Analysis of the influence of super high-rise building construction on large-span tunnels adjacent to overlapping tunnels

Shun Yu¹, Bo Xiao² and Xixi Zheng¹

¹China Merchants Chongqing Communications Research & Design Institute Co Ltd, Chongqing, 400067, China
²National Engineering Laboratory For Of Tunnel Construction Technology, Chongqing, 400067, China

*Corresponding author’s e-mail: 316810974@qq.com

Abstract. A building site consists of a garage and two super-high-rise towers. Two-way six-lane municipal double-arch tunnel and single-tunnel double-line long-span metro tunnel overlap above and below the building site. Finite element software is used to simulate the influence of surface construction on the two tunnels. The calculation results show that the construction above the tunnel has little influence on the structural deformation of the two tunnels, and the structural displacement of the metro tunnel meets the requirements of the safety control index of the rail transit structure; because the metro tunnel bears large rock, soil and building loads above, the structural design of the metro tunnel should be strengthened to meet the bearing capacity requirements.

1. Preface
In the process of urban construction, the development of rail transit is an important approach to solve urban congestion. Restricted by surface buildings and track planning routes, metro tunnels will inevitably pass through existing high-rise buildings, or there will be new high-rise buildings adjacent to existing metro tunnels or ride over the situation; there are many domestic engineering examples and a lot of related research [1-9]. However, there are no similar engineering cases and research reports on the construction of super high-rise buildings near overlapping large-span tunnels. Therefore, this paper takes the super high rise building under the double overlapped metro tunnel with single ten tunnels and the two-way six Lane Municipal double arch tunnel as an example to simulate the influence of the whole process of building foundation pit unloading and floor loading on the two large-span tunnels, so as to provide theoretical support for the decision-making of the project.

2. Introduction
The construction site of the project is located in the track protection area of the interval tunnel of metro line ten. According to the plan, there is a two-way six lane municipal tunnel under the subway. The proposed site belongs to the hilly slope landform along the Bank of the Jialing River valley. It is high in the north and low in the south, with a relative height difference of about 71.5m. The venue mainly consists of two super high-rise towers (T3, T2) and a 5 garage (including community houses). The T3# tower is located on the west side of the subway. There are 35 floors on the ground and 4 layers on the ground. The minimum horizontal distance from the outer side of the subway structure is
29.65 meters. The T2# building is located on the east side of the subway. There are 40 floors on the ground and 7 layers on the ground. The minimum horizontal distance is about 17.34m from the outer side of the subway structure. The 5 # garage has 8 storeys, which is located directly above the Metro tunnel. The planar relationship between the proposed high-rise building project and Metro Line 10 and municipal tunnels is shown in the following figure.

The foundation of T3# building is pile foundation. The minimum vertical distance between the pile foundation and the vault of tunnel in line 10 is 9.75 meters. The foundation of T2# building is pile foundation, and the minimum vertical distance between pile foundation and vault of tunnel in line 10 is 4.75 meters. Project 5 # garage foundation is raft foundation, the minimum vertical distance between the foundation and the vault of the tunnel in line 10 is 12.5 meters. A two-way six-lane municipal tunnel is located between line 10 of Metro and the overhead public activity room of garage No. 5. The minimum vertical distance between the vault of municipal highway tunnel and the base of garage raft is 1.73 meters.

According to the layout of Metro plane route, the tunnel entrance section of Metro Line 10 section adopts large-span single-tunnel and double-line tunnel structure, and the tunnel body section adopts small cross-section single-tunnel and single-line tunnel structure.
Figure 3. cross section of single tunnel double track section of Metro

The municipal tunnel between the garage of the building district and the tunnel of the Metro Line 10 is a double-tunnel and six-lane multi-arch tunnel. As the municipal tunnel extends longitudinally to the interior of the slope, the two routes are separated into ramp A and ramp B tunnels, and the main tunnel is reduced to a double-tunnel and four-lane tunnel with small spacing. The cross section of the multi-arch tunnel is shown in the following figure.

