

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/267574693>

Case Study of Innovative Top-Down Construction Method with Channel-Type Excavation

Article in *Journal of Construction Engineering and Management* · May 2014

DOI: 10.1061/(ASCE)CO.1943-7862.0000828

CITATIONS

5

READS

9,853

5 authors, including:



Mingguang Li

Shanghai Jiao Tong University

33 PUBLICATIONS 69 CITATIONS

[SEE PROFILE](#)



Jin-Jian Chen

Shanghai Jiao Tong University

92 PUBLICATIONS 416 CITATIONS

[SEE PROFILE](#)



An-Jun Xu

shanghai foundation engineering gp.co.ltd

3 PUBLICATIONS 11 CITATIONS

[SEE PROFILE](#)



J. H. Wang

Shanghai Jiao Tong University

219 PUBLICATIONS 1,379 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Wave-current-structure-seabed interaction [View project](#)

Case Study of Innovative Top-Down Construction Method with Channel-Type Excavation

Ming-Guang Li¹; Jin-Jian Chen, A.M.ASCE²; An-Jun Xu³; Xiao-He Xia⁴; and Jian-Hua Wang⁵

Abstract: Although the conventional top-down construction method is widely used in deep excavation, it has the drawback of low efficiency attributable to the long hauling distance and the possibility of the occurrence of excessive excavation deformation and construction risk. This paper introduces a case of deep metro station excavation at West Shanghai Railway Station. The top-down construction method must be used because the excavation is located under a running high-speed railway, and an innovative excavation scheme is proposed to improve construction efficiency and to control excavation deformation. In this method, an operation channel for earth hauling is first excavated in the middle of the excavation. With the available operation channel, the soil on both sides of the channel is excavated simultaneously in a segment pattern, and the required strut systems are subsequently constructed. Both the excavated soil and the construction materials are transported through the channel. This channel-type construction method that resolves the conflict between soil excavation and substructure construction allows for continuous excavation and, thus, reduces construction time and decreases excavation deformation. The case study demonstrates that the presented channel-type excavation is very effective in shortening construction time and reducing both construction cost and excavation deformation. DOI: 10.1061/(ASCE)CO.1943-7862.0000828. © 2014 American Society of Civil Engineers.

Author keywords: Top-down method; Excavation; Channel type; Construction efficiency; Deformation; Construction materials and methods.

Introduction

Given the rapid development of underground space, deep excavations in urban areas are becoming much larger in dimensions and considering the environmental effect during the construction process is becoming increasingly important. Deep excavation causes significant change in stresses and leads to deformation of the surrounding ground (Long 2001). When the excavation is close to existing buildings or underground facilities, selecting a proper construction method is extremely important to prevent the service condition of adjacent buildings and facilities from being adversely affected. The top-down construction method is one of the recently developed methods to control deformation attributable to deep excavation and to protect the surrounding buildings and facilities.

The top-down construction method, as the name states, excavates and constructs an underground structure from top to bottom. Because the ground floor slab is first constructed as the top slab of excavation, the top-down construction method allows excavation of

the substructure and construction of the superstructure to be carried out simultaneously (Paek and Ockz 1996). In the top-down construction method, the frame and slabs of the substructure are constructed during excavation and work as the supporting structure for excavation. Therefore, the construction time is reduced by reducing the time required for installation and removal of temporary struts. The deformation of the surrounding ground and adjacent buildings and facilities attributable to the excavation is also decreased because of the high stiffness of the supporting structure. Extensive field measurements and numerical analyses (Paek and Ockz 1996; Long 2001; Xu 2007; Wang et al. 2010) indicate that the top-down construction method is effective in controlling the retaining wall's displacements and ground movements, improving construction efficiency and reducing the cost of deep excavation. Therefore, the top-down construction method has been widely adopted in deep excavations in recent years (Kuta et al. 1994; Paek and Ockz 1996; Ou et al. 1998; Wong and Goh 2009; Cotton and Luark 2010).

For the top-down method, construction time is primarily affected by the efficiency of earthwork and substructure construction. Because earthwork is carried out below the substructure, the excavated soil must be hauled to the outlets on the slab and then taken out, which adversely affects the efficiency of the excavation. In contrast, the time required for construction and curing of underground reinforcement concrete (RC) slabs is much longer than that required for the installation of temporary struts. The working face conflict between substructure construction and earthwork also results in a discontinuous excavation process and, thus, a delayed construction schedule. Therefore, researchers and engineers have attempted to improve the efficiency of the top-down method by modifying the construction procedure (Brown 2003; Li et al. 2009).

Some researchers attempted to improve the top-down construction method by using modified formwork systems for the RC substructure to resolve the conflict between the slab construction and earthwork. For example, Lee et al. (1999) proposed a nonshored top-down formwork system to provide sufficient workspace for excavation below

¹Ph.D. Student, Dept. of Civil Engineering, Shanghai Jiao Tong Univ., 800 Dongchuan Rd., Shanghai 200240, China. E-mail: Lmg20066028@163.com

²Associate Professor, Dept. of Civil Engineering, Shanghai Jiao Tong Univ., 800 Dongchuan Rd., Shanghai 200240, China (corresponding author). E-mail: chenjj29@sjtu.edu.cn

³Deputy General Manager, Senior Engineer, Shanghai Foundation Engineering Co. Ltd., 406 Jiangxi Middle Rd., Shanghai 200002, China. E-mail: xuanjun@sfc.sh.cn

⁴Professor, Dept. of Civil Engineering, Shanghai Jiao Tong Univ., 800 Dongchuan Rd., Shanghai 200240, China. E-mail: xhxia@sjtu.edu.cn

⁵Professor, Dept. of Civil Engineering, Shanghai Jiao Tong Univ., 800 Dongchuan Rd., Shanghai 200240, China. E-mail: wjh417@sjtu.edu.cn

Note. This manuscript was submitted on December 2, 2012; approved on December 6, 2013; published online on February 3, 2014. Discussion period open until July 3, 2014; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Construction Engineering and Management*, © ASCE, ISSN 0733-9364/05014003(10)/\$25.00.

the suspended forms. Hong et al. (2010) presented a deep basement top-down construction technique that uses hanging pour forms and eliminates the requirement for conventional temporary supports.

Other researchers attempted to improve the efficiency of earth hauling by using larger or more outlets on the top slab to decrease the covered hauling distance of excavated soil. Wang et al. (2006) described a unified construction method used in a large excavation, in which the top-down method was applied to the annex building part to control the movement of the retaining structure and surrounding ground, whereas the bottom-up method was adopted in the main building part to provide a large outlet for earth moving for the top-down method. Zhou (2010) introduced a modified unified construction method, in which the central part of the excavation was constructed using the bottom-up method and the peripheral part was constructed using a step-like top-down method. This method improved the earthwork efficiency of the unified excavation method by providing docks for earth moving.

