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J. Jia
Architectural Design & Research Institute of Tongji University, Shanghai, China

J. H. Wang
Shanghai Jiaotong University, Shanghai, China

C. P. Liu
Shanghai Jiaotong University, Shanghai, China

L. L. Zhang
Shanghai Jiaotong University, Shanghai, China

X. L. Xie
Shanghai Jiaotong University, Shanghai, China

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BEHAVIOR OF AN EXCAVATION ADJACENT TO A HISTORICAL BUILDING AND METRO TUNNELS IN SHANGHAI SOFT CLAYS

J. Jia
Architectural Design & Research Institute of Tongji University
1239 Si Ping Road, Shanghai, P. R. China

J.H. Wang, C.P. Liu, L.L. Zhang and X.L. Xie
Civil Engineering Department, Shanghai Jiaotong University
1954 Hua Shan Road, Shanghai, China

ABSTRACT

In this paper, a case history of a deep excavation in Shanghai, which was adjacent to a historical building founded on 27 m long wooden piles and operating Metro tunnels, is presented. The effects of the excavation on the nearby pile foundation and the existing tunnels are investigated using two-dimensional finite element modeling. The predicted maximum horizontal and vertical displacements of the wooden piles are 15.8 mm and 7.6 mm, respectively. The horizontal and vertical movements of the utility tunnel and Metro tunnel are all less than 10 mm, which satisfies the current design criteria for controlling the deformation of the Metro tunnels in Shanghai. The results indicate that the design and construction measures of this excavation can effectively limit the deformation of the soils and therefore the impact of the excavation on the adjacent piles and the tunnels can be reduced to an acceptable level. The field monitoring results show that the maximum wall deflection near the historical building was 23 mm. At the site boundary near the tunnels, the maximum displacement of the walls was 30.7 mm. The earth pressures and pore water pressure at the active side were reduced gradually during the excavation.

INTRODUCTION

To meet the increasing demand for economic growth, extensive underground structures have been rapidly constructed in the urban area of Shanghai. Some of them are very close to existing metro tunnels, underground facilities and sensitive structures. The safety of the adjacent metro tunnels, underground facilities and surrounding structures may be significantly affected by the ground movement induced by the construction of excavation if no appropriate construction measures are provided.

Hu et al. (2003) presented the design and construction for a deep excavation located above and beside the Shanghai Metro tunnels. The paper discussed the design criteria and measures for controlling the soil and tunnel deformation. It was concluded that it is very important to adopt deformation control based design and construction measures. In their study, a finite element

In this paper, a case study of a deep excavation in the urban area of Shanghai is presented. The site is the site of the New Yi Bai Commercial Center (Fig. 1) which is located in the Nanjing Road Commercial Zone of Shanghai. In the south of the site, there was a historical building which is founded on 27 m long wooden piles. The minimum distance between the diaphragm wall of the excavation and the historical building is only about 4 m. An underground power line tunnel with a diameter of 3.2 m and two 6.2 m diameter metro tunnels of Line No. 8 are in the west side of the excavation. The minimum distance between the excavation and the power line tunnel is 5.6 m. In this study, two-dimensional finite element analyses are conducted to investigate the effects of the excavation on the pile foundation of the historical building and the existing tunnels and predict the movement of the pile foundation and tunnels.

In order to verify design assumptions and to reduce risk during the construction of underground structures, field monitoring is normally adopted to provide immediate feedback to designers during construction (Ng 1998, Ou et al. 1998). In this case history, a comprehensive field monitoring system was installed in the site. In this paper, the observed performance of the diaphragm walls and the measured lateral earth pressure and pore water pressures along the excavation boundaries which are adjacent to the historical buildings and the existing tunnels are presented.

DESIGN AND CONSTRUCTION MEASURES

The site of the New Yi Bai Commercial Center is approximately rectangular in shape as shown in Fig. 1.

According to the site investigation result, the site is underlain by silty clay, clay and silty sand deposits. Table 1 presents the thickness and basic geotechnical parameters of the soil layers.

