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Performance of a deep excavation in soft clay

G.B. Liu & J. Jiang
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, P.R. China
Department of Geotechnical Engineering, Tongji University, Shanghai, P.R. China.

C.W.W. Ng
Department of Civil Engineering, the Hong Kong University of Science and Technology, HKSAR

ABSTRACT: The observed response of diaphragm wall and the surface settlement of a deep excavation for a metro station in Shanghai soft clay are presented, compared with the similar excavations (retained by a diaphragm wall) in soft clay areas in Asia and five metro station excavations (similar depth) in Shanghai. Results show that the maximum lateral wall deflection (δ_{hm}) and ground settlement (δ_{vm}) are 0.32% and 0.1% of final excavation depth (H_e), respectively. Lateral wall deflections are near the average magnitude value in Shanghai, smaller than those in Singapore. The largest lateral wall deflection is near the excavation center and the ratio of $\delta_{hmcor}/\delta_{hmcen}$ of the maximum wall deflection is 0.39–0.74. The ground settlement is relatively small and falls in the Zone I limit described by Peck (1969). The adoption of prestressed steel struts, short excavation sections, fast workmanship sequences and compaction grouting may contribute to the deformation characteristics of deep excavations for metro stations in Shanghai.

1 GENERAL INSTRUCTIONS

Excavations for metro stations are in general deep, long and narrow, and located in urban environments. In Shanghai, China, some metro lines have been built and several lines are under construction or planned, to cross the large and congested city. Thick soft-to-medium alluvial and marine deposit strata exist in this area. Under such circumstances, movement control, rather than stability at the deep excavation site becomes the governing factor for design and construction (Liu & Hou 1997).

Research shows that field monitoring and performance analysis are essential to deep excavations in soft soils. Monitoring the field performance of the excavation and the magnitude of movements in the surrounding soil (Peck 1969; O'Rourke 1976; Clough et al.1989) along with estimating the effects of such movements and field performance on adjacent structures (Burland & Wroth 1974, Boscardin & Cording 1979) are important to design engineers. The observed performance of deep excavations and case histories are very useful to verify design assumptions and reduce the construction risk in the excavation process (Whittle et al. 1993; Ng 1998, Ou 1998, Long 2001, Finno & Bryson 2005, 2007, Leung & Ng 2007).

The observed responses of diaphragm walls and the ground surface of a deep multistrutted metro station excavation in Shanghai soft clay are presented here. Diaphragm wall deformations and ground movements are compared with some case histories in Shanghai and excavations in soft clay in other locations in Asia. From the measured data in this study, some recognition of the characteristics of deep excavations can be obtained and can offer references for back analysis and case studies.

2 SITE CONDITION

2.1 *Introduction*

Shanghai is located in the front fringe of the Yangtze River Delta in China. The Da Muqiao excavation is situated in the southwest of Shanghai and there is an interchange for two lines, Metro 4 and Metro 9. The site plan is shown in Figure 1. Note that the excavation width is variable.

The site crosses two roads, Da Muqiao Road and Ling Ling Road. The shadowed area in Figure 1 shows the interchange excavation (35 m × 25 m × 20.7 m), in the shape of "cross". The excavation depth is 3.8 m deeper than the excavation depth in other parts (16.9 m). There are several concrete, three-story to six-story buildings along the sides of the excavation.

Figure 2 shows a cross section of section 1-1 of the interchange part (INP); including the support system,