Note that all of the modified methods are only applicable to large excavations. When outlets are not allowed on the top slab, the earth hauling distance cannot be reduced and the efficiency of the top-down method remains low. This paper analyzes a case study of the top-down construction method without outlets on the top slab. To resolve the conflict between excavation and substructure construction and to improve construction efficiency, a channel-type excavation method is presented for this long and narrow top-down metro station excavation.

Project Overview

Project Information and Site Condition

The metro station excavation is part of a comprehensive transportation hub project. The transportation hub, located at West Shanghai Railway Station, includes the railway station and two underground metro stations. A north-south underpass was constructed to connect two sides of the railway and a transfer channel was constructed to connect the railway station and the two metro stations (see Figs. 1 and 2). The West Shanghai Railway Station and the metro station of line #11 were already in operation.

The underpass is approximately 82 by 108 m in plane, and its bottom slab is 9.5 m below the ground surface. The underpass was recently constructed and partly undercrossed the 64-m wide Huning high-speed railway, indicating that the top slab of the underpass is the subgrade of the operating railway. The transfer channel is below the underpass at a height of approximately 5 m and was constructed simultaneously with the underpass.

The metro station of line #15 is 240-m long and 23.5-m wide, and was constructed after the underpass was finished and the railway was in operation. The excavation of the metro station was divided into five parts (Part A-1 to A-5 in Fig. 1), considering metro line #11 and Huning high-speed railway. After the construction of the underpass and the transfer were completed, Part A-3 was first constructed and then the excavation of Part A-2 was carried out. This paper investigates the excavation process of Part A-2, which is completely located below the underpass.

Part A-2 is a two-floor metro station beneath the underpass with in-plane dimensions of approximately 23.5-m wide and 84-m long. The upper floor is primarily used for storing facilities and the lower floor is an island platform metro station for line #15. The excavation depth of Part A-2 is 23.5 m below the ground surface, which is approximately 14 m below the bottom slab of the underpass. Because the underpass is under the Huning high-speed railway

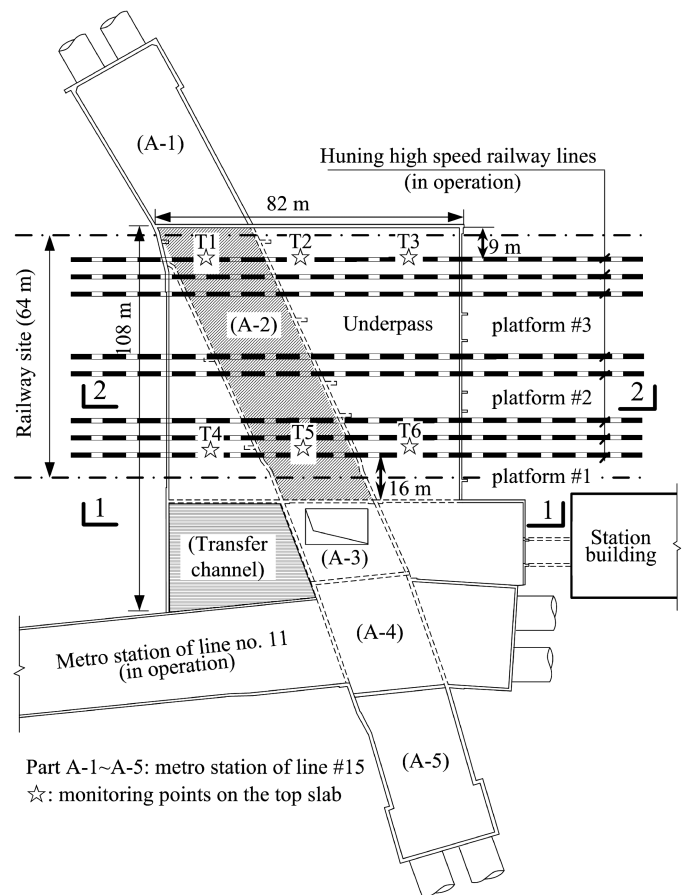


Fig. 1. Plan view of site

and the excavation of Part A-2 is located under it, the top-down method was adopted and an earthwork outlet was set in Part A-2.

Geotechnical Profile and Soil Properties

The construction site is generally flat with a ground level (WuSong elevation system) from 3.160 m to 4.180 m. The subsoil consists of quaternary deposits, which are primarily saturated clay, silt, and sand. The geotechnical investigations included both laboratory and in situ tests and were carried out before the construction. Fig. 3 shows the results of the geotechnical investigations. The nine soil layers have a total depth up to 78 m at the site, of which the fourth and fifth layers are very soft saturated clay with the characteristics of creep. The observed long-term groundwater table is 0.5 m to 1.5 m below the ground surface.

Design of Retaining and Supporting System for Excavation Part A-2

For the excavation of Part A-2, RC diaphragm walls were adopted as the retaining structure because of their high stiffness for deflection control (Wang et al. 2010). The thickness and depth of these diaphragm walls are 1 m and 47.5 m, respectively.

For the top-down construction method, the conventional supporting structures (that is, steel or concrete struts) are replaced by the underground structure slabs to control the diaphragm wall deflections. Therefore, the bottom slab of the underpass works as the conventional top slab of deep excavation in this project, and the middle slab is used as the supporting structure during the top-down construction. The thicknesses of the top, middle, and bottom slabs are 1,000 mm, 500 mm, and 1,200 mm, respectively.

