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Deep and extra deep diaphragm walls – increasing demand for infrastructure in Megacities drives the requirement of increasing depth for diaphragm walls

Parois moulées profondes et très profondes – demande croissante des infrastructures dans les mégapoles, entrainant un besoin en parois moulées de plus en plus profondes

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ABSTRACT: Diaphragm walls (D-walls) are known as underground structural elements commonly used for retention systems and permanent foundation elements. In addition, they are also quite often used as deep groundwater barriers, called Cut-Off-Walls (COW). Shanghai ranks third among the most densely populated metropolises in the world. In 1990, only eight million people lived there. Today, Shanghai has about25 million inhabitants. The increasing demand to accommodate the infrastructure of growing megacities like Shanghai pushes the required depth for subway, sewage and foundation projects to the limit. Future projects will demand excavation depths of more than 100 m (328 ft) on a regular basis. Already carried out reference projects will be described and a general outlook for upcoming projects will be given. The paper also explains the installation process in general focusing on the use of trench cutter technology.

RÉSUMÉ: Les parois moulées sont des éléments de structures souterraines, utilisées communément comme systèmes de rétention ou éléments de fondations permanentes. Elles sont utilisées également comme barrières contre les eaux souterraines profondes, ce que l'on nomme aussi des parois d'étanchéité. L'adaptation continue aux exigences des infrastructures dans les mégapoles, comme dans la ville de Shanghai, pousse à atteindre des profondeurs limites dans les projets de métro, d'évacuation des eaux usées et de fondations. Shanghai à titre d'exemple est classée troisième métropole au monde en terme de densité de population. En 1990, cette ville comptait seulement 8 millions d'habitants. Aujourd'hui elle en compte environ 25 millions. Par conséquent, les projets futurs dépasseront régulièrement des profondeurs d'excavation de 100 m. Ceci requière des développements spécifiques en terme de contrôle qualité, équipement et matériel. Des projets déjà réalisés de cette envergure seront présentés, tout en illustrant l'augmentation rapide des exigences en profondeur, et donnant une perspective générale des projets à venir.

Keywords: Diaphragm wall; Trench Cutter

1 INTRODUCTION

D-walls are known as underground structural elements, commonly used as retention systems for excavation pits and shafts as well as permanent foundation walls or elements. It is anticipated that, with the increasing trend of utilizing more and more underground space to accommodate environmental considerations and urban/suburban development, there will be an increasing requirement for diaphragm wall usage in even more difficult conditions and with increasing depth.The trench cutter is the most important tool for performing this work. The hydraulic grab, a well-known and valuable excavation tool for d-walls reaches its limits in terms of depth and when cutting rock. Therefore the trench cutter technology will be in the focus of this paper.

The trench cutter itself is a reverse circulation excavation tool. It consists of a heavy steel frame with two drive gears attached to its bottom end, which rotates in opposite direction around the horizontal axis. Cutter wheels are mounted onto the drive gears. As they rotate, the soil beneath the cutter wheels is continuously broken up, removed, mixed with the bentonite slurry in the trench and moved towards the opening of the suction box of the pump? A centrifugal pump located right above the cutter wheels conveys the slurry via a hose system up to a desanding plant. There the slurry loaded with soil and rock particles is cleaned and returned into the trench.

