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Safety Assessment of the Impacts of Foundation Pit Construction in Metro Station on Nearby Buildings

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ABSTRACT

During the construction of metro station, it is important to ensure the safety and normal use of nearby buildings. Focusing on a foundation pit project in Hefei Metro, this paper fully examines the foundation type, structural form, construction period and use state of a nearby building, and explores the relationship between foundation pit support plan, metro station construction plan, and the residual deformation capacity of the building foundation. Based on the design files and different construction plans of the station, the finite-difference method and deformation observation were adopted to analyze the foundation settlement and residual deformation of the nearby building during metro station construction. The support plan and construction plan were adjusted and improved continuously. Finally, it is planned to support the foundation pit with reinforced concrete retaining piles and four-layer steel supports, and excavate and reinforce the pit layer by layer. Under the final plans, deformation of the building foundation does not exceed its remaining deformation capacity. This research provides an effective construction plan for the metro station, and specifies the way to observe the foundation settlement of the nearby building. The research results provide a good reference for similar risk projects to conduct safety assessment and evaluation in the design and construction phases.

1. INTRODUCTION

Underground transport is an effective way to alleviate urban traffic congestion, which is intensified by the growing population in cities. Metro stations are important components of underground transport system. During the construction of metro stations, one of the key tasks is to excavate the foundation pit. The excavation causes the settlement of foundation pit, and creates a soil stress field, exerting significant impacts on the surrounding environment. In severe cases, the excavation of foundation pit may result in engineering accidents. This calls for strict management and control of the risks induced by the environmental impacts. In most risk models, the risks are managed, analyzed and controlled based on weighted evaluation indices and the data on environmental changes near the foundation pit [1-6]. Based on computer aided design (CAD) [7] designed a foundation pit monitoring system that dynamically reflects the state and problems of the project.

In a metro station, the foundation pit excavation brings the following adverse impacts to the surrounding environment: (1) The cracking, tilting and even collapse of the surface buildings; (2) The damages of roads and facilities; (3) The rupturing of underground pipelines [8-10]. The risks induced by different kind of impacts should be managed and controlled by different types of models. For example, the collapse risk is often mitigated by an uncertain risk analysis system, which couples fuzzy comprehensive evaluation (FCE) and Bayesian network (BN) [11].

Taking building information modelling (BIM) as the risk identification platform, Ganbat et al. [12] set up a mechanism that can identify the risks accurately and timely in the early stage of construction. With the aid of engineering software [13-15] simulated how excavating deep foundation pit disturbs the soil and affects the displacement of underground pipelines, and introduced additional reinforcement to the hazardous areas [16, 17] regarded tunneling risk as the equivalent of excavating risk of foundation pit, designed reinforcement measures against instability and deformation, and successfully applied the measures in metro station construction.

In addition, the FCE results on the safety of buildings near deep foundation pits [18] are widely used in engineering. Instead of using two adjacent fuzzy evaluation levels, Bureika et al. [19] effectively evaluated the risks by cross-utilizing two or more adjacent levels, providing a good solution to the excavating risks of largescale foundation pits, Zhu and Chen [20] introduced the deformation coordination theory to the numerical calculation of foundation pit excavation. Apart from technical measures, De Graaf and Wessels [21] comprehensively managed the excavating risks of foundation pit from the angles of economy and education. Most of the above results are about the risk management, safety techniques, and management models for the damages to the foundation pit, the surface, and facilities, as well as the rupture of underground pipelines.

Overall, there are not many reports on the safety assessment and analysis of how the construction of new metro station impacts existing buildings, leaving an ample room to improve the relevant assessment and analysis methods [22, 23]. With the boom of metro construction in Chinese cities, it is imperative to mitigate the impacts of metro construction on the existing buildings. Targeting the phase 2 project of State Academic Mariinsky Theatre in Saint-Petersburg (SAMT-2), Benin et al. [24] investigated the deformations of foundation pit support and load-bearing structure and the yield of nearby buildings during soil excavation and each stage of substructure construction, kicking off the safety assessment of construction impacts on existing buildings.

