Safety Analysis for Construction of Building Structures in Close Proximity to Existing Tunnel

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Abstract: As a core component of urban public transport, rail transit must meet very strict requirements for operational safety. Constructing houses over an operating subway tunnel will result in changes in structural load. Improper design and construction would have bad social implications from structure cracking to tunnel collapse. In the context of Cangbai Road Community Building Project in Chongqing, analyses are performed of the performance of existing Line 6 section tunnel and Yuzhong connecting tunnel under axial force and bending moment and deformations of surrounding ground and structure during the project construction to assess the safety implications of the building structure on the existing tunnel structure underneath. The results show: the rail tunnel experiences a maximum horizontal displacement of 0.93mm and vertical displacement of 3.87mm during construction of the community building; after the community building is completed, the verified sectional factor of safety is 2.9 and maximum crack width is 0.18 for Yuzhong connecting tunnel and the sectional factor of safety is 3.0 and maximum crack width 0.11 for the rail tunnel, meeting specified control requirements. Through strict construction control and intelligent monitoring measurement, main structure of the project has been completed without inducing any rail safety accident. The successful development of this project provides helpful experience to similar projects and more reference for multi-purpose development of urban land.

1. Introduction

Underground rail transit plays an incomparable and essential role in relieving traffic pressure in cities which are expanding rapidly. Soil excavation and backfilling during construction of housing over an operating tunnel would disrupt existing soil/rock mass equilibrium and cause tunnel structure displacement and deformation. This is likely to compromise safe operation of the rail tunnel if improperly controlled. It is therefore important to analyze the effect of building construction on existing operating tunnel and propose construction control measures so as to ensure the safety of existing structure during construction[1].

Global scholars have studied the effects of underground project construction and control measures. In the context of Xi'an Metro Line 5 Wang Lixin et al. (2019) used numerical modeling method to analyze changes in crown and arch bottom displacement and stresses when loess TBM tunnel goes beneath existing line under 5 vertical clear distances from existing tunnel to the tunnel being constructed. The analysis results show as the vertical clear distance from existing tunnel to the tunnel being constructed decreases the displacements of ground surface and the crown and arch bottom of existing tunnel increase linearly[4]. Du Wen et al. (2019) analyzed the use of six-drift Pile-Beam-Arch...
(PBA) method in combination with jacking method for construction of new metro station under existing tunnel and used numerical modeling method to verify bending moment in bottom slab of light rail tunnel. Their analysis results show the floor settlement curve has a single trough shape and maximum deformation is controllable[5]. In the context of the first tramway in Beijing to be built over Metro Line 10, Liu Tianzheng (2019) studied the effects of U-shaped foundation pit excavation in sandy cobble stratum on TBM tunnel and through analysis of monitoring data, concluded that the uplift value was maintained within 1.5mm and transverse deformation value within ±0.5mm after soil improvement by deep hole grouting[6]. Existing researches focus on spatial intersection of new structure and tunnel structure with a lack of attention to buildings constructed over stacked double tunnel. In addition, the particularity of engineering geological conditions and construction environments makes it difficult to directly apply these research results.

On the basis of structural design and geotechnical investigation data for Cangbai Road Community Building Project in Chongqing, Midas GTS finite element software is used in this paper for numerical analysis and theoretical derivation to analyze the performance of existing Line 6 section tunnel and Yuzhong connecting tunnel under axial force and bending moment and deformations of surrounding ground and structure during the project construction to assess the safety implications of the building structure on the existing tunnel structure underneath[7] to assess the feasibility of the project execution, propose pertinent control measures and ensure safe construction.

2. Project Overview

2.1 Project overview
The project is located on the south side of Qiansimen Bridge in Yuzhong District, Chongqing City and on the west side of Cangbailu Tower. It consists of a community administration building with 4 floors above ground and 1 floor under ground within the project land area. This building has a plan view size of 26.8m×30.0m and a rectangular shape, with a total building area of 3234.98m², total footprint of 706.56m², building height of 18.5m and independent or pile foundation.

It is surrounded by dense buildings/structures, with high-rise buildings on its east, west and south sides. Its north side adjoins existing Cangbai Road and east and west sides adjoin existing Cangbailu Tower. This building structure is designed for a service life of 50 years. The building structure has a Class II safety level; the foundation (or pile foundation) has a design level of Class C; the waterproofing level for underground works is Class II; the impermeability grade of waterproof concrete is Class P6. The project is designed for seismic fortification intensity of 6 degrees on Class 2 site.

