K + 4G}{3}} \rho
\]
\[
C_s = \sqrt{\frac{G}{\rho}}
\]

Where: $K$ is bulk modulus (GPa); $G$ is shear modulus (GPa); $\rho$ is rock density (kg/m$^3$). Considering that the surrounding rock of Jun-Xi tunnel is mainly moderately weathered granite, the corresponding material parameters are selected to calculate the S-wave and P-wave velocities. Through calculation, the cell size shall be controlled within 2m, so as to meet the requirements of dynamic load waveform.

3. Analysis of simulation results

3.1. Standard model analysis

In the standard model, the moderately weathered rock layer is 0.5m lower than the tunnel vault to simulate the actual situation of the section.

Figure 3 shows the vertical and horizontal displacement of the subgrade at the tunnel central axis and at -4m and -8m away from the central axis after the tunnel excavation.

From Figure 3, it can be seen that the peak value of vertical displacement of Subgrade at 0m, -4m, -8m from the tunnel central axis is 24.17mm, 18.66mm and 7.69mm respectively. The peak value of horizontal displacement of subgrade is $2.035 \times 10^{-2}$mm, 6.85mm and 7.26mm respectively. With the increase of the distance from the axis of the tunnel, the horizontal displacement of the subgrade increases. This change can be considered that in the process of construction, the subgrade on both sides of the axis of the tunnel moves to the middle.

Because the vertical displacement of subgrade is mainly monitored in the construction process, and horizontal displacement monitoring projects is not common, so it is inconvenient to determine the accuracy of horizontal displacement of subgrade by comparing the monitoring with the simulation results. Through comparison, it is found that the horizontal displacement of the subgrade is smaller than the vertical displacement, especially the corresponding subgrade displacement at the central axis of the tunnel. Therefore, in this study, we will not discuss the influence of drilling and blasting.
construction on the horizontal displacement of subgrade. The results of numerical simulation will mainly consider the vertical displacement of subgrade.

3.2. Comparison between monitoring results and simulation results

The monitoring points near calculation section K21 + 710 are shown in Figure 4.

It can be seen from Figure 4 that the displacement monitoring points DC06-02~DC06-06 and DC07-01~DC07-05 is arranged near the calculation section K21 + 710. In this study, the vertical monitoring displacement of DC06 is compared with the numerical simulation to determine the accuracy of the calculation model.

Figure 4 shows the comparison between the vertical displacement of subgrade settlement by the simulation model and the vertical displacement monitored by DC06.

It can be seen from the Figure 5 that the settlement value of the subgrade corresponding to the central axis of the tunnel is 24.17mm from the simulation and 26.33mm from the monitoring. The monitoring value is slightly larger than the value in simulation. The simulation value of subgrade settlement on both sides of the central axis of the tunnel is in good agreement with the monitoring value. Therefore, the simulation model in this study is reliable. And the method and parameters of simulation in drill-blasting tunnelling is reliable.

4. Conclusion

Based on the tunnel between Junfeng road-Xiliuzhuang of Qingdao metro, the tunnel excavation model is established by FLAC3D software. The established calculation model mainly includes:

(1) Free field boundary conditions are adopted around and at the bottom of the model;
(2) The blasting load is simulated by triangle pulse wave;
(3) According to the peak value V of the surface velocity, the peak value Pmax of the velocity in the triangular pulse wave is calculated by Sadovsky formula.
(4) The calculation results show that the vertical settlement of subgrade is more significant when compare with horizontal settlement;
(5) The calculation results are in good agreement with the field monitoring data. It shows that the method can simulate the dynamic characteristics of the model and reflect the dynamic response of subgrade settlement.

References

[1] Mao Yuanfeng, Shen Yupeng, Ma jiannan, et al. Feature analysis of express highway pavement's deformation caused by metro shield tunneling under the express highway[J]. Railway Standard Design, 2013,(08):84-88.
[2] Yao Xuande, Wang Mengshu. Statistic analysis of guideposts for ground settlement induced by shallow tunnel construction. [J]. Chinese journal of rock mechanics and engineering, 2006,25(10):2030-2035.

[3] Wang shichuan, Li yunfeng, Shao yan, et al. Influence of shallow-buried subway excavation on urban pavement structure [J].Journal of disaster prevention and mitigation engineering,2014,34 (06): 725-730.

[4] Liu Zegui. The research on road surface of shallow buried tunnel blasting. [D].Southwest Jiaotong University,2014.

[5] Cheng Xingxin, Wange Xuancang, Gao Zhiwei. Control criterion of subgrad differential settlement based on pavement damage response [J]. Journal of Chang’an University (National science edition) , 2010,(09):31-34.

[6] Qi Taiyue, Wu Zhanrui, Luo Chi, et al. Influence of metro tunneling methods on environment and its control[J]. Journal of southwest jiaotong university, 2013,48(05): 792-797+817.

[7] Yang Mingxin. Analysis of road surface collapse in metro tunnel construction by mining method and preventive measures. [J].Modern urban transit ,2017(07):32-34+38.

[8] YU Yongyan, GAO Yongtao. Effect of subway tunnel excavation by drill-blasting method on pipeline. [J]. Engineering Blasting, 2015 (04) :6~10

[9] Wang Haitao, Wang kai, Song Ci , et al. Research on safety management of adjacent buried pipelines in blasting excavation of subway tunnel. [J]. Science Technology and Engineering, 2015, 15(11): 106-110.

[10] Song Ruicheng. The research of the tunnel excavation blasting vibration impact on the surface buildings [D]. Shijiazhuang Tiedao University,2017.

[11] Zheng Darong. Excavation by blasting and vibration control of tunnel in Nanjing subway [J]. Journal of railway engineering society ,2004(03):73-75.

[12] Xue Li, Sun Fufeng, Shi Yanlong, et al. Research on blasting vibration control of tunnel excavation of Qingdao subway. [J]. Journal of railway engineering society,2011,28(05):98-101.

[13] Wang Dong, He Lichao, Wang Kai. Field measurement and numerical simulation for influence of blasting excavation on adjacent buried pipelines. [J]. China civil engineering journal,2017,50(S2):134-140.

[14] Xue Li, Shi Longyan, Sun Fufeng. Research on blasting vibration control of subway shallow tunnel excavation [J]. Chinese Journal of Underground Space and Engineering, 2012,8(04):791-795+814.

[15] Sun Jun, Hou Xueyuan. Underground structure [M].Beijing: Science Press, 1987:696-697

[16] Liu Guohua, Wang Zhenyu. Dynamic response and blast-resistance analysis of a tunnel subjected to blast loading [J]. Journal of Zhejiang University (Engineering Science) ,2004(02):77-82.