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Design and construction of deep excavations in Shanghai

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ABSTRACT: Numerous deep excavations have been carried out in Shanghai for constructing high-rise buildings, subway transportation networks and other underground structures in the past two decades. There is significant advancement in design and construction practice of deep excavations in Shanghai. This paper presents the current status of design and construction practice adopted. Firstly, geological and geotechnical conditions are presented. Secondly, commonly used deep excavation support systems are introduced. Then, a few cases which are benchmarks of deep excavations are presented. These include the largest deep excavation, the deepest excavation, the largest circular excavation, the basement excavation for the tallest building in china, and the largest excavation constructed by top-down method in Shanghai. Finally, concept of performance-based design, criteria of deformation control, and measures in mitigating the impact of deep excavations on adjacent structures and properties are introduced. These measures include top-down method, reinforcement of soils inside the excavation, zoned excavation, and "Time and Space Effect" excavation method.

1 INTRODUCTION

Shanghai is the largest city in China with a population of about 20 million. It is also the financial and commercial center of this country. It has become one of the most energetic municipalities in the world. With the rapid economic growth in the past two decades, the city has achieved drastic economic and social reforms with construction industry playing an important role. A large number of high-rise buildings, subway transportation networks and other underground structures have been built in Shanghai during the past two decades. Figure 1 shows a bird view of a corner of the city showing numerous skyscrapers. Figure 2 shows the map of the Shanghai metro network in operation. Up to now, there have been 11 lines and 280 stations put into operation. The operation length of the Shanghai rail transit network is about 420 km and it has become the longest rail transit network in the world. Most of these construction involved deep excavations. As a result, there is significant advancement in design and construction practice of underground works. Presented herein is the current status of design and construction of deep excavations in Shanghai.

Figure 1. A bird view of a corner of the Shanghai city showing numerous skyscrapers (from http://bbs.home.news.cn/).

Figure 2. Map of the Shanghai metro network in operation (http://www.shmetro.com).

2 GEOLOGICAL AND GEOTECHNICAL CONDITIONS

Shanghai is washed by the East China Sea on the east and Hangzhou Bay on the south. North of the city, the Yangtze River pours into the East China Sea. The 'shallow soils', from ground surface to a depth of about 135 m, were deposited during the Quaternary period (SCMC, 1997). These shallow soils have important significance to engineering activities. Figure 3 shows a typical soil profile in Shanghai and the geotechnical parameters of the soil. It should be noted that compressibility modulus $E_{s0.1\sim0.2}$ was obtained by oedometer tests at stresses ranging from 100 kPa to 200 kPa while undrained shear strength s_u was obtained from in situ vane shear tests.

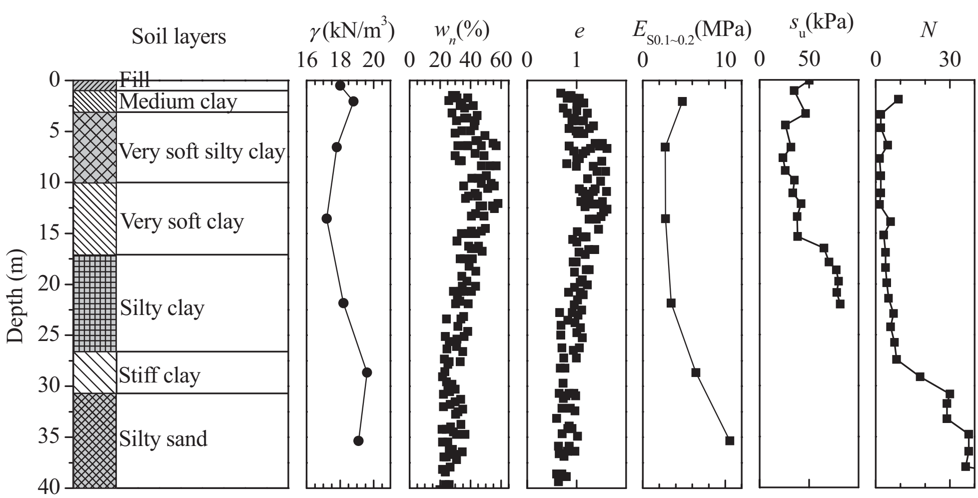
The top layer is artificial fill with a thickness of less than 2 m. The second layer is yellowish dark brown inorganic clay, with low to medium plasticity and medium compressibility. This layer has a lower water content and void ratio and a higher undrained shear strength than the underlain soft clay. The second layer is lightly overconsolidated, perhaps due to climate effect such as evaporation. The third layer is very soft silty clay with a thickness of about 7 m. It is in a medium plastic and high compressible state. Mean value of water content of this layer is about 46% and the mean s_u value is about 28 kPa. The horizontal permeability coefficient of this layer is the order of 10^{-6} m/s. The fourth layer is 7 m thick very soft clay, which contains mica, organic matter, and silty sand. It has the largest void ratio and compressibility, but has the lowest coefficient of permeability (the order of 10^{-8} m/s) among the 'shallow soils'. The mean value of s_u of this layer is about 37 kPa. Sensitivity values of both the third and fourth layer soils are larger than 5. The fifth layer is grayish silty caly with a thickness of about 10 m. It is low to medium plastic with medium to high compressibility. Mean value of s_u of this layer is about 75 kPa. The sixth layer is dark green stiff clay with a thickness of 4 m. It is overconsolidated with an OCR of about 2.0 and low to medium plastic. SPT N value of this layer ranges from 18 to 30. The seventh layer is silty sand with a thickness of about 15 m. SPT N value of this layer ranges from 28 to 70. Coefficient of permeability of this layer is the order of 10^{-5} m/s. The groundwater table is generally 0.5 m below the ground surface.

3 DEEP EXCAVATION SUPPORT SYSTEM

3.1 *Retaining wall*

Support systems for deep excavations consist of three main components, namely, retaining walls, lateral support system and vertical support system. For retaining walls, six types of walls are commonly used in Shanghai.

The first kind of retaining wall is diaphragm wall which has relatively high stiffness and provides effective water tightness. As its cost is quite high, it is usually used in project with more than three levels of basements. In most cases, diaphragm wall is adopted as retaining wall as well as outside wall of basement. The most commonly



Note: γ = unit weight, w_n=water content, e = void ratio, $E_{s0.1\sim0.2}$ = compressibility modulus, s_u = undrained shear strength, N = SPT N value

Figure 3. Typical soil profile and geotechnical parameters in Shanghai soft ground.

used wall thicknesses are 800 mm, 1000 mm, and 1200 mm. In order to guarantee water-tightness at the joints of wall panels, high pressure rotary jet grouting piles are usually used at the back of wall, while RC pilasters are used in front of the wall (see Fig. 4(a)).

