Design and Behavior of A Deep Excavation Adjacent to Existing Buildings and Tunnels

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ABSTRACT: An excavation, 19.8m deep with an area of 20000m^2, was constructed near existing historic buildings and tunnels in Shanghai. The excavation was supported by diaphragm walls and five levels of reinforced concrete struts. In order to minimize the influences of excavation on the buildings and tunnels, the soil at the excavated side was improved by the deep mixing method and excavated using zoned excavation technique subsequently. Moreover, underpinning piles were introduced to reinforce the historic building while a row of bored piles was constructed between the excavation and tunnels. To verify the proposed design measures, extensive instruments were installed to investigate the performance of the excavation. The field observations showed that the maximum settlement of the historic building was 30 mm during excavation. The largest tunnel heave was 15.5 mm which was less than the regulation of 20 mm in Shanghai. The design measures adopted proved to be effective in protecting existing buildings and tunnels adjacent to the excavation.

1 INTRODUCTION

With increasing infrastructure construction in urban areas, there has been increased concerns regarding the influence of deep excavations on adjacent buildings, tunnels and other underground structures (Ou et al., 2000, Huang et al., 2011). A four-story basement for a tall building was constructed in the bund area located in Huangpu district in downtown Shanghai. Fig.1 shows the plan view of the site. The construction of the basement involved an excavation of 20000m^2 in area and 19.8m in depth supported by diaphragm walls.

As the site is located in downtown area, the environments in the proximity of the excavation are complicated. There are three buildings, i.e., main building, south building and north building, which were built in 1906 and have been preserved as historical buildings on the northeast of the excavation. The main building is a 5-story composite structure, made of brick, wood, steel and reinforced concrete, founded on isolated reinforced concrete footing. The south and north buildings are 4-story reinforce concrete structure and 5-story steel and concrete composite structure, respectively. Both are founded on isolated reinforced concrete footings as well. The closest distance from the excavation to the buildings is only 3.0m.

On the south of the excavation is Renmin Road tunnel which runs across Huangpu River underneath connecting Pudong and Puxi areas. The 11.36m diameter tunnels constructed by using the shield tunneling method are lined by reinforced concrete segments. The two tunnels are 6.7m apart and embedded about 14m to 22m below the ground surface. As shown in Fig.1, the closest distance between the excavation and the tunnels is 9m. Moreover, there are bund tunnels and a lot of pipelines around the excavation. But the details of the bund tunnels and pipelines are not reported due to the limited paper length.

This paper firstly describes the design considerations of the excavation. Subsequently, measures taken in an attempt to mitigate the influence of excavation-induced movements on adjacent buildings and tunnels are reported. Finally, field observations on the performance of the excavation and the responses of adjacent buildings and tunnels are presented.

2 DESIGN OF THE EXCAVATION

2.1 *Geological conditions*

The top two layers at this site are fill and silty clay followed by a 14.5m-thick soft clay layer, which has relatively high water content and void ratio, but low shear strength. Underneath the soft clay layer are a 3m-thick firm clay layer and a 30m-thick stiff silty clay layer. The fine sand layer (Aquifer I), is located about 51m below ground. The water table is located at 0.5m below ground surface. Geotechnical parameters for soil strata at varied depths are summarized in Table 1.

