

Case Study of Top-Down Construction Method in Upper-Soft and Lower-Hard Stratum

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ABSTRACT

With the continually exploitation of underground space in urban, the deep and large braced excavations are frequently reported and the surroundings are complex. The deformation and precision control, and structure durability are the main problems in the construction process using top-down excavation method. Based on Dadongmen transfer station braced excavation project of Hefei Metro 1 and Metro 2 in China, the construction technology of top-down excavation method in upper-soft and lower-hard is proposed. The technologies contain the deformation control of diaphragm wall excavation and deep-large foundation-pit excavation, the high precision construction technology of belled steel pipe pile and newly connection method of diaphragm wall and underground station structure. From the field application, the construction quality, precision and structure durability are satisfied, and can be applied to the similar projects.

KEYWORDS: Deep and large braced excavation; top-down excavation method; upper-soft and lower-hard stratus; belled steel pipe pile

INTRODUCTION

With the continually exploitation of underground space in urban, the deep and large braced excavations are frequently reported and the surroundings are complex. The deformation and precision control (e.g., Liu and Lu 2004, Long 2001, Kung et al. 2007, Kung 2009, Osman 2006, Zhu et al. 2013) are the main problems in the construction process. There are two main construction methods for deep and large brace excavation: bottom-up method (e.g., Finno 1989, Hashash 2008, Tan and Wei 2012) and top-down method (e.g., Ikuta 1994, Ou 1998, Tan 2011). In top-down method, the floor slab having high stiffness is the strut, and the deformation of the surrounding is

minimized (Wang et al. 2010). So, the top-down method has been widely adopted in deep and large foundation pits (Tan 2011, Kung 2009; Cotton and Luark 2010).

Although the top-down method has the advantage in deformation control, there is still a gap from mm-level deformation control. So, the deformation control including the diaphragm wall construction (Farmer and Attewell 1973, Liu and Lu 2004, Ng and Yan 1998) and foundation-pit excavation (Long 2001, Kung 2007, Kung 2009, Osman 2006) are still the problems. The belled pile has the advantage of high uplift capacity (Ismael et al. 1994, Wu et al. 2008), and has been widely used in anti-float project. But the construction precisions of the bored pile in upper-soft and lower-hard and long steel pipe jacking are very difficult. The structure construction of top-down method is from the upper floor slab to the lower floor slab. The construction quality of the structure can not compare with the bottom-up method, and the seepage appears frequently. So the waterproof performance and durability of top-down method underground structure are the main problems.

This paper is based on the Dadongmen transfer station of Hefei Metro 1 and Metro 2 in China, which is a deep-large braced excavation. The top-down excavation method is adopted in this project. The technologies of micro-deformation control for surroundings and high-precision construction for belled steel pipe piles are investigated. Meanwhile, the tenon-groove connection method between diaphragm wall and underground station structure is proposed to strength the connection strength and waterproof performance. By using these technologies, the transfer station was completed safely.

PROJECT OVERVIEW

Project information and site condition

Dadongmen metro station is the transfer station of Hefei Metro 1 and Metro 2, China. The transfer station is located at the intersection of Shengli Road and East of Changjiang Road, and the station of Metro 1 is located under the Shengli Road and the station of Metro 2 under the East of Changjiang Road. The transfer station is T-shape, and the station of Metro 1 is under the station of Metro 2. The excavation depth of Metro 1 is 31.7 m and 24.4 m for Metro 2. The buildings nearby are the Gujing Holiday Hotel with the spacing of 10.7 m and Shengda International Hotel with the spacing of 10.0 m. The west and the south of the transfer station is Nanfei River. The minimum spacing between the transfer station and the Nanfei River is 4.5 m. The plan view of the transfer station is shown in Figure 1.

All the stations of Metro 1 and Metro 2 are island platform with the width of 14.0 m. The station of Metro 1 is a four-floor underground frame structure with three-span, and the length, width and excavation depth of standard section are 145.44 m, 23.5 m and 31.7 m respectively. The maximum excavation depth of the station of Metro 1, the end well, is 33.1 m, the deepest station of Metro 1. Figure 2 is the elevation view of the Station of Metro 1. The station of Metro 2 is a three-floor underground frame structure with three-span, and the length, width and excavation depth of standard section are 220.5 m, 23.5 m and 24.4 m respectively. The excavation depth of the end well is 25.3 m. The intersection of the two stations is a three-floor underground frame structure with multi-span. The total floor area of the transfer station is 34837m².