The maximum depth of the most part of the site was 15.9 m while in the south part of the site the maximum excavation depth was 18.7 m. In the south of the site, there was a historical building, which is founded on 27 m long wooden piles (Fig. 2). A diaphragm wall was constructed prior to excavation and used together with horizontal struts as the earth-retaining structure. The diaphragm wall along the south site boundary was 1.2 m thick and 40 m deep. Along the western site boundary, the diaphragm wall was 1.0 m thick and 31.5 m (Fig. 3). To minimize the impact of ground movement due to excavation to the historical building and the existing Metro tunnels and utility tunnel, a 850mm thick soil mixing wall (SMW) was constructed along the south and western boundaries. The SMW wall was formed by three independent rotary drives drilling and pushing the mixing tool into the ground and mixing the self-hardening slurry which is continuously injected through the drill stem with the native soils in-situ. As the distance between the diaphragm wall and the historical building was only 4 m, a jet grout pile wall was constructed before the SMW wall to further reduce the soil deformation around the wooden piles (Fig. 2). To reduce the ground movement and wall deflection due to excavation, the soils within the excavation zone were improved with jet grouting. The excavation was completely using the bottom-up construction method in five stages (Table 2).

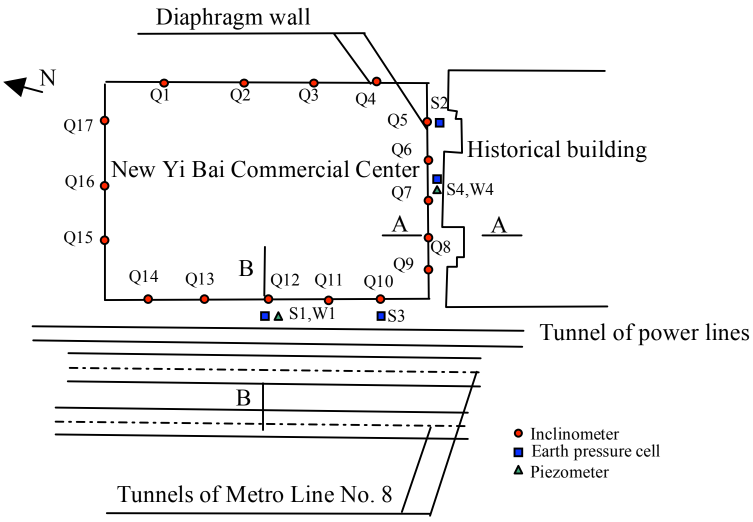

Fig. 1. Location of the site and instrumentation plan.

A comprehensive monitoring system was installed on this site. Various monitoring instruments such as inclinometers in the wall and soil, earth pressure cells on the wall, piezometers, rebar stress meters and settlement gauges, were installed. In Fig. 1, only the locations of the inclinometers in the wall, the earth pressure cells and the piezometers are illustrated. Totally, thirty-two earth pressure cells and sixteen piezometers were installed at various depths of four locations outside of the diaphragm walls.

Table 1. Geological descriptions and properties of the soils at the site of New Yi Bai Commercial Center

Soil layer no.	Soil classification	Thickness (m)	γ (kN/m^3)	c (kPa)	ϕ (°)
①	Fill	2.5-5.5			
③	Soft silty clay	4.5-7.5	17.6	13.0	16.5
④	Soft clay	6.0-7.0	16.8	14.0	10.5
⑤$_{1-1}$	Silty clay	9.8-11.9	17.8	16.0	16.5
⑤$_{1-2}$	Silty clay	9.2-12.0	18.0	19.0	19.0
⑥	Silty clay	2.0-4.4	19.7	47.0	18.0
⑦	Silty sand	8.0-14.0	19.1	3.0	34.5

