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ABEF

Diaphragm Walls – From the past to the future

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ABSTRACT: Diaphragm walls are known as underground structural elements commonly used for retention systems and permanent foundation walls or elements. Another common use are deep groundwater barriers, namely Cut-Off-Walls. It can be 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 and Cut-Off-walling in even more difficult conditions.
The paper will describe the construction method, from the history to the actual state of the art and the sequence of activities required for the construction of diaphragm walls. It will describe also the main equipment which is required to execute these works. In addition to the general description of the system and the required equipment the paper will show some site references around the world.

KEY WORDS: Diaphragm Walls, Cut-Off-Walls, Grab, Trench Cutter, Hydromill

1 Introduction

Diaphragm walls are constructed using the slurry trench technique. The technique involves excavating a narrow trench that is kept full of an engineered fluid or slurry. The slurry exerts hydraulic pressure against the trench walls and acts as shoring to prevent collapse. Slurry trench excavations can be constructed in all types of soil, even below the ground water table.

2 The History of diaphragm wall technique

2.1 The Invention

Searching in the history of the diaphragm wall technique, one can find a first patent which was approved back in 1912 by a company called "Carl Brand" in Germany. This based on the experiences for the use of clay slurries and it's stabilizing effect in uncased boreholes. Another patent was approved in the US by Ranney back in 1936. Booth patents were almost forgotten before the method really started. The reason therefore could be seen in the knowledge of concreting under slurry support and the fear to place reinforcement in a clay slurry.

A kind of revival and the real start could be seen in the late 1940's and early 1950's. A number of publications discussed the thixotropic fluids and were patented by Lorenz 1950/51. Also Veder received an Austrian Patent in 1950 for a methodology of installing water tide walls by using contiguous, uncased boreholes, stabilized by slurry and concreting after excavation. As well company "ICOS" applied for patents on slurry wall constructions by the end of 1940's in Italy.

The observation that bentonite slurry not only keeps solids in suspension but also stabilizes the excavation and therefore eliminates the need of using casing support forces ICOS to start experiments also with rectangular excavations to see whether these can be stabilized as well. This initial success led to the installation of the first underground concrete wall.

At that stage of the development, intensive research has taken place in the field of stabilization slurry design, trench stability effects, concrete and its placement under bentonite slurry as well as reinforcement.

First full scale projects have been finally carried out by ICOS for the Metro in Milan e.g. in 1956. With the success of the projects the interest in this technology increases. In addition, with expiring patents, a number of international acting construction companies, mainly in Europe and Japan, started to develop additional and alternative equipment for the purpose of installing Diaphragm walls.

2.2 The Equipment

2.2.1 The Grab

To install the first rectangular diaphragm wall panels, ICOS designed a first special grab/clamshell, named crocodiles (Figure 1), which can be seen as the predecessor of today's grab/clamshell technology.

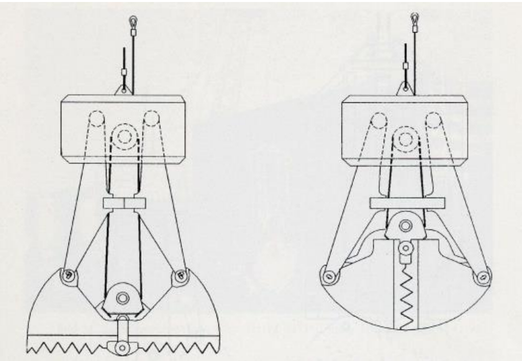

Figure 1. Wire rope grab (ICOS 1960)

A mechanically operated wire rope grab was used as the first type of excavating tool. The closing mechanism is actuated by a pulley block system inside the grab body, whilst the opening of the jaws is actuated by the weight of the block sliding on guides. The grabbing capacity of the initial generations of grabs was limited. The development of heavy duty crawler cranes with two hydraulically operated winches made it possible to build grabs with jaw widths up to 4,5 m and a weight of over 15 tons. The excavation capacity of the grab system could therefore be increased significantly. Figure 2 shows a later generation of various rope grabs.

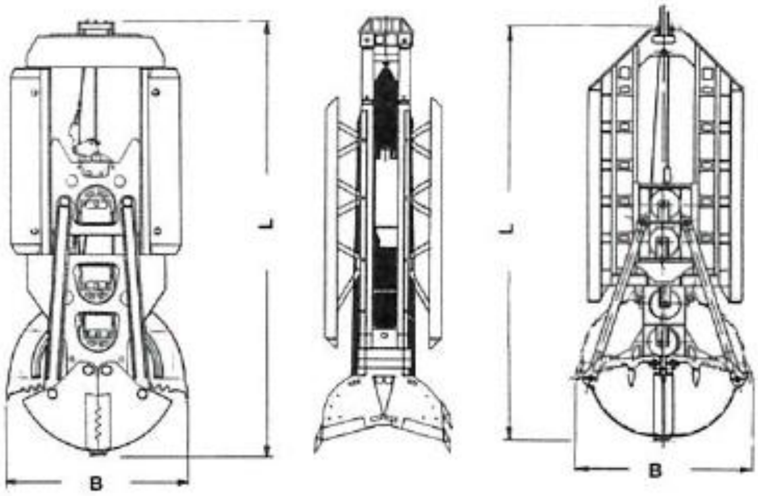

Figure 2. Wire rope grabs, Casagrande (left), Bauer (middle), Leffer (right)

