Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)

Study on deformation laws under the construction of semi-reverse method

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ABSTRACT: Taking a 24.09-m-deep foundation pit of Shanghai Metro Line 1 which uses the semi-reverse construction process of "three open excavating-one tunneling" as an example, through gathering and analyzing field monitoring data and making use of forward and back analysis methods, we found out deformation laws of foundation pit under the construction of semi-reverse method. The implementation results of this project indicated that the semi-reverse method is an effective way to improve rigidity of the exterior support, control the deformation of excavation, and ensure safety of the surrounding buildings and pipelines. Meanwhile, the results coincide essentially with time-space effect. The deformation of the excavation is closely correlative with excavation speed and exposure time. It provided some useful reference for the design of deep excavation in soft soil.

1 INTRODUCTION

With the development of urban construction, more attentions have been paid to the utilization of underground space, and the construction technology level of foundation engineering has been improved continuously. At the existing construction process of deep foundation engineering, open excavation method is the most common construction method at present. Because it boasts many advantages, such as more construction operation surface, short period and less cost. However in the application of some deep excavations which have complicated adjacent environment, narrow operation space, and complicated geological conditions, open excavation method would cause great influence on the traffic flow. At the same time, the pollution of mud fluid, dust particle, acoustic noise, and vibration which caused in the construction would induce discommodity to the residents' life. Especially, open excavation method would go against with deformation control of pits, which would cause perimeter buildings and structures cracking, and bring great economic loss or unfavorable social influence. The complete reverse method has little effect on adjacent environment, but its speed of excavation is slow, construction technologic process is complicated, and the cost of pillar piles is high.

Combined with advantages of open excavation method and complete reverse method, semi-reverse construction method emerges as the time require, and has been used more and more widely in Shanghai deep foundation constructions. Taking a pit of Shanghai metro line 1, which uses semi-reverse construction method, as an example, through getting field monitoring data and setting up the finite element model, this paper has given an evaluation for the characteristics of semi-reverse method such as construction technology and deformation control laws, kindly expected to provide with a beneficial reference to those similar projects in future.

2 ENGINEERING CASE

2.1 *General engineering situation*

A railway station of Shanghai Rail Transit Line No. 10 (metro line 1) is situated at the intersection of South Xi Zang Road and Fu Xing Road, and "cross" transferred with metro line 8. The geographical position of this station is shown in Figure 1.

The station of metro line 1 is below that of line 8. The structure form of this subway station with three floors is two pillars and three spans, the outside dimension are 179.2 m (length) ×23.8 m (width). And the size of east and west end well is 27.8 m × 16.1 m, which bottom floor buried depth are 24.06 m, −24.09 m.

According to the requirements of waterproof design and construction plan, the whole railway station main body structure is divided into two construction region with eight parts. The subsection construction drawing of this station is shown in Figure 2. The west end well is the first construction part, which requires higher environment protection. This end well approaches the

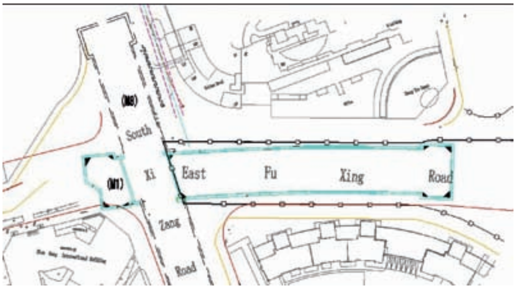


Figure 1. Geographical position of the station.

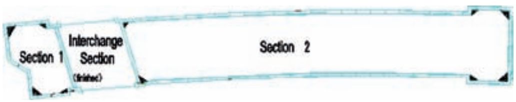


Figure 2. Subsection construction of the station.

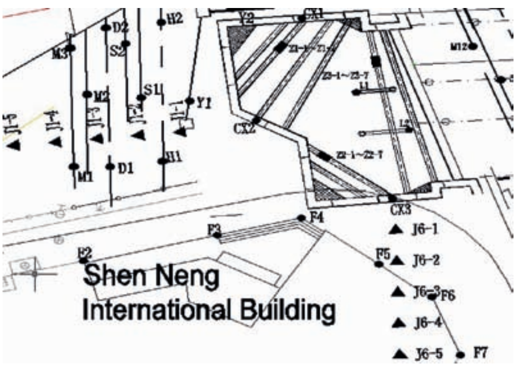


Figure 3. Distribution of monitoring points in west end well.