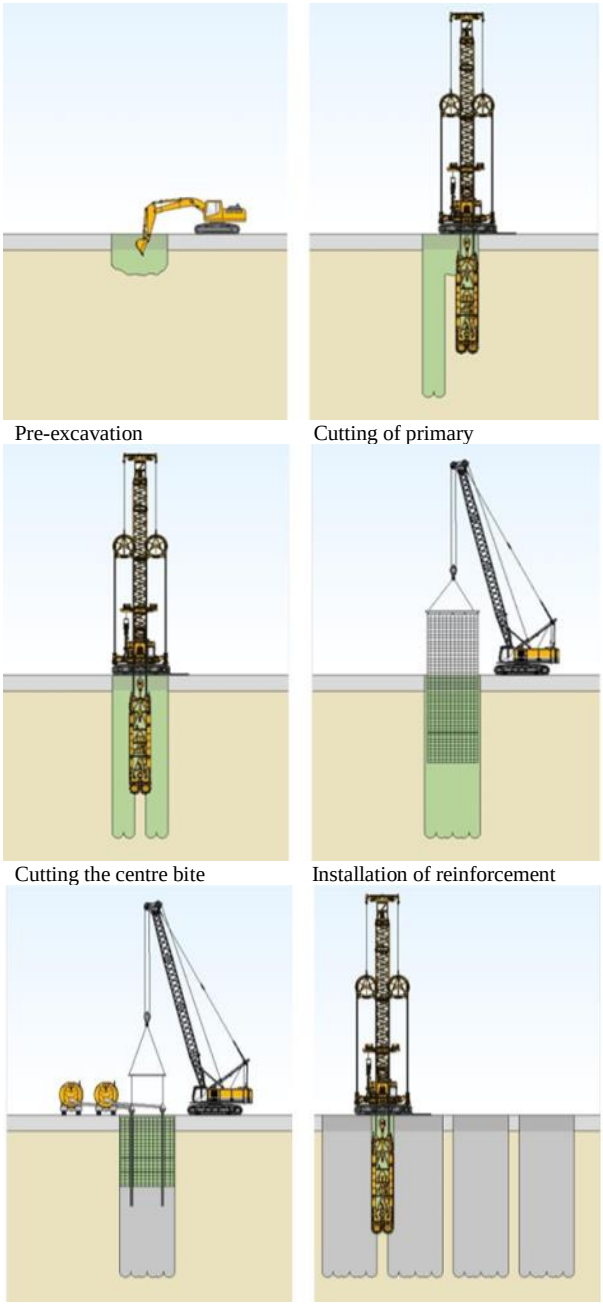
The torque of the cutter wheels combined with the weight of the cutter is strong enough to cut into hard soils, crush stones up to a certain grade and overcut into the concrete of adjacent panels.Depending on the soil, different types of cutter wheel configurations and teeth can be deployed, ranging from aggressive teeth for cutting fine-grained soil to percussive teeth for crushing boulders. Cutter wheels may conveniently be changed to suit different types of rock. Experiences were made with cutting strengths of up to 250 MPa.

2 EQUIPMENT AND TOOLS

2.1 Working Sequence

The typical working sequence for the construction of a diaphragm wall using a trench cutter as shown in figure 1 comprises the following key steps:

- Site preparation,
- Guide wall construction
- Trench pre-excavation
- Panel excavation
- Panel cleaning (desanding)
- Reinforcement installation (for retaining walls)
- Concreting



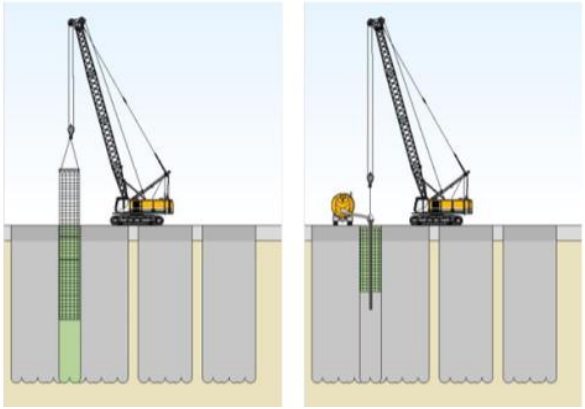


Figure 1: Construction process, exemplary for the diaphragm wall process

2.2 Wheels and teeth

The use of the most appropriate cutting wheels and teeth is one of the main key factors to reach optimal productivity. Trench cutters are typically equipped with one of three types of wheels and teeth. Their different features are depending on the range of rock strengths they are being used.. Figure 2 shows the three types of wheels.

Figure 2: Standard Cutter Wheel (left), Round shank chisel cutter wheel (centre), Roller bit cutter wheel (right)

The “Standard Cutter Wheels” are usually used in all types of soils with various types of teeth, but are also able to cut into weak to moderately strong rock conditions. Starting from rock strengths in the range of approx. 50 MPa, which means cutting strong and hard rock, using a more aggressive wheel like the “Full Face Cutter Wheel (or Round shank chisel Cutter Wheel (RSC))” equipped with special chisels, will result in a better cutting process. At the upper end of the scale, when dealing with rock strengths exceeding 120 MPa, using the “Roller bit cutter wheel” has to be considered.