2.2 Location
The project is directly over Yuzhong connecting tunnel and above Metro Line 6 Xiaoshizi Station-Grand Theater Station tunnel. Part of the building foundation directly acts on the middle wall of the Yuzhong connecting tunnel. The site has a landform of the Yangtze River alluvial terrace and tectonic denudation and low hills and strata of Quaternary Holocene artificial fill (Q4ml) and Jurassic middle upper Shaximiao Formation (J2s) sedimentary sandy mudstone and sandstone. The spatial location of the building structure relative to the existing tunnel is shown in Fig. 1. The rail transit started formal operation in 2013. The Yuzhong connecting tunnel is completed and will be put into service. Construction on the community building commenced in January 2018.
3. Analysis of Deformation Impact

3.1 Calculation model
Midas-GTS finite element software is used for calculation. For fill and rock mass, M-C constitutive model in Midas is used and for others elastic model is used. During the ground-structure calculation process, left and right sides are subject to normal constraints and the bottom boundary is fixed. The strata are divided and strata mechanical parameters set according to geological exploration profile. The most adverse section 2-2 with the highest risk level is selected to simulate the effects of the proposed project on viaduct and tunnel within the section[10]. See Fig. 2 for the calculation model.

3.2 Parameter selection
On the basis of lab test and in-situ test results and according to applicable specifications, regional experience and comprehensive analysis, recommended parameters are selected for geotechnical calculation, as shown in Table 1.

Table 1 Mechanical parameters of surrounding ground and support.

| Geotechnical parameter | Unit weight γ (kN/m³) | Elasticity modulus E (GPa) | Poisson's ratio ν | Cohesion c (kPa) | Internal friction angle Φ (°) |
|------------------------|------------------------|---------------------------|------------------|-----------------|-----------------------------|
| Fill layer             | 21.0                   | 0.04                      | 0.45             | 0               | 28                          |
| Sandy mudstone         | 25.9                   | 1.655                     | 0.36             | 988             | 34                          |
| Sandstone              | 25.2                   | 3.488                     | 0.13             | 2.024           | 41.7                        |
| C40 concrete           | 25.0                   | 32.5                      | 0.2              | —               | —                           |
| C30 concrete           | 25.0                   | 30.0                      | 0.2              | —               | —                           |
3.3 Simulation process
To study the effects of pit excavation and construction of the community building on existing tunnel, the following control steps are taken during calculation: step 1: calculate initial stress and reset displacement; step 2: construct the rail tunnel and reset displacement; step 3: construct Liangjiangqiao Tunnel and reset displacement field; step 4: excavate the foundation pit for the community building; step 5: apply load onto the foundation.

3.4 Analysis of structural deformations
During construction of the Cangbai Road Community Building, the first effect is from pit excavation which reduces loads above the tunnel, leading to uplift of Yuzhong connecting tunnel and rail tunnel roofs and compressional deformation of existing tunnel due to reduced constraints in horizontal direction. After the community building load is applied, the roof and floor of Yuzhong connecting tunnel and rail tunnel experience settlement.

After the building is completed, the deformations of surrounding ground and the operating rail tunnel are illustrated in Fig. 3 and 4. After construction of the Cangbai Road Community Building is complete, maximum horizontal deformation of surrounding ground is 4.92mm and its vertical deformation is 9.37m. Maximum horizontal displacement of the track structure is 1.12mm and its maximum vertical displacement is 4.94mm.

Fig. 3 Deformations of surrounding ground after construction of the Cangbai Road Community Building is complete.

Fig. 4 Deformations of track structure after construction of the Cangbai Road Community Building is complete.

4. Analysis of Structural Performance

4.1 Load values
Values of loads on the Yuzhong connecting tunnel which is at ultra shallow depths due to soil excavation are obtained in accordance with applicable codes. During design of the building foundation, part of the foundation is supported by the middle wall of the Yuzhong connecting tunnel to reduce the building structure's span. This part of foundation load is expressed as concentrated load during
calculation and obtained from building foundation calculation. See Fig. 5 and 6 for loadings and foundation base loads.

![Fig. 5 Distribution of loads on Yuzhong connecting tunnel structure.]

