Study on the Uplift-resistant Design of Oversized Ultra-deep Underground Structural Foundation above Subway Lines

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Abstract. For an oversized ultra-deep underground foundation in areas with shallow water level and crossing subway lines, an unreasonable anti-floating design may be dangerous to the safe operation of the subway lines. In this paper, numerical analysis is employed to the anti-floating design scheme of the foundation for an actual project, where two parallel and adjacent subway tunnels are laid under the underground structure. Three rows of large diameter bored piles are densely distributed along the sides and centerline of the two tunnels to restrict the foundation excavation. The simulation results show that the displacement of the tunnels caused by foundation rebounding can be limited to 3~4 mm, the fluctuation of vertical displacement caused by floating ranges from 11.0 to 15.4 mm, and the maximum value of the uplift gradient is only 0.019‰. On the other hand, a reasonable design of anti-floating anchors in the area of excavation far from the subway can be effective to lower bending moment in the integral concrete floor and thereby avoid the appearance of cracks. The scheme of combining design of uplift piles with anti-floating anchors in different regions can not only meet the requirements of anti-floating performance of the foundation and the safe operation of the subway, but also reduce the construction costs. The proposed design scheme can provide practical reference for the design and construction of similar projects.

1. Introduction
With the rapid development of urban construction, more underground spaces are employed to provide extra space for our daily life. In central urban areas where complicated subway lines are distributed in all directions, oversized ultra-deep underground spaces often span over those subway lines[1]. In case of a shallow water level, the base plate of the foundation of such underground spaces requires an anti-floating design[2]. Uplift piles and anti-floating anchor are currently the most widely used forms of anti-floating foundation. However, the construction of such a base plate after foundation excavation may rises safety issues of the normal operation of underlying subway lines[3, 4].

Piles and anti-floating rock bolts have been studied for a long time[5]. Sulaimain [6]explored the influence of elastic tension of piles on their lateral resistance. Reddy [7]proposed a modified T-Z model to accurately predict the load-displacement behavior of uplift piles. Mochtar and Edil[8] introduced a model test to study the influences of vertical and horizontal effective stress, over-consolidation ratio, pile diameter, pile-soil contact length, surface roughness and other factors on the load transfer of piles. Sawwaf and Nazir[9] employed an indoor centrifuge model test to investigate the bearing capacity of uplift piles in sandy soil of different degrees of compactness. Kilic et
al.[10] conducted an uplift-resistant test to investigate the influence of grouting properties on the ultimate bearing capacity of rock bolts.

Although the anti-floating design of foundation for underground structures[9, 11] is concerned, few studies and engineering applications exist about the simultaneous adoption of uplift piles and anti-floating rock bolts, especially for complicated construction environments[12, 13] such as crossing of subway lines[14]. The rationality of an anti-floating design for foundation influences the safe operation and engineering[15] costs of subway lines. Therefore, a case study of an oversized ultra-deep underground structure crossing subway lines are investigated in this paper, where the influence of the anti-floating design scheme of foundation on the deformation and stresses of subway tunnels and raft foundation are also explored.

2. Project Overview

2.1. Overview

The major structure of the project was a fully-buried four-storey building (three stories in some parts). By constructing permanent structural joints, the structure was divided into five areas, they are, Area A, Area B, Area C, Area D and Area E (as shown in Figure 1 and Figure 2).
2.2. Selection of uplift-resistant design scheme
A comprehensive assessment was made for various factors including types of structures, materials and construction conditions, forms of foundations of surrounding buildings and construction experience accumulated from previous projects [16]. Based on this assessment [17, 18], piles were selected for the foundation of this project for different areas as follows:

(1) Area A: A base plate was located in the destructive-weathered layer, so cast-in-place bored (punched) uplift piles were adopted;

(2) Area B: A base plate was located in the intensely-weathered and moderately-weathered layers (and partially in the partially-weathered layer), so cast-in-place bored (punched) uplift piles were adopted;