Figure 4. Lining structure of double tunnel six lane multi arch municipal tunnel

The overburden of the tunnel entrance is mainly composed of miscellaneous fill or block stone soil with relative permeability, and its thickness is about 2.5m. The underlying bedrock is mainly moderately weathered sandstone with poor caving conditions, and the surrounding rock grade is V. Groundwater is relatively poor and the geological conditions are simple.

3. Site Engineering Geological Conditions

The construction site is located in the paraxial part of Longwang hole anticline. The strata are monoclinic with a dip of 190 degrees and an inclination of 10 degrees. There are no faults passing nearby. The geological structure is relatively simple. According to the drilling revealed, the sand and mudstone layer in the field contains mud weight, and the combination is very poor. According to ground investigation and drilling, the Quaternary artificial fill (Q4ml), quaternary alluvium (Q4col), Jurassic Middle Jurassic formation (J2S-SS) and mudstone (J2S-MS) are revealed in the depth of site investigation. The main physical and mechanical parameters of each layer are shown in the table as follows:
Table 1. geotechnical mechanical parameters of each layer

| Material properties                | Natural severe (kN/m²) | Modulus of elasticity (GPa) | Poisson's ratio | Cohesive force (MPa) | Friction angle (°) |
|-----------------------------------|------------------------|-----------------------------|-----------------|----------------------|--------------------|
| Qml                               | 20.0                   | 0.02                        | 0.4             | 28                   | 22                 |
| Moderately weathered sandstone 1 | 24.9                   | 1.9                         | 0.23            | 0.57                 | 38.0               |
| Moderately weathered sandstone 2 | 24.9                   | 2.2                         | 0.42            | 1.12                 | 37.5               |
| Moderately weathered sandstone 3 | 24.9                   | 1.4                         | 0.25            | 0.64                 | 35.0               |
| Moderately weathered sandy mudstone | 25.5               | 1.7                         | 0.35            | 0.76                 | 31.8               |

4. Numerical simulation calculation
The construction of high-rise building and garage mainly includes two processes: the block excavation of foundation pit and the increase of building floors after excavation. On the one hand, the excavation of building foundation pit is an unloading process for surrounding rock and soil mass, which will cause the movement and deformation of surrounding rock and soil mass, and then may cause additional stress to the adjacent tunnel structure, which will have an impact on tunnel safety; on the other hand, the increase of building floor is a loading process for surrounding rock and soil layer, which may also cause the displacement and deformation of surrounding rock and soil layer, and also cause the adjacent deformation of surrounding rock and soil layer. Additional stresses in tunnels bring hidden dangers to tunnel safety [10]. This project is close to high-rise buildings, overlapping metro tunnels and municipal tunnels are large-span cavern structures, the structural stress is very complex, and high-rise buildings in the construction process may have a greater impact on the construction of metro tunnels and municipal tunnels. Therefore, the feasibility analysis of the whole project and the safety evaluation of the subway tunnel structure need to be carried out through the finite element simulation calculation.

4.1. 3-D Computational Analysis

4.1.1. computational model
Considering the terrain and the influence range of high-rise building foundation pit excavation, a true three-dimensional model is established for simulation calculation. The model takes 100m in longitudinal direction, 250m in width and 80m in height along the tunnel, and adopts four-sided solid element. The calculation is appropriately simplified according to the relative position relationship between the building and the tunnel and the geological conditions, as shown in the following figure.
4.1.2. Computation step
In order to ensure the construction space and safety of high-rise buildings, Metro Line 10 tunnels and municipal tunnels, and in combination with the construction schedule among them, the project first implements the T3# tower and T2# tower on both sides of the tunnel, then implements the Metro tunnel, then implements the upper municipal tunnel, and finally constructs the garage and community activity room directly above the municipal tunnel. The computational simulation is carried out in the following order:

1. Initial in-situ stress application
2. Flat field of foundation pit of building tower
3. Constant load application of building tower
4. Excavation of foundation pit of open tunnel section of tunnel
5. Construction of underground excavation tunnel of metro tunnel
6. Construction of underground excavation tunnel of highway tunnel
7. Construction of open excavation structure of highway tunnel
8. Construction of open excavation structure of foundation pit in overhead area
9. Construction of overhead area under constant load
10. Live Load and Road Load Exercise of Empty Area Buildings

4.1.3. Calculation results
When the model is loaded, the self-weight of rock mass is applied by acceleration. The building load is 20 kPa per floor and the road load is 20 kPa. The boundary conditions are: the vertical Y-DOF of the bottom node, the X-DOF of the lateral node and the surface freedom of the surface are constrained.

The following figure shows the displacement distribution of the structure after the construction of the tower. The incremental displacement vector of the foundation pit bottom caused by the dead load of the building is about 7.41 mm.

Figure 6. Distribution of the whole displacement before the implementation of the tunnel.

Figure 7. Distribution of the whole displacement after the implementation of the tunnel.
The large amount of excavation in the open-cut section of the tunnel results in a large rebound of rock and soil. After loading the garage and community activity room above the tunnel, the incremental displacement vector of the foundation pit bottom caused by building loading is about 11.08mm.

After the implementation of municipal tunnel, the displacement vector increment of metro tunnel is about 6.11 mm. The displacement caused by excavation of foundation pit above the tunnel increases slightly to 7.85 mm. After loading, the displacement of building and municipal tunnel is stable at 6.18 mm. The construction above the tunnel has little influence on the structural deformation of Metro tunnel, and the structural displacement of metro tunnel structure changes slightly before and after construction. The vertical displacements of the above three key steps are 5.98mm, 7.76mm and 6.03mm respectively. The lateral displacements of the left and right side walls of the subway tunnel are less affected by the construction and loading above, and the lateral displacements are less than 1.3mm.

The influence of construction on surrounding rock of interval tunnel is analyzed. The three-dimensional calculation results are cut and the stress distribution of surrounding rock is observed. There is no plastic zone distribution in the surrounding rock of the tunnel. The stress level of the surrounding rock is -2570kPa ~ 491kPa, the compressive strength is about 13.1MPa, and the tensile strength is about 230kPa. The rock layer between the municipal tunnel and the subway tunnel is thin.
and the tensile zone appears. In this position, engineering measures should be taken to increase the stiffness of the tunnel below the metro section to meet the requirements of the upper bearing capacity.

![Figure 12. Distribution of First Principal Stress in Surrounding Rock.](image)

![Figure 13. Distribution of Third Principal Stress in Surrounding Rock.](image)

According to the result of calculation, the safety control index of Metro structure is determined. The three-dimensional calculation results show that the structural displacement of the tunnel in line 10 meets the requirements of the safety control index of metro traffic structure.

1) Horizontal displacement
   The horizontal displacement of tunnel structure is about 1.3 mm < 20 mm.
2) Vertical displacement
   The vertical displacement value of large section tunnel structure is about 4.17 mm < 20 mm.
3) Relative Curvature
   The relative curvature of large section tunnel deformation is about 1/10000 < 1/2500

4.2. Calculation and Analysis of Metro Intersection Tunnels

Considering the influence of the upper municipal tunnel, the reaction of the surrounding rock at the bottom of the tunnel caused by the load of rock and soil above the municipal tunnel and the building load is taken as the load of the Metro tunnel, and the lateral load is calculated according to the actual buried depth. The calculation results are shown in the following figure.

![Figure 14. Nephogram of Internal Force Calculation of Interval Tunnel Structure](image)

According to the calculation of the internal force of the structure and the analysis of the longitudinal spacing of steel bars by 100mm, the safety factor and crack width of the structure are obtained according to the different diameter of steel bars, as shown in the table below.
According to the calculation table, the structural safety at the arch shoulder position is the smallest, so the safety factor is extracted when the spacing of reinforcing bars is 100 mm at the arch shoulder position, and the following graph is obtained (see FIG. 15 below). From the chart, it can be seen that the secondary lining of the lower metro tunnel needs to increase the strength, reduce the spacing of the stressed steel bars, increase the diameter of the stressed steel bars or set double-layer steel bars at the vault and shoulder to meet the requirements of bearing capacity and crack resistance.