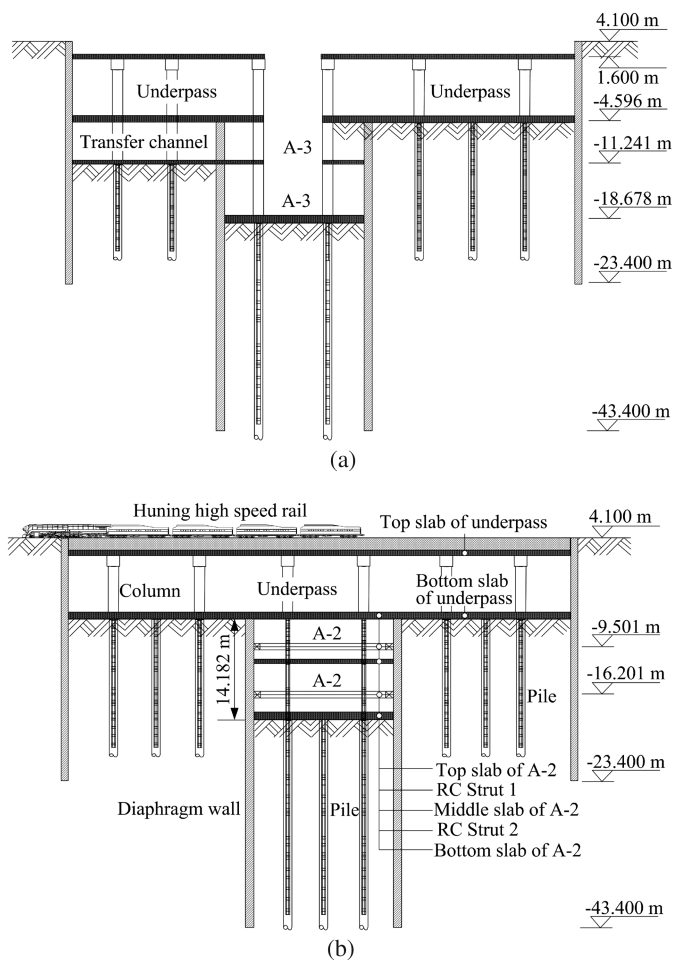


Fig. 2. Site profile: (a) profile of 1-1; (b) profile of 2-2

Moreover, two additional temporary RC struts, with the 1,200 mm $\times$ 800 mm section, were installed during excavation to control the displacements of the diaphragm walls and the running railways. Fig. 2(b) shows the central high levels of the slabs and struts.

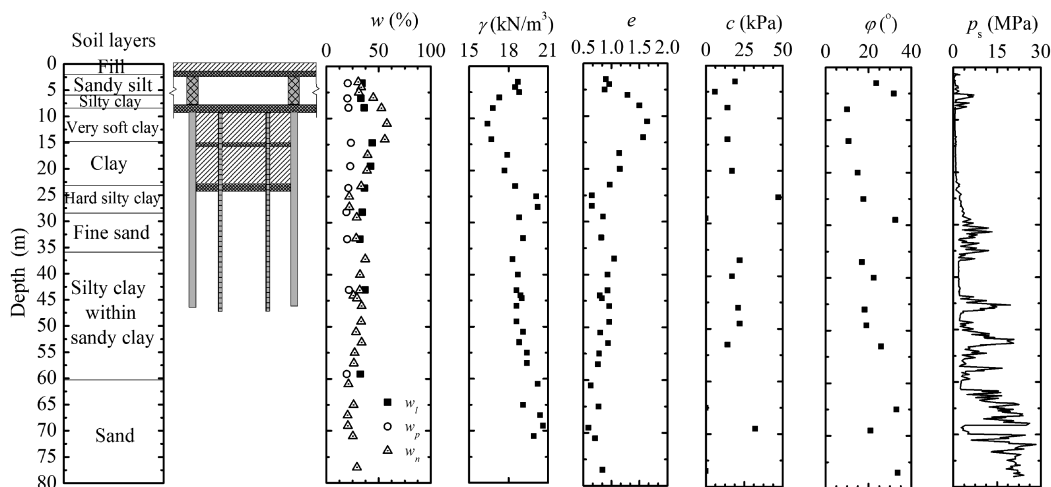
Ninety-nine drilled piles were constructed as the deep foundation of the underground station, with 79 bearing steel columns to support the slabs and struts during the excavation. The piles had a diameter of 1,000 mm and an effective length approximately 48 m below the bottom slab of the station.

Strengthening soft soil through ground improvement such as jet grouting and soil mixing has proven to be an effective method for reducing the retaining wall's displacement and ground movement during excavation (Hsieh et al. 2003; Xu 2007; Chen et al. 2013). In this project, jet grouting was adopted to partially improve the soil mass within the excavation zone. The improvement depth was 2 m below the top slab and the middle slab of Part A-2. The 28-day unconfined compressive strength (UCS) of the improved soil was more than 1.2 MPa.

Conventional Top-Down Excavation Methods

The earthwork is the most time-consuming part for conventional the top-down excavation. Therefore, a proper excavating and hauling scheme should be adopted to improve the construction efficiency and decrease the deformation of the retaining structure. In this project, two main factors need to be considered when selecting the excavating scheme.

1. The deformation of the surrounding environment should be controlled within a small value. As previously mentioned, the Huning high-speed railway was in operation over the underpass. Controlling the excavation deformation and ensuring the safety of the running railway is a great challenge.
2. The main outlet for the earthwork must be located in Part A-3, indicating that the maximum horizontal hauling distance in the top-down excavation is more than 84 m. Typically, the cut-and-cover method is used in the construction of deep metro stations in Shanghai because of its high earthwork efficiency (Tan 2012). However, the top-down method had to be adopted in this project because the Huning high-speed railway lines overcross the metro station and the excavation needs to be carried out below the constructed underpass. In contrast, the large earthwork outlets cannot be located on the top slab of the underpass over Part A-2 because of the railway. When



Note: w_n =water content, w_p =plastic limit, w_l =liquid limit, γ =unit weight, e =void ratio, c =cohesion, ϕ =angle of internal friction, p_s =tip resistance of CPT.