Usually, when using the Roller bit cutter wheels, a high weight of the cutter is required, as each roller bit requires a load of at least 4-8 metric tons for a reasonable functionality.

3 JOB SITE REFERENEC

More than 10 years back, Shanghai started the application of deep and ultra-deep diaphragm walls.

The geology in Shanghai can be generally described as follows. The first 30 – 40 m a soft to firm, silty clay was encountered. This is followed by various layers of

stiff to very stiff, silty clay and medium dense, sandy silt to a depth of 60 - 75 m. To approx. 90 m dense to very dense sand was encountered. For the following 20 m hard clay was found. Very dense sands and very hard clays alternate several times down to a depth of 145 m. Finally a hard clay layer was found to the final depth of 150 m.

More detailed description of the various soil sonditions are given for each single reference project.

Looking to the variety in soils which were encountered, it can be anticipated that severeal procedures for the execution of the works had to be considered to ensure the best techical and most economical approach.

The following references will describe projects of the more recent past., starting with a depth of 58.5 m ending with the latest trials reaching a depth of 150 m.

3.1 Shanghai 2010 World Expo 500 kV Transformer Substation (2006)

Shanghai 2010 World Expo 500 kV Transformer Substation was the first cutter project in Shanghai. Located in the centre of Shanghai city, the 500 kV substation is the first 130 m diameter underground station built in China. It did not only provide electric power to 2010's Expo, but also ensures the energy supply to sustain the urbanization development of Shanghai ever since.

3.1.1 Geology

After approx. 2 m of backfill, the geology could be described as mainly soft to firm silty clay to clay down to a depth of 27 m, followed by stiff clay to a depth of 30 m. Underneath the sandy silt was very stiff to a depth of 36 m. Thereafter very dense, silty sand was encountered with SPT values in a range of 50 - 80 blow counts to a depth of 47 m. To the final depth of 58.5 m and underneath it changed back to a stiff to very stiff silty clay.

3.1.2 Execution

The installation of the diaphragm wall with a thickness of 1,200 mm was carried out using a combination of hydraulic grab and trench cutter. For the soft to stiff clays down to a depth of 30 m the hydraulic grab was used. The system was then changed to the cutter mode to reach the final depth of 58.5 m. A specific requirement of trench verticality was defined by 1/600. The layout of the joint and the used H-Beam system is shown in figure 3.

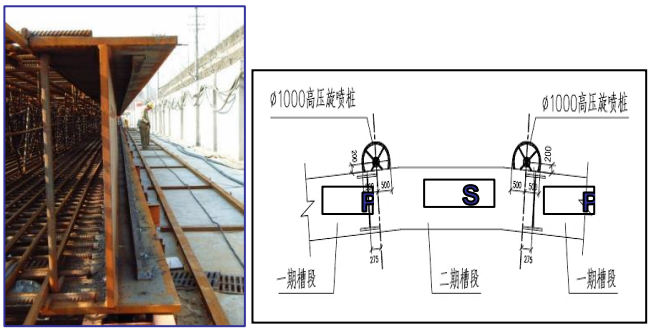


Figure 3: Used H-Beam joint system (left), detail layout of the joint (right)

3.2 Shanghai Tower (2009)

The Shanghai Tower is a 632-meter, 128-story tall skyscraper in Lujiazui, Pudong Shanghai. With Shanghai World Financial Center (height 492 m) to the east and Jin Mao Tower (height 420 m) to the north, Shanghai Tower is China's tallest building. Beside the installation of 2,758 piles of various diameters and depths, the project required two diaphragm walls, one for the tower area with a depth of 50 m and one for the podium area with a depth of 48 m. (see figure 4). Both walls had a width of 1,200 mm with a total volume of 66,400 m³.