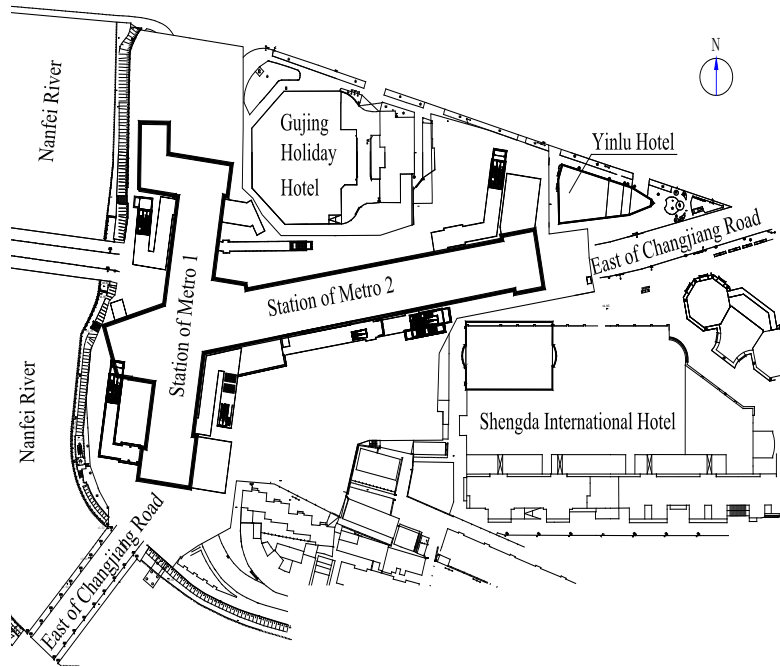


Figure 1: The plan view of the transfer station

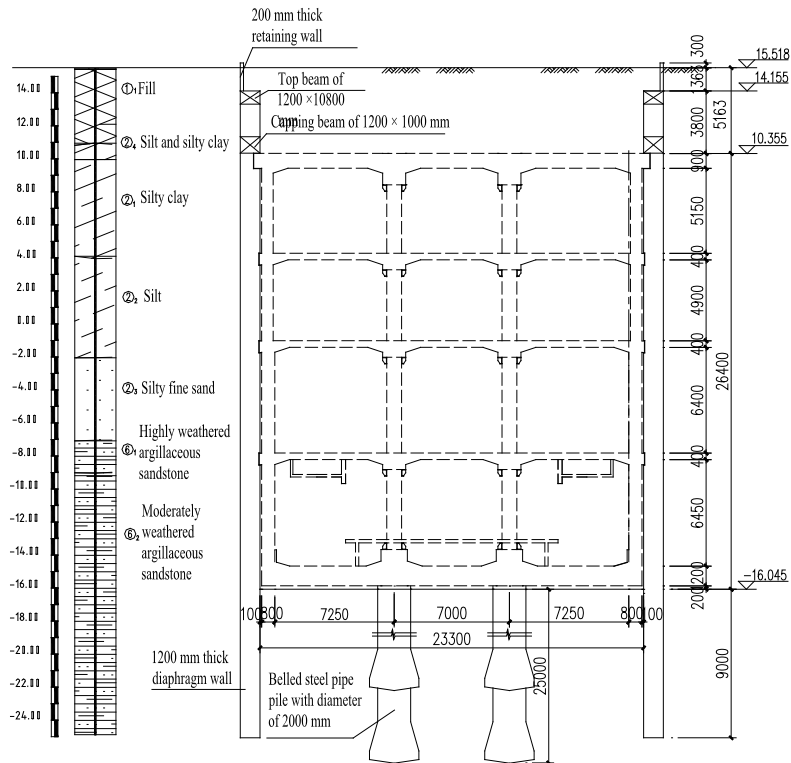


Figure 2: The elevation view of the Station of Metro 1 (unit: mm)

Considering the excavation depth and the surrounding, the top-down construction method (Ikuta 1994; Ou 1998; Kung 2009; Tan 2011) is adopted for this project. The construction process is shown in Figure 3.