(3) Area C: A base plate was located in the partially-weathered layer, so cast-in-place bored (punched) uplift piles were adopted in the area defined as the scope of subway (both sides of two subway tunnels and area between them). However, a natural foundation base was adopted for the area beyond the scope of subway. The bearing stratum for foundation consisted of partially-weathered siltstone, and uplift-resistant rock bolts;

(4) Areas D and E: The base plates were located in the partially -weathered layer (and partially in the intensely or moderately-weathered layer), so a natural foundation base was adopted in these areas. The bearing stratum for foundation consisted of partially -weathered siltstone, and uplift-resistant rock bolts;

(5) In combination with the design of underground structural columns, each column was supported on an uplift pile with the spacing as 9×9m. Uplift-resistant rock bolts were designed based on the principle of full utilization of structural self-weight. However, no rock bolt was provided for resisting the axial force of columns caused by the permanent load. Beyond this scope, rock bolts were used at an interval of 1.5x1.5m. Figure 4 shows the typical layout of a standard span.

3. Uplift-resistant Design of Foundation Excavation

3.1. Numerical modeling
The numerical calculation software Midas/GTS was adopted for stress and deformation analysis on base plates, rock bolts, uplift piles and subway tunnels during and after construction in the project [19]. The soil layer was modeled using hexahedral elements. Mohr-Coulomb constitutive model [20] was used for soil for which the physico-mechanical parameters are shown in Table 1. The base plates of the foundation excavation and the uplift piles were modeled by plate and beam elements respectively. All the contacts between concrete parts and stratum are considered. Anti-floating rock bolts were modeled as truss elements [21]. Figure 5 shows the finite element model.

Figure 5. Schematic diagram of Finite element model
Table 1. Mechanical parameters of soil layer

| Geotechnical name | Density ρ (g/cm³) | Consolidated quick shear experiment | Compression Modulus (MPa) | Poisson's ratio μ | Thickness (m) |
|-------------------|------------------|------------------------------------|--------------------------|------------------|--------------|
|                   |                  | Cohesion c (kPa) | Friction angle φ (°)     |                  |              |
| 1 Earth fill       | 1.8              | 10              | 10                       | 2.5              | 0.33         | 11           |
| 2-1 Silty clay     | 1.93             | 20              | 15                       | 4.98             | 0.3          | 9            |
| 2-2 (Local) mud    | 1.55             | 6               | 4                        | 1.62             | 0.4          | 2.5          |
| Argillaceous siltstone |            |                  |                          |                  |              |
| Residual soil      | 1.9              | 20              | 14                       | 10.5             | 0.3          | 2.8          |
| 3                 |                  |                  |                          |                  |              |
| Argillaceous siltstone |            |                  |                          |                  |              |
| Intensely-weathered mudstone | |                  |                          |                  |              |
| Partially-weathered mudstone | |                  |                          |                  |              |
| 4                 | 2.1              | 50              | 26                       | 30               | 0.29         | 4.6          |
| Argillaceous siltstone |            |                  |                          |                  |              |
| Intensely-weathered mudstone | |                  |                          |                  |              |
| 5                 | 2.4              | 281.6           | 250                      | 50               | 0.27         | 22.3         |

3.2. Analysis of numerical results

3.2.1. Stress analysis of anti-floating foundation

After the foundation excavation was completed, the soil on site may rebound. As the piles in Areas A, B and C were cast-in-place, corresponding rebounding effects of the soil can be significantly restricted, with a maximum rebounding displacement of 4mm (as shown in Figure 6). However, in Areas D and E, the employment of anti-floating rock bolts yield larger rebounding displacement as about 7.7 mm. Nevertheless, since no subway line was near Area D or E, the relatively large rebound will not induce any safety threat to subway operation.