Fig. 3. Geotechnical profile and soil properties of construction site

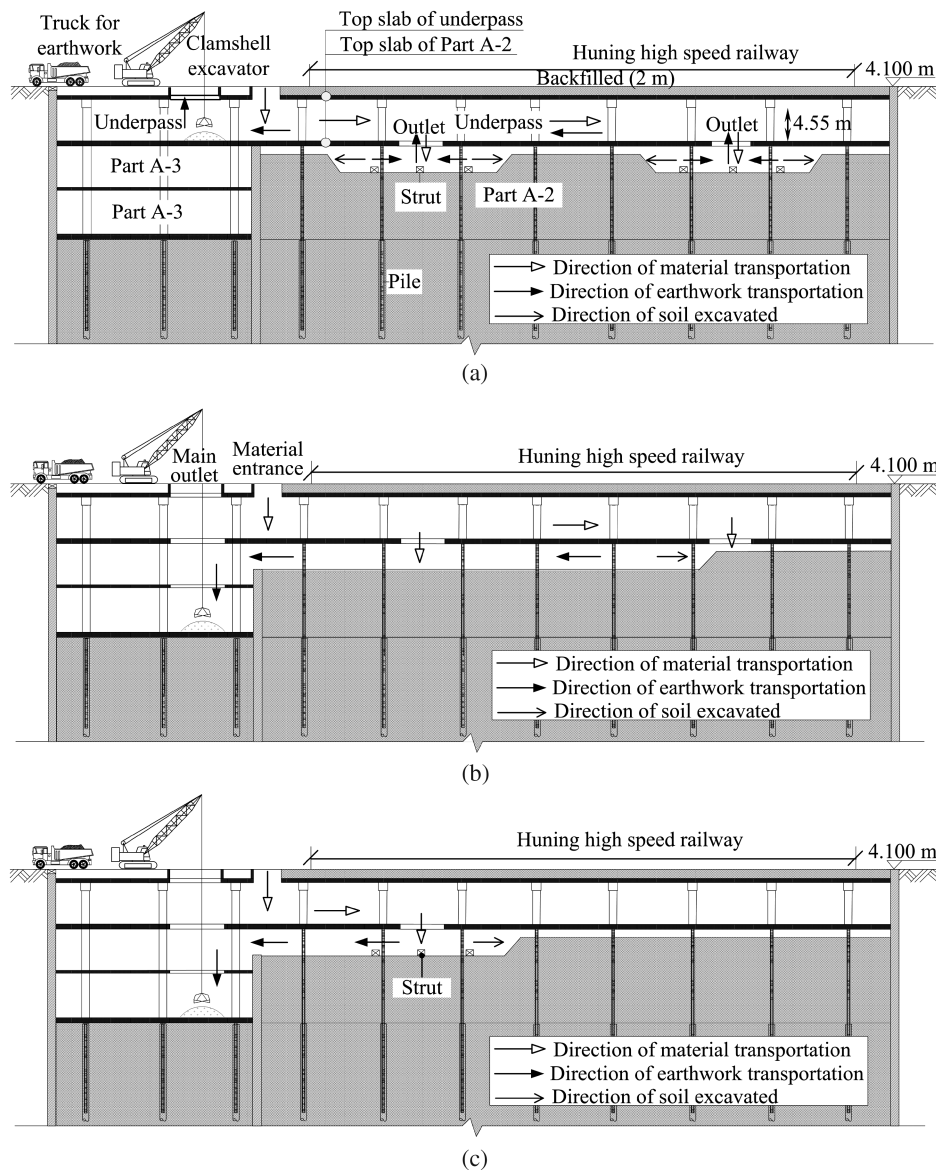


Fig. 4. Conventional excavation schemes: (a) divided excavation with top outlets; (b) entire excavation and construction; (c) segment-type excavation

the main outlet is set in Part A-3, all of the excavated soil has to be hauled horizontally to Part A-3 before taken out.

Considering these two factors, three top-down excavation schemes for this long and narrow metro station could be used (as shown in Fig. 4).

Divided Excavation with Top Outlets

As shown in Fig. 4(a), two (or three) outlets are set on the top slab of Part A-2, which also works as the bottom slab of the underpass. The excavation starts simultaneously at each outlet, indicating the excavation is divided into several small parts and each part is excavated independently. The excavated soil is transported vertically through these outlets and then hauled horizontally on the slab to the main outlet. In the vertical direction, the total excavation of Part A-2 is divided into four layers according to the slabs and struts. The RC supporting system needs to be constructed immediately after earth removal. A small hole is reserved at the south edge of the underpass top slab in Part A-2 to supply construction materials. In this scheme, all excavated soil and construction material are horizontally hauled on the top slab of Part A-2.

This scheme is not suitable for this project because the minimum clearance height of the underpass is only approximately 4.5 m and the clamshell excavators cannot be used for vertical transportation of the soil. Small excavators are used to haul the excavated soil on the top slab of Part A-2 but the efficiency is extremely low. Because the Huning high-speed railway is in operation, large outlets on the top slab of Part A-2 should not be used considering the potential decrease in bear capacity and related construction risk.

Entire Excavation and Construction

Because the excavated soil cannot be hauled on the top slab of Part A-2, an entire excavation method as shown in Fig. 4(b) is used. The excavation of Part A-2 is also divided into four layers vertically, but the soil of each layer is consecutively excavated from the south side and hauled to the outlet on the excavated surface. After the entire layer is excavated, the struts or slab must be constructed immediately.

This scheme is also not suitable for this project because of the potential large displacement of diaphragm walls and railway

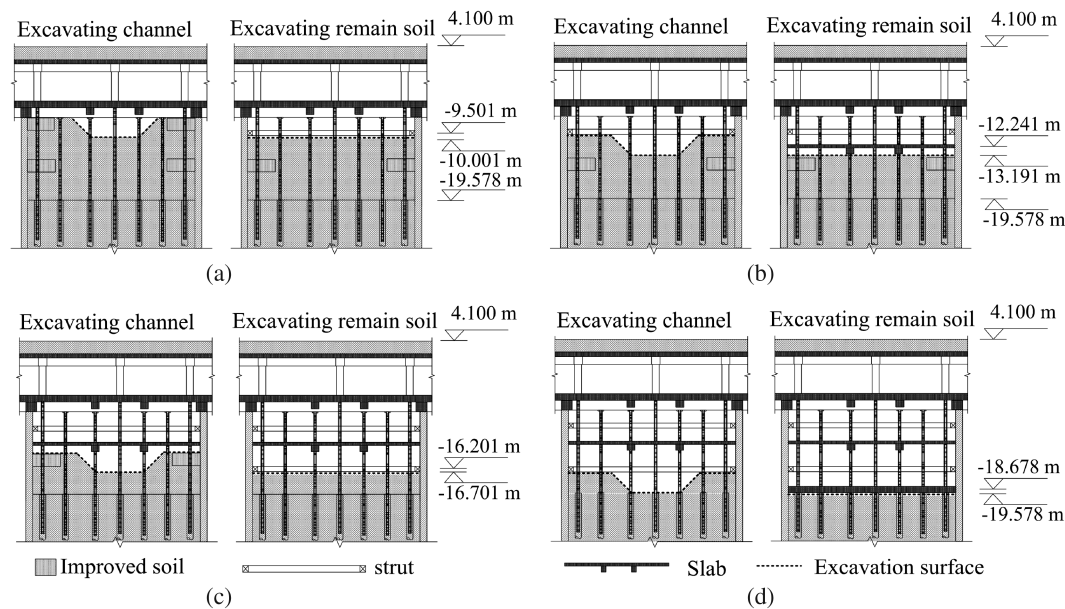


Fig. 5. Profile of excavated stages

embankments. Field measurements show that the deformation of diaphragm walls caused by entire excavations is much larger than that attributable to divided excavation (Xu 2007). In this project, the excavation time for each layer is more than 12 days, and the construction and curing time for the strut or slab is much longer. The long time during which the diaphragm walls have no strut support leads to large deflection because of the soft clay in Shanghai (Xu 2007).

Segment-Type Excavation

Segment-type excavation as shown in Fig. 4(c) is used to control the deflection of diaphragm walls. The entire excavation for each layer is divided into several segments. In each segment, the soil

is quickly excavated and hauled out, and the struts or slabs are constructed immediately after the excavation to minimize the deflection of diaphragm walls. After the concrete reaches approximately 70% of its design strength (usually after seven days curing), the next segment is constructed by repeating the aforementioned process.