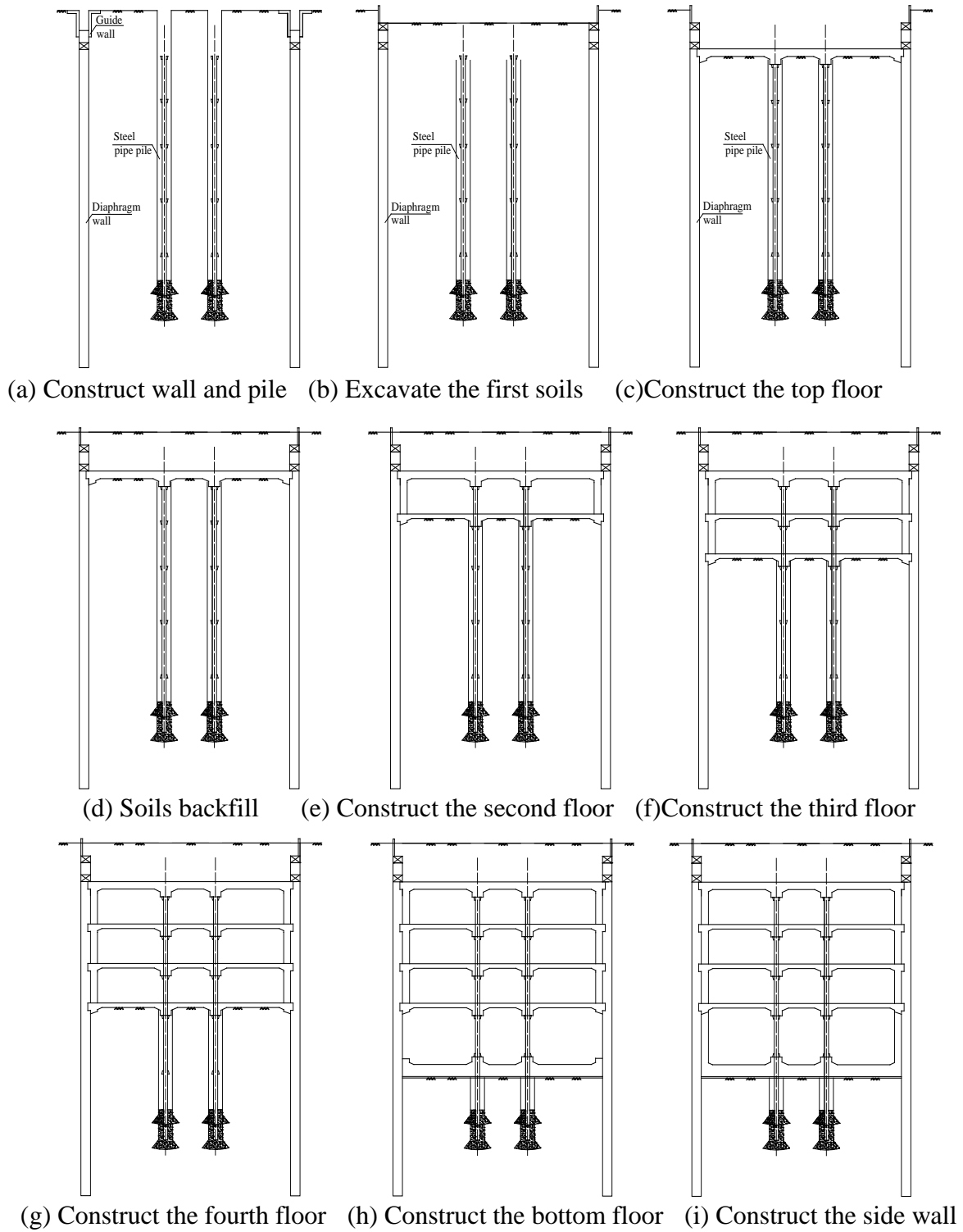


Figure 3: The construction process of top-down method

The retaining structure of the station of Metro 1 is diaphragm wall with the width of 1.2 m, and depth of 40.7 m for the standard section (in reference to Figure 2), 42.1 m for the end well. The retaining structure of the station of Metro 2 is diaphragm wall with the width of 1.0 m, and the depth of 29.85 m for the standard section, 31.30 m for the end well. For the need of anti-float, there are many belled steel pipe piles in the transfer underground station. The underpart of the belled steel pipe piles are in the sandstone layer.

Geotechnical profile and soil properties

The construction site is generally flat. The stratum from the ground surface to a depth of 50.0 m is divided into seven layers in terms of soil characteristics, namely, fill layer ①, silty clay layer ②₁, silt layer ②₂, silty fine sand layer ②₃, silt and silty clay layer ②₄, highly weathered argillaceous sandstone layer ⑥₁ and moderately weathered argillaceous sandstone layer ⑥₂. The mechanical properties of the soils are listed in Table 1. The cohesion and the inner friction angle are obtained by consolidated-undrained triaxial shear test (CU). The bottom floor of the station of Metro 1 is located in moderately weathered argillaceous sandstone layer ⑥₂, and the uniaxial compressive strength of layer ⑥₂ is about 2.45 MPa. The bottom floor of the station of Metro 2 is located in highly weathered argillaceous sandstone layer ⑥₁. From Table 1, it shows that the stratum has the characteristic of upper-soft and lower-hard.

Table 1: Mechanical properties of soil

| NO. | Name | Unit Weight (kN/m ³) | Compression modulus (MPa) | CU | | Permeability coefficient (m/d) | |
|----------------|---|----------------------------------|---------------------------|----------------|--------------------|--------------------------------|----------|
| | | | | Cohesion (kPa) | Friction angle (°) | Horizontal | Vertical |
| ① | Fill | 17.5 | — | 0 | 8 | — | — |
| ② ₁ | Silty clay | 19.9 | 8 | 30 | 7 | 0.05 | 0.05 |
| ② ₂ | Silt | 20.5 | 8.3 | 20 | 11 | 0.5 | 0.5 |
| ② ₃ | Silty fine sand | 20.1 | 9.6 | 10 | 25 | 2.0 | 2.0 |
| ② ₄ | Silt and silty clay | 17.6 | 3 | 5 | 6 | 0.01 | 0.01 |
| ⑥ ₁ | Highly weathered argillaceous sandstone | 21.0 | 30 | 35 | 30 | 0.2 | 0.2 |
| ⑥ ₃ | Moderately weathered argillaceous sandstone | 23.2 | — | — | — | 0.05 | 0.05 |

There are two types of groundwater within the construction site, namely, phreatic water in the shallow clay layer, confined water in silt layer ②₂ and silty fine sand ②₃. The buried depth of the phreatic water table is approximately 1.35 ~ 5.50 m. The buried depth of water table of confined water is approximately 1.20 ~ 4.90 m below the ground surface, and having the depth of 6.10 m ~ 14.55 m.

