Numerical analysis of the impact of foundation excavation on the immediately adjacent subway station

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Abstract. The excavation adjacent to an existing subway station is a high-risk project during the underground engineering, which has an inevitable impact on the subway structure to affect the safety of train operation. This paper studies the excavations adjacent to a subway station on its both sides. A 3D numerical simulation with finite element code MIDAS GTS/NX is conducted to analyze the proposed excavations’ impact on the subway station as well as the accessory structure. The deformation law and the corresponding technical measures to contain the deformation of station structure are proposed afterwards, which could be a guideline for the design and construction of similar projects.

1. Introduction
With the rapid development of urban rail transit in China, it has been a trend to develop and utilize the underground space. The excavation adjacent to an existing subway station has to be taken into account therefore. The kind of foundation pit excavation will break the initial stress balance of the station structure’s surrounding soil and therefore deform the structure. On the other hand, the subway station structure is under a harsh deformation control, so it is important to evaluate the excavation’s impact on the adjacent subway station reasonably and effectively [1-2].

A 3D numerical simulation of an excavation project adjacent to a subway station in Beijing with finite element code FLAC3D was conducted by Ren Weiming [3]. The result shows that the unloading process of excavation has triggered a soil dislocation and thus the vertical displacement of the subway structure. A simulation of an excavation right next to a subway station in service in Suzhou, Jiangsu with the code Plaxis, focusing on its influence on the deformation of both the station’s support structure and green field settlement trough, was carried out by Chen Feifei [4]. Also, the effect of excavation on the structural deformation of the adjacent subway station was studied by Kuang Qinghua [5] using ABAQUS code from which a set of measures to contain the deformation of the station structure was summarized. Although a large number of studies of excavation right near a subway station has been conducted, their focus is mainly on the excavation’s impact on one side of the station rather than both sides, which, together with the geotechnical body’s characteristics of locality, diversity and inhomogeneity [6], makes it very important to study the geotechnical problems for different areas.

The paper will thus be based on the excavation project adjacent to a subway station on both sides, and analyze the impact on the station structure by conducting a three-dimensional numerical
simulation with MIDAS GTS/NX, in order to obtain some effective conclusions for a guideline of similar projects.

2. Project Overview

2.1 Project Overview

The proposed subway station superstructure project consists of a commercial podium and two towers, the north tower being located in the northwest of the site (pit A) and the south tower the southwest (pit B). The perimeter of the subway station is 298.5 m, the width of the standard section is 22.5 m, and the retaining structure is chosen as diaphragm wall with a thickness of 1.0 m. A three-span box frame makes up the main structure, where the approximate buried depths of the bottom slab are 23.91 m and 17.00 m, and the overburden atop the top slab has a thickness of about 3.0 m. The main structure of the subway station was existed before the excavation of the proposed project, of which the diaphragm wall should be also that of the foundation pit. Figure 1 illustrates the planar location of the proposed pit and the existing subway station.

![Figure 1. Plan view of the proposed pit in relation to the subway station.](image)

2.2 Geological conditions

The excavation is located in the geomorphologic unit of alluvial and diluvial sloping plain, and the green field is relatively flat. The surface layer of the site is miscellaneous fill, beneath which is mainly silty clay mostly in plastic to hard plastic condition. The groundwater distribution conditions and hydraulic characteristics show the groundwater of the site is relatively confined Quaternary pore water, distributed in the Quaternary silty clay layer and recharged by the lower karstic water.

2.3 Protection criteria for existing subway stations

In order to minimize the impact of the excavation on the existing rail transit structure and contain the deformation of the building or structure within a limit range, according to the relevant provisions of the code [7] and with experience of similar projects, the safety control criteria of the completed urban rail transit structure are shown in Table 1.

| Safety control indicators                  | Early warning value | Threshold values |
|-------------------------------------------|---------------------|------------------|
| Tunnel horizontal displacement            | <10 mm              | <20 mm           |
| Tunnel vertical displacement              | <10 mm              | <20 mm           |
| Tunnel radial displacement                | <10 mm              | <20 mm           |
3. Three-dimensional FE modeling

3.1 Numerical model and basic assumptions
In the Paper, Midas GTS/NX 3D finite element analysis code is used to analyze the effects of excavation of pits A and B on the subway station and accessory structures.

Based on Saint-Venant’s principle and empirical formulations, the horizontal influence range of excavation is taken as twice to three times the excavation depth and the vertical as twice to four times in order to eliminate the influence of boundary conditions. Therefore, the model size is taken as X×Y×Z: 192 m×323 m×45 m. After the installment of foundation pit and the underground main body, the overground structure is instantaneously added to the main body with the load of 15 kPa per layer, in order to simulate the completion of main body and service afterwards. Fixed constraints and normal constraints are applied to the lower and the left and right boundaries of the model respectively, which finally build up the calculation model illustrated in Figure 2.