Although the deflection of the diaphragm walls is controlled within small values by adopting this scheme, the construction efficiency is very low because of the discontinuous construction schedule. Excavation of the next segment does not start until the RC structure of the previous segment is cured for approximately seven days, indicating that the excavation must be paused during the pouring and curing period of the struts or slabs. As a result, both construction costs and construction risk increases.

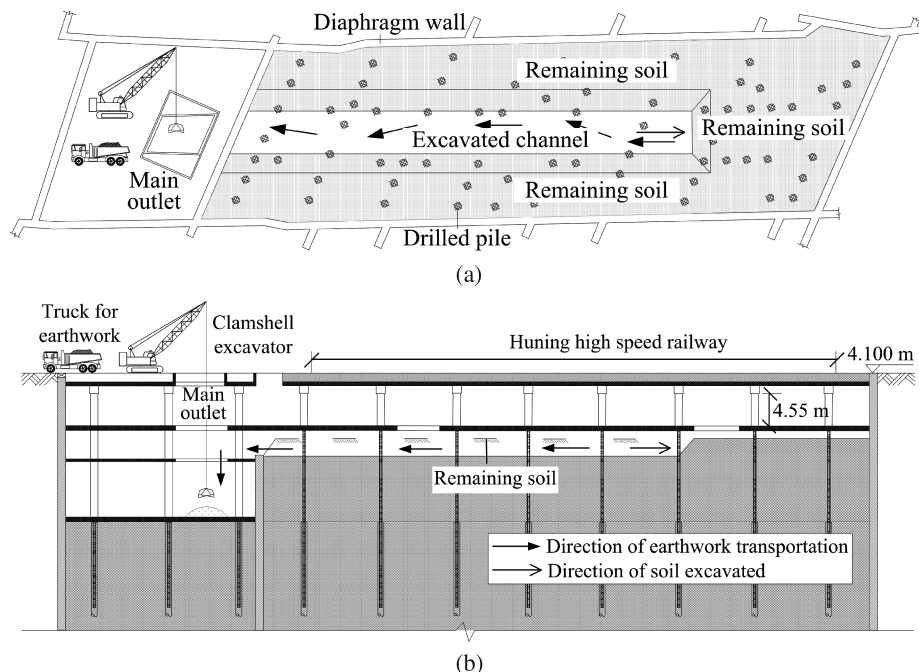


Fig. 6. Excavating channel in the middle of excavation: (a) plan view of channel excavated; (b) profile of channel excavated

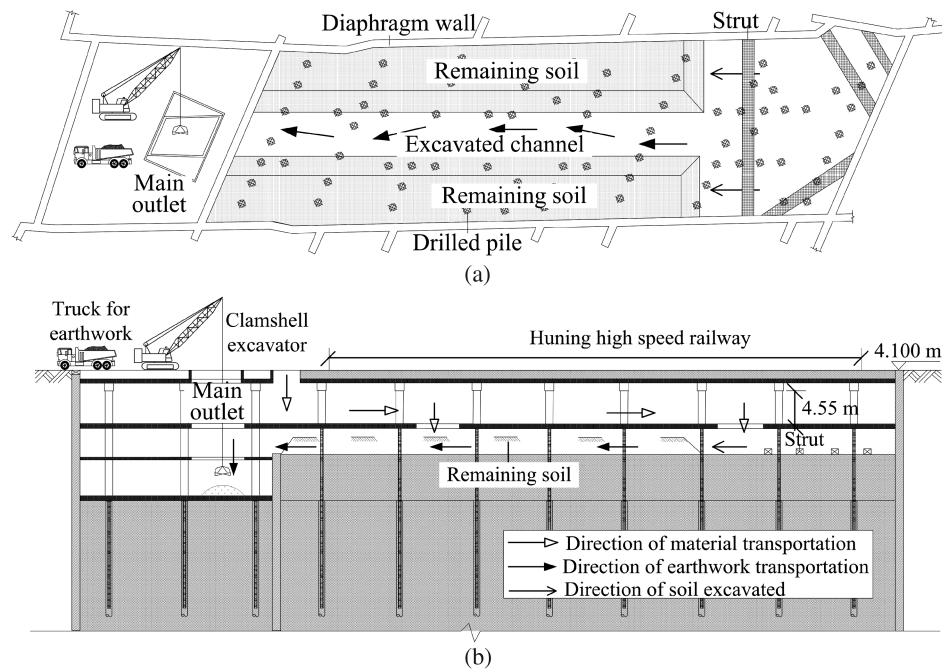


Fig. 7. Excavating remaining soil on both sides of channel: (a) plan view of remaining soil excavated; (b) profile of remaining soil excavated

Channel-Type Excavation and Application

Channel-Type Excavation Scheme

To improve the segment-type excavation method, a channel-type excavation scheme as subsequently described is proposed to achieve continuous excavation and construction.

At the beginning of construction, an operation channel for earth hauling is cut in the middle of the entire excavation area, and the remaining soil on both sides of the channel is left to resist deflection of the diaphragm walls. Using this channel, soil excavation may be started at the farthest end from the outlet, and the backward excavation is not paused by the construction of struts or slabs. After the channel forms, the remaining soil on both sides may be excavated