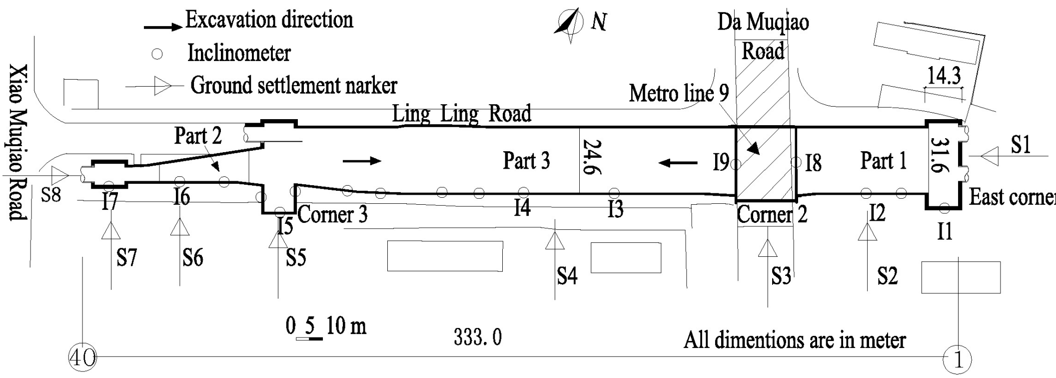

Figure 1. Site plan of the metro station and excavation direction.

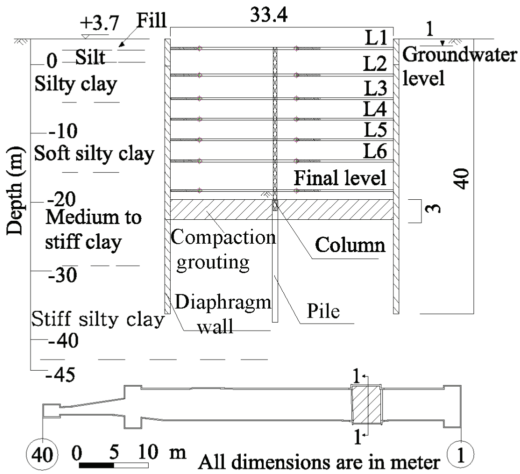

Figure 2. Cross section of the INP (Section 1-1).

the strut level and excavation depth. The concrete diaphragm wall for the INP is 40 m deep and 0.8 m thick; the 16.9 m deep excavation is retained by a 34 m deep and 0.8 m thick perimeter concrete diaphragm wall. The ground level of the site is 3.75 m above the Shanghai City Datum (SCD). There is 3 meter compaction grouting below the final excavation to increase that soil strength in this part. Six steel struts were used at the INP in vertical plane while there were five steel strut levels in other excavation parts. All struts are steel tubes and the first one has a 580 mm diameter and other ones are 609 mm in diameter and are 16 mm thick. Two steeltubes (12.45 m) were inter-joined to form the struts (24.6 m). The struts have a 3 m lateral spacing. The specific installment of struts was described by Wang (2005).

2.2 *Geology*

The strata of Shanghai are thick soft soils comprising Quaternary alluvial and marine deposits. A high water

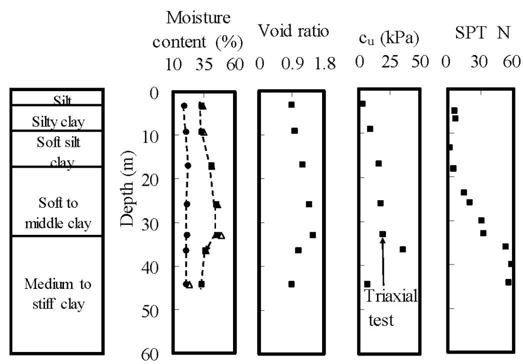

Figure 3. A typical soil profile and soil parameters.

content, low shear strength, high compressibility and low ground bearing capacity are typical characteristics of the soft soil in Shanghai.

The ground is underlain by relative soft to medium–soft marine deposits, which generally consist of uniform bedding planes. A typical soil profile from up to down obtained during site investigation is shown in Figure 3. The top layer is artificial fill, 1.6 m in thickness. About 45 m thick clay underlies the fill. The inside of the excavation is among the clay, which is a quaternary alluvial and marine deposit. In general, groundwater conditions are approximately hydrostatic 1.0 m below ground level.

3 CONSTRUCTION PROCEDURE OF THE EXCAVATION

From installing the diaphragm wall to the completion of casing the bottom slab, the working period is divided into eight main construction stages, listed in Table 1. The excavation depth of the INP is 3.8 m deeper than other parts (see Figure 2) so there is one more excavation stage indicated by italics Table 1.