Under the construction effects of Yuzhong connecting tunnel and the Cangbai Road Community Building above, the rail tunnel is no longer in a deep embedment state and its stresses are mainly influenced by the Yuzhong connecting tunnel above. During determination of structural loads, the Liangjiqiao foundation reaction is applied as load to the rail tunnel taking into account the soil cover load acting on the rail tunnel. The distribution of loads acting on the rail tunnel is displayed in Fig. 7.

![Fig. 6 Distribution of foundation reaction for Yuzhong connecting tunnel.]

Based on the above load calculation, the axial force and bending moment distribution in Yuzhong connecting tunnel is obtained as shown in Fig. 8. Extreme values are extracted to check safety factor and crack width, as shown in Table 2. Analysis shows the sectional safety factor of the rail tunnel after construction of the Cangbai Road Community Building is complete is 3.00, above the control value.
2.4 given by the Specifications for Design of Highway Tunnel; its maximum crack width is 0.11 which is less than the control value of 0.2 prescribed by the Specifications, meeting the capacity and durability requirements of structural design.

![Fig. 8 Distribution of track structure stresses.](image)

| Section location | Thickness (mm) | Main bar | Bending moment (kN·m/m) | Axial force (kN/m) | Sectional safety factor | Crack width |
|------------------|----------------|----------|--------------------------|--------------------|-------------------------|-------------|
| Crown            | 650            | C25@100  | -356.0                   | -260.3             | 3.00                    | 0.11        |
| Spandrel         | 650            | C25@100  | 249.7                    | -327.0             | 5.27                    | 0.06        |

4.2 Control Measures

Based on the above analysis results, disturbances to surrounding ground, the operating subway tunnel and ongoing Yuzhong connecting tunnel during pit excavation and construction of the Cangbai Road Community Building and aged-care center building meet specification requirements. However, to regulate construction activity and ensure safe construction, control measures are proposed as follows:

1. The new Cangbai Road Community Building and aged-care center building should be supported by pile or independent foundation. The foundation design shall avoid existing tunnel structures where possible. Manual excavation shall be employed to minimize disturbance from construction.

2. Site drainage shall be enhanced to effectively reduce ground softening due to construction water infiltration and reduce additional hydrostatic pressure behind tunnel lining in adverse weather such as storm.

3. During construction it is prohibited to stack construction materials over the tunnel and operate loaded construction equipment over the tunnel; soil excavation and backfilling shall be in strict accordance with applicable design and specification requirements.

4. Protection and monitoring of existing tunnel structures shall be enhanced. Prior to construction, existing tunnel structures shall be monitored for relevant control indicators and construction protection measures implemented to prevent building construction causing damage to existing tunnel structures.

5. Conclusions

Based on survey and design documents and construction status quo of the Cangbai Road Community Building, Yuzhong connecting tunnel and Metro Line 6 tunnel, the ground-structure method and load structure method were used to calculate existing tunnel deformations and performance during construction of the Cangbai Road Community Building and aged-care center building, assuming excavation of existing tunnel meets design requirements, the quality of tunnel lining structure meets specification requirements, tunnel surrounding ground conditions are consistent with geological exploration data, existing tunnel has no structural damage, building loads are not asymmetrical and there is no hydrostatic pressure around existing tunnel perimeter. The calculation does not take into account joint/fissure surfaces in surrounding ground. The calculation results show:
(1) After construction of the Cangbai Road Community Building is complete, maximum horizontal deformation of surrounding ground is 4.92mm and its vertical deformation is 9.37m. Maximum horizontal displacement of the track structure is 1.12mm and its maximum vertical displacement is 4.94mm. Both values are much less than the 10mm limit specified by the Technical Code for Protection Structures of Urban Rail Transit (CJJ/T202-2013). Construction and operation of the proposed project will not influence the safety of track structure;

(2) The sectional safety factor of the rail tunnel after construction of the Cangbai Road Community Building is complete is 3.00, above the control value 2.4 given by the Specifications for Design of Highway Tunnel; its maximum crack width is 0.11 which is less than the control value of 0.2 prescribed by the Specifications, meeting the capacity and durability requirements of structural design.

(3) Surrounding ground parameters and tunnel boundary conditions require further verification during construction of the project in strict accordance with design requirements. In the case of discrepancy between actual conditions encountered and calculation parameters including calculated loads and boundary conditions, re-evaluation is needed based on actual conditions.

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