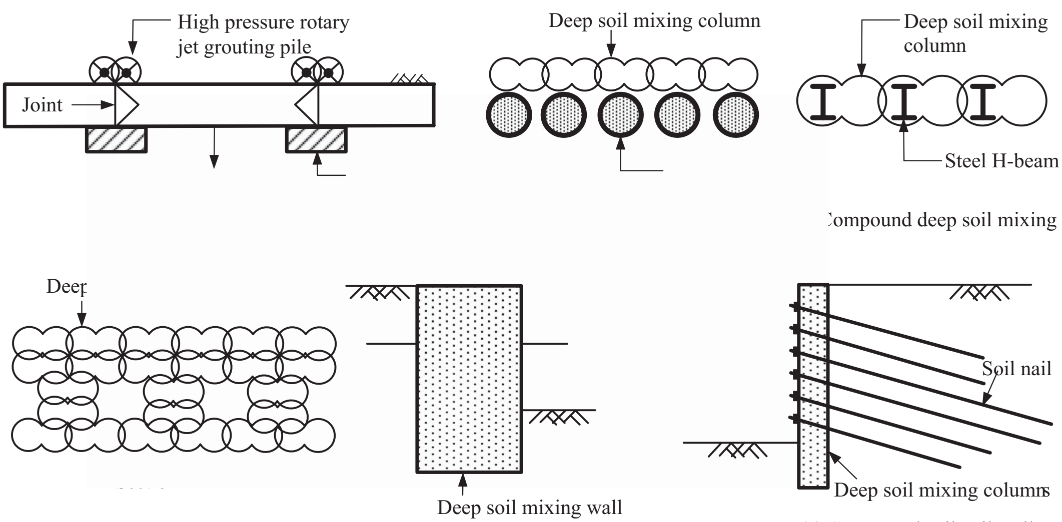
The second kind of retaining wall is contiguous pile wall (see Figure 4(b)) which is usually adopted as temporary wall in Shanghai. The gap between two bored piles typically ranges from 150 mm to 200 mm. Deep soil mixing columns, constructed at the back of contiguous pile walls, are used as waterproof curtains. The cost of this kind of retaining wall is lower and construction speed is higher comparing with diaphragm wall.

The third type of retaining wall is compound deep soil mixing wall which is formed by deep soil mixing columns and the steel H-beams inserted inside the deep soil mixing wall (see Figure 4(c)). In this kind of wall, the deep soil mixing columns are used as waterproof curtains, while steel H-beams are used to bear bending moments. The deep soil mixing columns, with commonly used diameters of 650 mm, 850 mm and 1000 mm, are usually performed by machine with three shafts of augers and mixing paddles in Shanghai. In order to form continuous waterproof curtains, the deep soil mixing columns are constructed by overlapping adjacent soil mix elements. After finishing the construction of the underground structure, the steel H-beams can be pulled out and can be reused in other projects. The soil mix method can be very effective at providing stiff and waterproof retaining systems. However, it is rather limited to medium and large-scale projects because of high mobilization costs.

The fourth type of retaining wall is the deep soil mixing wall (see Figure 4(d)) which has enjoyed success and popularity since the 1990s. According to the experience in Shanghai, thickness of the cross section of a deep soil mixing wall ranges from 0.7 to 1.0 times the excavation depth, while the penetration depth of the wall range from 1.0 to 1.4 times the excavation depth. As the cross section of a deep soil mixing wall is very thick, it performs like a gravity wall. Excavations supported by deep soil mixing walls are usually excavated without struts. Wang et al (2010) collected 34 excavations supported by deep soil mixing walls in Shanghai. They found that maximum lateral displacements of the wall range from 0.3%H to 2.4%H with an average value of 0.91%H, where H is the excavation depth.

The fifth type of wall is compound soil nail wall (see Figure 4(e)) which is a combination of single or double rows of deep soil mixing columns with soil nails. Deep soil mixing columns is also used as waterproof curtain. Distance of soil nails range from 0.8 m to 1.0 m, while length of the soil nails ranges from 1.5H to 2.5H. Cost of compound soil nail wall can be very competitive. As a result, it has been developed quickly in recent years.

Other uncommonly used retaining walls include sheet pile wall and secant pile wall. Sheet pile walls were popular in the 1980s in Shanghai. Due to some severe problems such as nose pollution and effect of vibration on nearby building during installation, and large displacement during excavation,



(d) Deep soil mixing wall
(e) Compound soil nail wall

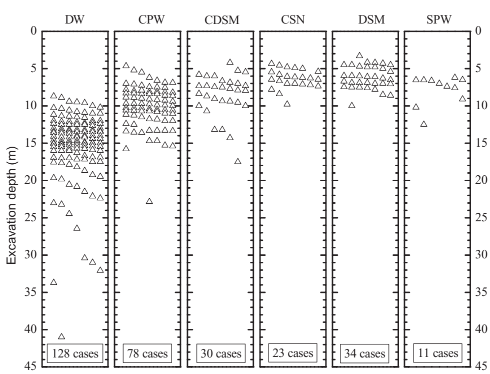
Figure 4. Sketch maps of different type of commonly used retaining walls in Shanghai.

sheet pile walls are now seldom adopted in deep excavations in this region.

A database of 304 deep excavation case histories in Shanghai was set up. The number of excavations retained by diaphragm walls, contiguous pile walls, compound deep soil mixing walls, compound soil nail walls, deep soil mixing walls, and sheet pile walls are 128, 78, 30, 23, 34, and 11, respectively. Figure 5 depicts the excavation depth distribution of different types of retaining wall. It shows that diaphragm walls are the most frequently used retaining walls. It is frequently adopted in 10 m to 25 m deep excavations and the maximum excavation depth reaches 41.2 m. Contiguous pile walls are frequently used in excavations with depth of 5 m to 15 m. Compound deep soil mixing walls are frequently used in excavations with depth of 5 m to 10 m and there is a trend to be used in much deeper excavations. Compound soil nail walls and deep soil mixing walls are generally used in excavations with depth less than 8 m. Sheet pile walls are generally adopted in 6 m to 9 m deep excavations. However, it has been rarely used since the 1990s. Excavation depth distributions in Figure 5 can be used as a guide in selecting supporting system according to excavation depth.

3.2 *Lateral support system*

Due to the poor ground condition, it is considered that anchors are not very applicable in Shanghai. As a result, temporary steel and Reinforced Concrete (RC) struts as well as slabs of the underground structure are used as lateral support system. Steel tubes and H-beams are frequently used steel struts. Commonly used diameter of steel tubes is 609 mm with thickness of 10 mm, 12 mm, or 14 mm. While the H700 × 300 and H500 × 300 are frequently used H-beams. Steel struts are generally arranged orthogonally, as shown in Figure 6(a) and Figure 6(b). For excavations with depth less than 7 m, sometimes inclined struts with one end supported on the bottom slab are used, as shown in Figure 6(c). For narrow excavations (such as subway stations) retained by diaphragm walls, steel struts without wale (see Figure 6(d)) are used to accelerate construction speed. Steel struts are generally preloaded and sometimes they are reloaded during the excavation procedure when stress lost is severe. Steel struts are rather limited to irregular excavations. Moreover, it is not suitable for large-scale projects because that it is difficult to guarantee the installation quality and control deformation of the excavation.



Note: DW=Diaphragm wall; CPW=Contiguous pile wall; CDSM=Compound deep soil mixing wall; CSN=Compound soil nail wall; DSM=Deep soil mixing wall; SPW=Sheet pile wall

Figure 5. Excavation depth distribution of different types of retaining wall.

RC struts, which have good integrity and quite high stiffness, are suitable for most excavations especially for irregular and large-scale excavations. RC struts can be arranged orthogonally (see Figure 6(e)) or formed by truss system (see Figure 6(f)). In order to gain large working space, sometimes RC ring struts (see Figure 6(g)) are used. In some cases, a combination of steel and RC struts is adopted (see Figure 6(h)). In this kind of strut system, the first level struts are RC struts while the following level struts are steel struts. This combination is benefit to deformation control because it can take the advantages of good integrity and quite high stiffness of the RC struts and quick installation of the steel struts. Temporary RC struts are not benefit to environment protection as they have to be demolished after the construction of underground structure. However, due to low cost of labor in China and its reliability in deformation control, RC struts are still the most popular struts form in Shanghai.