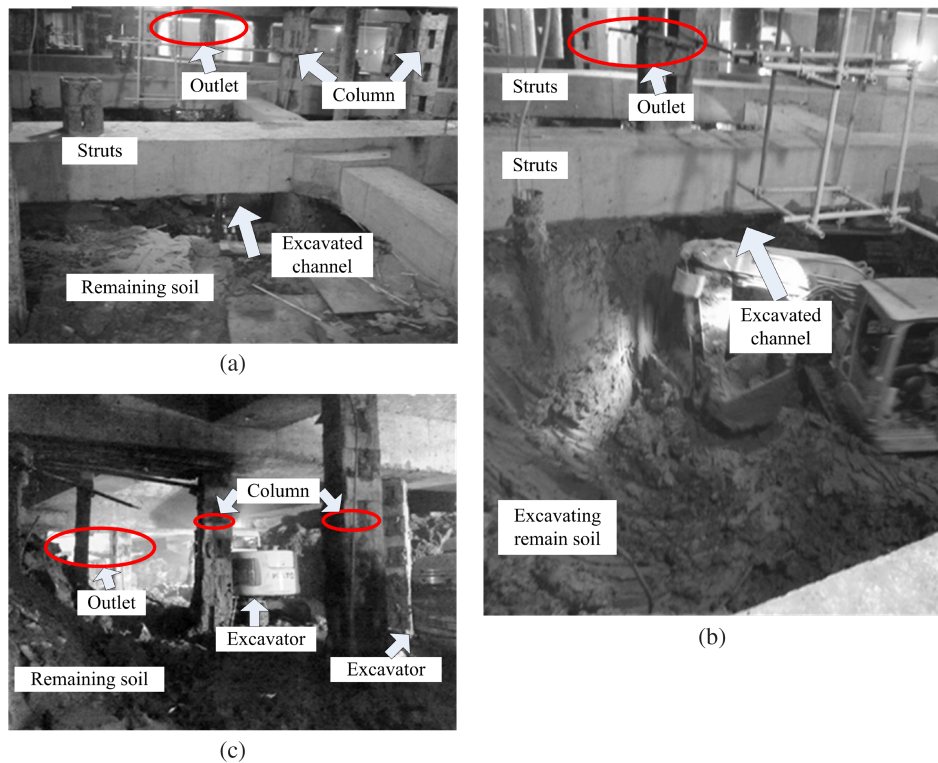


Fig. 8. Pictures of channel-type excavation in this project: (a) excavating channel; (b) excavating remaining soil; (c) soil transported through excavated channel

Table 1. Timetable of Construction Activities

Stage	Events	Date (mm/dd)	Days
Stage 1	Excavating channel	07/01–07/05	5
	Excavating remaining soil	07/06–07/22	17
	Constructing strut 1	Since 07/09	12
	Curing of strut in last segment	07/26–08/01	7
Stage 2	Excavating channel	08/02–08/05	3
	Excavating remaining soil	08/05–08/13	9
	Constructing slab	Since 08/07	26
	Curing of slab in last segment	09/03–09/09	7
Stage 3	Excavating channel	09/10–9/12	3
	Excavating remaining soil	09/13–09/25	12
	Constructing strut 2	Since 09/15	16
	Curing of strut in last segment	10/01–10/07	7
Stage 4	Excavating channel	10/08–10/10	3
	Excavating remaining soil	10/11–10/22	12
	Constructing slab	Since 10/12	30
	Curing of slab in last segment	11/11–11/18	7

using the segment-type method, and struts or slabs may be constructed simultaneously. Both the excavated soil and the construction materials may be transported through the channel.

The width of the channel is determined through two factors: (1) the channel should be wide enough for excavator moving and earth hauling, a wider channel indicating a more convenient excavation and (2) the width of the remaining soil should be large enough to resist the deformation of the diaphragm walls, which indicates that a narrower channel is better. Therefore, a reasonable channel width is the minimum value that provides sufficient workspace for equipment.

In the channel-type excavation, excavation and construction are continuous because the operation direction is backward, and a pause in time occurs, as required in the segment-type excavation. The remaining soils on both sides of the channel resist the deformation of the retaining walls before being excavated using the segment-type excavation. Therefore, the deformation attributable to deep excavation may be controlled within a small value and construction efficiency is improved using the channel-type excavation scheme.

Application Channel-Type Excavation in Part A-2

Considering the characteristics of the excavation in Part A-2, the channel-type excavation method was applied as follows.

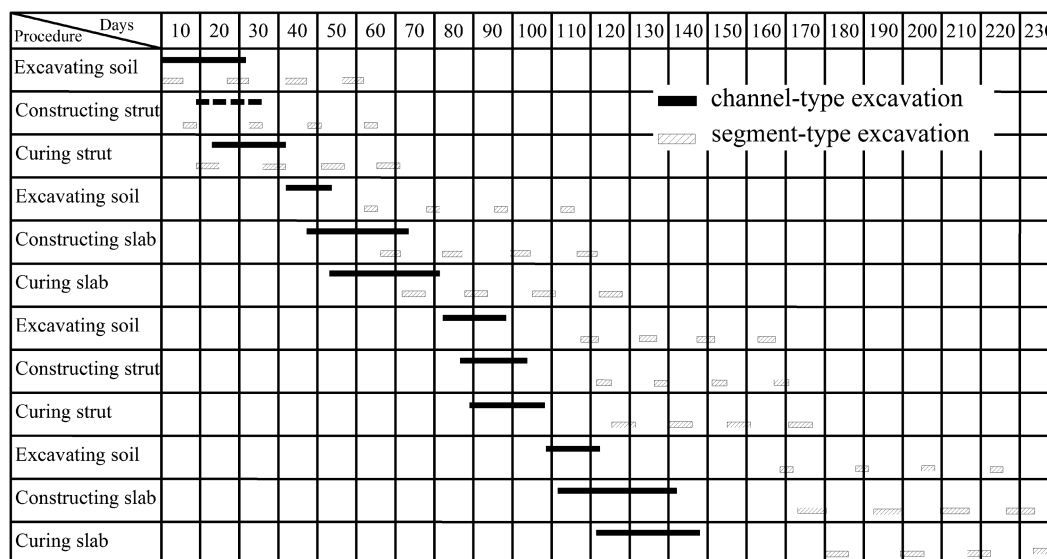
The excavation of Part A-2 was divided into four stages in the vertical direction, and the excavation of each layer was divided into four segments. Fig. 5 shows the profile of the four excavation stages. A work channel was first excavated in the middle of the entire excavation area from south to north after the temporary diaphragm walls between Part A-2 and Part A-3 was demolished (see Fig. 6). The width of the channel was 6 m considering the excavator's size. Then the remaining soil on both sides of the channel was quickly excavated from north to south in segments and hauled through the channel (see Fig. 7). After a segment excavation was completed, struts or slabs were constructed immediately to minimize deflection of the diaphragm wall. To resolve the interference between earth hauling and construction material transportation, three material transportation entrances were used, one on the top slab of the underpass and two on the top slab of Part A-2 (see also Fig. 7). After the soil was excavated to the final level, a 300-mm thick concrete cushion was cast immediately and the base slab was constructed right away.

The channel-type excavation scheme was successfully applied during the construction of Part A-2; Fig. 8 shows some of the pictures taken at the site. As shown in Fig. 8(c), several small excavators worked simultaneously to haul the excavated soil through the work channel.

Construction Efficiency and Cost-Benefit of the New Method

Construction Efficiency Analysis

Table 1 summarizes the excavation activities. The excavation started on July 1, 2011 and ended on November 18, 2011 after the bottom slabs were cured for seven days. The entire excavation took only 139 days. After that, the inner wall and other underground facilities were constructed and the two temporary struts were removed in sequence.