Table 2. Construction sequence of the excavation

Stage	Construction activities
1	Construct diaphragm wall and pile foundation, ground improvement
2	Excavate to elevation of -2.7 m, install 1st level of RC strut,
3	Excavate to elevation of -7.6 m, install 2nd level of RC strut,
4	Excavate to elevation of -12.4 m, install 3rd level of RC strut
5	Excavate to elevation of -15.9 m, construct bottom slab
6	Install steel struts in the south of the site
7	Excavate to elevation of -18.7 m in the south of the site
8	Construct bottom slab in the south of the site

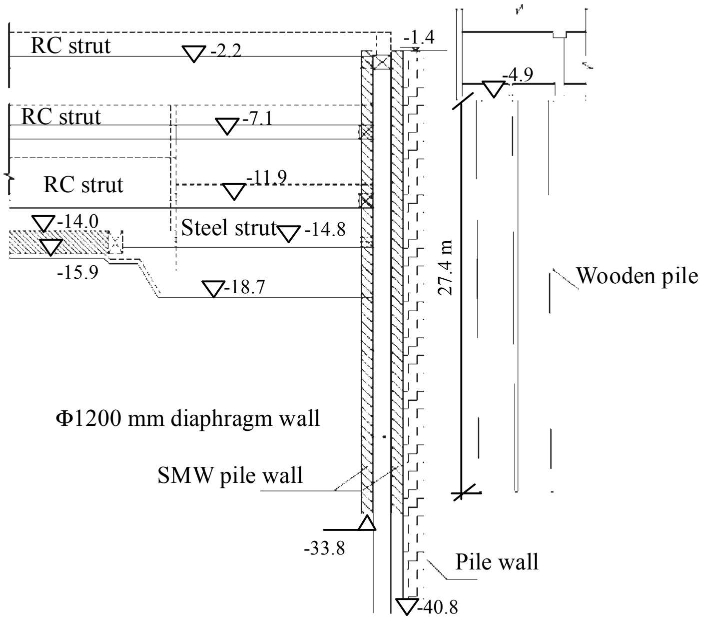

Fig. 2. Cross section A-A (elevations in meters).

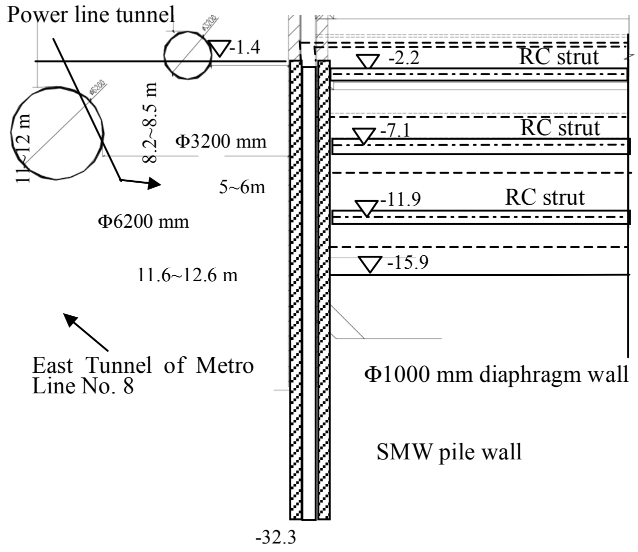

Fig. 3. Cross section B-B (elevations in meters).

FINITE ELEMENT MODELING

It was important to effectively and accurately predict the displacements induced in the soils by the deep excavation for the operation of the tunnels and the stability and integrity of the historical building. Accordingly, in design stage, two-dimensional finite element analyses are conducted to investigate the impact of the excavation on the pile foundation of the adjacent historical building and the tunnels.

Figure 4 presents the finite element mesh for cross-section A-A. The model of the soils is Mohr-Coulomb model. The structure and foundation piles of the historical building and the diaphragm walls are modeled using beam elements.

Figure 5 shows the displacement vectors in soils when the excavation depth reaches the design bottom level. As shown in the graph, the soils outside of the excavation move inward to the excavation while the soils at the bottom of the excavation move upwards. The maximum soil displacement is 37 mm.