Focusing on a foundation pit project in Hefei Metro, this paper explores how foundation pit excavation affects the settlement of a nearby building, from the aspects of field testing, numerical calculation, and foundation pit support plan. The numerical results were effectively combined with the observed deformation of building foundation, and used to finalize the foundation pit construction plan, with the aim to guarantee building safety. The research results provide an important reference for structural safety assessment on the buildings near the metro station or along the metro line before the construction of metro station, and offer a good guidance for safety assessment and evaluation of risk projects in the design phase.

The remainder of this paper is organized as follows: Section 2 specifies the contents of the safety assessment; Section 3 introduces the current state of the target metro station; Section 4 assess and predicts the safety of the nearby building; Section 5 puts forward the conclusions.

2. CONTENTS OF SAFETY ASSESSMENT

The safety assessment mainly covers the following contents:

(1) Working state of the foundation;

(2) Current state of a nearby building;

(3) Dimensions of building structural members;

(4) Appearance, surface crack distribution, strength and carbonation depth of concrete;

(5) Inclination of the main structure, the relative settlement difference of the pile foundation, etc.;

(6) Structural safety of the building;

(7) Residual deformation capacity of the building;

(8) Impacts of the deep foundation pit construction on the building.

3. CURRENT STATE OF THE METRO STATION

3.1 Overview

The metro station is located near the intersection of Changfeng South Road and Changjiang West Road. The nearby plots are mainly used for education, scientific research, commerce, finance, residence, and public greens. On the south of the station are Jinjiang Building and the Dormitory Building of Anhui Provincial National Tax Bureau. Both buildings are right on the boundary line of roads. On the north of the station are the Office Building of Anhui Provincial Environmental Protection Bureau, and the Office Building of the Exchange Center, Anhui Agricultural University (under construction).

The main structure of the station is a two-story, two-span reinforced concrete frame. The station has a total length of 193.0m, and a relatively large difference in surface elevation: the surface elevations of the upline and downline ends differ by about 3.76m. The roof of the hall layer is partly raised to maintain a sufficiently thick overburden. In the standard section, the station is 20.7m-thick, the overburden is 3.0-3.76m-thick, and the floor is 17.7-20.4m in burial depth. There is a 24.6m-wide shaft at the eastern and western ends. The shaft at the upline end has a 3.76m-thick overburden and a 20.4m-deep floor, while that at the downline end has a 3.0m-thick overburden and a 17.9m-deep floor.

The station has a total of 5 entrances/exits. Among them, entrance/exit 2 is adjacent to Jinjiang Building. Covering 40,000m^2, the building (length: 61,100mm; width: 36,800mm) has a frame-supported shear wall structure, with 2 floors underground and 32 floors aboveground. Completed in 2003, the building has been in service for 17 years. The minimum horizontal clear distance between entrance/exit 2 and Jinjiang Building is about 1.7m. Figure 1 shows the relative positions between the building and the deep foundation pit of the station. Figure 2 illustrates the current state of the building façade. The underpass from the station hall to entrance/exit 2 is excavated underground. The foundation pit of the hall and the foundation trench of the entrance/exit are supported during the excavation.

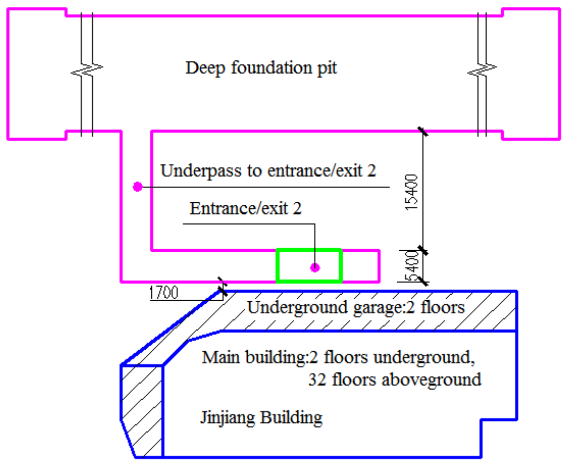


Figure 1. Relative positions of between the building and the deep foundation pit of the station