**Fig. 9.** Timetable of new and traditional construction technology

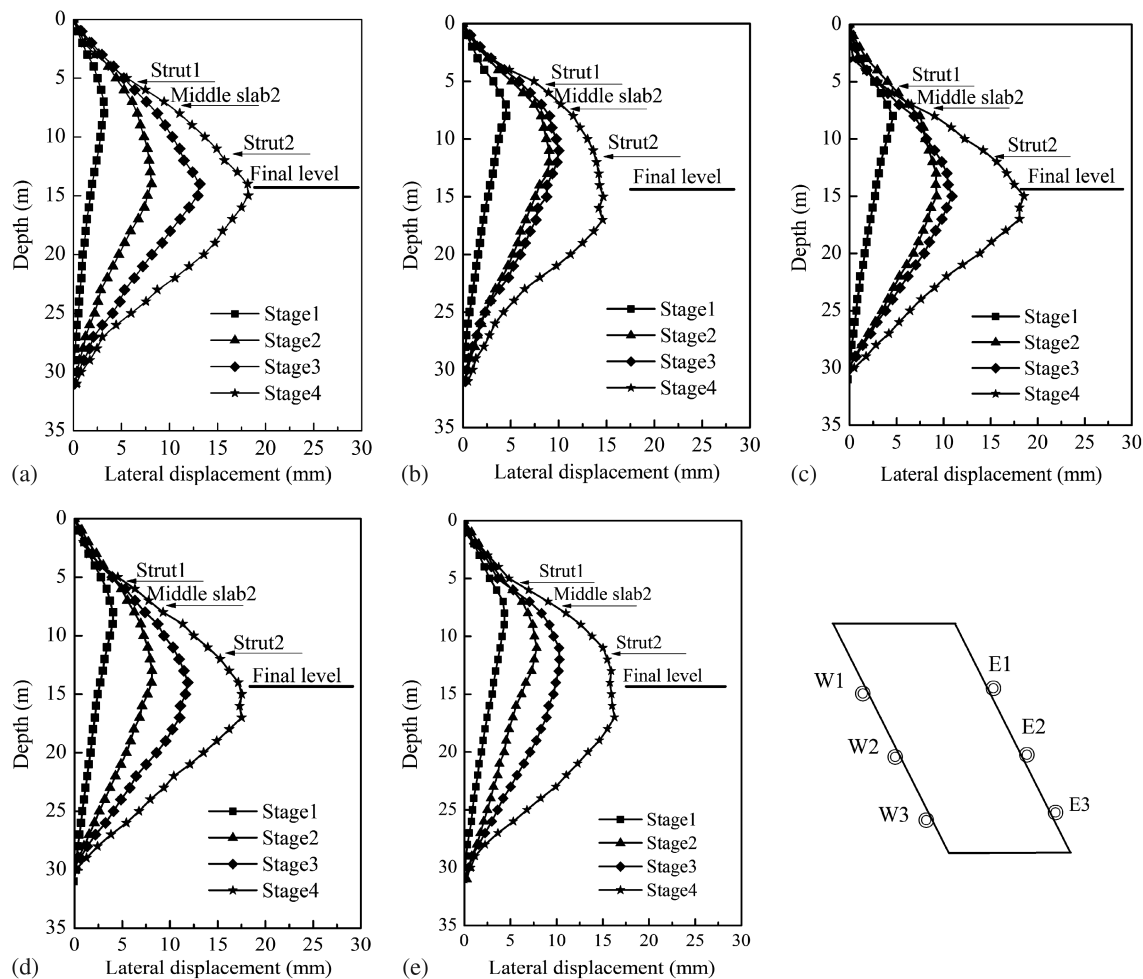


Fig. 10. Diaphragm wall deflections measured at completion of each excavated stage

Compared with the conventional segment-type excavation, the channel-type excavation ensures continuous soil excavation and structure construction by coordinating the workspace and saving construction time. Fig. 9 compares the construction schedules of the channel-type excavation and the conventional segment-type excavation. The channel-type excavation saves the time needed to cure struts (or slabs) at each segment. Using the channel-type excavation method reduced construction time by almost 90 days from the original plan that used the segment-type excavation.

Benefit-Cost Analysis

In this case, the original budget for the conventional segment-type excavation was \$564,516, whereas the cost of the actual channel-type excavation was \$483,870. Therefore, the construction cost was reduced by 14.3% compared with the traditional top-down method.

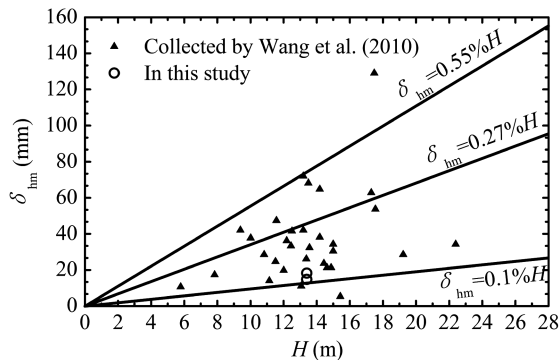


Fig. 11. Relationship between maximum wall deflection and excavation depths

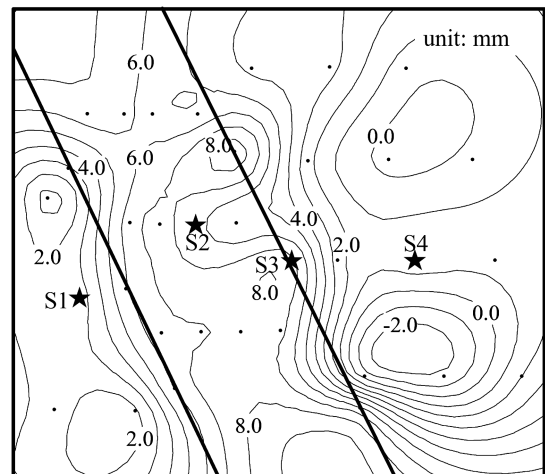


Fig. 12. Vertical displacement contour of bottom slab of underpass

Table 2. Vertical Displacement of Slab after Each Excavated Stage

Construction stages	Bottom slab of underpass				Top slab of underpass					
	S1	S2	S3	S4	T1	T2	T3	T4	T5	T6
Stage 1	−1.90	−1.16	−1.28	−2.82	−1.39	−1.33	−0.55	−2.00	−1.27	−1.19
Stage 2	0.43	−0.99	−0.38	−1.75	−1.60	−0.83	−0.85	−2.13	−0.66	−0.45
Stage 3	4.85	5.6	4.82	3.90	4.82	4.52	2.24	3.87	3.03	3.02
Stage 4	2.38	6.39	7.67	1.61	4.80	5.00	3.39	4.88	4.07	5.56

Moreover, considering the timesaving effect, the cost-saving amount will be much greater because of the indirect financing cost effects.

Field Measurement Results

During excavation and construction, the deformation of diaphragm walls and structure slabs was monitored to ensure the safety of both the excavation and the operating railways.