Construction problems

The Dadongmen transfer station of Hefei Metro 1 and Metro 2 has the features of deep excavation, abnormal shape, upper-soft and lower-hard stratum and high protection level of surroundings. Furthermore, the construction precision (horizontal deviation and verticality deviation) of the steel pipe pile will affect the architectural appearance and using function of the station, as the steel pipe piles are permanent structures. Meanwhile, the waterproof properties and durability are the construction challenges of top-down method (Wang 2015; Zhang 2010). In a word, the construction problems of this project mainly contain the following aspects:

- (1) Micro-deformation control technology for deep and large top-down construction method.
- (2) High-precision construction technology of belled steel pipe piles in upper-soft and lower-hard stratum.
- (3) High waterproof ability and high durability of the underground structure of top-down construction method.

According to the problems aforementioned, the cross-steel joint of diaphragm wall and two-phase deformation control are proposed for controlling the deformation, three-stage boring technology of belled pile and two-point jacking steel pipe pile are adopted for the precision control of belled steel pipe pile and tenon-groove connection method is proposed for the structure construction of top-down method. The specific scheme is described as below.

TECHNOLOGY FOR DEFORMATION CONTROL

The deformation caused by foundation-pit construction mainly contains two parts, diaphragm wall trench construction (Farmer and Attewell 1973, Liu and Lu 2004, Ng and Yan 1998) and foundation-pit excavation (Long 2001, Kung 2007, Kung 2009, Osman 2006). So the technology for deformation control also includes the two aspects.

Construction technology of diaphragm wall

In the construction of diaphragm wall, the quality of joint will directly influence the waterproof capability of diaphragm wall (Van Tol et al. 2010, Spruit et al. 2014) and the construction deformation (Liu and Lu 2004). There are many joint forms of diaphragm wall, such as fore shaft pipe joint, I-beam steel joint, cross-steel joint and joint case (Huang 2004), in which the fore shaft pipe joint is flexible joint and the other joints are rigid joints. The waterproof capability and the bearing capability of flexible joints are relatively lower than the rigid joints (Xu et al. 2011). The Dadongmen transfer station of Hefei Metro 1 and Metro 2 is near the river and construction method is top-down method, in which the diaphragm walls have the double functions of retaining soils and water, and bearing the loads of permanent structures and construction. So the cross-steel joint form of diaphragm wall is adopted for this project. The sectional view of the cross-steel joint is shown in Figure 4 and the Figure 5 is the picture of the joint.

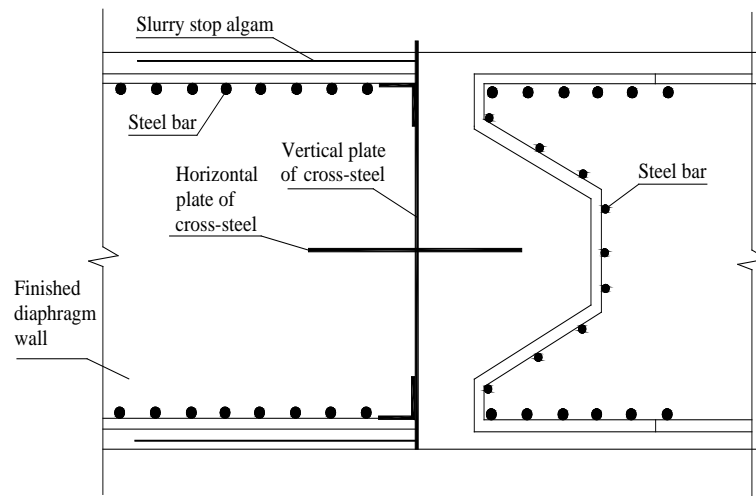


Figure 4: The sectional view of cross-steel joint



Figure 5: The picture of cross-steel joint

The local failure of slurry trench for diaphragm wall (Filz et al. 2004) will occur in the soils of sand (in reference to Figure 6), and cause excessive deformation (Farmer and Attewell 1973, Liu and Lu 2004). In order to control the stability of slurry trench, the high-pressure rotation jet piles along the outside of diaphragm wall are constructed, as shown in Figure 7. The reinforcement layers are mainly the confined water aquifers, silt layer ②₂ and silty fine sand ②₃. The parameters of the high-pressure rotation jet piles are diameter of 850 mm and spacing of 1000 mm. The unconfined compression strength of the reinforced soil should be greater than or equal to 1.0 MPa. The ultrasonic test images of the slurry trenches are shown in Figure 8. From Figure 8, it is shown that the slurry trenches reinforced by high-pressure rotation jet piles are in stable and the local failures are not occurred.