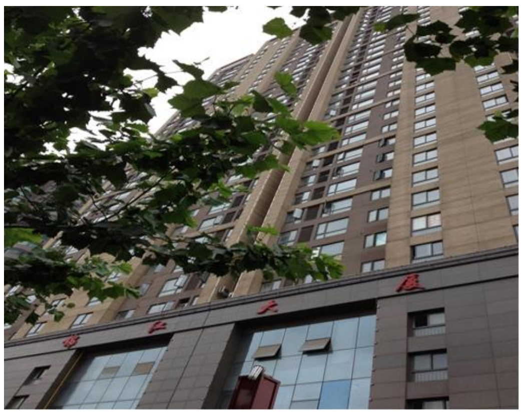


Figure 2. Façade of Jinjiang Building

3.2 Survey and assessment of the current state of the building

3.2.1 Foundation testing

The substructure survey shows that the building foundation had a good bearing capacity. There was no superstructure reaction (local subsidence, cracking and tilting) to foundation deformation. The foundation was working in good condition.

3.2.2 Superstructure testing

Through field survey, no obvious cracks or other abnormal deformations, which are induced by load or deformation factors, was observed on the load-bearing members; no obvious appearance defect was found on the load-bearing components.

3.2.3 Settlement and residual deformations of the pile foundations of the building

According to the type of building and the deformation control standard, the deformation measuring points were arranged on pile foundations (as shown in Figure 3).

The deformations of pile foundations were measured with a Leica TCR1202 total station. Based on the measurements and the original deformation observation records of the building, the relative settlements, the authors calculated the settlement deformations and residual deformations between pile foundations in the horizontal and lateral directions (Tables 1-2) before the construction of the foundation pit in the station and the foundation trench at entrance/exit 2 (hereinafter referred to as pre-construction). The relative settlement Δ (mm) between pile foundations can be computed by:

$$\Delta = H - H_1 \tag{1}$$

where, H and H_1 are the design elevation and actual elevation of a measuring point, respectively (mm).

As shown in Table 1, the pre-construction relative settlement between pile foundations peaked at 20mm, where the two pile foundations were 29.3m apart; in the longitudinal direction, the maximum and minimum settlement deformations were 1.25‰L and 0.23‰L, respectively.

As shown in Table 2, the pre-construction relative settlement between pile foundations also peaked at 10mm, where the two pile foundations were 10.7m apart; in the lateral direction, the maximum and minimum settlement deformations were 0.93‰L and 0.94‰L, respectively.

The above results show that the building suffered varied degrees of settlements between pile foundations. Before the construction, the settlement difference between pile foundations maximized at 1.25‰L and minimized at 0.04‰L. Both values are within the range (2‰L) allowed in *Technical Code for Building Pile Foundations* (JGJ 94-2008). In addition, the residual deformations of the pile foundations in the building concentrated in 0.75‰L-1.96‰L.

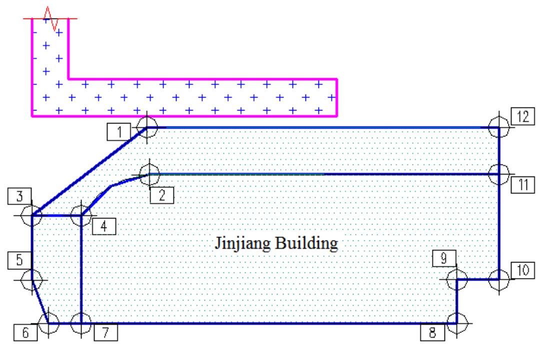


Figure 3. Arrangement of deformation measuring points on pile foundations

Table 1. Pre-construction settlement deformations and residual deformations between two pile foundations in horizontal direction