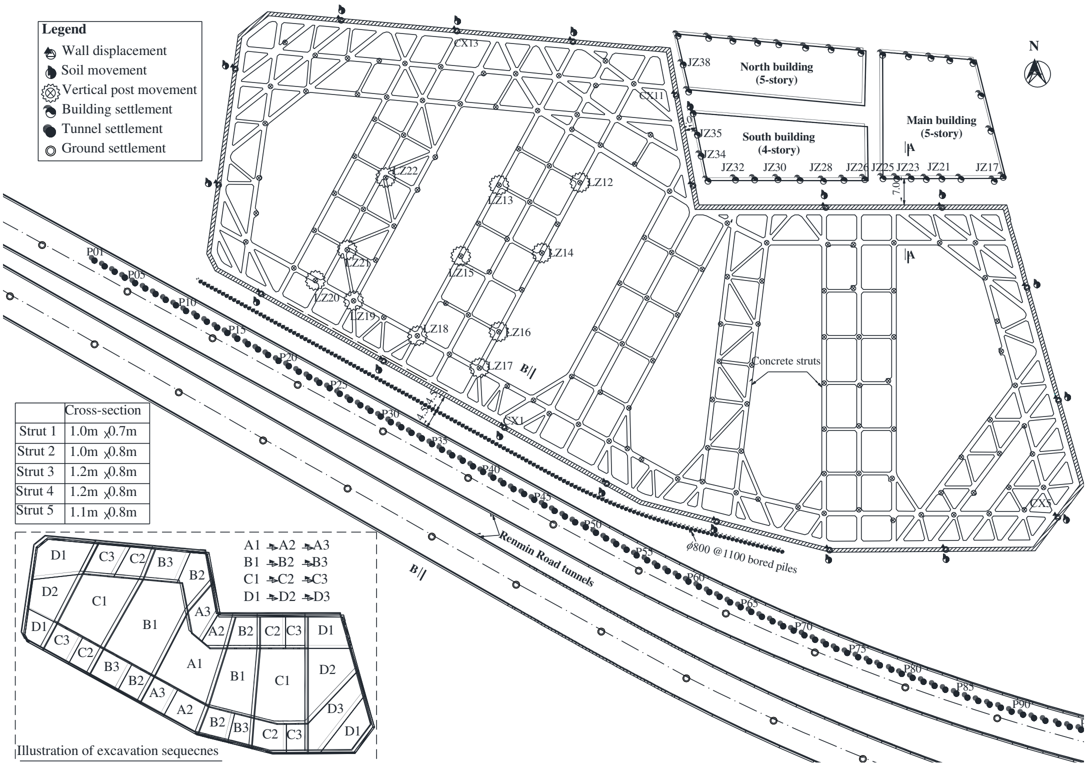

Fig. 1 Plan view of the site and monitoring layout

Table 1. Geotechnical parameters (h-thickness; γ-unit weight; c-cohesion; φ-fiction angle; k_V, k_H-vertical and horizontal permeability)

Stratum	h	γ	c^*	φ^*	k_V	k_H
	(m)	(kN/m^3)	(kPa)	(°)	10^{-9}m/s	
Fill	2.7	-	-	-	-	-
Silty clay	1.3	18.2	16	18	1.0	1.5
Soft (silty) clay	1.6	17.5	11	17	2.6	3.1
	1.6	18.5	5	31	486	996
	2.4	17.5	11	17	2.6	3.1
	8.9	16.8	11	12	0.8	1.0
Firm clay	3.0	17.5	13	14	0.9	1.3
Stiff silty clay	8.8	18.0	15	18.5	2.0	2.7
	16.5	18.1	13	22.5	1.9	2.5
	3.3	19.6	39	21.5	1.0	1.2
Fine sand	5.0	18.9	3	34.5	2930	4150

Note:* c, φ obtained from direct shear tests

2.2 *Design considerations*

As the environments around the excavation were complicated, 1000mm-thick diaphragm walls which were supported by five levels of concrete struts were adopted for most areas. The dimensions of each strut are given in Fig. 1. The first level of struts used C30 concrete whose 28-day compressive strength was 14.3MPa. For the rest struts, C40 concrete of compressive strength of 19.1Mpa was adopted. The embedded depth of the diaphragm wall varied from 18.0m to 34.0m along the perimeter of the excavation depending on both geological conditions and adjacent environments to be protected. The diaphragm wall used in the project is referred to as "dual-purpose diaphragm wall" which serves as a retaining wall during the excavation period and the exterior wall of the basement after construction as well. Two rows of mixed-in-place piles were constructed along the either side of the diaphragm wall to reduce the influence of wall construction on adjacent environments. Besides, soil at the excavated side as shown in Figs 2 and 3 was improved by deep mixing method.

In order to protect the historical buildings, the diaphragm wall near the buildings was increased to 1200mm thick. In addition, all the three buildings were reinforced by underpinning. As shown in Fig. 2, the underpins were 30m long steel encased concrete piles with a diameter of 219mm. To reduce the influence of excavation-induced soil movement on Renmin Road tunnels, a contiguous pile wall which consist of 800mm diameter bored piles at 1100mm centers was constructed in the middle of the excavation and the tunnel (see Fig. 3).

2.3 *Construction sequences and instrumentation*

The excavation was made by the bottom-up method using the zoned excavation technique. The soil in middle of the excavation, i.e., Zone A, is first removed followed by Zones B to D in sequence. For each zone, soil is excavated in numerical order (see the inset of Fig. 1). Principal construction activities are summarized in Table 2 which only includes activities for excavation work.