Deflections of Diaphragm Walls

Six inclinometers monitored the lateral deflection of the longitude diaphragm walls, in which point W3 was destroyed during excavation. Fig. 10 shows the layout of the six inclinometers and the measured deflections of diaphragm walls after each excavation stage. As the excavation depth increases, the deflection profiles develop into an inward bulged profile. The excavation depth for the metro station is approximately 14 m below the bottom slab of the underpass, and the corresponding maximum diaphragm wall deflection is 18.2 mm, which is only 0.13% of the excavation depth. This ratio is close to the smallest value of the compiled data (see Fig. 11) and may be attributed to the channel-type excavation method in which the construction duration is reduced and the remaining soil resists the deflection of the diaphragm walls.

Vertical Displacement of Top Slab of Part A-2

In this excavation, the bottom slab of the underpass bears the moving loads of the trains. One part of the slab acts as the top slab of the Part A-2 excavation and the other part is located on the ground. The displacement of this slab is complicated because of the interaction between the moving loads from the trains and the unloading of the excavation.

The vertical displacement of the bottom slab of the underpass was monitored using 28 measurement points, of which 12 points were located on the top slab of Part A-2. Fig. 12 shows the contour of the vertical displacements of the bottom slab of the underpass after the excavation was completed. The maximum heave and settlement are approximately 8 mm (on the top slab of Part A-2) and −2 mm (bottom slab of the underpass outside the excavation), respectively.

To facilitate a thorough understanding of the general behavior of slabs, Table 2 summarizes the vertical displacements after the completion of each excavation stage at four typical points, S1 to S4. The settlement at the end of the first stage was seen to be very small. During the second stage, the settlement decreased and a small heave of approximately 0.43 mm happened at point S1. All of the points heaved dramatically during the third stage and maximum heave occurred after the excavation was finished.

Vertical Displacement of Railways

The Huning high-speed railways were in service during the excavation and construction. According to the relevant codes, the maximum settlement of the tracks must be controlled within 20 mm. Instruments were installed on the top slab of the underpass (2 m below the railway subgrade) to monitor the vertical displacement of the tracks. Table 2 summarizes the measured vertical displacements at six typical points on the top slab. The variation of vertical displacements at the six points is similar to that at monitoring points S3 and S4 on the bottom slab of the underpass. The maximum vertical displacement of the top slab of the underpass after excavation is 5.56 mm (at T6), which is much smaller than the limit value of 20 mm.

Conclusions

In this paper, an innovative excavation scheme for the top-down construction method was proposed and successfully applied in the case of a deep metro station excavation in Shanghai. On the basis of the case study, the following conclusions are drawn.

1. The channel-type excavation method resolves the working face conflict between structure construction and earthwork, and achieves continuous excavation and construction by excavating an earth-hauling channel. Compared with the conventional excavation schemes, the channel-type excavation method has the advantages of shorter construction time and smaller deformation attributable to excavation.
2. The excavation time of this case is only 139 days, which is less than two-thirds of the planned time for the conventional segment-type excavation. Field monitoring shows that the displacements of the diaphragm walls and the railway subgrade are controlled within a small value. The maximum deflection of the diaphragm walls is 18.2 mm (approximately 0.13% of the excavation depth), which is much smaller than the average of the compiled data for top-down excavations in Shanghai.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (Nos. 41330633, 41372282, 41272317).

References

- Brown, D. C. (2003). "Novel method of excavation." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2003)129:2(222), 222–225.
- Chen, J. J., Zhang, L. Y., Zhang, J. F., Zhu, Y. F., and Wang, J. H. (2013). "Field tests, modification and application of deep soil mixing (DSM) method in soft clay." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0000746, 24–34.
- Cotton, D. M., and Luark, R. D. (2010). "Recent advances in the top-down construction of a 26.4 meter deep soil nail retention system—Bellevue

- technology tower." *Proc., 2010 Earth Retention Conf.*, Vol. 208, ASCE, Reston, VA, 375–381.
- Hong, W. K., Kim, J. M., Lee, H. C., Park, S. C., Lee, S. G., and Kim, S. I. (2010). "Modularized top-down construction technique using suspended pour forms (modularized RC system downward, MRSD)." *Struct. Des. of Tall Spec. Build.*, 19(7), 802–822.
- Hsieh, H. S., Wang, C. C., and Ou, C. Y. (2003). "Use of jet grouting to limit diaphragm wall displacement of a deep excavation." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2003)129:2(146), 146–157.
- Kuta, Y., Maruoka, M., Aoki, M., and Sato, E. (1994). "Application of the observational method to a deep basement excavated using the top-down method." *Geotechnique*, 44(4), 655–664.
- Lee, H. S., Lee, J. Y., and Lee, J. S. (1999). "Nonshored form work system for top-down construction." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1999)125:6(392), 392–399.
- Li, J., Chen, J. Y., and Sun, Y. S. (2009). "Application of cyclone in the optimization of top-down earthwork construction machine arrangement." *Proc., Int. Conf. on Management and Service Science*, IEEE Computer Society, Piscataway, NJ, 1–4.
- Long, M. (2001). "Database for retaining wall and ground movements due to deep excavations." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(2001)127:3(203), 203–224.
- Ou, C. Y., Liao, J. T., and Lin, H. D. (1998). "Performance of diaphragm wall constructed using top-down method." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)1090-0241(1998)124:9(798), 798–808.
- Paek, J. H., and Ockz, J. H. (1996). "Innovative building construction technique: Modified up/down method." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1996)122:2(141), 141–146.
- Tan, Y., and Wei, B. (2012). "Observed behaviors of a long and deep excavation constructed by cut-and-cover technique in shanghai soft clay." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0000553, 69–88.
- Wang, J. H., Xu, Z. H., Di, G. E., and Wang, W. D. (2006). "Performance of a deep excavation constructed using the united method: Bottom-up method in the main building part and top-down method in the annex building part." *Underground Construction and Ground Movement Proc., GeoShanghai Conf.*, Vol. 155, ASCE, Reston, VA, 385–392.
- Wang, J. H., Xu, Z. H., and Wang, W. D. (2010). "Wall and ground movements due to deep excavations in Shanghai soft soils." *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0000299, 985–994.
- Wong, I. H., and Goh, A. T. C. (2009). "Performance of top-down basement excavation for the Singapore esplanade car park." *Geotech. Eng. J.*, 40(2), 49–59.
- Xu, Z. H. (2007). "Deformation behavior of deep excavations supported by permanent structures in Shanghai soft deposit." Ph.D. thesis, Shanghai Jiao Tong Univ., Shanghai, China (in Chinese).
- Zhou, Z. Q. (2010). "Central part by bottom-up method and peripheral part by step-like top-down method construction craft and key technologies." *Chinese J. Geotech. Eng.*, 32(2), 455–458 (in Chinese).