Over recent years, the mechanically operated wire rope grab has been improved by replacing the pulley block system with hydraulically operated rams. Now, with both closing and opening of the jaws being actuated by hydraulic rams, the output capacity has increased significantly. Because of their heavy weight, these types of grabs do not need to be operated in a freefall mode. Hydraulic hoses and electric cables can, therefore, follow the grab into the trench without difficulty. The electric cables attached to the grab also allow the installation of inclinometers, and if necessary, deviations can be corrected by hydraulically operated steering plates as shown in Figure 3.

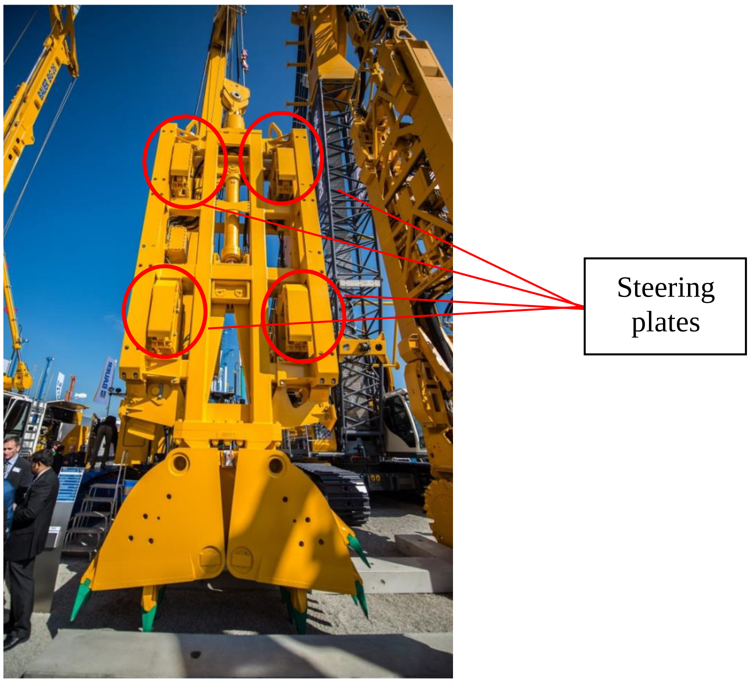

Figure 3. Hydraulic grab with steering plates

The grab excavation technology is a widely used and common system. There are, however, some limitations in the system:

- The excavation output reduces with increasing trench depth as a result of the intermittent excavation process.
- It is difficult to excavate hard soil formations.
- For deep walls it is difficult to construct a sufficient joint system

The introduction and development of the hydraulic trench cutter system made it possible to overcome these problems and it opened new horizons for the use of the diaphragm wall technique.

2.2.2 The Cutter

In 1962, a kind of suction cutter unit was launched in Germany, which can be seen as one of the predecessor of today's cutter/hydro-fraise technology.

Also two Japanese companies (Tone Boring and Okumura Corporation) developed in the early 1960's a new reverse circulation concept for rectangular panels. While Tone Boring cutting blades rotating around vertical axes, Okumura used two cutting wheels, driven by a chain and rotating around horizontal axes. Both systems used suction pumps located outside the trench for removing the mud-soil mixture. The concept of cutting wheels rotating around a horizontal axis was further advanced by the introduction of powerful hydraulic motors instead of electric drives.