Figure 6 illustrates the horizontal displacement of the wooden piles at stage 7. It can be seen that the first three piles (Pile no. 1 to 4) which are close to the excavation move towards the excavation due to excavation. The maximum horizontal displacement of the piles is 15.8 mm, which occurred in Pile no. 1 at the depth of around the bottom of the excavation. For piles no. 5 to 8, the maximum horizontal displacement occurs at the top of the pile because the movements of these piles are mainly induced by the horizontal movement of the ground slab of the building basement.

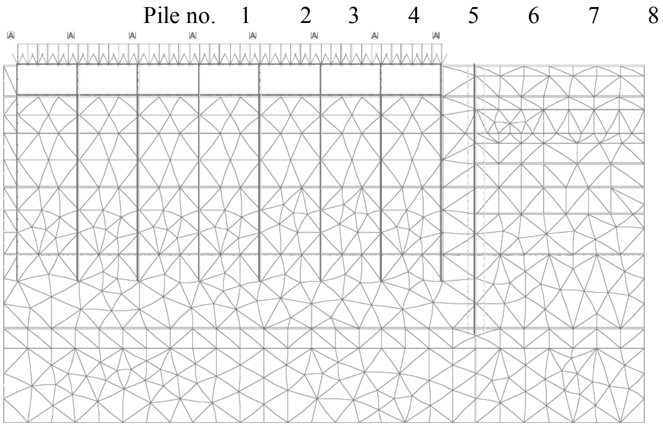

Fig. 4. 2-D Finite element mesh (cross-section A-A).

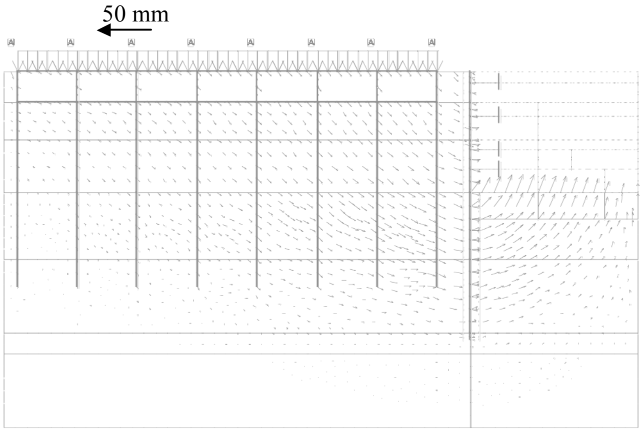

Fig. 5. Displacement vectors at stage 7 (cross-section A-A).

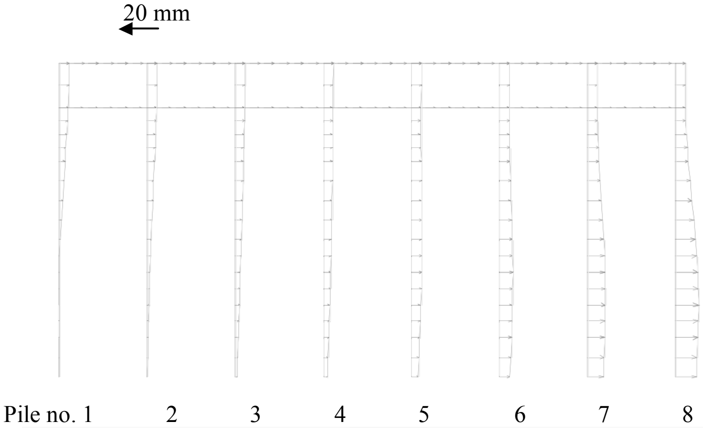

Fig. 6. Horizontal displacement of wooden piles of the historical building at stage 7.