International Squire (28 floors) and Shen Neng International Building (26 floors), and surrounding with lots of pipelines. According to the requirements of the first class environment protection specified for Shanghai subway station, the horizontal deformation of diaphragm wall should be $\leq 1.4‰H$ (H is the depth of excavation), and the maximum settlement of perimeter ground surface should be $\leq 1‰H$. The excavation depth of the west end well is about 24.09 m. It adopts the underground diaphragm wall with width 1000 mm and depth 44 m. The brace system applies 1 piece concrete brace of 900×800 and 7 pieces steel tube brace of $\Phi 609 \times 16$. The distribution of monitoring points is shown in Figure 3.

2.2 *Geological condition*

Basing on the geological prospecting data, the soils of engineering site are divided into 9 layers from up to bottom. They are ①fill soil layer, ②silt clay layer, ③mud-silt clay layer, ④muddy clay layer, ⑤$_{1-1}$clay layer, ⑤$_{1-2}$silt clay layer, ⑤$_3$silt clay layer, ⑤$_4$silt clay layer, ⑦$_2$fine sand layer. Table 1 shows physical and mechanical characteristics of different soil layers. Figure 4 shows Geotechnical section of excavation.

Main hydrology condition of this station is as follows: the shallow groundwater field is phreatic aquifer, which mainly comes from infiltration of precipitation and seepage of surface water. The annual average water stage of Shanghai ranges from 0.50 m$\sim$0.70 m, and generally 0.5 m is chosen as design value.

In the report of geological prospecting data, the soil of ⑦$_2$fine sand layer is distributed in the site, whose buried depth is 44–46 m and confined water head is 10.5–11.0 m. Considering the worst factors, when the pit excavated to 24 m, the coefficient of upheaval in the bottom of the pit would not meet the requirement of safety factor, so it should be adopted measurement for decreasing confined water head.

2.3 *Construction procedure*

Considering the actual factors such as construction period, traffic organization, underground pipelines and environment protection, the semi-reverse construction process of "three open excavating-one tunneling" was adopted in this project.

The detail of the process is as follows: Firstly excavate the soil to the fifth brace, and then construct the second median plate between the forth and fifth brace. With the top reinforced concrete brace, the reversed median plate and underground diaphragm wall formed a frame system. While the pavement maintenance of median plate has been finished, utilize two shield structure holes of the end well to dig the soil below the plate until the bottom plate finished.

The semi-reversed construction has brought lots of inconvenience to excavating and supporting of the pit under the second median plate. This inconvenience generally reflects at the narrow perpendicular channel and the complicated supports installation. Commonly, installation procedure of supports under the construction of semi-reversed method is that, divide the brace into several pieces, bring these pieces to the bottom one after another, and then assemble them together to the design elevation. For the process as it is mentioned, installing one straight brace generally needs 7hours, and installing one diagonal brace needs 10 hours, which far from the requirement of "time-space effect". "Time-space effect" requires that the excavation width should be no more than 6m, and the excavation plus supporting time should be no more than 24 h (excavation time-16 h; supporting time-8 h). The deformation should be control ineffectively, if the pit was not supported within such time. So based on the engineering traits, the project excavate the soil as soon as possible while in the open cut period. It uses open cut method to excavate the soil until 0.5 m below

Table 1. Physical and mechanical characteristics of different soil layers.