No. of measuring point	Relative settlement between pile foundations (mm)	Settlement difference (mm)	Spacing between pile foundations (m)	Settlement deformation	Allowable settlement deformation	Residual deformation
1 2	24 12	12	14.3	0.84‰L		1.16‰L
3 5	25 10	15	22.5	0.67‰L		1.33‰L
4 7	28 8	20	29.3	0.68‰L	2.0‰L (L is the spacing between pile foundations.)	1.32‰L
8 9	0 13	13	11.6	1.12‰L		0.88‰L
10 11	3 10	7	30.6	0.23‰L		1.77‰L
11 12	10 29	19	15.2	1.25‰L		0.75‰L

Table 2. Pre-construction settlement deformations and residual deformations between two pile foundations in lateral direction

No. of measuring point	Relative settlement between pile foundations (mm)	Settlement difference (mm)	Spacing between pile foundations (m)	Settlement deformation	Allowable settlement deformation	Residual deformation
1 12	24 29	5	45.6	0.11‰L		1.89‰L
2 11	12 10	2	49.3	0.04‰L		1.96‰L
3 4	25 28	3	12.6	0.24‰L	2.0‰L (L is the spacing between pile foundations.)	1.76‰L
6 7	3 8	5	9.4	0.53‰L		1.47‰L
7 8	8 0	8	51.3	0.16‰L		1.84‰L
9 10	13 3	10	10.7	0.93‰L		1.07‰L

4. SAFETY EVALUATION AND PREDICTION OF THE NEARBY BUILDING

4.1 Calculation model

Our calculation model was established on the finite-difference software: Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D). As shown in Figures 4 and 5, the model (X×Y×Z=441.6m×211m×50m) consisting of 335,708 hexahedral units. The unit size in the model is transitioned reasonably to mirror the impacts of excavation disturbance on the foundation.

The building foundation was simulated by changing the parameters of the equivalent layer. The building was simulated by imposing an evenly distributed load on the foundation. The cast-in-place bored piles, i.e. the envelope of the station, were treated as a thin wall with equivalent bending stiffness.

The constraints are as follows: The soil mass was constrained in horizontal X-direction on the left and right sides, in horizontal Y-direction on the front and rear ends, in vertical direction at the bottom, and free on the top surface.

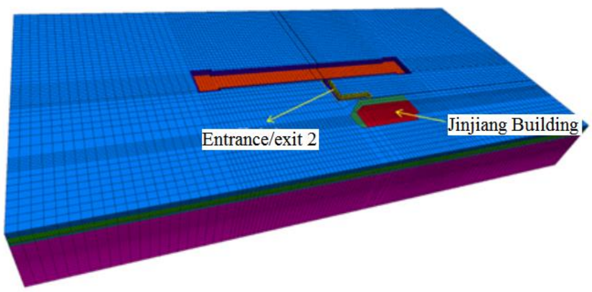


Figure 4. Relative positions between metro station and the building

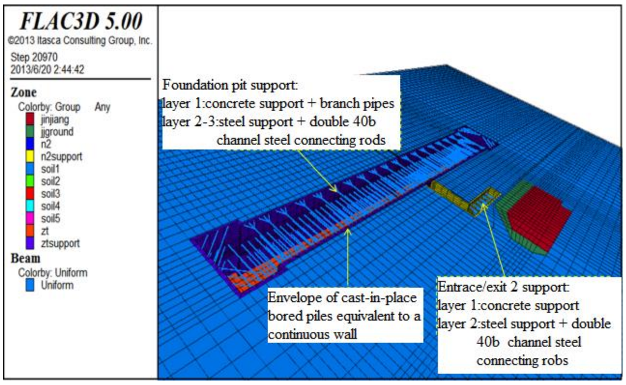


Figure 5. Envelope and internal support structure

4.2 Constitutive model and calculation parameters

The earthwork excavation was simulated with the zero model. The soil mass was assumed to obey the Mohr-Coulomb criterion. The physical-mechanical parameters of the rock and soil in each soil layer were obtained from the geotechnical survey report (Table 3).