Figure 6: Local failure of slurry trench

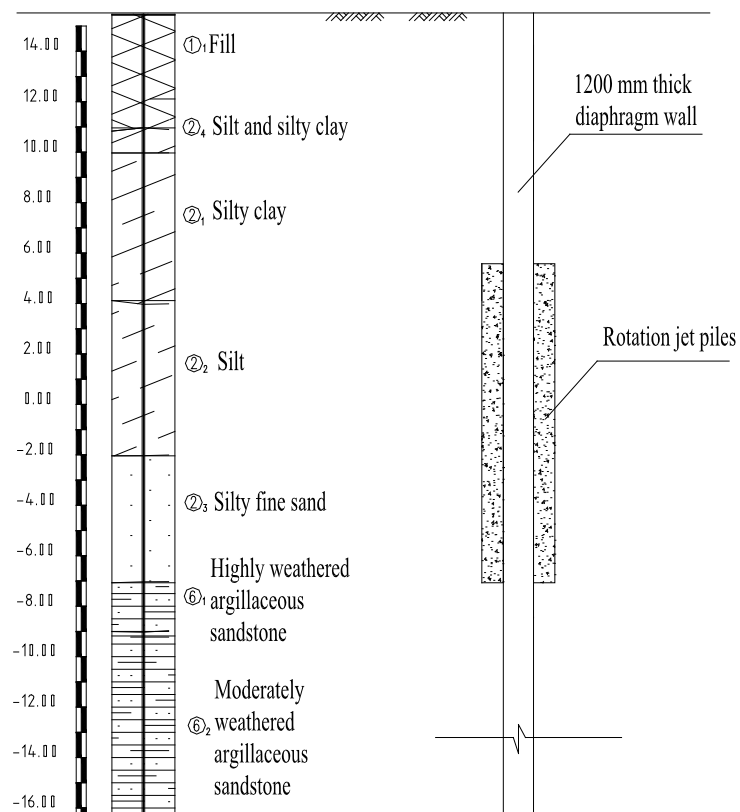


Figure 7: The profile of reinforcement

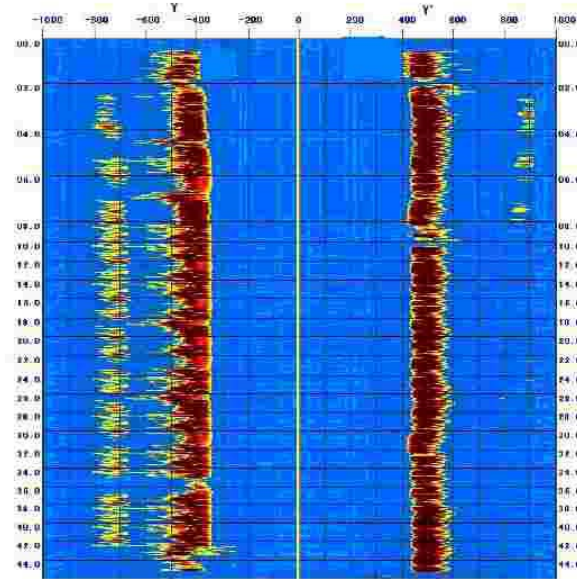


Figure 8: The ultrasonic test image of slurry trench

According to the design drawing, the diaphragm walls will insert into the moderately weathered argillaceous sandstone layer ⑥2. The depths that insertion into layer ⑥2 for Metro 1 and Metro 2 are 20 m and 14 m respectively. The construction efficiency of clamshell grabs trench cutter in hard stratum is lower and the verticality of diaphragm wall trench is hard to meet. For the hard stratum, the percussion drill and double wheels trench milling machine (Wang et al. 2008, Bai 2007) are effective. While the cost of double wheels trench milling method is high. So in this project, the synthetic trenching method of clamshell grabs trench cutter and percussion drill is adopted. In the upper-soft stratum, the clamshell grabs trench cutter is used to form trench. As the length of a single trench is about 6.0 m, it is divided into three grabs (first grab, second grab and third grab in Figure 9) to complete. In the lower-hard stratum, the percussion drill is used to form trench. The holes are divided into main holes and accessory holes (in reference to Figure 9), and the construction sequence is main holes first and accessory holes afterward. Finally, the interlayer of slurry trench is cleaned by plane set-hammer with the plane size of 1.2 m (thickness) \times 1.0 m (length). From the application, it is shown that the construction time of single trench is about 12 hours and the verticality can fulfill the requirement.

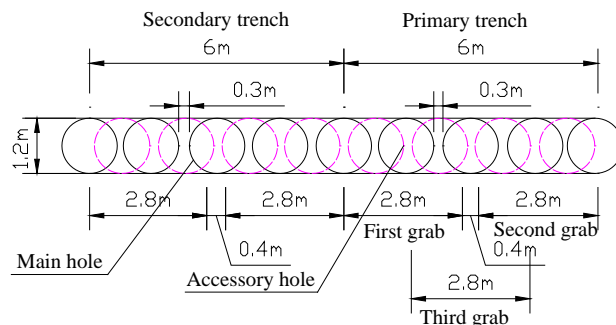


Figure 9: The trenching sequence



Figure 10: The percussion drill

Excavation technology of foundation-pit

As this project belongs to deep and large excavation, the deformation control of soils, especially for the existed buildings, is very important. The following methods have been adopted for this project to control the deformation.

The method of setting isolation piles is very effective to control the deformation of existed building caused by deep excavation (Ding et al. 2011). There are two important buildings near the transfer station, Gujing Holiday Hotel and Shengda International Hotel. Both are high-rise buildings, having the piles as the bearing structures. In order to effectively protect the existed buildings, the soils near the existed building are reinforced by three-row high pressure rotation jet piles with the diameter of 800mm and spacing of 600 mm, as shown in Figure 11. The bottom of the reinforced soils should insert into the highly weathered argillaceous sandstone layer at least 1.0 m. The roles of the isolation piles mainly contain the following two aspects, assuring the stability of the diaphragm wall trench and intercepting the deformation caused by deep excavation.