When environmental protection is extremely strict or working space and construction time is limited or excavations are very large, the top-down method is used. On this occasion, retaining walls are supported by permanent concrete floor slabs of underground structure (see Figure 6(i)). Design and construction of top-down method are quite complicated. Though thousand of deep excavations have been constructed in the past two decades in Shanghai, only about 30 of them were constructed by top-down method. However, there is a trend of increase of adopting this method.

3.3 *Vertical support system*

Lateral support system is propped by vertical support system. Vertical support system is composed of steel lattice column and bored pile. Steel lattice column, which is erected in the bored pile, is usually made up of four pieces of hot-rolling equilateral angle steel welded with tie plates, as

Figure 6. Types of lateral support system commonly used in Shanghai.

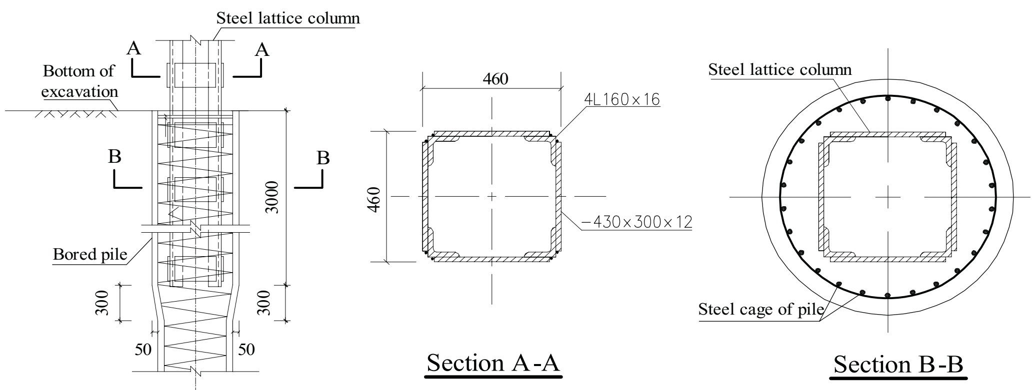


Figure 7. Steel lattice column erected in bored pile to form vertical support system.

shown in Figure 7. Commonly used section of the steel lattice column is 460 mm × 460 mm. Sometimes the diameter of bored pile is expanded in the range of about 3 m at the top of pile to facilitate the penetration of steel lattice column (see Figure 7).

For top-down method, steel lattice columns (see Figure 8(a)) or steel tubes (see Figure 8(b)) filled with concrete, are used as vertical support system during the excavation stage. They will finally be encased in concrete to be transferred into permanent columns of underground structure (see Figure 8(c)). Perpendicularity of less than 1/250 is required for the installation precision of the steel lattice columns and steel tubes in top-down method (SCMC, 2010).

(a) Steel lattice column used in top-down method during excavation stage

(b) Steel tubes used in top-down method during excavation stage

(c) Steel tubes encased in concrete to be transferred into permanent columns in top-down method

Figure 8. Steel lattice column and steel tubes used in top-down method.

4 BENCHMARKS OF DEEP EXCAVATIONS IN SHANGHAI

4.1 *The largest deep excavation*

The Shanghai Hongqiao Comprehensive Transportation Hub (SHCTH) is the biggest modern city comprehensive transportation engineering in China. It is a comprehensive transportation center including the new Western Terminal, the Eastern Metro Station, the Eastern Traffic Square, the Maglev Station, the High-Speed Railway Station, the Western Metro Station, and the Western Traffic Square. The project involves ultra-large and deep excavations. The excavation area of the project was about 580,000 m^2, and the excavation depth ranged from 9 m to 29 m. It is so far the largest deep excavation in Shanghai. A combined supporting system was adopted according to the characteristics of the excavation. Sloped excavation and deep soil mixing walls (with a thickness of 5.7 m and depth of 13 m) were used for the shallow excavation area, while 800 mm thick diaphragm walls which were braced by two levels of RC struts was adopted for the deep excavation area. Figure 9 shows a sectional view of typical supporting system adopted in this project. Figure 10 shows a photo of the construction site when the soil was cut to the final elevation. The excavation was completed in 2009 and the whole SHCTH project was put into service in March, 2010. Despite the poor ground condition and long time construction, deflections of the deep soil mixing walls were generally less than 74 mm while deflections of the diaphragm walls were generally less than 55 mm. The combined supporting system was proved to be quite successful for this ultra-large and deep excavation.

4.2 *The deepest excavation (Tang and Zhu, 2009)*

The remediation project of the collapsed tunnel of Metro Line 4 is so far the deepest excavation in Shanghai. The length of the shield tunnel between the South Pudong Road Station and Nanpu Bridge Station was 2000 m, among which 440 m was under the Huangpu River. The tunnel collapsed due to quick sand caused by the construction of the passage of the air shafts on July 1, 2003. The collapse caused large ground settlements and many adjacent buildings had to be disposalled. It was decided to conduct the remediation at the original place using cut-and-cover method. The remediation was divided into three parts, namely, the east part, the middle part, and the west part, as shown in Figure 11. The lengths of the three parts were 174 m, 62.5 m and 28 m, respectively. The maximum excavation depth was 41 m. The excavation was retained by 1.2 m thick diaphragm wall with a depth of 65.5 m. The diaphragm walls, which were penetrated into the second sand layer (usually adopted as bearing layer for piles of super high-rise buildings), were the deepest walls in Shanghai. As the diaphragm walls were extremely deep and there were so many obstacles caused by the collapse, construction of the diaphragm wall was a great challenge. The diaphragm walls were supported by 9 levels of RC struts. In order to improve the properties of the collapsed soils inside and outside of the excavation, triplex pipe jet grouting with a maximum depth of 50 m was adopted to strengthen the soils. Dewatering was conducted in the excavation by wells with depth of 60 m to satisfy the requirement of safety against confined water upheaving. The remediation commenced in August, 2004 and it was completed in the first half of the year 2007. Figure 12 shows a photo of the construction site. Maximum lateral displacement of the diaphragm wall was 48 mm.

4.3 *The largest circular excavation*

The Shanghai 500 kV World Expo Underground Transmission and Substation (SWEUTS) project is located in the center district of the city. It is an important attached project of the 2010 Shanghai World Expo. Completion of the project will make it one of the largest and most advanced underground

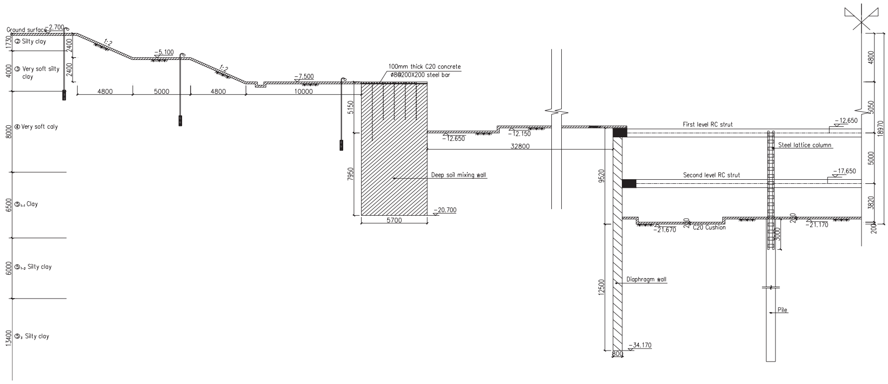


Figure 9. Sectional view of the typical supporting system adopted in the SHCTH project.

