Study on safety analysis of raw water pipe under large section bored tunnel of shallow buried excavation

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Abstract. In the process of urban construction and development, more and more large cross-section tunnels are excavated by shallow mining method for the improvement of traffic demand. The tunnel underpasses the important raw water pressure pipeline for water supply, which brings great challenges to pipeline operation and tunnel construction. In this study, the numerical finite element method is used to analyse the engineering case of the shallow buried large section tunnel under the raw water pipe. Using reasonable tunnel excavation construction method, this paper analyses the influence of large diameter primary water pipe of DN2700 and summarizes the relevant laws and control measures. It is find that when the temporary support of upper steps is removed during tunnel construction, the water pipe displacement will suddenly change. The surface settlement is about 1.9mm at most, and the vault settlement is about 3.5mm at most, which is mainly caused by the excavation of the upper steps and the removal of the temporary support of the upper steps and the arches. The calculation shows that through the DN2700 raw water pipe, the tunnel construction with reserved core soil method under IV grade surrounding rock can ensure the safety of raw water pipe and the stability of stratum. According to the measured data, the calculated results are in good agreement with the measured data.

1. Introduction
It is well known that mining tunnel construction will cause deformation of surrounding strata, which may affect the normal operation of adjacent pipelines. How to accurately judge the influence of tunnel construction on the deformation of adjacent pipelines has become a difficult problem to be solved in urban highway tunnel engineering. In the study of the pipe-soil interaction caused by tunnel construction, the analytical calculation method has clear physical concepts and can provide instructive opinions for the project efficiently. At present, the two-stage method is a commonly used method to study the pipe-soil interaction caused by shield tunnel construction. The study on the effect of shield tunnel construction on pipeline deformation is divided into two steps: (1) the vertical displacement of adjacent strata under the influence of shield tunnel construction is calculated by analytical expression; (2) Calculate pipeline deformation based on a reasonable tube-soil interaction model. Loganathan et al. [1] put forward a three-dimensional calculation formula that can accurately predict ground displacement caused by shield tunnel construction, and this formula has been widely used in the two-stage method due to its good calculation accuracy [2-4]. However, the above researches on the influence of tunnel construction on adjacent buried pipelines are mostly focused on the shield method. In the rocky areas such as Shenzhen, the mine method has become the main application of highway tunnel considering the factors of capital, technology and safety working method. The research on the vibration characteristics of adjacent buried pipelines, the failure mechanism of pipelines and the
interaction between pipes and soil by drilling and blasting method is obviously insufficient[5-6]. In this paper, a numerical analysis method is used to simulate the interaction among tunnel, soil and pipeline in mining construction. Taking the deformation, stress and strain of the pipeline as the control target, the influence of reasonable construction scheme control on the pipeline is analysed.

2. Project profile
During the construction process of the N XK1+840-800 section of the south line tunnel under the East Lake Pumping Station, it was informed that there was DN2700 raw water pipe near the East Lake Pumping Station under the tunnel. The geophysical exploration of the geological prospecting company shows that there is a steel DN2700 water pipe on the right side of N XK1+685~N XK1+767 section. The minimum horizontal distance between the tunnel and the pipe is 11.3m (figure 1). The rock mass is broken with the developed cracks. The groundwater is enriched along the fracture zone and the groundwater level is shallow. The covering depth of the tunnel is 18.5m, which is defined as a shallow covering depth according to tunnel design criteria.

The N XK1+767-755 section is designed as S4W type lining, and the upper half section is designed as S5W type lining by curtain grouting and Φ 42 leading conduit (spacing 3m). The N XK1+755-685 section is designed as S5W type lining, and the surrounding curtain grouting is designed as Φ 50 leading conduit (spacing 3m).

As DN2700 raw water pipes is for domestic water supply, it has extreme importance and must be ensured safe. Therefore, based on the design parameters, the stress and deformation of surrounding rock, earth's surface and water pipe at each stage in the construction process are analysed to judge the safety of the construction. It is proposed to select the nearest excavation section from the water supply pipe for the analysis on account of the most unfavorable working conditions.

![Figure 1. Plan of the underpass pumping station](image)

3. DN2700 water pipe analysis
According to the field investigation, the section N XK1+767 is the closest place to the deep water supply pipe, and the horizontal distance of DN2700 water pipe from the tunnel is 12.135m. The buried depth of the pipe is 2m.