In the top-down excavation method, the floor slabs are not only permanent structures, but also the struts in the construction (Ikuta 1994). The construction methods of floor slab in top-down method contain scaffold formwork method and “soil formwork” method (Sun and Xiao 2016). For the convenience of installation and dismantling, the height of the scaffold is about 1.5 m. That is to say the depth of over-excavation is about 1.5 m, if the scaffold form-work method is used. That may cause large deformation of surrounding. In order to control the deformation caused by excavation, the “soil formwork” method is adopted in this project. The structure of the “soil formwork” is shown in Figure 12. It mainly contains two layers, the plastic flooring and fine aggregate concrete with the thickness of 10 cm. The fine aggregate concrete is the supporting body and the plastic flooring can improve the surface quality of the floor slab.

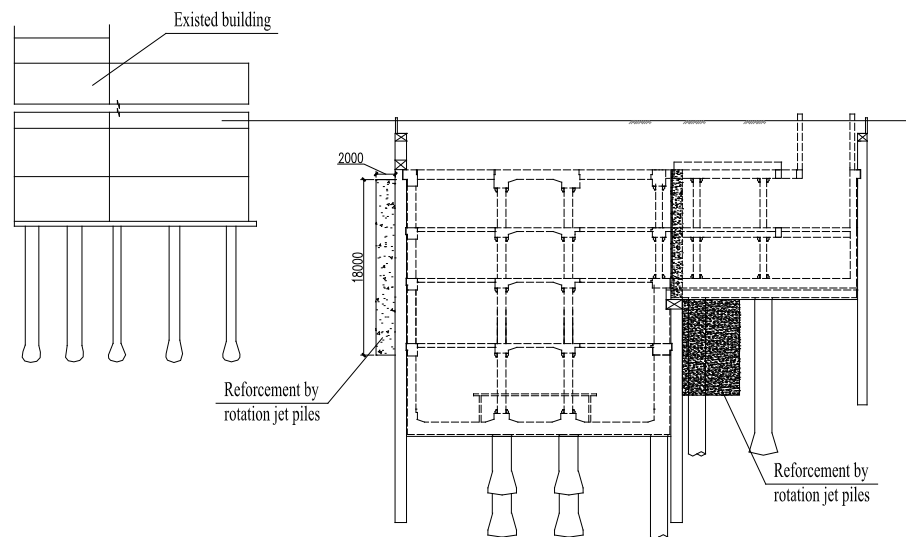


Figure 11: The elevation view of reinforcement

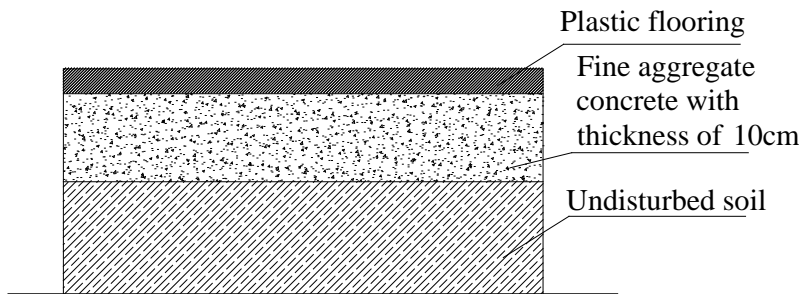


Figure 12: The structure of “soil formwork”

The excavation method of stratification and segmentation is adopted to control the construction deformation. This project is divided into eight segmentations (in reference to [Figure 13](#)) and five stratifications for the station of Metro 1 and four stratifications for the station of Metro 2 (in reference to [Table 2](#)). According to the segmentations, the layout of soil shifting holes is shown in [Figure 13](#). The layout should meet the following two needs, convenient for soil shifting and using the permanent structure. Meanwhile, the over-excavation is prohibited.

Table 1: Mechanical properties of soil

| Station | Excavation depth (m) | | | | |
|---------|----------------------|--------|-------|--------|-------|
| | First | Second | Third | Fourth | Fifth |
| Metro 1 | 4.90 | 6.85 | 5.30 | 6.80 | 7.85 |
| Metro 2 | 4.50 | 6.85 | 5.30 | 7.60 | — |