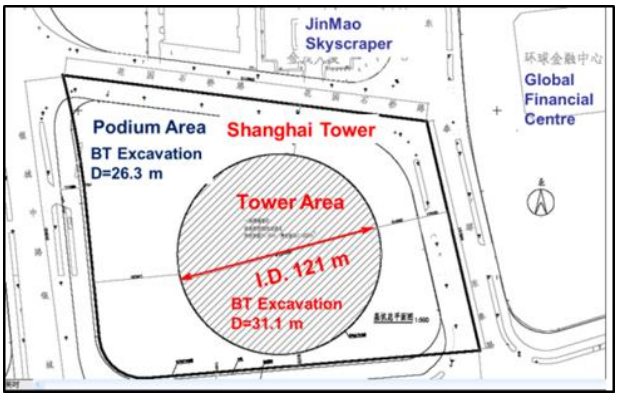


Figure 4: Site layout

3.2.1 Geology

The geology can be described as mainly soft to firm silt and clay down to a depth of approx. 30 m, followed by hard, sandy silt to a depth of approx. 38 m. To the final depth of 50 m very hard, silty sand was encountered.

3.2.2 Execution

The installation of the diaphragm wall was carried out using a combination of hydraulic grab for the soft to stiff clays down to a depth of 30 m. The system was then changed to the cutter mode to reach the final depth of 50 m. A specific requirement of trench verticality was defined by 1/400. As a joint system for the general installation in the tower area a v-steel joint system was used (see figure 5).

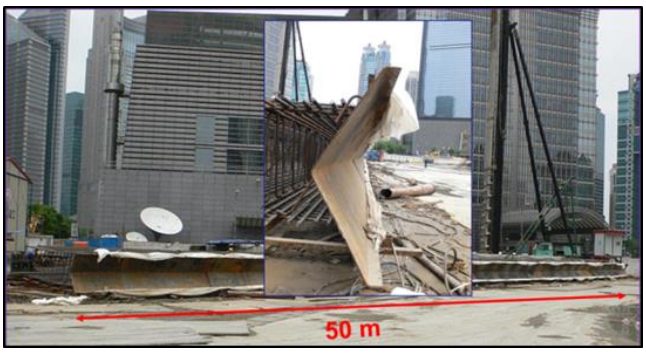


Figure 5: V Steel Plate Joint (Tower area)

In addition, a trial using the Overlap Cutter Joint (OCJ) system was carried out for the first time. Three primary and two secondary test panels were installed to prove the alignment during overcutting was kept as well as to check the influence on performance cutting into a C55 concrete with an overcut of 200 to 295 mm. The layout for the test is shown in figure 6.

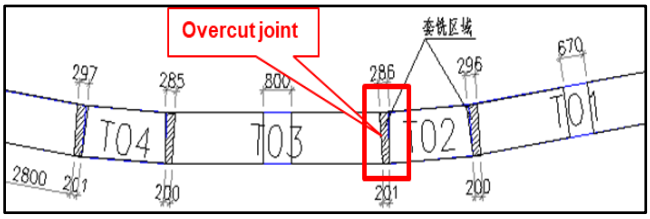


Figure 6: Trial panels for verifying the Overlap Cutter Joint system

The results of this test showed that the requirements for the trench alignment were fully satisfied in both directions and the performance being 10 -13 m³/h was within a reasonable range. Figure 7 shows the exposed wall face at excavation depths of 26 m. Dry and watertight.

The successful test of the OCJ system and the fact that the joint system is in principle without depth limitation opened the door to reach bigger depths.

3.3 Shanghai MRT Line 13 Huaihaichonglu Station (2011~2012)

The Huaihaiconglu station is a station on Line 13 of Shanghai Metro. It is the first SMRT diaphragm wall project using Overlap Cutter Joint (OCJ) and a maximum wall depth of 72 m (236ft) was reached.

3.3.1 Geology

The geology could be described as soft to stiff silt and clay down to a depth of 27 m (88ft), followed by very stiff to hard sandy silt to a depth of approx. 37 m. Underneath it changed to dense to very dense silty sand with SPT values of up to 75 blow count down to 57 m.

After a layer of approx. 10 m of stiff silty clay, a very dense to extremely dense silty sand was encountered again to the final depth of 72 m.

3.3.2 Execution

The installation of the diaphragm wall with a thickness of 1,200 mm (4ft) was carried out using a combination of hydraulic grab and trench cutter. For the primary panels, down to a depth of 30 m (98ft) the hydraulic grab was used. The system was then changed to the cutter mode to reach the final depth. As the Overlap Cutter Joint (OCJ) system was used, the secondary panels were installed by the trench cutter only. A specific trench verticality of 1/400 was required.