Table 1. Summary of the main construction.

Stage (1)	Construction operation (2)	Day (3)
1	Construction of diaphragm wall	81
2	Construction of bored pile	116
3	Reduce level dig to L1 & installation of L1 strut	122
4	Excavation to L2 & installation of L2 strut	129
5	Excavation to L3 & installation of L3 strut	136
6	Excavation to L4 & installation of L4 strut	143
7	Excavation to L5 & installation of L5 strut	151
8	Excavation to L6 & casting bottom slab	160
9	Excavation to L7 & casting the bottom slab	168

The excavation of this long metro station was divided into several short sections in the horizon plane. Note that the excavation was from the two short sides to the middle part. The INP and the east part were synchronously excavated, indicated as Part 1. Part 2 was at the west end and was excavated one month after Part 1 was started. After finishing these two excavations, Part 3 was excavated from both ends. A short section of soil excavation was adopted in Part 3 also. Each excavation depth was dug to 0.3 m below the strut level to offer space for installing the struts.

4 INSTRUMENTATION

Inclinometer tubes were fixed to the steel reinforcement cages and concreted in the retaining walls. The casing was installed with a pair of grooves oriented in the expected direction of movement. To avoid twisting of the casing, the grooves were checked before installment to ensure that their twist angle was no more than 0.1%. The casing was fixed tightly to the steel cages of the retaining wall. The groove direction was checked again after lowering the cages into the bentonite. The twist angles of the grooves were measured after the concreting. The allowable value of each twist angle was 0.2%. Probes with a resolution of 0.02 mm/50 mm and temperature of $-20°$ to $+50°$ were used in the inclination monitoring.

Ground surface settlement monitoring markers were located on the sides of the excavation. The markers were located about 1.5–35 m perpendicularly away from wall at each rectangular box station and were secured 0.5 m below the ground surface. The section settlements were monitored with a leveling instrument with a stated accuracy of 0.5 mm/km.

5 OBSERVED WALL DEFLECTION

5.1 *Lateral diaphragm wall deflection*

Along the south side of this deep and long excavation, seventeen inclinometers were placed to monitor the lateral wall deflection. Only nine of these inclinometers are pictured, as I1 to I9, in Figure 1, representing three typical locations of the diaphragm walls. (1) Inclinometers I1, I2, I5, I6 and I7 were at or near the corners; (2) Inclinometers I3 and I4 were at the centers of the excavation; (3) Inclinometers I8 and I9 were set for the INP. These nine inclinometers measured the data that are analyzed here for lateral wall deflection.

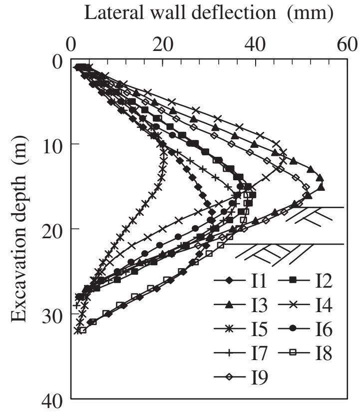

Figure 4. Maximum lateral wall deflection at the final excavation depth.

Figure 4 shows the lateral wall deflection at I1 to I9 at the end of the final excavation (Stage 8). The upper final excavation depth is that of the general part while the lower one is that of the INP. As indicated in this figure, the profiles of lateral wall deflection at the inclinometers are similar but with different deformation magnitudes.

The lateral wall deflection of type (1) is smaller than type (2). This finding shows that wall deflections were affected by the stiffness of the corners. The maximum wall deflection of this deep excavation was at the center of excavation I3, with a value of 54.5 mm; while the minimum wall deflection was at I5, with a value of 20.2 mm. I5 is at Corner 3 and the excavation width on the west side (see Figure 1) is significantly shorter than that on east side. This varied excavation width may contribute to the smallest wall deflection at I5.

The lateral wall deflection of type (3) (INP) is between type (1) and type (2). The maximum values for I8 and I9 were 38.2 mm and 51.0 mm, respectively. Note that the locations of all lateral wall deflections were above the final excavation level.