No.	Buried depth (m)	gravity r (kN/m^3)	peak value of consolidated quick shear C (kPa)		Compression module Es (MPa) ψ (°)	Permeability coefficients (m/s) Kv	Kh
①	2.31						
②	3.41	18.6	18	14	4.80		
③	9.21	17.5	11	16	3.51	1.97E-9∼2.18E-9	2.08E-09
④	19.81	16.7	13	12	2.27	1.17E-9∼1.48E-9	1.33E-09
⑤$_{1-1}$	22.91	17.5	16	14	3.93	1.77E-9	1.77E-9
⑤$_{1-2}$	27.81	18.1	15	17.5	4.98	1.52E-9	1.52E-9
⑤$_3$	42.11	18.2	15	19.5	5.08	1.60E-9∼2.13E-9	1.87E-09
⑤$_4$	44.71	19.7	39	15.0	8.00	9.3E-10∼1.46E-9	1.20E-09
⑦$_2$		19.3	0	31	15.11	2.48E-8∼2.57E-8	2.53E-08

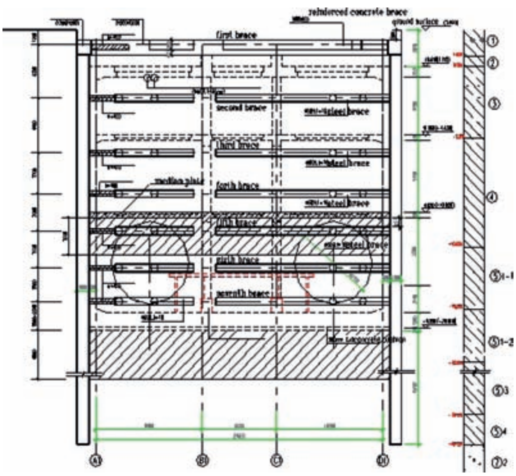


Figure 4. Geotechnical section of excavation.

the fifth brace (3 m below the second median plate). When the seventh soil was excavated, disassemble the supports form the location of the fifth brace and install them to the location of the seventh brace. So the installation of every brace just needs 0.5 hours, which should accelerate the construction speed as well as control the deformation of the pit effectively.

3 FINITE ELEMENT MODELING

Combined with field monitoring data, the finite element software PLAXIS 8.2 (Brink Greve & Vermeer 1998) was used to compute the response of the soil around the excavation for effective analysis. The problem was simulated assuming plane-strain conditions and chosen half of the pit as the research subject. The side boundaries of the mesh (total size 90 m × 75 m) were established beyond the zone of influence of the settlements induced by the excavation (Caspe 1966; Hsieh & Ou 1998). The finite element mesh boundary conditions were set using horizontal restraints for the left and right boundaries and total restraints for the bottom boundary. The soil stratigraphy was assumed to be uniform across the site. Those soils with similar properties would be combined by weighted similarity method. So six soil layers were compartmentalized for the calculation simplify.

The soil model used to characterize the clays in the PLAXIS simulation of the excavation is the hardening-soil (H-S) model (Schanz et al. 1999).

This effective stress model is formulated within the framework of elastoplasticity. Plastic strains are calculated assuming multisurface yield criteria. Isotropic hardening is assumed for both shear and volumetric strains. The flow rule is nonassociative for frictional shear hardening and associative for the volumetric cap. The initial values of the basic H-S input parameters for the soil layers are referenced as Table 1 and calibrated by inverse analysis.

The linear spring-layer model is adopted to simulate the braces; the plate element model is adopted to simulate the underground diaphragm wall, reversed median plate and bottom plate. Considering the buildings around the pit, 50 kN/m^2 overload is applied for calculation.

Figure 5 shows the calculation model. Table 2 shows 11 calculation phases and the construction stages used in the finite element simulations. PLAXIS employs a penalty formulation so that undrained conditions can be explicitly modeled. Because there was a long time interval between Phase 6 and Phase 7, the displacements are due to partially drained conditions. So consolidation should be considered in this stage. Other stages which not noted as "consolidation" in Table 2 were modeled as undrained and the excess pore water pressures were computed relative to some steady-state value (1m) that changes with dredge line level.

Table 2. Calculation phases and the construction stages used in the finite element simulations.