3.4 Shanghai Zongshan Park Shaft (2016)

The Zongshan Park shaft with a total length of 19.1 km, including 8 km underground section located in northern part of Shanghai city centre, is part of North Cross Passage Project. It was built for arriving and re-launching of a mega tunnel boring machine with a diameter 15.56 m. Besides the diaphragm wall to the final depth of 65 m, 3 test panels with a minimum depth of 110 m were constructed: The aim was not only to prove the cutter capacity in cutting deep trenches, but also to provide a detailed study on ultra-deep diaphragm walls for future deep excavation projects in Shanghai. These test panels were included in the general layout of the project (see figure 8).

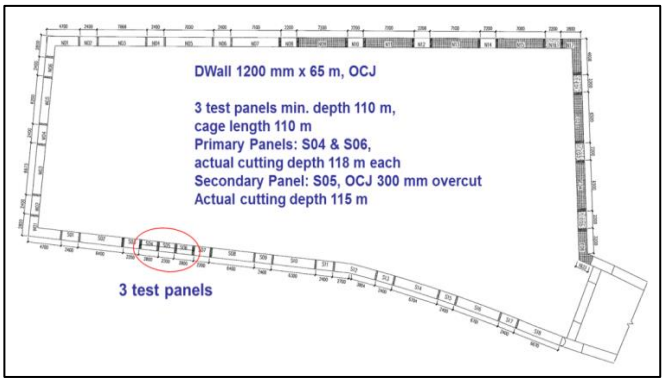


Figure 8: Site layout

3.4.1 Geology

The geology could be described generally as soft to stiff cohesive soils down to a depth of 30 m. Followed be varying layers of hard, silty clay and dense, silty sands to a depth of 65 m.

The soil conditions down to the final depth of the test panels can be described as follows: Very dense, fine sand and extremely dense, medium to coarse sands existed for the next 20 m followed by varying layers of extremely dense, silty sands and very hard, silty clays.

3.4.2 Execution

The installation of the diaphragm wall was carried out using a combination of hydraulic grab and trench cutter. For the primary panels, down to a depth of 30 m (98ft) the hydraulic grab was used. The system was then changed to the cutter mode to reach the final depth. As

the Overlap Cutter Joint (OCJ) system was used, the secondary panels were installed by the trench cutter only.

For the test panels the procedure was slightly changed. Only the upper 5 m (16ft) were excavated using the grab. From there onwards to the final depth the cutter was used to assure trench verticality. A typical Koden record proved the success of the required alignment showing deviations less than 10 cm in both directions (figure 9).

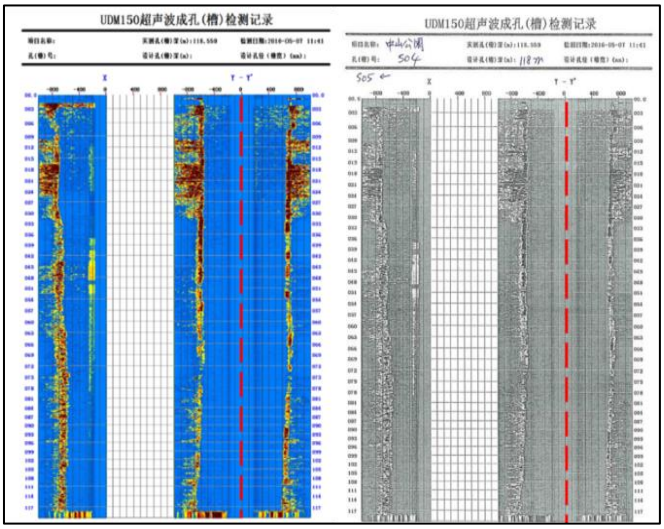


Figure 9: Typial Koden record

3.5 Xuhui Center (2017.03-2018.01)

Currently, two new skyscrapers with 43 and 69 floors are under construction in the Xuhui district, the commercial centre of Shanghai. Due to a demanding project programme, Shanghai Foundation deployed 3 units of trench cutters, mounted on duty-cycle cranes equipped with either a BC 40 cutter or a CBC 30 compact cutter for the diaphragm wall work. 393 panels with a total volume of 115,240 m³ were installed in a 10-month period.

3.5.1 Geology

The geology was described as soft to stiff, silty clay down to a depth of 47.5 m followed by a 3 m hard layer of sandy silt. To the final depth 75.5 m very dense silty sand was encountered.