The covering depth of the tunnel is 18.7m. The lining type is S4W shown in the figure 2 and figure 3 below. The curtain grouting of the upper half section is added with Φ 42 leading conduit (spacing 3m). The tunnel contour in the grouting area is expanded by 1.54m. The surrounding geological rock is defined by IV grade according to the tunnel design criterion.
3.1. Style and spacing

1. Calculate parameters

According to the design rules and geological prospecting report of the tunnel, the surrounding rock is defined by IV3. The values of physical and mechanical parameters of surrounding rock and stratum supporting material parameters are shown in the following table 1. Parameter values of tunnel supporting materials are shown in the following table 2.

| Surrounding rock classification | γ (kN/m³) | E (GPa) | μ | ψ (°) | c (MPa) |
|-------------------------------|-----------|---------|---|-------|---------|
| IV3                           | 21        | 1.8     | 0.34 | 28    | 0.3     |
| Curtain grouting              | 21        | 2       | 0.34 | 31.4  | 0.35    |
| Forepoling                    | 21        | 2.34    | 0.34 | 34.7  | 0.39    |

Table 2. Parameters of tunnel supporting materials
| material category          | γ (kN/m³) | μ   | E (GPa) |
|---------------------------|-----------|-----|---------|
| initial lining            | 25        | 0.2 | 25.5    |
| bolt                      | 78.5      | 0.3 | 200     |
| temporary support         | 25        | 0.18| 20      |
| secondary lining          | 25        | 0.2 | 31      |
| raw water pipe            | 78.5      | 0.2 | 200     |

2. Model building
Two-dimensional finite element simulation was used. Plane strain element was used for soil and Mohr-Coulomb constitutive calculation was performed. The length of the soil model is 160m and the height is 80m, thus the boundary effect can be eliminated. The left and right boundary are horizontal displacement constraints, and the bottom boundary is a fixed constraint. Water pipe is simulated by beam elements. The initial lining and temporary support of tunnel are simulated by beam elements, and the bolt is simulated by truss element. Advanced grouting, advanced support and concrete backfilling invert are simulated by plane strain element and realized by changing boundary attributes. As shown in the figure 4.

![Figure 4. Finite element simulation model of multi-step excavation method](image)

3. Construction process simulation
The construction sequence of multi-step construction method (reserved core soil method for arch guide pit) is described as follows:
1) Advanced grouting of small conduit -- excavation of upper arch guide pit -- initial support of arch
2) Excavation of the upper step on the left -- Initial support on the left side wall -- Excavation of the upper step -- Initial support on the right side wall -- Excavation of the reserved core soil on the upper step
3) Excavation of the left lower step -- initial support applied to the left arch foot -- Excavation of the right lower step -- initial support applied to the right arch foot -- core soil reserved for the lower step -- initial support applied to the invert

This simulation only considers the deformation and stress law of surrounding rock during the construction period, so it hasn’t considered the effect after the application of secondary lining.

3.2. Analysis of computing result
1. Deformation analysis of water supply pipe
As shown in Fig.5, the DN2700 water supply pipe is generally deformed towards the excavation position along with the tunnel excavation. The maximum vector displacement value of the water pipe is about 1mm, of which the maximum horizontal displacement is about 0.5mm and the maximum vertical displacement is about 0.8mm. When the temporary support of the upper step is removed in
tunnel construction, the displacement of water pipe will suddenly change, and the deformation value is about 0.4mm, accounting for about half of the total displacement. With the construction of invert and the closure of primary lining, the displacement of water pipe will decrease.

![Figure 5. Maximum vector displacement cloud of water pipe](image)

2. Vertical displacement analysis of tunnel and ground
As shown in Figure 6-7, the surface settlement is about 1.9mm at most, and the vault settlement is about 3.5mm at most, both of which occur after the removal of the temporary support procedure of the upper steps. From the perspective of the settlement of the vault, the settlement of surrounding rock is mainly caused by the excavation of the upper steps and the removal of the temporary support in the upper steps and the arches. It is suggested that the displacement monitoring should be strengthened in this construction procedure and temporary support should be added in other parts. The surface settlement groove is about 72m wide, which is symmetrically distributed to the Central Line of the tunnel. The maximum settlement value is located at the axis of the tunnel.