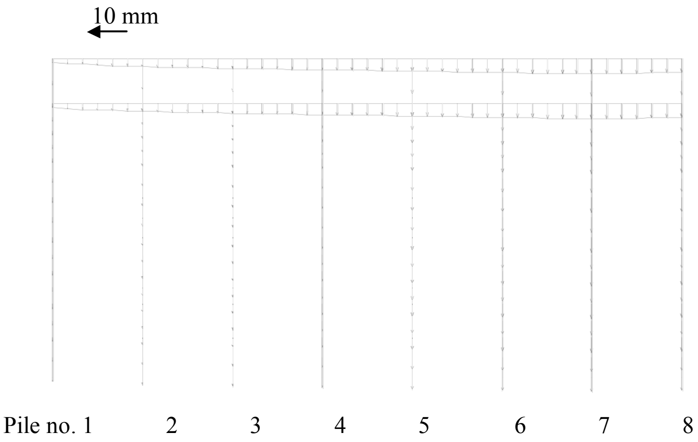

Fig. 7. Vertical displacement of wooden piles of the historical building at stage 7.

Table 3. Maximum calculated displacements of the historical building (unit: mm)

	Horizontal	Vertical
Ground slab	8.6	7.3
Wooden piles	15.8	7.6

Figure 7 presents the vertical displacement of the pile foundation at stage 7. According to Fig. 7, the vertical movement of the foundation piles and the ground slab are mainly settlement. The maximum settlements of the ground slab and wooden piles are less than 10 mm. Table 3 summarizes the maximum displacements of the wooden piles and the ground slab of the historical building.

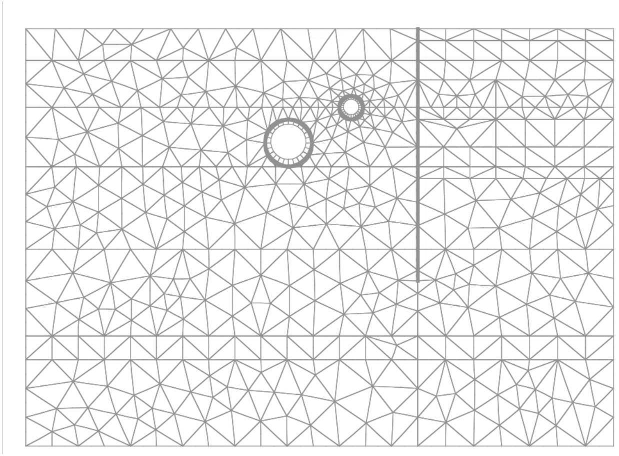

Fig. 8. 2-D Finite element mesh (cross-section B-B).

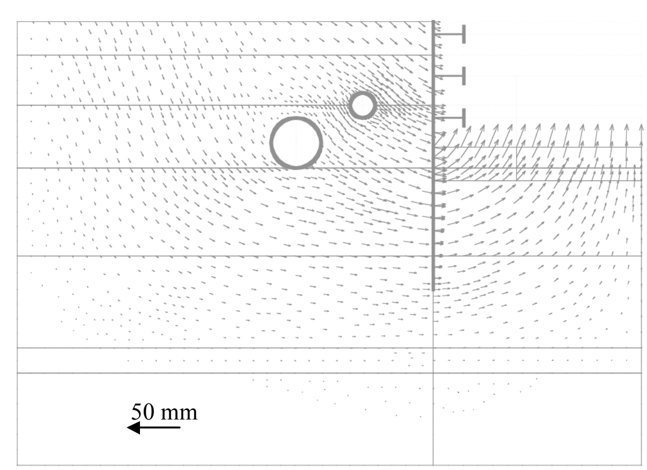

Fig. 9. Displacement vectors at stage 7 (cross-section B-B).

Table 4. Maximum calculated displacements of tunnels (unit: mm)

	Horizontal	Vertical
Tunnel of power lines	6.6	5.5
Metro tunnels	6.4	3.8

Figure 8 shows the 2-D finite element mesh of the numerical modeling for cross-section B-B. The soil models are Mohr-Coulomb models with the same parameters as those in the previous numerical modeling. The metro tunnel and the utility tunnel are modeled using beam elements.