3.5.2 Execution

The diaphragm wall was split in two different widths and depths using different joint systems. One section was a 1,000 mm and 1.200 mm wide wall to a depth of 58 m using a cross steel plate joint (see figure 10). This covered about 20,400 m³. The main section with a width of 1,200 mm and a depth of 75.5 m was carried out using the Overlap Cutter Joint (OCJ) system. This section covered a volume of 94,840 m³.

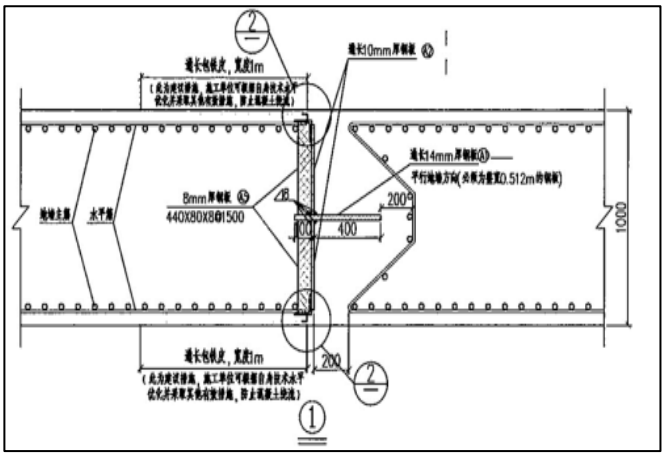


Figure 10: Cross Steel Plate Joint for wall thickness 1,000 mm / 1.200 mm

3.6 Yunlingxi Deep Shaft (2017~2018)

The Yunlingxi Deep Shaft is part of the Suzhou River "Deep Tunnel" Project in Shanghai. The deep drainage, regulation and storage pipeline is the advanced section of this with a total length of 15.3 km (9.5 miles). Considering lower water surface ratios, higher construction density, complexity of underground pipelines, dense population, high pressure of flood prevention security and other characteristics of the central urban area in Shanghai, the use of large-scale deep regulation and storage tunnels supplemented by run-off control systems are the construction requirements of Shanghai Municipal Government.

This particular shaft requires diaphragm walls with various widths of 1,000 mm, 1,200 mm and 1,500 mm to a maximum depth of 105 m and is presently under construction.

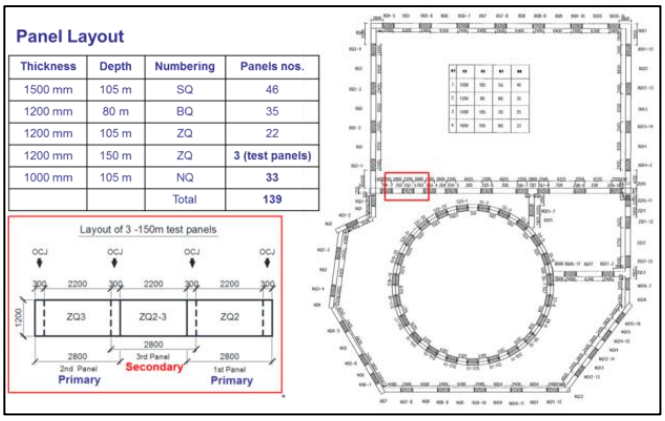


Figure 11: Site layout

In order to gain not only valuable experience, but to prove the technological feasibility of the construction of diaphragm walls to depths of more than 120 m for future underground projects in the Shanghai area, a test program was defined and carried out. For the first time 3 test panels were cut down to 150 m by using the trench cutter only (see figure 11).

3.6.1 Geology

The geology was described as soft to firm, silty clay and clay down to a depth of 35 m, followed by various layers of stiff to very stiff, silty clay and medium dense, sandy silt to a depth of 65 m. To approx. 90 m dense to very dense sand was encountered. For the following 20 m hard clay was found. Very dense sands and very hard clays alternate several times down to a depth of 145 m. Finally a hard clay layer was found to the final depth of 150 m.

3.6.2 Execuion

The installation of test panels was done with the cutter only after a 3m pre-excavation using a backhoe. During their excavation, the three diaphragm wall panels penetrated multiple soil layers – more specifically ten to eleven layers of alluvial and marine sediments, comprising six clayey layers which were sandwiched by five layers of sand deposits (aquifers). As a result, both the stability of the trench and the verticality control of the cutter became key issues during trench construction.