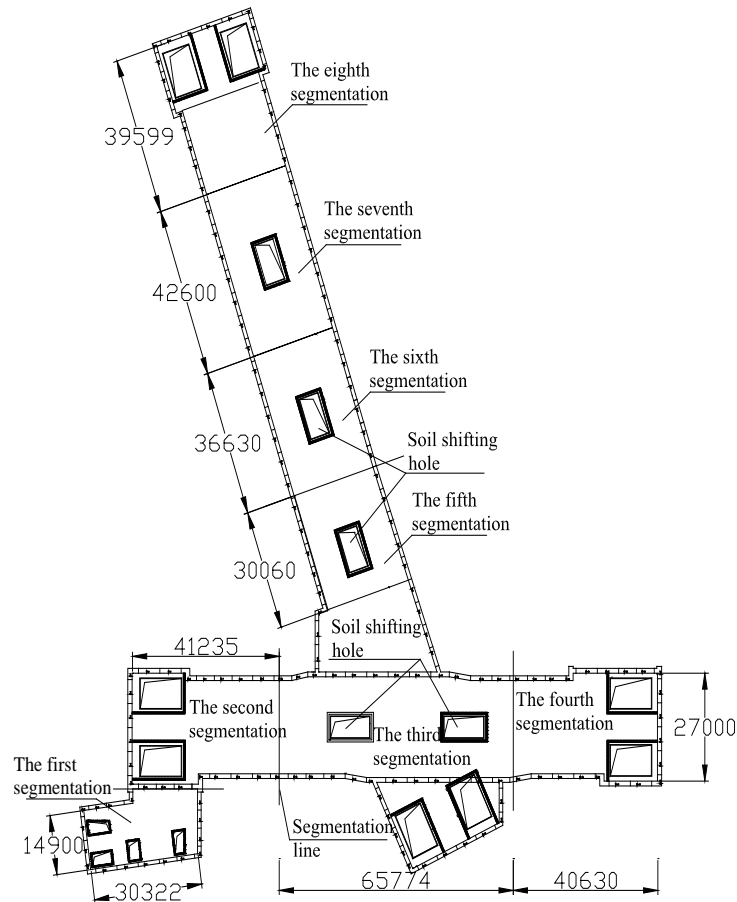


Figure 13: The layout of excavation scheme

By adopting the methods aforementioned, the surroundings are in safe state. The maximum ground settlement is 27.3 mm. The maximum settlement and declivity ratio of Gujing Holiday Hotel are 6.9 mm and 2% respectively, and 6.6 mm and 2% for Shengda International Hotel. The maximum horizontal deformation of diaphragm wall is 21.55 m, only 0.68‰ of the excavation depth (31.7m). According to PSCG (2000), all the values monitored are within the control values.

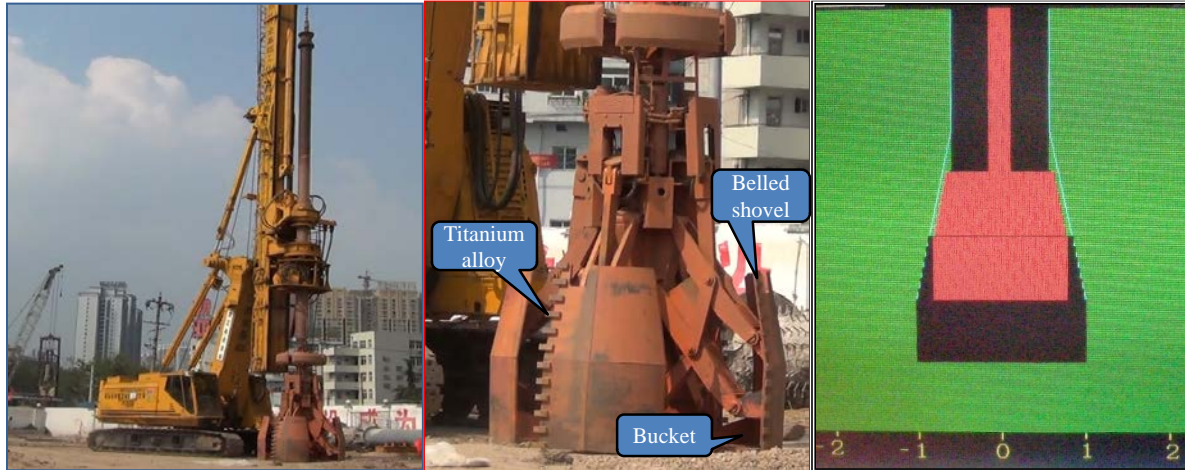
CONSTRUCTION TECHNOLOGY OF BELLED PIPE PILES

In the upper-soft and lower-hard stratum, the construction quality and precision of belled steel pipe pile is difficulty. According to the actual conditions, the three-stage boring technology of belled pile and two-point jacking steel pipe pile are adopted.

Three-stage boring technology

According to the stratum conditions, the three-stage boring technology is adopted for this project. In soft stratum, the rotary drilling rig is used for hole formation. In hard stratum, the rotary drilling rig is replaced by percussion drill, which can ensure the construction quality and efficiency. When the depth of hole is equal to the designed value, the visible hydraulic belled rotary drilling rig (in reference to Figure 14) is adopted. The belled shovel is divided into four equal parts, and the titanium alloy is inlaid in the cutter head, as shown in Figure 14(b). The expanding hole is completed by

rotating the belled shovel and cutting the soils. The soils cut down are carried away by the bucket under the belled shovel. The construction of expanding hole is controlled by automatic management center based on image monitoring results (in reference to Figure 15). The shapes and sizes of the piles are input into the automatic management center before the construction. The construction process can be visually monitored and the quality can be ensured.



(a) The machine

(b) The belled shovel

Figure 14: The visible hydraulic belled rotary drilling rig**Figure 15:** The image

Two-point precision control

In this project, the lengths of steel pipe piles are 15.9 ~ 31.1 m (in reference to Figure 16). All the steel pipe piles are permanent structures, so the verticality deviation should be not more than 1/1000. In order to control the construction precision of the steel pipe piles, the hydraulic vertical jacking machine is devised (in reference to Figure 17). The construction process is as follows.