Identification	Phase no.	Calculation	Stages
Initial equilibrium	0	Plastic	construction
Set up diaphragm wall and apply overload	1	Plastic	construction
Excavate the first soil and support the first brace	2	Plastic	construction
Excavate the second soil and support the second brace	3	Plastic	construction
Excavate the third soil and support the third brace	4	Plastic	construction
Excavate the forth soil and support the forth brace	5	Plastic	construction
Excavate the fifth soil and support the fifth brace	6	Plastic	construction
Construct median plate	7	Plastic	construction and consolidation
Excavate the sixth soil and support the sixth brace	8	Plastic	construction
Excavate the last soil	9	Plastic	construction
Construct bottom plate	10	Plastic	construction

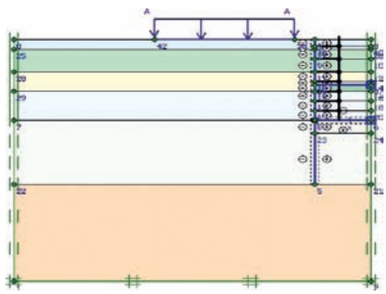


Figure 5. Calculation model.

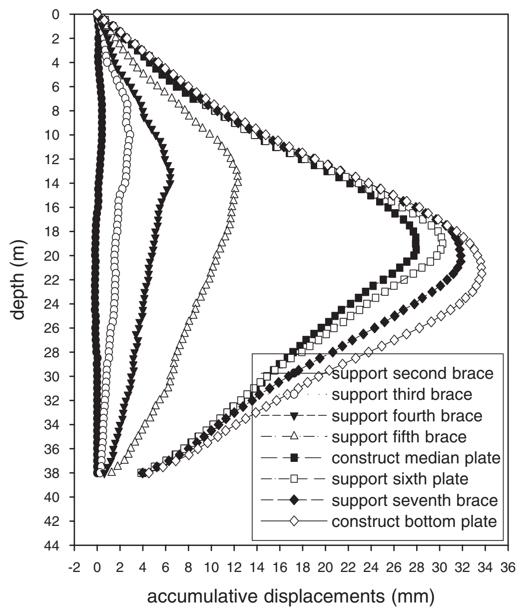


Figure 6. Displacement curve of CX3 at different depth which changed with the working condition.

4 COMPARISON OF FIELD DATA WITH CALCULATION RESULTS OF FINITE ELEMENT SOFTWARE

In order to study the deformation laws under the construction of semi-reversed method, lots of field monitoring data of west end well have been finished from the second brace has been supported to the roof plate has been finished. Choose the inclination survey point CX3 and the settlement points J6-1, J6-2, J6-3, J6-4, J6-5 which have the same cross section with CX3 as representative points. Combined with calculation results of finite element software, it could be got detailed analysis.

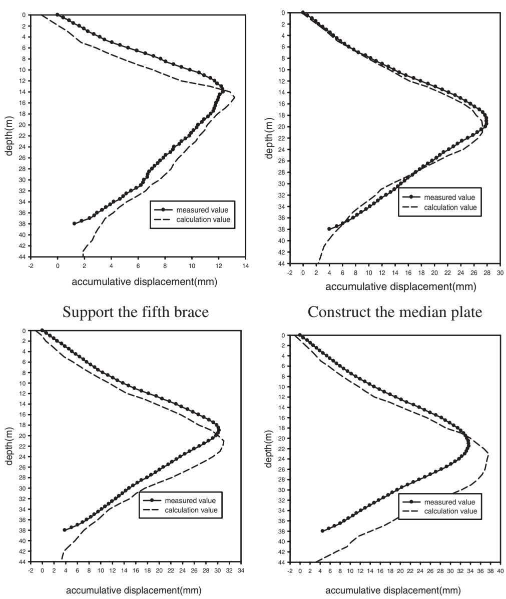
4.1 *Inclination deformation of underground diaphragm wall*

In the construction process of foundation pit, the displacement curve of inclination point CX3 at different depth which changed with the working condition is shown in Figure 6.

From Figure 6, it could be found that the maximum inclination displacement of diaphragm wall is only 33.69 mm when the bottom plate has been poured, which is satisfied with the requirement of Class 1 environment protection. Based on the experiences of Shanghai underground works these years, with the similar excavation depth, excavation size, geological conditions and peripheral circumstance, if the foundation pit adopts open cut method, the deformation value could not be controlled at so small range.

Calculation results of finite element software and field data were compared from the time that fifth braces had been installed, which is shown in Figure 7. In the figure, dashed line represents the calculation value, and solid line with circle represents measured value. Table 3 shows the specific comparative value.