5.2 *Relationship between maximum lateral wall deflection and excavation depth*

Lectures on lateral retaining wall deflection caused by deep excavations in Asian soft clay were reported by some researchers (Ou et al. 1993, 1998, Wong et al. 1996, Tamano et al. 1996, Lee et al. 1998, Wang et al.

Table 2. Summary of the six metro excavations.

Name	H_e (m)	Strut No.	K_s	FOS_{base}	δ_{hm}/H_e (%)
Pudian	16.3	4	626.4	2.58	0.42
Yangshupu	16.5	4	626.4	2.59	0.57
Pudongdao	16.5	4	626.4	2.61	0.15
Luban	18.2	5	777.6	2.35	0.40
Pudong	17.3	5	1101.6	2.53	0.28
Damuqiao	16.9	5	1414.3	2.43	0.32

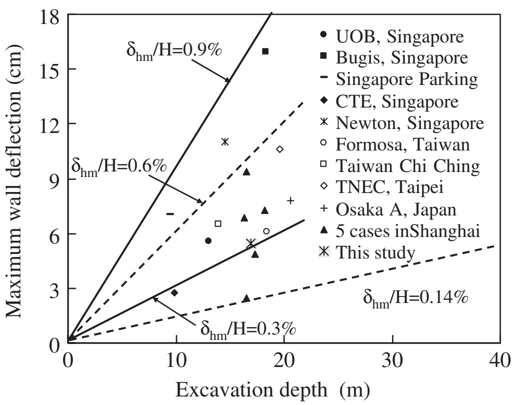

Figure 5. Relationship of the maximum lateral wall deflection to the excavation depth.

2005, Wallace, 1992, Hulme et al. 1989,) Figure 5 shows the measured lateral wall deflection compared to the excavation depth of this deep excavation. Data of five other deep excavations in Shanghai (listed in Table 2.) and several excavations in Taiwan, Japan and Singapore soft clay are plotted in Figure 5 for comparison. Note that all the excavations were in soft clay and the retaining walls were all diaphragm walls.

Figure 5 shows that the magnitude of the maximum wall deflection in Shanghai soft clay is smaller than that in Singapore soft clay while it is similar to that in Taiwan and Japan soft clay. The ratio of δ_{hm}/H_e in metro excavations in Shanghai is between 0.14%–0.6%, while that in Singapore is between 0.3%–0.9%, and that in Taipei and Japan is in 0.3%–0.6%. The ratio of δ_{hm}/H_e in this study is 0.32%. A comparison of geotechnical parameters of the soil in Shanghai clay and Taiwan clay shows that undrained strength and water content are similar, but the average measured deflections in the Shanghai soil were smaller than in the Taiwan soft soil. The use of the multistrutted support system, the prestressed steel struts, the short excavation sections and the fast workmanship sequences in Shanghai probably account for these differences.

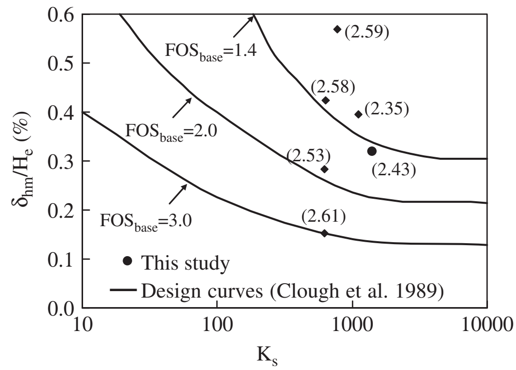

Figure 6. Normalized lateral wall deflection (δ_{hm}/H_e) versus system stiffness (K_s).

5.3 *Effect of the stiffness of the support system on the maximum wall deflection*

The effect of the stiffness (K_S) of the support system on lateral wall movement was proposed by Clough et al. (1989). K_S is expressed as follows:

$$K_S = \frac{E_W I}{\gamma_W h^4} \tag{1}$$

where E_W is the Young's modulus of the wall; I is the second moment of the area of the wall section, $I = t^3/12$, t is the wall thickness; h is the average vertical prop spacing of the multistrutted support system and γ_W is the unit weight of water.