Figure 9 illustrates the total displacement vector plot in the soils at stage 7. The maximum displacement of the soils is 29.4 mm. The maximum displacement of the two tunnels are listed in Table 4. According to the numerical modeling results, the maximum calculated displacements of the metro tunnel are 6.4 mm in horizontal direction and 3.8 mm in vertical direction, which are less than the deformation control limit of Shanghai Metro tunnels, i.e., 20 mm. These results illustrate that the design and construction measures effectively limit the deformation of the soils and walls and therefore the influence of the excavation on the adjacent historical building and the tunnels can be reduced to an acceptable level.

FIELD MONITORED RESULTS

Figure 10 presents the measured wall deflections at different construction stages by the inclinometer Q7 which was installed in the diaphragm wall near the historical building. When the excavation depth was 7.6 m and the second level of RC struts was constructed, the deflection of the wall at Q7 was still almost zero. It was because the jet grout pile wall, the SMW piles and the diaphragm wall (Fig. 2) worked together to restrict ground movement and wall deflection towards the excavation. At subsequent stages, the wall deflection increased. The maximum wall deformation for each stage occurred near the excavation surface. When the south part of the site was excavated down to the depth of 18.7 m, the maximum wall deflection was about 23 mm. Compared with the calculated ground movement by finite element modeling (Fig. 5), the actual displacements of the wall and soils are slightly smaller than the predicted values.

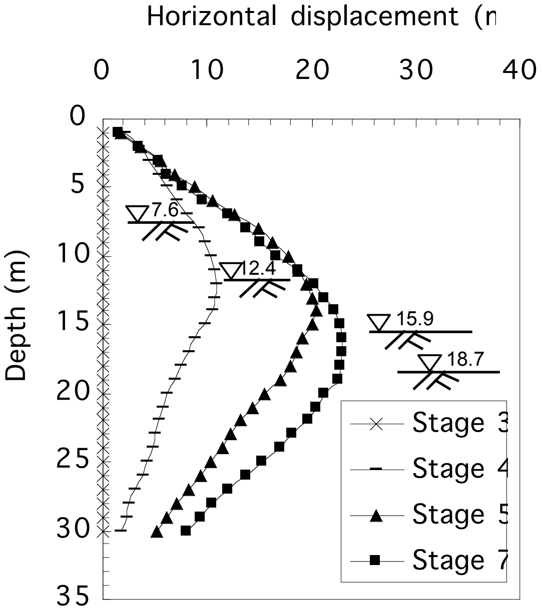

Fig. 10. Horizontal wall displacement at inclinometer Q7.

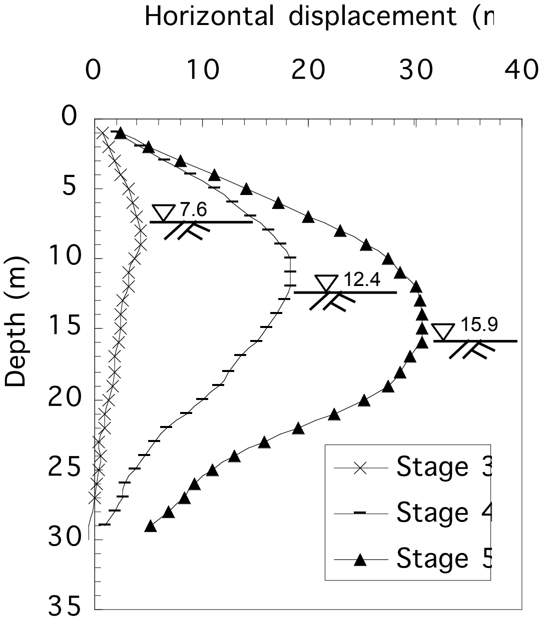

Fig. 11. Horizontal wall displacement at inclinometer Q12.