![Figure 6. Distribution of the rebounding displacement at the bottom of the foundation excavation](image)

Dewatering of the foundation excavation was stopped after completing the construction of the entire project, upon which time the base plates were subjected to anti-floating water pressure as shown in Figure 3. Figure 7 gives the displacement of the base plate under the combined action of a) the buoyance of water, b) the tensile force of uplift piles and rock bolts, and c) the pressure of upper structures. It is shown that the maximum and minimum uplift heights were, respectively, 15.4 mm and 6.4mm. On the upper surface of the entire base plate, the vertical displacement fluctuated between 12.6 mm and 15.4 mm. The difference in the non-uniform uplift displacement was relatively small, and thereby makes negligible effects on upper structures.
Since the base plates were below the water level throughout the year, relatively large bending moment in the plates may lead to cracks and corrosion may occur and affect the durability of the base plates and even the entire underground structure. Thus, the crack control of the base plates’ concrete should be the primary concern to be considered in the foundation design. Figure 8 shows the bending moment distribution in the base plates under long-term loads. It is shown that the overall bending moment in the base plates was relatively small and far less than the cracking strength of concrete. However, in areas where the local water level varied significantly, sudden increasing of the bending moment may present. At the same time, the protective walls erected around the subway tunnels to relieve the influences of the foundation on these tunnels were continuously subjected to the action of multiple loads and thereby in a complicated stress state. Therefore, reinforcing bars were added to the base plates and protective walls in areas where local water level varied significantly, so as to avoid concrete cracking.
3.2.2. Analysis of influence on the subway tunnel

The excavation of foundation pit led to the stress releasing of the soil masses around the subway tunnels, stresses variation and destructive cracks of the tunnel structures, and the failure of the waterproof facilities. Therefore, corresponding measures should be taken during the anti-floating design of foundation to reduce the influences of construction-related stresses and buoyancy on the subway tunnels. In this project, large-diameter cast-in-place bored piles were installed between two subway lines to reduce subway uplift caused by foundation rebounding (uplift displacement: 3-4mm, as shown in Figure 7). Moreover, thickened base plates of foundation excavation and side protective walls spanning over subway lines were provided to isolate the disturbance of soil masses around subway tunnels by foundation excavation and to minimize the influence of the construction of underground structures on the safety and normal operation of the subway lines.

Dewatering was stopped after the accomplishment of base plates. Before the construction of the upper structures, the tunnels were subjected to the maximum upward load, that is, the most unfavorable working state. Figures 9(a) and (b), respectively, show the vertical displacement and Mises stress of a subway at this stage. The vertical displacement of the subway fluctuated between 11.0mm and 15.4mm, i.e., the variation was 4.4mm, and the maximum subway uplift gradient caused by construction was 15.4mm/(217m+262m+343m)=0.019‰, which is far smaller than the maximum vertical design gradient for tunnels provided in the Chinese national standard ‘Code for the Design of Metro’. Therefore, the construction of this project makes negligible influence on the normal operation of the subway. The maximum tunnel Mises stress caused by buoyant load was 4.45 kPa, far less than the tensile and shear strength of concrete and far less than the reserve strength for tunnel design. Hence, it would not give rise to the issue of water leakage due to the prevention of concrete cracking in tunnel structures.

![Figure 9. The distribution of (a) vertical displacement and (b) Mises stress of the subway tunnel](image)

4. Conclusions

For excavating a foundation pit for a large underground construction above subway tunnels, large-diameter cast-in-place bored piles were densely distributed at both sides of and between two subway tunnels. As a result, the tunnel displacement caused by foundation rebounding was limited to 3-4mm,
the vertical displacement caused by floating fluctuating in the range of 11.0-15.4mm, and the maximum value of the uplift gradient was limited to 0.019‰. The normal operation of subway was not affected.

Under the combined action of the buoyancy of water, the tensile force of uplift piles and uplift-resistant rock bolts, and the pressure of upper structures, the maximum and minimum uplift height of the base plates are 15.4mm and 6.4mm respectively. On the upper surface of the entire base plate, the vertical displacement fluctuated between 12.6mm and 15.4mm. The non-uniform uplift displacement was too small to cause significant influences on the upper structures. When the buoyancy of water was relatively large, the constructed uplift piles in the middle of the plate can lessen the span of the plate. As a results, the reinforcement ratio and therefore the construction costs can be reduced.

As rock bolts were used, the base plate had a relatively uniform bending moment, a low reinforcement ratio and a high cost performance. During the design, efforts should be made to properly set post-cast strips, add concrete admixtures, and select concrete with low heat of hydration, low shrinkage factor and high crack resistance.

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