![Overall model drawing](a) Overall model drawing ![Retaining structure layout](b) Retaining structure layout

Figure 2. Three-dimensional numerical calculation model

In order to facilitate the analysis, the following assumptions are adopted: 1) Mohr-Coulomb elastic-ideal plasticity constitutive model is adopted for geotechnical body, and 3D solid elements are used for simulation; 2) each part of the structural components is simplified as perfect linear elastic materials, the main body of the station and the accessory structure, as well as the diaphragm wall are simulated as slabs, and the struts and wales as beams; 3) structural stress is not taken into account in the simulation of initial stress field, but the effect of gravity stress is considered. Table 2 lists the material mechanical parameters required in the numerical model.

| Material       | Layer thickness | Unit weight (kN/m³) | Cohesion (kPa) | Friction angle (°) | Compression modulus (MPa) | Poisson's ratio |
|----------------|-----------------|---------------------|----------------|-------------------|---------------------------|-----------------|
| ① Misc. fill   | 2.20            | 18.0                | 5.0            | 15.0              | 1.4*                      | 0.30            |
| ③ Silty clay   | 1.80            | 19.3                | 27.5           | 10.9              | 7.0*                      | 0.31            |
| ⑦ Silty clay   | 4.00            | 19.4                | 31.3           | 10.3              | 7.5*                      | 0.32            |
| ⑩ Silty clay   | 6.00            | 19.0                | 34.5           | 10.7              | /                         | 0.30            |
| ⑪ Silty clay   | 10.50           | 19.1                | 34.2           | 12.0              | /                         | 0.25            |
| ⑮ Silty clay   | 20.50           | 19.2                | 46.1           | 11.8              | /                         | 0.25            |
| C30 concrete   | /               | 25.0                | /              | /                 | 6.0×10³                   | 0.20#           |
### Table 1: Material Properties

| Material  | Modulus (GPa) | Density (kg/m³) | Poisson’s Ratio | Yield Strength (N/mm²) |
|-----------|--------------|-----------------|----------------|------------------------|
| C35 concrete | / | 25.0 | / | / | 6.3×10³ | 0.25# |
| Steel     | / | 78.5 | / | / | 41.2×10³ | 0.30# |

Note: (1) The data with "#" are suggested values based on lab tests and regional experience.
(2) The data with "*" are empirical values.

#### 3.2 Construction work conditions

Under the consideration of initial stress, pit B is excavated and installed the bottom slab before A is excavated. The excavation process is divided into 12 conditions for simulation in following sequence: ① retaining wall and pile installment in pit B; ② excavation + first layer of concrete struts; ③ excavation + second layer of concrete struts; ④ excavation + third layer of concrete struts; ⑤ excavation to the substrate; ⑥ bottom slab installment; ⑦ retaining wall and pile installment in pit A; ⑧ excavation + first layer of concrete struts; ⑨ excavation + second layer of concrete struts; ⑩ excavation + third layer of concrete struts; ⑪ excavation to the substrate; ⑫ bottom slab installment.

#### 4. Analysis of results

##### 4.1 Excavation A’s impact on horizontal deformation of subway stations and accessory structures

Figure 3 to 5 illustrate the overall horizontal displacement of subway station and accessory structure during the excavation of pit A. The deformation of station and accessory structure towards pit B reverses just after the decrease of soil pressure in the excavation, with a displacement measure from 3.67 mm to 3.23 mm; on the other hand, as the excavation going on, the deformation towards pit A side shows an increased value, the maximum horizontal displacement being -8.35 mm. The bottom slab of pit A is completed before the maximum horizontal displacement of the station is reduced to -7.68 mm due to the neutralization of the excavation’s horizontal soil pressure by slab. The deformation is always within the limit range.

![Figure 3. X-directional displacement of the subway and accessory structures in condition 8](image)

![Figure 4. X-directional displacement of the subway and accessory structures in condition 11](image)
4.2 Excavation’s impact on vertical deformation of subway stations and accessory structures

The overall vertical displacements of the subway station and accessory structures varying with the excavation steps are shown in Figure 6 to 8. The maximum vertical displacement 5.58 mm can be found at the mid-slab of the accessory structure of wind pavilion 2, while that of wind pavilion 1 reaches 4.48 mm during the excavation of pit A. Again, the deformation of the structure is always within the limit range.
5. Conclusion

Based on the excavation project adjacent to a subway station on both sides, this paper analyzes its impact on both sides of the station and accessory structure by conducting a three-dimensional numerical simulation with finite element code MIDAS GTS/NX. In summary of the aforementioned study, the preliminary conclusions obtained are as follows.

(1) The deformation of the subway station and accessory structures due to the excavation is observed as vertical heave and displacement inwards the pit. Due to the unloading of excavation, the main and accessory structures perform an obvious horizontal displacement inwards the pit, and the overall deformation is characterized by a "bulging" type as the middle part deforms more than ends. In order to reduce the vertical heave of the station due to the excavation of the pit, it is recommended that the construction of the building above the main body of the station and the A pit be synchronized.

(2) The simulation results suggest the deformation of the subway station and the accessory structures during the excavation always meets the safety control criteria. If the deformation exceeds the threshold value of 20mm during the actual engineering, some measures such as reinforcement by grouting at the bottom, should be taken at the joint part of pit and subway station.

(3) Considering the difference between the model, material parameters, etc. used in the calculation and the actual one, the enhanced monitoring of the foundation pit and the subway station in service should be applied during construction to ensure the construction safety.

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