Figure 11 shows the measured horizontal wall displacement by the inclinometer Q12 which was installed in the diaphragm wall near the Metro tunnels and the utility tunnel. As indicated in the figure, the maximum wall deflection was about 4 mm at stage 3. At stage 4 (excavation depth = 12.4 m), the wall deflection became more pronounced than stage 3. The maximum wall deflection was increased to 18.3 mm. When the excavation was conducted to the final level, the maximum wall deflection was 30.7 mm. Compared with the result in Fig. 10, the wall deflection at Q12 was greater than that at Q7 although the excavation depth was smaller. The reason of this is that the diaphragm wall at Q7 is thicker and an extra jet grout pile wall was installed between the diaphragm wall and the historical building.

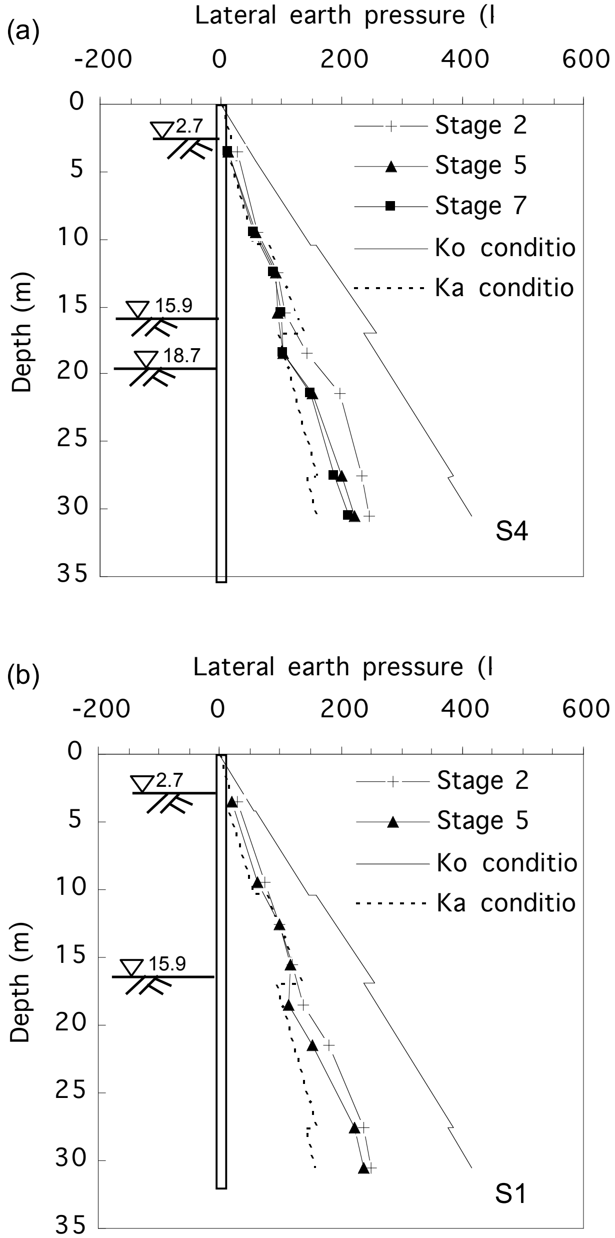

Fig. 12. Observed lateral earth pressures vs. theoretical earth pressures at (a) S4 and (b) S1.