The shape of calculation curve was in good agreement with the measured curve, and the maximum value of calculation deformation was in accordance with field data while the bottom plate has been constructed. The results show that finite element method can correctly reflect excavation deformation regularity. It shows that the diaphragm wall engendered comparative larger deformation within the period from the fifth brace supported to the median plate constructed. This is because the discrepancy of the two work conditions lasts as long as 20 days. Though soils weren't excavated, exposure time for the foundation pit with braces was comparative long. The excavation face is situated in ④muddy clay layer which has very strong flow property, and the permeability of the soil is relatively large ($\cong 1.77 \times 10^{-9}$ m/s). For above reasons the diaphragm wall engendered larger deformation. In the finite element calculation, consolidation has been considered, so it could correctly reflect the actual deformation.



Support the fifth brace — Construct the median plate — Support the sixth brace — Support the bottom plate

Figure 7. Measured versus computed horizontal displacements.

In order to analyze the relationship between deformation of diaphragm wall and time, we chose the department of the maximum deformation for filed data CX3 (CX3-43 point whose depth is 21.5 m) as a key point. The variations of deformation with time for this point in the whole excavation construction are inspected as Figure 8 shows.

From Figure 8, we can find that though the diaphragm wall engendered large deformation from the fifth brace supported to the median plate supported, in the process of concrete maintenance, the deformation stopped to grow and it even had a little falling, and also when the soil under the reversed media plate was excavated, the deformation rate is smaller than that of previous. With the top reinforced concrete supports, the reversed median plate and underground diaphragm wall could be formed as a frame system, which constrained the spreading of soil deformation. The reduction of deformation rate in this phase has released the comparatively large deformation, which engendered as a result of soil creep in forward phase. This is beneficial for the reduction of foundation deformation and assurance of pit stability.

4.2 *Ground settlement*

Ground settlement points J6-1, J6-2, J6-3, J6-4, J6-5 are in the same section with the inclination point CX3, which is distributed with the distance of 3 m for every point from the edge of pit. Figure 9 shows the field settlement curves in the process of construction.

From Figure 9, it shows that ground settlement increased with excavation depth. When the bottom plate has been finished, the maximum settlement is only 7.1 mm. The soil presented a little uplift at 6 m from the edge of excavation. With reference to the actual engineering project, high pressure jet grouting was used in the end well for the stability of shield access to tunnel. It might be the reason that caused the soil uplifting.

4.3 *Building settlement and pipeline settlement*

To March 2007, while the roof plate has been finished, the maximum building settlement was only −3.3 mm, which is at F05 point. The variations of deformation

Table 3. Specific values of measured versus computed horizontal displacements.

Project database		Fifth brace	Median plate	Sixth brace	Seventh brace	Bottom plate
Completion time		06-11-16	06-12-6	06-12-29	07-1-1	07-1-15
Measured Value	Maximum value	12.33	27.94	30.25	31.85	33.69
	Depth	14	19	19	21	21.5
Calculation value	Maximum value	13.19	27.32	31.05	35.35	37.68
	Depth	15	20	21	21	22

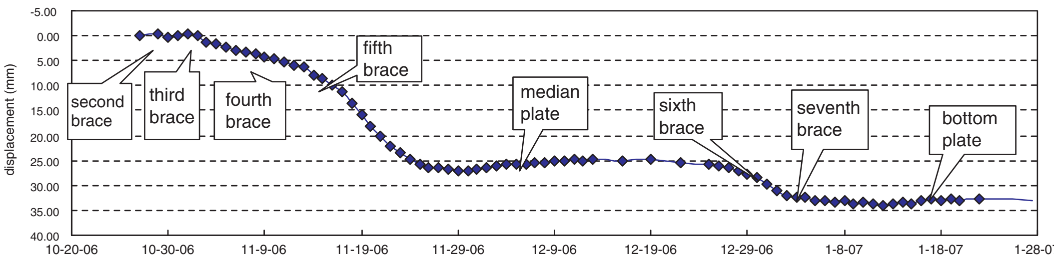


Figure 8. Variations of displacement with time for CX3-43 in the whole excavation construction.