For the C30 concrete in the retaining piles, the elastic modulus, Poisson's ratio, and bulk density were empirically set to 25GPa, 0.20, and 25kN/m^3, respectively. The steel support was simulated as linear elastic rods with an elastic modulus of 200GPa, and a Poisson's ratio of 0.26. The other parameters of foundation pit support and internal support are given in Table 4.

The bulk density, bulk modulus, and shear modulus of the building foundation were 25kN/m^3, 6e^{3}MPa, and 4e^{3}MPa, respectively. During the excavation of foundation pit, there is no need for dewatering, because the groundwater is deep at the station. Hence, the effects of groundwater on the envelope deformation were neglected.

Table 3. Stratum parameters

Name of rock and soil	Soil state	Bulk density γ kN/m^3	Shear strength (direct shear) Cohesion C kPa	Internal friction angle φ °	Modulus of deformation E_0 MPa	Poisson's ratio υ	Static lateral pressure coefficient ξ
<3-1> Artificial fill	/	18.50	16	12.0	2.2	0.39	0.64
<3-1> Clay	Plastic	19.40	25	9.0	6.5	0.34	0.52
<3-2> Clay	Hard plastic	19.50	45	11.0	10.0	0.32	0.47
<10-1> Fully weathered argillaceous sandstone	Hard plastic to hard	19.80	32	12.0	32.0	0.30	0.43
<10-2> Strongly weathered argillaceous sandstone	/	21.20	120	25.0	45.0	0.22	0.28
<10-3> Moderately weathered argillaceous sandstone	/	23.20	140	30.0	108.0	0.21	0.27

Table 4. Parameters of internal support

Type of support	Specification	Moment of inertia Ix/m^4	Moment of inertia Ix/m^4	Polar moment of inertia Ip/m^4
First lateral support	800×1000/mm	6.6667E-02	4.2667E-02	1.0933E-01
Second to fourth lateral supports	800×800/mm	3.4133E-02	3.4133E-02	6.8267E-02
Branch pipes or connecting rods	600×800/mm	1.4400E-02	2.5600E-02	4.0000E-02
Steel pipe lateral support	φ609-16	1.3112E-03	1.3112E-03	2.6223E-03
Double channel steel pipes	40b	3.7280E-04	2.2720E-05	3.9552E-04

4.3 Results and analysis

According to the construction procedure, foundation pit excavation was divided into eight key processes: Simulation of initial geo-stress; envelope construction; excavation of the first soil layer; setting up the concrete support of the first layer; excavation of the second soil layer; setting up the steel support of the second layer; (the following layers can be excavated and supported in the same manner)… setting up the steel support of the fourth layer and excavating to the base; removal of the bottom layer of steel support.

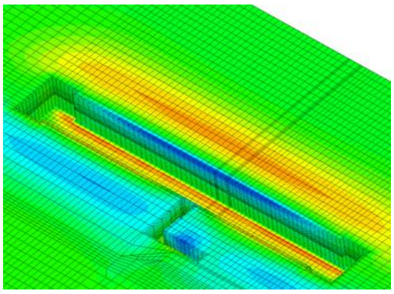
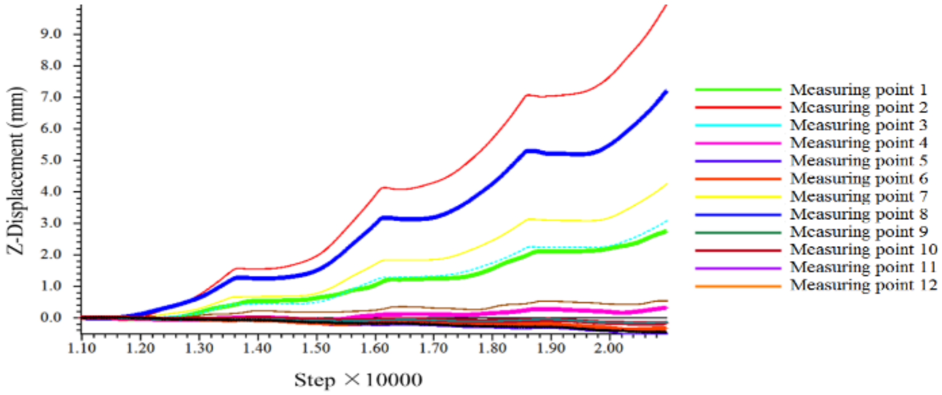