Figure 10. A photo of the construction site when the soil was cut to the final elevation.

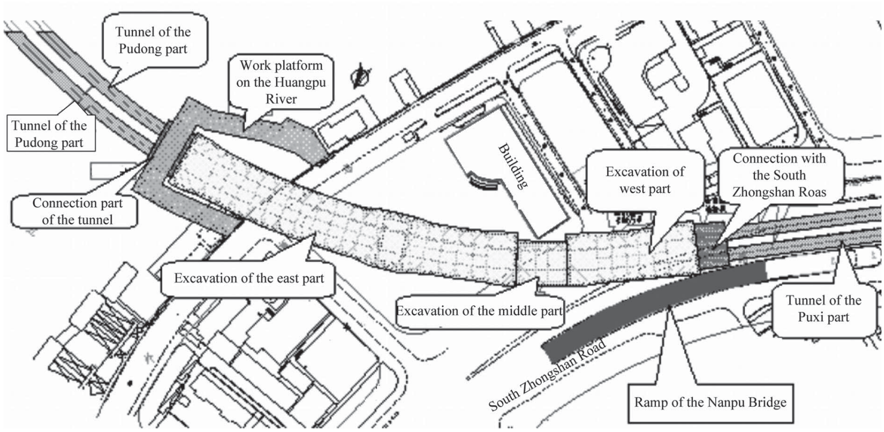


Figure 11. Plane view of the remediation project of the collapsed tunnel of Metro Line 4 (according to Tang and Zhu, 2009).

Figure 12. A photo of the construction site (from http://www.51xuewen.com/group/287/topic_11354.htm).

substations in the world. The project, constructed to a depth of 34 m below the ground surface has a diameter of 130 m. It is so far the largest and deepest circular excavation in Shanghai. It is also one of the largest circular deep excavations in the world. The project was constructed by top-down method. The ring was made of 80 panels of diaphragm walls of 1.2 m in thickness with their toes embedded in relatively competent stratum. The 57.5-meter long diaphragm walls were installed to the silty clay and silty sand interbedded strata through the firm sand soil layers with SPT *N* value of 28 to 50. The firm sandy soil layers had brought great difficulties to the installation of the diaphragm walls. To ensure quality and speed of diaphragm wall installation, the sectors of wall trenches in soft soils (above the sand soil layer) were excavated by conventional clamshell grabs while the deep sectors in the firm sandy soil layers and the silty clay and silty sand interbedded strata were formed by trench cutting machines. The diaphragm walls were braced at the floor levels by the four basement slabs. In order to reduce the spacing of the lateral struts and further restricting wall movements, temporary ring RC strut frame systems were installed between the slabs in the first, second and fourth level basement. Steel tubes with diameter of 550 mm and thickness of 16 mm, filled with Grade 60 concrete at the same position of the permanent columns were erected in bored piles to support the underground structure that was constructed from the top level downward at the excavation stage. The steel tubes would finally be encased in concrete to be transferred into permanent columns. Figure 13 shows a sectional view of the supporting system. Figure 14 shows photos of the construction site. It cost about three years to construct the project and it was put into service in 2009. Monitored results showed that maximum deflections of the diaphragm walls were less than 49 mm.

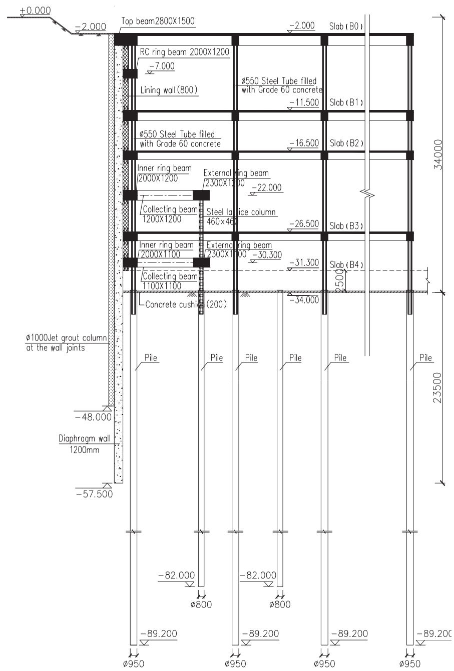


Figure 13. Sectional view of the supporting system of the SWEUTS project.

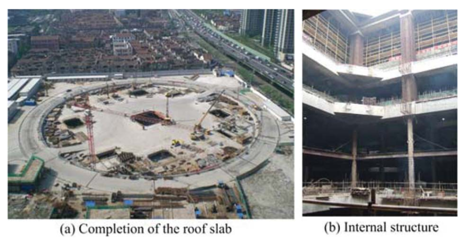


Figure 14. Photos of the construction site of the SWEUTS project.

Figure 15. A photo showing pouring concrete of the bottom slab of the tower block of the Shanghai tower (from http://news.xinhuanet.com/photo).

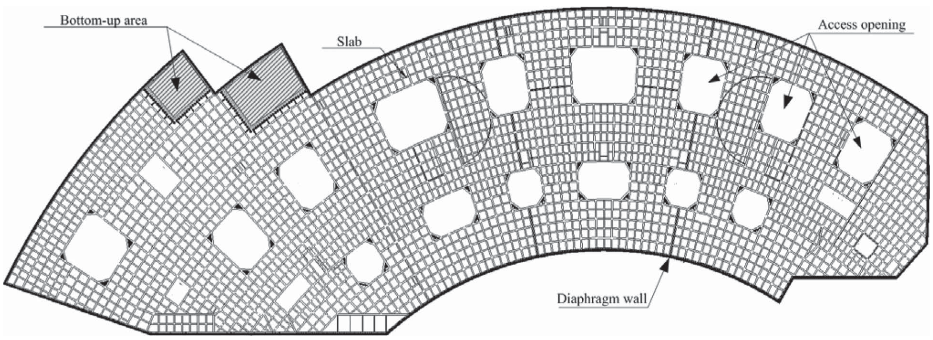


Figure 16. Plan view of the structure of the roof slab and distribution of access openings.

4.4 *Basement excavation for the tallest building in China*

Being the tallest building under construction in China at this moment for its height of 632 m, the Shanghai Tower deserves a space herein. The five-level basement of the project is one of the deepest building basements in Shanghai. Excavation area of the project is 34960 m^2. Excavation depth of the tower block is 31.2 m while that of the podium block is 26.7 m. It is decided to excavate the tower block by bottom-up method and excavate the podium block by top-down method. This united method was also used in the excavation of the basement of the Shanghai World Financial Center (Chu et al, 2005) which is now the tallest building in service (construction completed in 2008) in China with a height of 492 m. The tower block of the Shanghai Tower is firstly excavated and the podium block will be excavated after the B0 slab of the tower block is completed. The tower block is retained by 1.2 m thick circular diaphragm walls with depth of 50 m. The external diameter of the circular diaphragm wall is 123.4 m. Six levels of RC ring beams are constructed inside the wall to reinforce the diaphragm walls for reducing wall deflections. The 6 m thick mat of the tower block is supported on bored piles of 1.0 m in diameter to a maximum depth of 88 m from ground surface. Excavation of the tower block was completed in February, 2010 while construction of the basement was completed in September, 2010. Figure 15 gives a photo showing pouring concrete of the bottom slab of the tower block. Wall deflections observed were 76.5 mm or less (Jia et al, 2010). Excavation of the podium block will commence soon.