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### Table 2. Internal force calculation table

| Reinforcement | Section location | Axial force N(kN) | Shear force Q(kN) | Bending moment M(kN·m) | Safety factor | Crack width (mm) |
|---------------|------------------|------------------|------------------|------------------------|---------------|------------------|
| \(\Phi 34@100\) | Vault            | -1838            | -7.9             | 1274.3                 | 2.074         | 0.142            |
| \(\Phi 34@100\) | Arch shoulder    | -2770            | -28.0            | -1514.3                | 1.834         | 0.160            |
| \(\Phi 34@100\) | Arch foot        | -2771            | -155.9           | -635.0                 | 3.672         | 0.023            |
| \(\Phi 36@100\) | Invert arch      | -2576            | -60.7            | 705.6                  | 3.587         | 0.027            |
| \(\Phi 36@100\) | Vault            | -1838            | -7.9             | 1274.3                 | 2.269         | 0.119            |
| \(\Phi 36@100\) | Arch shoulder    | -2770            | -28.0            | -1514.3                | 1.981         | 0.134            |
| \(\Phi 36@100\) | Arch foot        | -2771            | -155.9           | -635.0                 | 3.822         | 0.019            |
| \(\Phi 36@100\) | Invert arch      | -2576            | -60.7            | 705.6                  | 3.752         | 0.022            |
| \(\Phi 38@100\) | Vault            | -1838            | -7.9             | 1274.3                 | 2.466         | 0.101            |
| \(\Phi 38@100\) | Arch             | -2770            | -28.0            | -1514.3                | 2.129         | 0.114            |
| \(\Phi 38@100\) | Arch foot        | -2771            | -155.9           | -635.0                 | 3.972         | 0.016            |
| \(\Phi 38@100\) | Invert arch      | -2576            | -60.7            | 705.6                  | 3.917         | 0.019            |
| \(\Phi 40@100\) | Vault            | -1838            | -7.9             | 1274.3                 | 2.638         | 0.094            |
| \(\Phi 40@100\) | Arch             | -2770            | -28.0            | -1514.3                | 2.255         | 0.105            |
| \(\Phi 40@100\) | Arch foot        | -2771            | -155.9           | -635.0                 | 4.051         | 0.015            |
| \(\Phi 40@100\) | Invert arch      | -2576            | -60.7            | 705.6                  | 4.058         | 0.017            |

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5. Conclusions and suggestions

(1) The results of three-dimensional calculation and analysis show that the excavation section of the proposed municipal tunnel is large, and the excavation unloading causes a certain uplift of the arch roof of the Metro tunnel, and the arch roof of the metro tunnel sinks under the action of building load and road load. The structural displacement of the metro tunnel structure changes little before and after the construction. The extreme value of vertical displacement and horizontal displacement is 4.17 mm and 1.3 mm respectively, and the extreme value of relative curvature of tunnel deformation is about
1/10000. It meets the requirement of safety control index value of metro traffic structure.

(2) Load structure calculation results show that the section tunnel bears large loads of rock, soil and building above, and the advance support, initial support and secondary lining design should be strengthened in order to meet the structural bearing capacity requirements.

(3) The construction sequence of Metro tunnel, municipal tunnel and garage and community activity room above the tunnel should be strictly followed.

(4) In the whole construction process of high-rise buildings, it is necessary to consider the protection of Metro Line 10 tunnel and municipal tunnel. Non-explosive excavation and strong support should be considered as far as possible to reduce the damage to tunnel structure and surrounding rock.

(5) The analysis and comparison of monitoring results and calculation conclusions should be strengthened during the construction period, and the construction scheme and design parameters should be adjusted in time to ensure the safe and smooth implementation of the project.

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