- (1) Repetition measurement the coordinate of bored pile, as shown in Figure 18.
- (2) Hoist the hydraulic vertical jacking machine upon the bored pile.

**Figure 16:** The steel pipe pile**Figure 17:** Hydraulic vertical jacking machine

- (3) Hoist the steel pipe on the hydraulic vertical jacking machine and fix.
- (4) Install the monitoring equipment on the upper fixed end (in reference to Figure 19(a)) and the uppermost connection of steel pipe (in reference to Figure 19(b)). The schematic illustration of the monitoring point arrangement is shown in Figure 20.

- (5) Vertically jack the steel pipe into the hole, and monitor and rectify the verticality of pipe in real-time.
- (6) Continuously jack until into the designed depth.



Figure 18: Repetition measurement

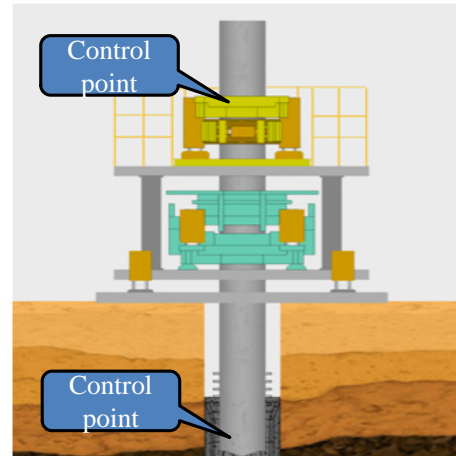


Figure 20: Two-point positioning



(a) Upper fixed point

(b) Pipe connection point

Figure 19: Install the monitoring points

By adopting the methods above, the values of belled pile construction and steel pipe jacking verticality are less than 1/300 and 1/1000, respectively. The construction quality and precision are well fulfilled.

CONSTRUCTION TECHNOLOGY OF STRUCTURE

As the stations of Metro 1 and Metro 2 are four floor-slab and three floor-slab ground structure, the anti-float stability of the transfer station can not be balanced by the self-weight. Only relying on anti-float piles, the project cost and construction difficult is higher. Besides, the diaphragm walls are good anti-float structure, if they are available. The problems of the traditional reserved steel bar connector method are as follows: easy seepage and small connection strength. Based on this, the method of tenon-groove connection composite structure (in reference to Figure 21) is proposed for this project. The tenon is on the floor slab (400 mm for the top floor slab and 70 mm for the other floor slabs) and the groove is in the diaphragm wall. The steel plate or L-bar and the waterproof layer

are installed between the tenon and groove in order to strengthen the connection strength and waterproof performance.

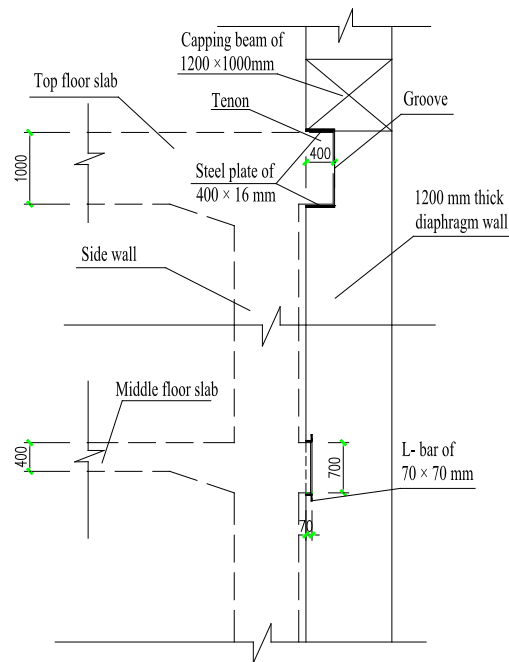


Figure 21: The schematic illustration of tenon-groove connection

The construction process of the tenon-groove connection is as follows:

- (1) According to the design drawing, the foam panels are bound onto the steel bar cage of the diaphragm wall at the locations of the connection.
- (2) Dismantle the foam panels when excavating to the elevation.
- (3) Level the groove using cement mortar, as shown in Figure 22(a).
- (4) Pave the waterproof roll (in reference to Figure 22(b)).
- (5) Bind the steel bar cage of the floor slab and pour concrete.



(a) Level the groove

(b) Pave waterproof roll

Figure 22: The construction of tenon-groove connection

CONCLUSIONS

Based on the Dadongmen transfer station of Hefei Metro 1 and Metro 2, the deformation control technology, high precision construction technology of belled steel pipe piles and structure connection technology are adopted. The construction quality and precision are well fulfilled from the field monitoring. The main conclusions are as follows:

- (1) The cross-steel joint form of diaphragm wall can improve the waterproof performance of the joints.
- (2) The method of high-pressure rotation jet piles reinforcement is effectively to avoid the local failure of slurry trench.
- (3) The method of clamshell grabs trench cutter and percussion drill is suitable for the construction of diaphragm wall in upper-soft and lower-hard.
- (4) The reinforcement method and excavation technology of deep and large top-down method are proposed in this paper.
- (5) The three-stage boring technology of belled pile and two-point jacking steel pipe pile are adopted for the precision control of belled steel pipe piles.
- (6) The tenon-groove connection method is proposed for the structure construction of top-down method.

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