4.5 *Largest excavation constructed by top-down method*

The excavation of the North Square of Shanghai South Railway Station (NSSSRS) is so far the largest deep excavation constructed by top-down method. The NSSSRS was a two stories underground structure with an excavation area of 40000 m^2 and depth of 12.5 m. The excavation was retained by 800 mm thick diaphragm walls with depth of about 27.5 m. The walls were supported by the slabs of the underground structure. In order to accelerate the cut and transportation of soils for this ultra large excavation, large size access openings were set in the slabs. The area of the largest access opening was about 700 m^2, while that of others ranges from 400 m^2 to 500 m^2. The areas of these access openings were much larger than those in conventional projects constructed by top-down method. Figure 16 shows the distribution of the access openings in the roof slab. Diaphragm wall deflections observed were 41 mm or less.

5 DEFORMATION CONTROL OF DEEP EXCAVATIONS

5.1 *Concept of performance-based design*

In the 1980s, environment protection problem was not very severe as excavation depth was generally quite shallow. Sheet pile walls and bored pile walls were commonly used to retain the soils. In those days, these retaining walls were generally designed in consideration of their structural capacity and the stability of the ground below the final excavation depth without due consideration given to their lateral deformations. Since the early 1990s, excavations have tended to go not only deeper and deeper but also larger and larger. Meanwhile, deep excavations are often constructed in close proximity to existing structures and properties including buildings, subway stations, metro tunnels, embankments and underground pipelines. As people have become more and more aware of their own rights and the government has recognized the importance of sustaining the safety of public facilities such as subway

Table 1. Protection grade of deep excavations (according to SCMC, 2010).

Environmental conditions	Distance of the structure or properties from the excavation (s)	Protection grade
Heritage buildings, factory buildings with precision instruments and machines, important buildings with shallow foundations or short pile foundations, metro lines, flood control walls, very important services such as water mains and gas mains	$s \leq H$ $H < s \leq 2H$ $2H < s \leq 4H$	I II III
Common building with shallow foundations or short pile foundations, important services such as water supply pipes, gas pipes, and sewage pipes	$s \leq H$ $H < s \leq 2H$	II III

Note: H is the excavation depth.

Table 2. Control criteria for protection environment (SCMC, 2010).

Protection grade	Maximum allowable displacement of wall	Maximum allowable ground settlement
I	0.18%H	0.14%H
II	0.3%H	0.25%H
III	0.7%H	0.55%H

stations and tunnels, protection of adjacent properties has become serious concern for deep excavations. In order to protect the adjacent buildings and properties, the concept of performance-based design, instead of capacity-based design, has been adopted in deep excavations since the 1990's. The purpose of performance-based design is to limit wall displacement and hence ground movements behind walls to fulfill the requirement of deformation control of adjacent properties.

Performance of deep excavations is governed by many factors (Manna and Clough, 1981) such as construction conditions (including soil properties, ground water, existing structures and properties, transient surcharge loads during and after construction), design parameters (including stiffness of the wall, stiffness of supports, support spacing, and depth and with of excavation), and construction parameters (including method and sequence of construction, and during of construction). It is difficult to evaluate the performance of deep excavations and its impact on adjacent structures and properties considering all of these factors. As a result, predicting the magnitude of ground movement and deformation of adjacent structures and properties is still the most challenging task facing the engineers involved in the design and construction of a deep excavation in urban environment.

As ground movements can not be predicted accurately (Gaba et al, 2003), case history data provide a useful guide when making prediction for new deep excavations or setting up criteria of deformation control in comparable conditions. To avoid damage to adjacent structures and properties, three different protection grades (see Table 1) was setup for deep excavations according to the local code of Shanghai (SCMC, 2010). Each grade is defined depending on the importance of the environmental condition and the distance of the structure or properties from the excavation. In order to setup criteria of deformation control of deep excavations, a large number of case histories of deep excavations were collected. They were then classified according to the protection grades defined by Table 1. Maximum lateral displacements of wall were analyzed for each protection grade. The mean value of the maximum lateral displacement of wall was considered as the allowable lateral displacement of wall for each protection grade. Allowable ground surface settlement for each protection grade was obtained by 0.8 times the maximum allowable lateral displacement of wall according to the statistical relationship between maximum ground settlement and maximum lateral displacement of wall. Criteria of deformation control of deep excavations were then obtained, as shown in Table 2. Control criteria listed in Table 2 can be used as a guide in the design of deep excavation. According to the experience in Shanghai, normal operating of the adjacent structures and properties will not be likely affected according to the control criteria listed in Table 2, as long as the excavations are constructed with normal construction activities.

5.2 *Deformation control method*

5.2.1 *Using top-down method*

Top-down method provides a stiff support system for the retaining wall. Therefore, top-down method is more effective in deformation control than bottom-up method. Study conducted by Wang et al (2010) shows that average value of maximum deformation of 32 excavations constructed by top-down method in Shanghai is 0.27%H, which is much smaller than the average value of 0.4%H for 200 excavations constructed by bottom-up method (see Figure 17). Top-down method is consequently a good choice to minimize ground movements for deep excavation adjacent to sensitive environment.

Figure 18 shows the plane view of the construction site of the Xingye Building which located in

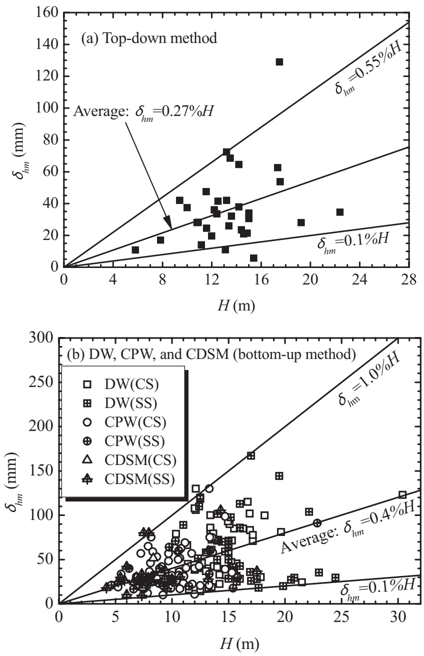


Figure 17. Maximum lateral displacement of wall δ_{hm} versus excavation depth H (Wang et al, 2010).

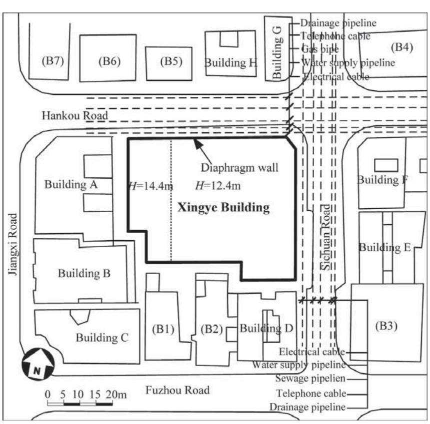


Figure 18. Plane view of the construction site of the Xingye Building.

the old city zone of Shanghai. The building has 19 floors above ground and three floors under ground. Excavation depth of the west side of the building was 14.4 m while that of the east side was 12.4 m. The excavation site was adjacent to 15 buildings, among which 8 (Building A to Building H) were heritage buildings with shallow foundations or strip foundations with short wooden piles. The minimum distance between the excavation and the heritage buildings was about 4.2 m. Meanwhile, many old pipelines were distributed under the Hankou Road and the Sichuan Road. Environmental protection was extremely strict in this project. Top-down method was adopted in order to protect the adjacent buildings and services. The excavation was retained by 1.0 m thick diaphragm walls on the west and south sides, and by 0.8 m thick diaphragm walls on the north and east sides. The diaphragm walls were supported by three levels of slabs of the permanent substructure. Monitored results showed that the maximum lateral displacement of the wall was 37.9 mm and the maximum ground settlement was 22.4 mm. Figure 19 shows a 3D settlement distribution of Building A at the final excavation stage. The maximum settlement of Building A was 27.2 mm. Building A was a RC frame structure. According to empirical limitation criteria proposed by Polshin and Tokar (1957), limiting distortion of the cracking of infill of RC frame structure was 1/500. The maxi-mum angular distortion of Building A was about 1/780, which was smaller than 1/500. As a result, no further development of the original old cracks of Building A was observed. Top-down method was very effective in deformation control in this project and the normal use of the adjacent buildings and services was not affected by the excavation.