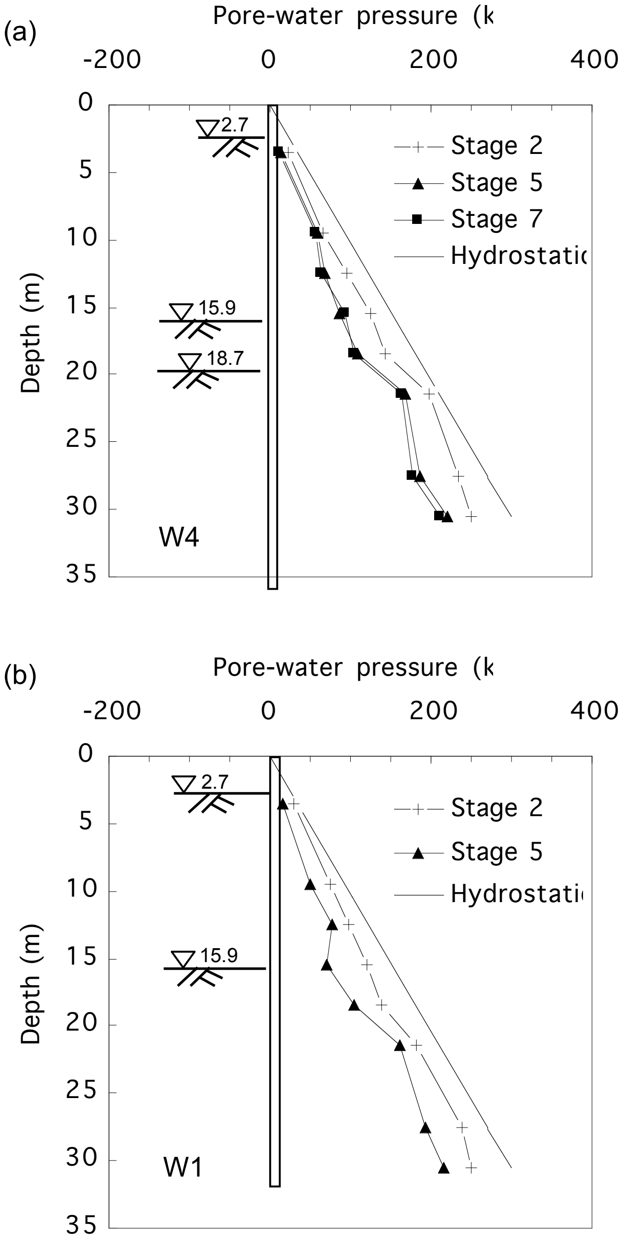

Fig. 13. Observed pore-water pressures at (a) W4 and (b) W1.

The total lateral earth pressures and pore-water pressures acting on the unexcavated side of the diaphragm wall were obtained by the earth pressure cells and piezometers.

Figure 12 illustrates the measured lateral earth pressures for stages 2, 5 and 7 by the earth pressure cells installed at S1 and S4. Compared with the theoretical total lateral earth pressure at rest (K_0 condition), the measured initial earth pressure at stage 2 (excavation depth = 2.7 m) was much smaller. The lateral total earth pressure decreased with excavation depth. However, the amount of the reduction of lateral earth pressures during the excavation was not significant. At shallow depth of soils, the measured earth pressure was slightly smaller than the calculated active earth pressure. For soils at deeper levels, the lateral earth pressure was still greater than the theoretical Rankie active earth pressure when the site was excavated to the bottom excavation level.

Figure 13 presents the measured pore-water pressures measured by piezometers installed in the soils on the unexcavated side. As shown in the graph, the observed pore-water pressure at stage 2 was close to the hydrostatic pore-water pressure. The pore-water pressure decreased gradually with the increase of the excavation depth.

CONCLUSIONS

In this paper, the case history of the deep excavation of New Yi Bai Commercial Center is presented. To predict the displacements induced in the soils by the deep excavation and evaluate the impact on the adjacent tunnels and the historical building, two-dimensional finite element analyses were conducted. According to the numerical results, the maximum horizontal and vertical displacements of the wooden piles are 15.8 mm and 7.6 mm, respectively. The horizontal and vertical movements of the utility tunnel and Metro tunnel are all less than 10 mm, which satisfies the current design control criteria in Shanghai.

The field monitoring results show that the maximum wall deflection near the historical building was 23 mm. At the site boundary near the tunnels, the maximum displacement of the walls was 30.7 mm. It was also observed that the earth pressures and pore water pressure at the active side were reduced gradually during the excavation.

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