Nevertheless, Shanghai Foundation Engineering Group Co. Ltd. successfully completed the construction of these three ultra-deep diaphragm wall panels in January 2018. For the construction of the three panels of 1,200 mm x 2,800 mm and depths of 150 m, a BC 40 trench cutter on a duty-cycle crane (see figure 12) was deployed. The specific requirement for the alignment of 1/1000 was proven by an ultrasonic probe which showed a maximum vertical trench deviation of less than 15 cm.

Figure 12: Cutter Configuration at final depth

4 CHALLENGES, LESSONS LEARNED AND OUTLOOK

Shanghai has very soft to soft cohesive soils with SPT values of N < 4 in the upper 20~30 m below surface. This requires continuous soil improvement like soil mixing to ensure the trench stability during panel excavation, cage installation and concreting. In fact the soil improvement before commencement of trench excavation became a standard procedure adopted for thick and deep d-wall projects, as one panel may take several days for installation.

There are also extremely strict requirements for trench verticality being 1/400 or less. This definitely requires experienced operators and time for trimming has to be considered. To get a clear Koden record when checking the trench alignment, slurry density shall be low. In most cases, hours of desanding is needed before the Koden measurement can be conducted.

It is common practice lifting 40~50 m long steel cage in one piece. That requires not only two big cranes for handling, but also R.C. working platform with a thickness of min. 300 mm.

In order to shorten the concreting time contractors nowadays deploy concrete mixers with a capacity of 18 m3 (23.5 cubic yard) per truck. The diameter of tremie pipes used on site is 305 mm (12 in) and minimum two numbers of sets are used for a big three-bite primary panel.

Besides, logistic issues especially during peak hours are crucial and have to be considered.

In figure 13, a few typical d-wall projects were selected using cutters in Shanghai, The purpose is to show the depths have gone deeper and deeper in the last few years, especially after OCJ has successfully been introduced to Shanghai market. For instance, two ultra-deep projects, Miaopu shaft widths 1,200 mm and 1,500 mm to a depth of 103 m and Zhangjiang shafts (4 numbers in total) with width 1,200 mm to a depth of 90 m, just recently started in Shanghai in June and July this year. It can be noticed and anticipated, that the request for deep and ultra-deep d-walls will increase in the future.

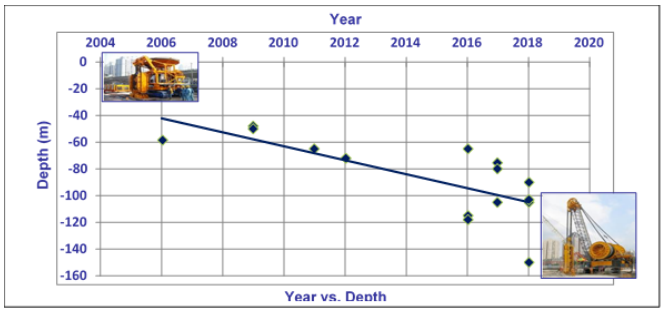


Figure 13: Selected cutter projects in Shanghai – Year vs. Depth

5 SUMMARY

As there is no rock in Shanghai, one may ask why a cutter is required for diaphragm wall construction. There are some reasons which can be summarized as follows:

- Extremely fast growing infrastructure, like subway flood control and sewage systems. The foundation for skyscraper projects demand deep and ultra-deep diaphragm walls where an excavation depth of more than 100 m (328ft) will be required more frequently.
- Very hard and dense soil layers are encountered, where the SPT values exceed 50 blow counts and rising even up to 200. The use of the grab system is no more practical, especially due to demanding project programmes as well as very tight construction schedules.
- High standard of trench verticality, e.g., 1/400, and long rebar cages with maximum lengths of 50 m (164ft) per section require very straight panels.
- The Overlap Cutter Joint (OCJ) is a simple and easy to handle joint system with almost no depth limitation.
- Trench cutter use becomes preferable as limited working space in city area requires high output, low noise and less vibration of excavation equipment.

Finally it can be said that the cutter technology provides good opportunities to handle the increasing demands of the future.

6 REFERENCES

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