Figure 6 shows the normalized lateral wall deflection of the long excavation in the chart as suggested by Clough et al. (1990). Another five metro excavations with the same retaining wall type and support system in Shanghai with excavation depths from 16.3 m to 18.2 m, are chosen for comparison. A summary of these metro excavations is listed in Table 2. The retaining structures of all these excavations were 0.8 m width diaphragm walls and the value of E_W was 30 kN/mm^2. This form by Clough (1990) is for excavation in soft-to-medium clay to account for system stiffness and FOS_{base}. The value of FOS_{base} is calculated by the definition proposed by Clough et al. (1989).

The K_s value ranges from 626.4 to 1414.3 and the ratio of δ_{hm}/H_e varies from 0.15 to 0.57 with the value of FOS_{base} from 2.35 to 2.61. However, for a given K_s, there is a relatively scatter in δ_{hm}/H_e values, there may be no very strong correlation between measured δ_{hm}/H_e and K_s value. It can be seen that measured lateral wall deflection decreases with increasing FOS_{base}. With similar system stiffness, the larger value of FOS_{base} the smaller the ratio of δ_{hm}/H_e. And the measured data do not seem to correspond very well with the design curves. The suggested chart only could give

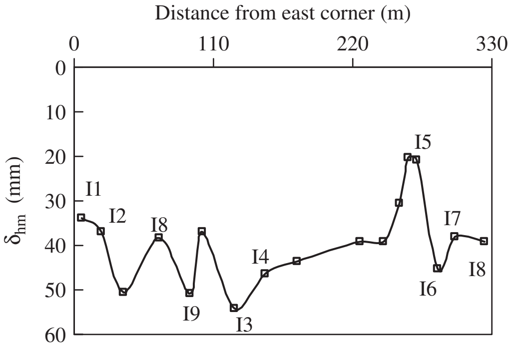

Figure 7. Maximum lateral wall deflection versus.

preliminary predictions of wall movement in six metro excavations in Shanghai.

5.4 *Three-dimensional deformation of excavation*

Researches on three-dimensional responses of excavations by measured data or finite analysis (Bono et al.1992, Ou et al. 1993, Wong 1993, 1996, Lee et al. 1998, Finno et al. 2007) showed that ratios of $\delta_{corner}/\delta_{center}$ in deeper excavations are smaller in general. Figure 7 shows the measured maximum lateral wall deflection (δ_{hm}) at the end of the final excavation in this study. The lateral wall deflection at and near the center of the excavation is larger than the wall deflection near or at the corners, which means that the stiffening effect of the corners affected the deformation of the diaphragm walls. Note that the reduced lateral wall deflection at I5 is significant. The ratio of each maximum wall deflection to the maximum wall defection at the center, $\delta_{hmcor}/\delta_{hmcen}$, of the wall was 0.39–0.74.

6 SURFACE SETTLEMENTS

In some cases, settlement was measured after the starting of construction of the diaphragm wall; some were measured at different times. Making consistent comparisons is therefore difficult. In this study, the settlement of the ground surface during and after the final excavation was measured.

Eight groups of ground settlements were measured along one of the long sides (south side) and two ends of the excavation (see Figure 1). All data were selected from one side of the site. Figure 8 shows the relation of the maximum surface settlements to the distance from the diaphragm walls at the final excavation depth of this study.

In comparison with surface settlements in Singapore and Taiwan soft clay, the measured data in this deep excavation fell into a relatively small range, despite the weak ground conditions in Shanghai.

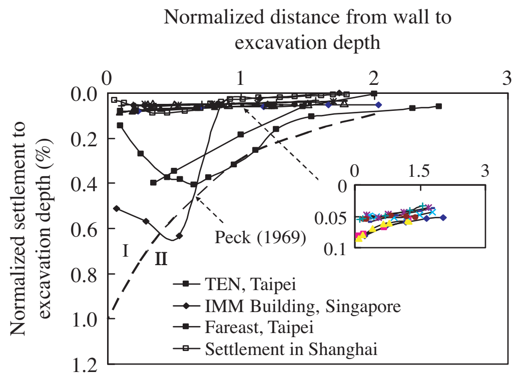

Figure 8. Distribution of the ground surface settlement normalized by the excavation depth.