Figure 6. Cloud map of settlements of the foundation pit, the building and the surface

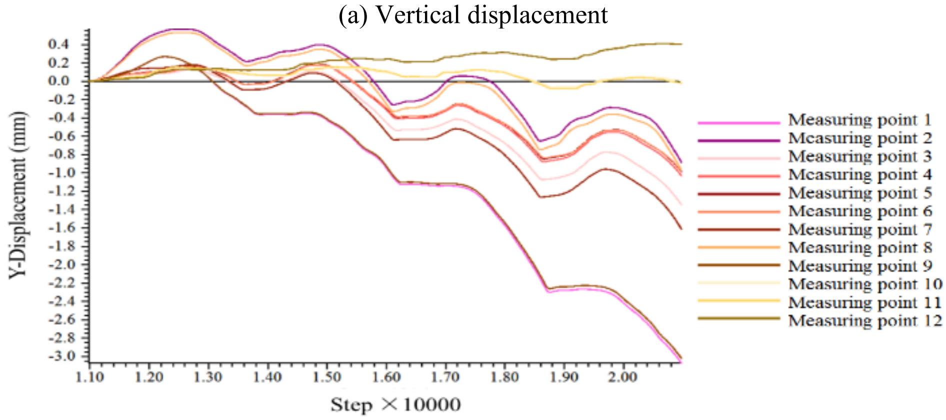
Figure 6 presents the calculated settlements of the foundation pit, the building and the surface. It can be seen that the settlement mainly occurred around the foundation pit, and no deformation was observed outside a certain distance from the pit.

To disclose the impacts of foundation pit excavation on the nearby building, a total of 12 settlement measuring points was arranged on the building foundation (Figure 3). The displacement of each point in the excavation process is recorded in Figure 7.

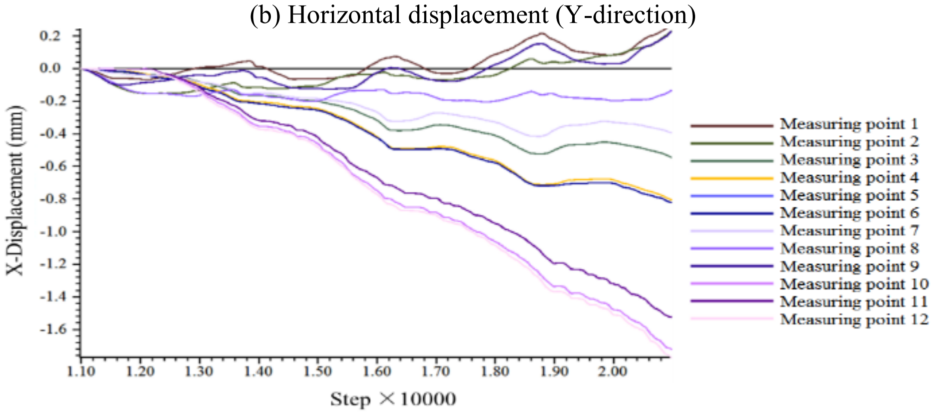
As shown in Figure 7, the deformation field of the near buildings is affected by the excavation of the foundation pit. The greater the excavation depth, the more obvious the deformation of the building. The building deformation mainly exhibited as vertical settlement and moving towards the foundation pit. When the deep foundation pit was excavated to the bottom, the building displacement peaked at 10.0mm. The peak displacement points upward, belonging to rebound displacement. At some measuring points, the vertical displacements point downward, belonging to settlement. But the settlement was very small (<1.0mm).