To verify the design assumptions, and to monitor the performance of the excavation, a number of instruments were installed. The layout of the monitoring points is shown in Fig. 1. Lateral wall displacements were measured by using inclinometers. The precise leveling method was adopted to measure settlements of center post and ground

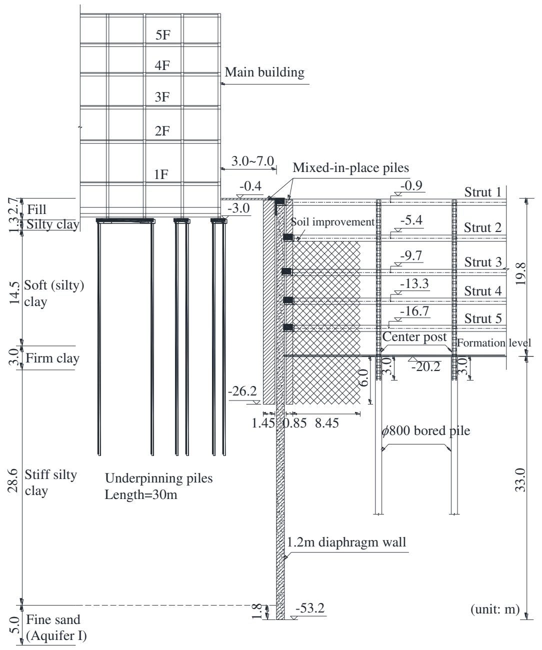

Fig. 2 Relationship between excavation and adjacent historical buildings (cross-section A-A)

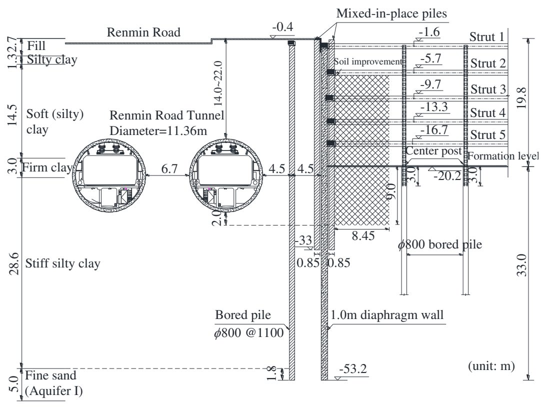

Fig. 3 Relationship between excavation and adjacent tunnels (cross-section B-B)

Table 2. Construction sequences during excavation

Stage	Construction activities
0	Construct diaphragm walls and piles
1	Excavate to -2.2m* and cast strut 1 (-1.6m)
2	Excavate to -6.3m and cast strut 2 (-5.7m)
3	Excavate to -10.3m and cast strut 3 (-9.7m)
4	Excavate to -13.9m and cast strut 4 (-13.3)
5	Excavate to -17.3m and cast strut 5 (-16.7m)
6	Excavate to formation level (-20.2m) and cast bottom slab

* Relative elevation to the roof of basement

settlements directly above the centerlines of Renmin Road tunnels. The tunnel settlement was recorded by an automatic monitoring system. In this paper, only the observed results of the labeled monitoring points are presented.

3 PERFORMANCE OF THE EXCAVATION AND AJACENT BUILDINGS AND TUNNELS

3.1 *Lateral wall displacements*

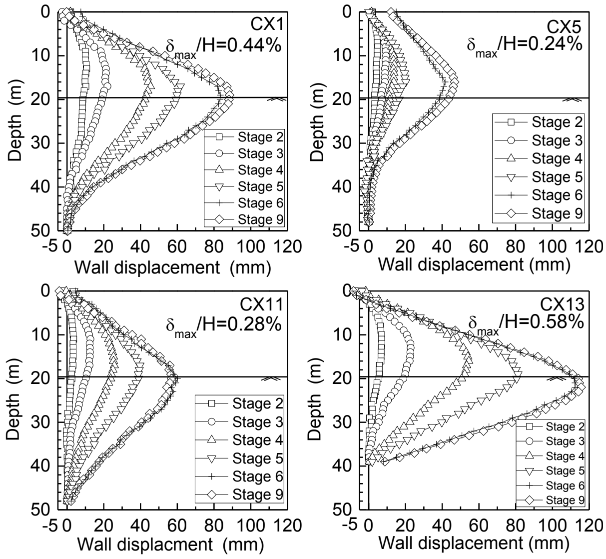

Fig. 4 Lateral wall displacements

Fig. 4 shows the lateral wall displacements behind the wall at each stage. The measured data at Stage 9 when the second level underground floor slab was constructed is also included for comparison. Before the bottom slab being cast, the lateral wall displacements increased significantly as the excavation proceeded. The wall deformed in a deep-seated profile and the maximum wall displacement occurred near the formation level. Once the bottom slab was completed, additional lateral wall displacements were negligible or even reduced. As shown in this figure, the maximum wall displacements δ_{max} fall in the range of 0.24%H~0.58%H (H is excavation depth) which are comparable to the measurements from various similar excavations in Shanghai (Wang et al., 2010). The lateral wall displacement at CX5 is smallest due to corner effects. Since diaphragm walls at CX11 are 1200mm thick and offered relatively stiffer supports, the measured wall displacements are smaller than those at points CX1 and CX13 where 1000mm-thick walls were used.