![Figure 6. Maximum ground settlement when removing upper steps support](image)
Figure 7. The surface subsidence occurs when the primary supports form a ring

3. Stress analysis of tunnel surrounding rock

It can be seen from Fig. 8-10 that Mises stress nephogram and maximum shear stress nephogram of surrounding rock show that the yield position of surrounding rock after initial supports ring formation is at the arch waist and curved wall. The nephogram of maximum principal stress of surrounding rock shows that tensile stress will occur around the arch foot, the arch and the arch shoulder of the tunnel. It is suggested that the above parts should be monitored and the supporting measures of surrounding rock should be strengthened.

![Figure 8. Mises stress nephogram of surrounding rock](image)

![Figure 9. Cloud map of the maximum shear stress of surrounding rock](image)

![Figure 10. Cloud map of the maximum principal stress of surrounding rock](image)

4. Analysis of measured data

Four points of DN2700 pipeline were selected according to the pile number, and displacement measuring points were installed on the pipe top during excavation to monitor the deformation of the pipeline during excavation. Three points of vault settlement in the tunnel were monitored through the construction under the DN2700 pipeline. The monitoring data are shown as follows:
According to the monitoring data, the deformation of DN2700 raw water pipe is about 3.1 mm at most. According to the requirements of the management department and relevant engineering experience, the maximum deformation of the pipeline should be controlled within 10 mm to ensure safe operation during construction. Therefore, the construction following the design scheme can guarantee the safety of the raw water pipeline reliably. Compared with the results of numerical simulation, the monitoring data are larger than those of numerical simulation. The reasons are analysed as follows according to the site construction conditions:

1. In the numerical simulation, the surrounding rock deformation of the support during the conversion process of excavation up and down steps is considered to be theoretical result. However, in the actual construction, there is a lack of slag on the initial support footing, and the support time of the step is long. Therefore the deformation is larger as it cannot be controlled to join the initial support in time.

2. In numerical simulation, the improved strength of surrounding rock after grouting is considered as the curing strength after 28 days. However, the actual construction period is short result in that the maintenance time of surrounding rock after grouting is limited and the strength improvement is limited.

3. The design grouting is curtain grouting, and the water seepage is strictly controlled. In the actual construction, the seepage control effect of curtain grouting in the tunnel is difficult to achieve extremely. Therefore a small amount of water seepage causes the drop of underground water level and additional deformation of the pipeline.

5. Conclusion
Through the finite element numerical simulation method, this paper simulates and analyses the water supply pipeline of Shenzhen East Connection Tunnel. The deformation of raw water supply pipe, the
deformation of tunnel surrounding rock and the law of stress redistribution in the construction process are carefully analysed. It provides reference for the site construction design and management. 

The maximum vector displacement value of DN2700 water pipe is about 1mm. When the temporary support of upper steps is removed during tunnel construction, the water pipe displacement will suddenly change. The surface settlement is about 1.9mm at most, and the vault settlement is about 3.5mm at most, which is mainly caused by the excavation of the upper steps and the removal of the temporary support of the upper steps and the arches. The yield position of surrounding rock after tunnel excavation and initial ring formation is located at the arch waist.

According to the analysis of monitoring data, the influence effect obtained by 2D finite element calculation is relatively large. Though the relevant trend of simulation and monitor date is relatively consistent, which has certain guiding value for construction. Combined with the actual construction situation, the problems existing in the construction can be demonstrated and suggested.

6. References

[1] Loganathan N, Poulos H G, 1998. Analytical prediction for tunneling-induced ground movements in clays. Journal of Geotechnical & Geoenvironmental Engineering, 124(9), 846-856.

[2] ZHANG Huan, ZHANG Zi-xin, 2013. Verical deflection of existing pipeline due to shield tunnelling. Journal of Tongji University (Natural Science), 41(8),1172-1179.

[3] ZHANG Z G, ZHANG M X, WANG W D, et al, 2014.Tunneling-induced ground movements in clays considering oval-shaped convergence deformation pattern. GeoShanghai International Congress: Tunneling and Underground Construction. Shanghai: [s. n.], 165-173.

[4] ZHANG Chen-rong, YU Jian, HUANG Mao-song,2013.Responses of adjacent underground jointed pipelines induced by tunneling. Chinese Journal of Geotechnical Engineering, 35(6),1018-1026.

[5] CHAO Dongping, WANG Mingnian,2007.Study on influence of blasting vibration on cross tunnels with small clearance. Chinese Journal of Rock Mechanics and Engineering,29(1),116 – 119.

[6] YU Yongyan, GAO Yongtao,2015. Effect of subway tunnel excavation by drill-blasting method on pipeline. Engineering Blasting, 21(4),6-10.

Acknowledgments

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