(a) Vertical displacement



(b) Horizontal displacement (Y-direction)



(c) Horizontal displacement (X-direction)

Figure 7. Displacement of each measuring point in the excavation process

4.4 Safety assessment

To evaluate the building safety during the excavation of deep foundation point, the relative settlements of each measuring point before construction and during construction were measured, and the settlement difference was calculated. On this basis, the post-construction relative settlements and settlement differences between the pile foundations in the horizontal and lateral directions were obtained (Table 5 and Table 6).

As shown in Table 5, the post-construction relative settlement between pile foundations peaked at 24.59mm; in the longitudinal direction, the maximum and minimum settlement deformations were 1.40‰L and 0.79‰L, respectively; As shown in Table 6, the post-construction relative settlement between pile foundations also peaked at 10.02mm; in the lateral direction, the maximum and minimum settlement deformations were 0.94‰L and 0.05‰L, respectively.

Considering the building deformation before and during the excavation of deep foundation pit, the settlement difference between pile foundations maximized at 1.40‰L and minimized at 0.05‰L. Both values are within the range (2‰L) allowed in *Code for Design of Building Foundation* (GB50007-2011). Hence, our foundation pit support plan and construction plan ensure the normal use and safe operation of the building.

Table 5. Post-construction settlement differences between pile foundations in horizontal direction

No. of measuring point	Relative settlement between pile foundations (mm)	Settlement difference (mm)	Spacing between pile foundations (m)	Settlement deformation	Allowable settlement deformation	Residual deformation
1 2	33.97 19.21	14.76	14.3	1.03‰L	2.0‰L (L is the spacing between pile foundations.)	0.97‰L
3 5	28.08 10.33	17.75	22.5	0.79‰L		1.21‰L
4 7	32.25 7.66	24.59	29.3	0.84‰L		1.16‰L
8 9	-0.46 12.86	8.12	11.6	1.15‰L		0.85‰L
10 11	2.84 10.54	7.70	30.6	0.25‰L		1.75‰L
11 12	10.54 31.75	21.21	15.2	1.40‰L		0.60‰L

Table 6. Post-construction settlement differences between pile foundations in lateral direction

No. of measuring point	Relative settlement between pile foundations (mm)	Settlement difference (mm)	Spacing between pile foundations (m)	Settlement deformation	Allowable settlement deformation	Residual deformation
1 12	33.97 31.75	2.22	45.6	0.05‰L	2.0‰L (L is the spacing between pile foundations.)	1.85‰L
2 11	19.21 10.54	8.67	49.3	0.18‰L		1.82‰L
3 4	28.08 32.25	4.17	12.6	0.33‰L		1.67‰L
6 7	2.49 7.66	5.17	9.4	0.55‰L		1.45‰L
7 8	7.66 -0.46	8.12	51.3	0.16‰L		1.84‰L
9 10	12.86 2.84	10.02	10.7	0.94‰L		1.06‰L

5. CONCLUSIONS

According to the building safety assessment standard, this paper firstly evaluates the current state of a building near the target metro station. Based on FLAC3D, a 3D mechanical model was established, and used to calculate the impacts of the foundation pit excavation on the nearby building. The safety and residual deformation capacity of the building were judged, in the light of the construction method and construction parameters. The main conclusions are as follows:

(1) Through current state analysis and numerical calculation, it is learned that, before and through the construction of the deep foundation pit, the settlement difference between pile foundations of the building maximized at 1.40‰L and minimized at 0.05‰L. Neither values surpassed the upper limit (2‰L) for the settlement difference between pile foundations of similar buildings in the national standard. This means our foundation pit support plan and construction plan ensure the normal use and safe operation of the building.

(2) The safety state of the nearby building under the effect of foundation pit construction can be evaluated in advance through the current state analysis and numerical calculation of the building. This assessment approach is simple and reliable, providing a good reference for similar projects.

(3) According to the results of safety assessment, the design company and construction company can decide whether to modify the design parameters or adjust construction techniques, such that the nearby buildings could be used normally and operated safety during the construction of the deep foundation pit at the metro station.

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