5.2.2 *Reinforcement of soils inside the excavation*

In order to increase the strength of soft soils and thus reduce the deformation of the soils during

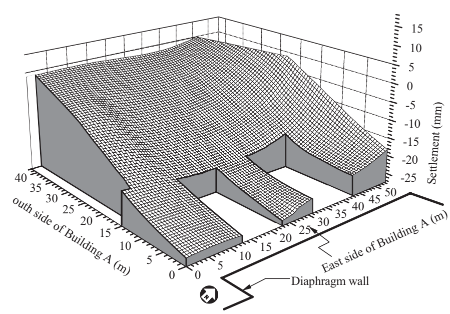


Figure 19. 3D settlement distribution of Building A at the final excavation stage.

excavation to protect the adjacent structures and properties, reinforcement of soils inside the excavation is widely used in Shanghai. The soils inside the excavation may be reinforced by deep mixing method (using double shaft machine or triple shaft machine) or jet grouting method. For deep soil mixing columns formed by double shaft machine, dosage of cement is generally required not less than 13% with a water-cement ratio of 0.45 to 0.6. The unconfined compressive strength (UCS) of the deep soil mixing columns is required not lower than 0.6 MPa after cured for 28 days. For deep soil mixing columns formed by triple shaft machine, dosage of cement is generally required not less than 20% with a water-cement ratio of 1.5 to 2.0. The UCS of these deep soil mixing columns is required not lower than 0.8 MPa after cured for 28 days. While for columns formed by jet grouting method, dosage of cement is generally required not less than 25% with a water-cement ratio of 0.8 to 1.5. The UCS of the columns is required not lower than 1.0 MPa after cured for 28 days. The layout of the reinforcement depends on the construction features and stratum conditions. Figure 20 shows the commonly used layouts of the reinforcement of soils inside the excavation.

The Nanjing West Road Block project located in the central district of Shanghai city. The excavation depth of the podium and tower part was 14.2 m and 15.5 m, respectively. On the south side of the excavation, the No.2 subway tunnels which

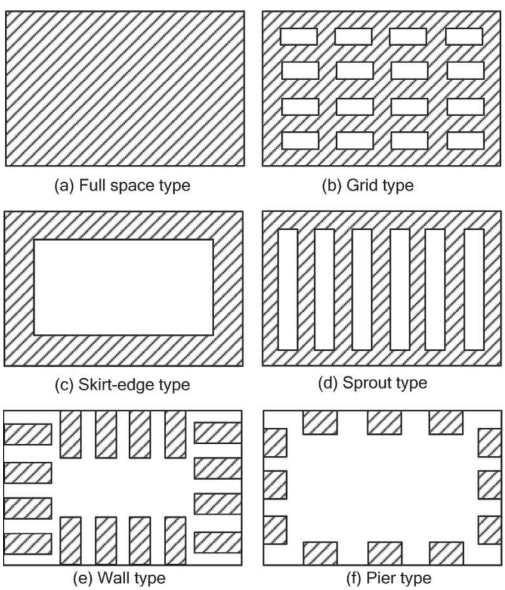


Figure 20. Layouts of the reinforcement of soils inside the excavation.

were laid about 8.5 m below the ground surface were only about 10.2 m away from the excavation (see Figure 21). The excavation was divided into two zones, namely, Zone I and Zone II. Zone I was retained by 0.8 m thick diaphragm wall which were supported by three levels of RC struts. Excavation of Zone I started after the finish of the construction of Zone I. Zone II was retained by 1.0 m thick "T" type diaphragm wall with a depth of 42 m on the south side. The "T" type diaphragm walls were supported by RC struts at the first level and three levels of steel struts. In order to reduce the effect of excavation on the tunnels, shirt-edge type soil reinforcement was adopted on the south side of the excavation. The soils inside the excavation were reinforced by deep soil mixing columns formed by triple shaft machine. The diameter of the columns was 650 mm. The width of the reinforcement ranged from 10 m to 15 m. The reinforcement started from the elevation of –5.400 m while ended at the elevation of –20.600 m, as shown in Figure 22. Dosage of the cement above and below the final excavation depth was 10% and 20%, respectively. Deep soil mixing columns were also used to reinforce the trench of the "T" type diaphragm walls. It was proved that the reinforcement of the soils inside the excavation was effective. Figure 23 show the lateral displacement of the diaphragm wall on the south side of the excavation. The maximum lateral displacement was only 21.8 mm. The maximum displacement of the tunnels was less than 5.0 mm. The metro in operation was successfully preserved.

5.2.3 *Zoned excavation*

Zoned excavation method is sometime used for excavation with very strict environmental protection requirement. In this method, the excavation is divided into a relatively big pit and a small pit. The small pit is just adjacent to the structures or properties which need careful protection. The big pit and the small pit are separated by temporary walls such as diaphragm walls and contiguous pile walls. The big pit is firstly excavated. The excavation of the big pit will have a very limited effect on the structures and properties adjacent to the small pit as the separation walls and the soils in the small pit form a barrier to the structures and properties. The small pit will then be excavated after the construction of the underground structure of the big excavation zone is finished. The excavation of the soil and installation of struts can be very quick as the area of the small pit is small. Previous study shows that the creep property of soft soils in shanghai (Huang and Gao, 2005) plays a critical role in soil deformation in deep excavations. Therefore, quick excavation of the soils will shorten the elapsed time of construction and this will be very effective in

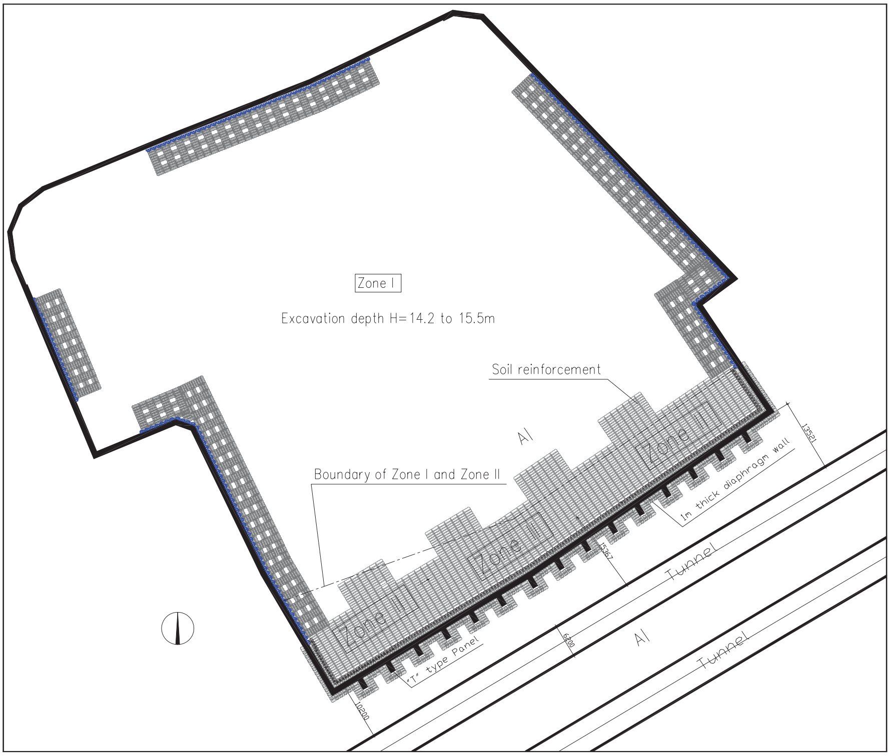


Figure 21. Layout of the reinforcement of the excavation of the Nanjing West Road Block project.