Wang (2005) summarized the surface settlements of some metro excavations in Shanghai and also indicated that the magnitude was relative small (δ_{hm}/H_e is less than 0.1%), plotted in Figure 8 also.

The 3 m thick compaction grouting below the final excavation level, which improved the ground condition, and the high-stiffness diaphragm wall and prestressed multistrutted steel struts and fine workmanship may contribute the small surface settlements.

7 DISCUSSION OF THE MOVEMENT MECHANISM

Compared with the lateral wall deflection and ground settlement caused by excavation in soft clay in Singapore, Japan and Taiwan, the measured deformations in this deep excavation for a metro station in Shanghai is relatively smaller (see Figure 7). The 3 m thick compaction grouting below the final excavation level, usage of prestressed multi struts and a stiffing diaphragm wall, the short soil excavation sections and quick and fine construction are main factors associated with this measured result. Among the above reasons, one that ought to be noted is that the vertical spacing of the struts in the Shanghai excavation was smaller than that in Singapore and Taiwan, which contributed to the small wall deflection. Generally in 12 m to 18 m deep Shanghai metro excavations, four to five struts are set to support the system, while in the 9.9 m deep excavation of CTE in Singapore, for example, only two struts were set in the vertical plane. The system stiffness in the Shanghai excavation was larger; it is not surprising to observe the smaller deformation in Shanghai.

8 CONCLUSIONS

Observed data from a deep and long metro excavation, with an interchange metro station ($35 \times 25\,m^2$)

crossing it, in Shanghai soft clay is presented. On the basis of the interpreted observed field data, the following conclusions are drawn:

1. The wall deflections along the long side and three corners are different, but with similar profiles. The ratio of δ_{hm}/H_e in this deep excavation is less than 0.32%. The measured maximum wall deflection is near the center. Three-dimensional analysis of this deep excavation shows that the corner effect is found. The $\delta_{hmcor}/\delta_{hmcen}$ of the wall was 0.39–0.74, though the aspect ratio was large.
2. Compared with the excavations in soft clay in Taiwan, Japan and Singapore retained by diaphragm walls and another five similar metro excavations in Shanghai, this maximum lateral wall deflection falls near the average magnitude for Shanghai and is at the low limit line for Singapore. The undrained strength and water content of Shanghai clay and Taiwan clay is similar, but the average measured deflections in Shanghai are smaller than in Taiwan. The use of prestressed steel struts, a support system, short excavation sections, a fast workmanship sequence, and compaction grouting below the final excavation level in Shanghai may contribute to this smaller deflection.
3. The influence of support stiffness on wall movement was analyzed. A smaller lateral wall deflection of excavation with large Ks values was observed. Though scatter exists in the chart proposed by Clough et al. (1990), the suggested chart seems to allow preliminary predictions of wall movements in excavations for metro stations in Shanghai soft soil.
4. The settlement along the corners and the long side is relatively smaller (δ_{hm}/H_e is less than 0.1%) than that in other Asian soft clay, though the soft clay strata is thick in this deep excavation. This settlement is located in the zone I as proposed by Peck (1969), which is consistent with the case study in Shanghai (Wang et al. 2005).

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SYMBOLS

E_W = Young's modulus of the wall;
FOS_{base} = factor of safety against the basal heave;
h = average vertical prop spacing of multi-strutted support system;
H_e = final excavation depth;
I = second moment of inertia of the wall section;
INP = interchange part excavation;
Ks = system stiffness;
t = the wall thickness;
γ_W = unit weight of water;
δ_{corner} = deformation at corner of excavation
δ_{center} = deformation at center of excavation
δ_{hm} = magnitude of maximum horizontal diaphragm wall deflection;
δ_{hmcor} = maximum lateral wall deflection at corner;
δ_{hmcen} = maximum lateral wall deflection at center;
δ_{vm} = maximum ground surface settlement;