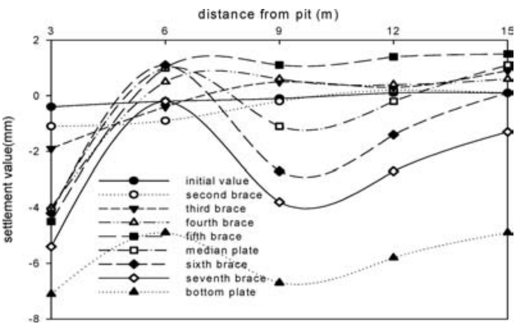


Figure 9. Field settlements in the process of construction.

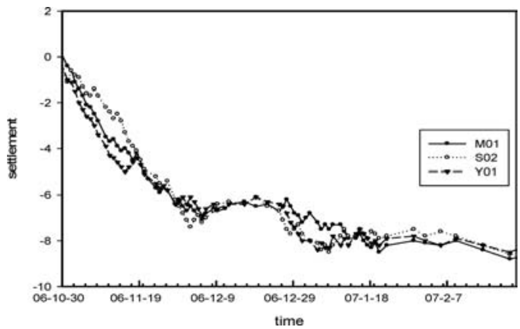


Figure 11. Time-history curves of M01, S02 and Y01.

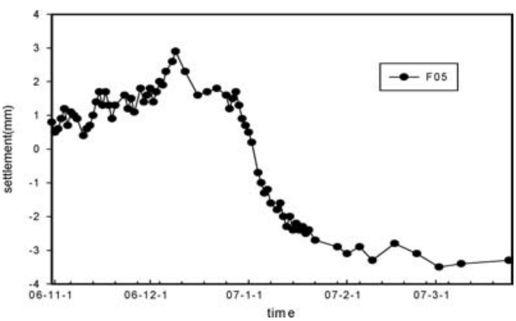


Figure 10. Variations of deformation with time for F05.

with time for F05 are shown in Figure 10. As a result of high pressure jet grouting, in the former phases of construction the vertical deformation of F05 presented an uplifting trend. It was not until January 2007 that the soil deformation fell back. This was one of the main reasons for the so small accumulative building settlement.

The conditions of pipeline settlement were as follows: the maximum deformation point of gas pipe was M01, whose accumulative settlement was −8.6 mm; the maximum deformation point of water supply pipe was S02, whose accumulative settlement was −8.4 mm; the maximum deformation point of rain pipe is Y01, whose accumulative settlement was −8.2 mm. Choosing pressure pipe point M01, S02 and non-pressure pipe point Y01 as key point, whose time-history curves is shown in Figure 11.

The settlement trends of these pipelines were uniform, and these time-history curve shapes were similar to that of inclination point in Figure 8. From December 6th to December 29th, when the median plate has been maintained, the deformation value of pipelines also presented a stable period. In 1969, Peck put forward stratum compensation theory, which indicated that the shapes and the enclosed area of lateral deformation curves caused by foundation pit excavation are similar to that of ground settlement curves. From Figure 11, it can be found that this similarity changed uniformly with time, that it is to say the ground settlement changed with the lateral deformation at any time, which is favorable for the environment protection.

5 CONCLUSION

1. Adopting semi-reverse construction method in metro foundation pit could control the deformation of pit effectively, and decrease the influence of excavation construction on its surrounding environment. Semi-reverse construction method owns a deep foundation support technology with practical value and brilliant prospects, which would

be further developed and applied in rail transit construction.
2. The reversed median plate and underground diaphragm wall formed a frame system. In the process of median plate maintenance, the deformation of soil behind retaining wall was stable. When the plate maintenance finished and the soil excavated, the deformation rate was smaller than those engineering works which adopted open-cut method of the same conditions.
3. In the process of reversed median plate supporting, a long period was needed for reinforcement assemble and scaffold erection. As a result of soil flow property, larger deformation may be generated at this period.
4. As the excavation is in clay, longer times of construction may result in partial drainage as well. Consolidation of the soil should be considered in finite element calculation.
5. The shapes of lateral deformation curves caused by foundation pit excavation are similar to that of ground settlement. This similarity changed uniformly together with time pass. It is conjectured that the ground settlement changed with the lateral deformation shape at any moment.

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