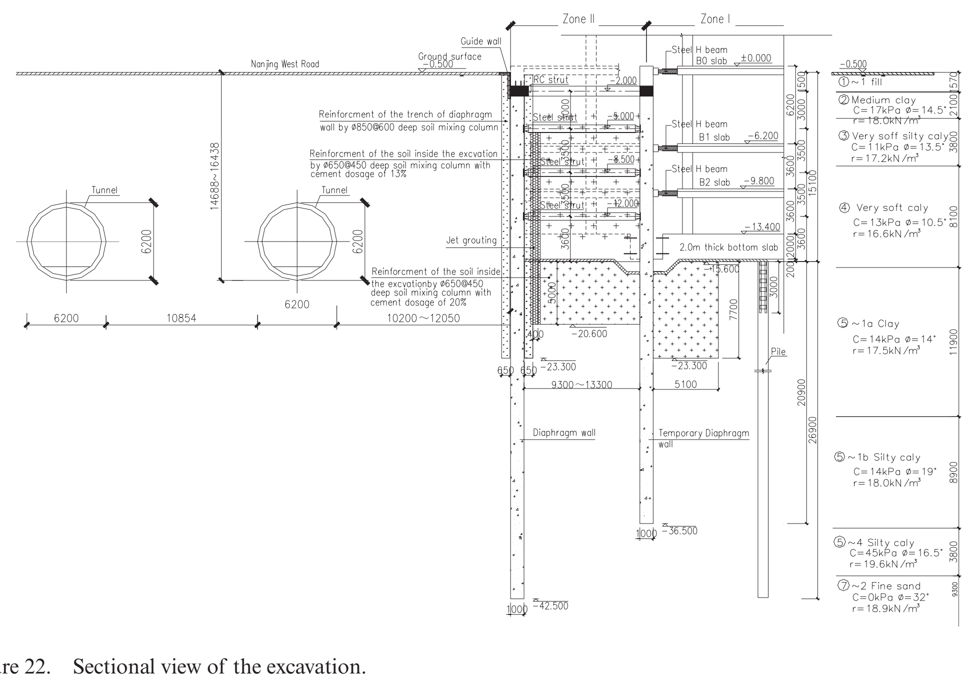


Figure 22. Sectional view of the excavation.

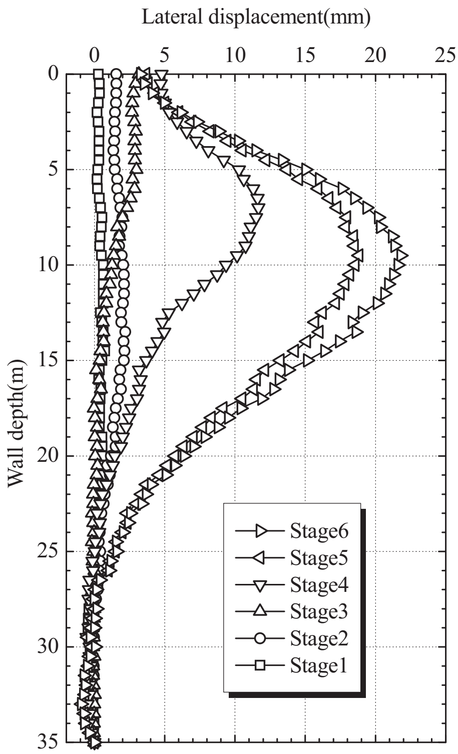


Figure 23. Lateral displacement of wall.

reducing the impact of the excavation on the adjacent structures and properties.

The Shanghai Shengda Center project was adjacent to the No. 4 metro and No. 2 metro. The No. 4 metro tunnels which were laid 16 m below the ground surface are only about 6 m away from the excavation. The excavation depth of the project ranged form 17.15 m to 22.15 m. In order to protect the tunnels of the No.4 metro, the excavation was divided into two zones, namely, Zone I and Zone II, as shown in Figure 24. Zone I and Zone II was separated by 1.0 m thick temporary diaphragm wall with a depth of about 41 m. The Excavation of Zone I was retained by 1.2 m thick diaphragm wall on the north side and 1.0 m thick diaphragm wall on the east side. The diaphragm walls of Zone I were retained by five levels of RC struts. The excavation of Zone II was retained by 1.0 m thick diaphragm walls. The diaphragm walls of Zone II were retained by the first level RC struts and four levels of steel struts below. Zone I was firstly excavated. Excavation of Zone II commenced after the construction of the underground structure of Zone I finished. Figure 25 shows a sectional view of the retaining system of the excavation. Figure 26(a) shows the lateral displacement of the inclinometer installed at monitored point Q16 (see Figure 25) in the diaphragm wall in Zone I. The maximum lateral displacement was 32.8 mm. Figure 26(b) shows the lateral displacement of the inclinometer

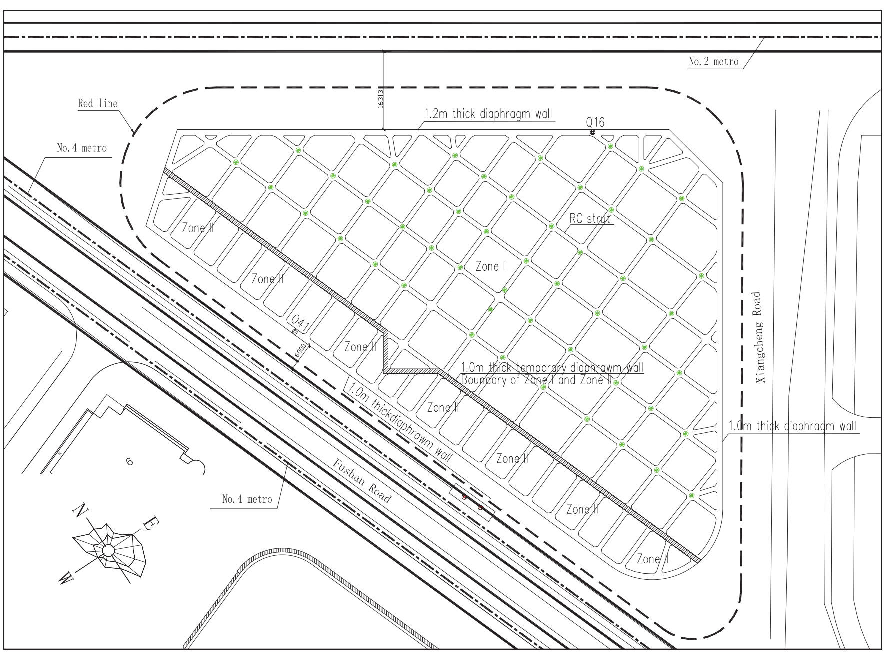


Figure 24. Plane view of the construction site of the Shanghai Shengda Center.