3.2 *Heave of center posts*

As soil was removed, stress relief resulting in ground heave and hence the center post began to heave consequently. As shown in Fig. 5, each center post seems to heave at an almost constant rate during excavation period. It is different from the observation by Liu et al. (2011) who found that the rate of post heave increased when the excavation was approaching the formation level. One possible reason may be attributed to the difference in geometries of these two excavations. The maximum heave was about 55mm. It worth noting that the construction of bottom slabs may be able to prevent further heave of center posts in such a large excavation.

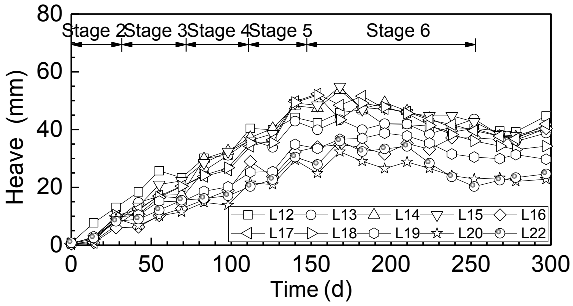

Fig. 5 Heave of center posts

3.3 *Building settlements*

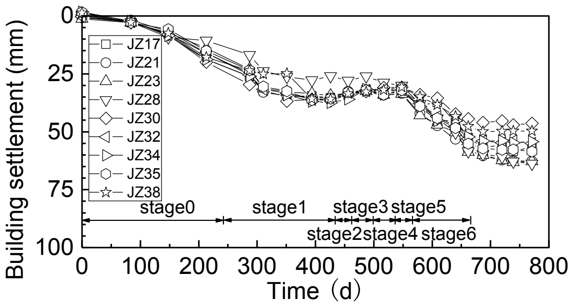

Fig. 6 Development of building settlements

Fig. 6 shows the building settlements with time. It should be pointed out that the historical buildings were not underpinned in the period of stage 0 when diaphragm walls and piles were constructed. Therefore, the unreinforced buildings were weak and the settlements caused by the construction of diaphragm walls were roughly 30mm. After completion of underpinning work, some additional settlement of around 30mm occurred as the excavation proceeded. It is found that the buildings settled significantly between stages 5 and 6. This may be caused by a large reduction on shaft frictions of the underpinning piles. No obvious structural damages were found for the buildings during excavation period.

3.4 *Tunnel displacement*

Fig.7 shows the development of tunnel displacements with time. Since P05 is beyond the excavation while P90 is 42m away from the excavation, the tunnel displacements due to excavation were less than 3mm at the two locations. For other locations, the tunnel continued to heave during the principal excavation period (stages 2-6). It is postulated that the ground heave due to stress relief was dominant in the period and soil took the tunnel to move upward together. The maximum tunnel heave was 15.5mm which was less than the limit of 20mm in Shanghai.

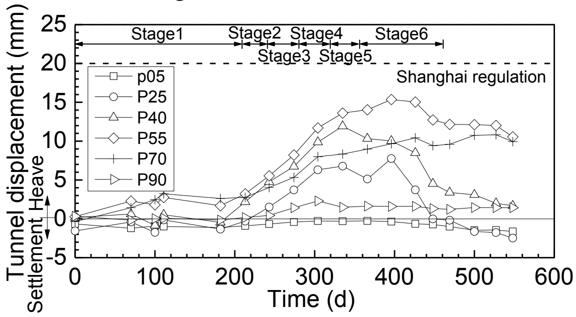

Fig. 7 Development of tunnel settlement with time

4 CONLCUSIONS

A deep and large braced excavation in proximity to existing historical buildings and tunnels was constructed in downtown Shanghai. To reduce the influence of the excavation, the buildings were underpinned by steel encased concrete piles while a contiguous pile wall was introduced between the excavation and the tunnels. The field observations show the underpinned buildings only settled 30mm and no obvious structural damages were found during the main excavation period. Although the diaphragm walls deflected up to 80mm, the adjacent tunnels only moved 15.5mm upwards within the limit of 20mm. The measures taken in this project proved to be effective in protecting buildings and tunnels near a similar excavation in Shanghai

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