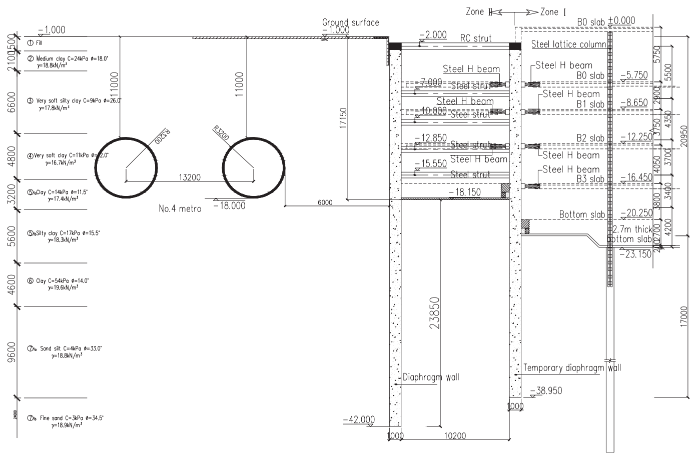


Figure 25. Sectional view of the retaining system of the Shanghai Shengda Center.

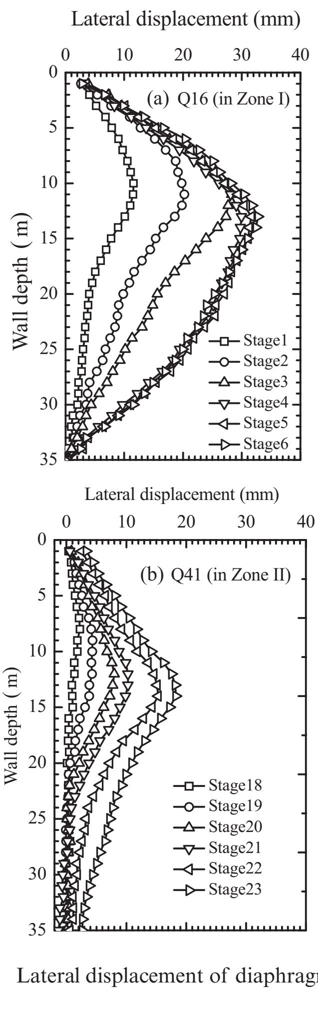


Figure 26. Lateral displacement of diaphragm wall.

installed at monitored point Q41 (see Figure 25) in the diaphragm wall in Zone II. The maximum lateral displacement was only 18.3 mm. It is obvious that deformation of Zone II was much smaller than that of Zone I. Monitored results also show that the maximum settlement of the tunnels of No.4 metro was about 5.2 mm. The normal operation of the tunnels was not affected by the excavation.

5.2.4 *"Time and space effect" excavation method*

The deformation of retaining structure and soils mass around the excavation relates to many important factors such as the volume of excavation, duration without struts due to creep effect, and sequence of the excavation. Liu et al. (1999) suggested excavation procedure taking into account the rational planning and sequence of the excavation, including the lifts, plots, symmetry, time, and bracing. This so called "Time and Space Effect" excavation method is an empirical method developed in Shanghai. Engineering practice has proved that this excavation method is efficient for deformation control of deep excavations in Shanghai soft soil.

The Shanghai Square project (Liu and Wang, 2009) consisted two parts, namely, the north part and the south part. The north part had 34 floors above ground and three floors under ground. Excavation area of the north part was 9656 m^2 and the excavation depth ranged from 15.1 m to 16.0 m. The No.1 metro tunnels were only about 2.6 m away from the excavation on the south side. The excavation was retained by 0.8 m thick diaphragm walls with depth ranging from 25.2 m to 28.2 m. The diaphragm walls were supported by 4 levels of RC struts. "Time and Space Effect" excavation method was adopted in this project.

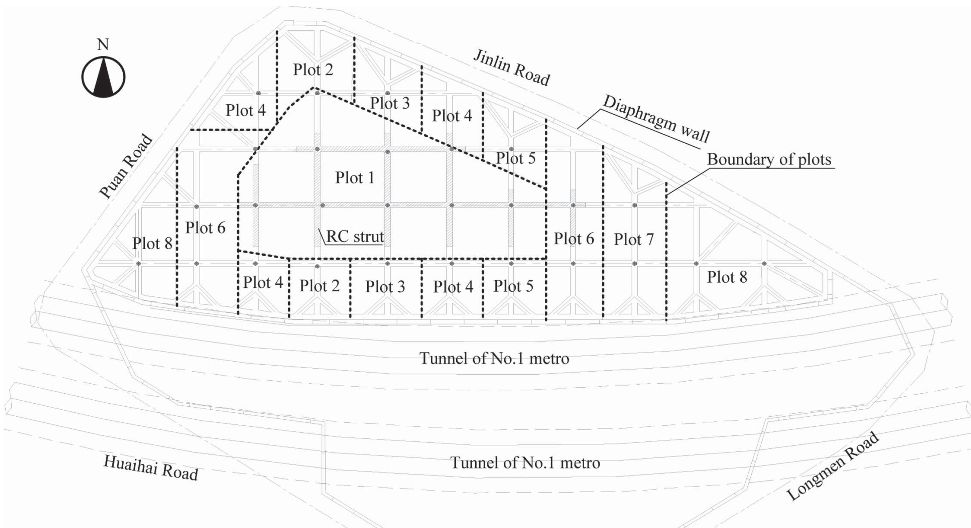


Figure 27. Plane view of the plots of the excavation of the Shanghai Square project (according to Liu and Wang, 2009).

The north part was excavated in five lifts. In each lift, the excavation was divided into 8 plots, as shown in Figure 27. The steps in the excavation procedure were as follows: (1) excavating the soil in Plot 1; (2) pouring the RC struts corresponding to the unloading space; (3) excavating the soil in Plot 2 ~ Plot 8 sequentially and promptly installing the corresponding struts in turn; and (4) continuing steps 1–3 for the second, third, fourth, and fifth lifts until the design depth of the excavation was achieved. It was required that the above excavation procedure should be strictly observed and over cut of the soil should be avoided. Moreover, RC struts should be poured in 48 hours after the soil was excavated. Monitored data showed that the maximum lateral displacement of the diaphragm wall was 28.2 m. Maximum lateral displacement and maximum settlement of the tunnel were 13.1 mm and 14.1 mm, respectively.

6 SUMMARY AND CONCLUSION

Numerous deep excavations have been carried out in Shanghai for constructing high-rise buildings, subway transportation networks and other underground structures in the past two decades. There is significant advancement in design and construction practice of deep excavations in Shanghai. The successful completion of the introduced cases which are benchmarks of deep excavations is an index of the technology level and the quality of the local construction industry.

For deep excavations adjacent to complex environment conditions, performance-based design is an essential concept for engineering practice so that the surrounding structures and properties can be protected effectively. Three different protection grades and corresponding deformation control criteria were setup for deep excavations according to the local experience. These can be used as a guide in the design and construction of deep excavations. Top-down method, reinforcement of soils inside the excavation, zoned excavation, “Time and Space Effect” excavation method are effective measures in mitigating the impact of deep excavations on adjacent structures and properties. However, due to limitations in the state of current knowledge in soil mechanics, the complex nature of soil behavior, and complex mechanism of soil-structure interaction, quantitative prediction of the effect of these methods is still very difficult and it needs further investigation. Therefore, use of instrumentations to monitor the performance of excavations and the surrounding structures and properties should be considered as an essential element of the total technique.

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