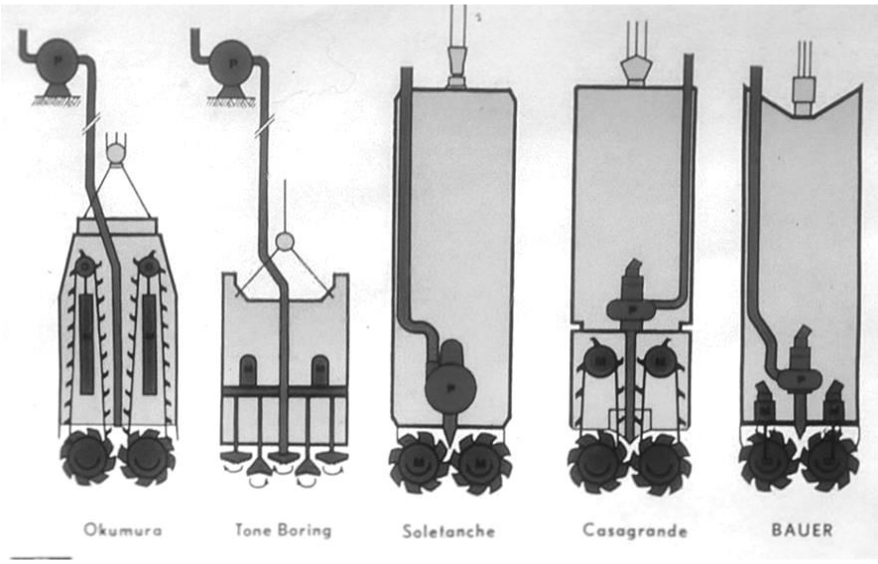

Figure 4. Cutter development

The idea of a hydraulically driven cutter was introduced in Europe around 1975 by the French company Soletanche with the brand name "Hydrofraise". The arrival of the cutter technology in Europe prompted other companies to greater activities during the 1980's. Casagrande of Italy brought a system with a chain drive, similar to Okumura. In 1984 Bauer in Germany brought their system of trench cutter BC on the market. The BC system was designed from the beginning to penetrate rock layers. The cutter wheels are driven by vertically mounted high speed hydraulic motors. A special gear system converts the high speed rotation of the hydraulic motors into slower rotation of the cutter wheels. With this system, the torque on the wheels can be increased in comparison to other design concepts. 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. An overview of the various concept is shown in Figure 4.

The trench cutter itself is a reverse circulation excavation tool (Figure 5). 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.

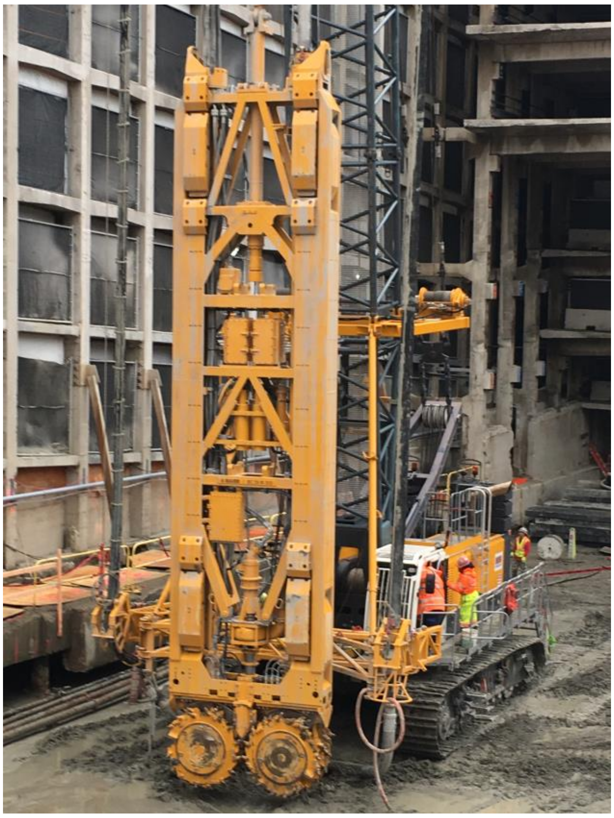

Figure 5. Trench Cutter

Wheels and teeth

Use of the most appropriate cutting wheels and teeth is one of the main keys to optimized productivity. Trench cutters are typically fitted with one of three types of wheels and teeth. Commonly they differ for the range of rock strength, where they usually are used. Figure 6 shows three types of wheels.

The "Standard Cutter Wheels" are usually used in all types of soils with various types of teeth but is also able to cut into weak to moderately strong rock conditions. Obviously, there is no strict borderline but starting with rock strengths approximately in the range of 50 MPa, which means dealing with strong/hard rock, a more aggressive wheel like the "Full Face Cutter Wheel (or Round shank chisel cutter wheel (RSC) Cutter Wheel)", equipped with special round shank teeth, will provide a better cutting performance. At the upper end of the scale, when dealing with rock strengths exceeding 120 MPa, there may be a need to consider using the "Roller bit cutter wheel". Usually, when using the Roller bit cutter wheels, a cutter with higher weight is required, as each Roller bit requires a load of at least 4-8 metric tons for a reasonable functionality.

Figure 6. Standard Cutter Wheel (left), Round shank chisel cutter wheel (centre), Roller bit cutter wheel (right)

Cutter wheels may conveniently be changed to suit different types of rock. Experiences were made with rock strengths of up to 250 MPa

Height restriction

Working under restricted height requires development of special equipment. Actual developments allow a height restriction for so called "low headroom cutter" of approx. 6.m (Figure 7).

Figure 7. Low headroom cutter

2.2.3 Slurry Handling and Storage

For the installation of a diaphragm wall, slurry is required to ensure stability of the excavated trench. In case of the cutter technology, the slurry acts as well as transport medium for the loosened soil.

The needed slurry volume is quite substantial, and the storage volume is normally separated in several areas:

- Swelling basin for hydrating freshly mixed bentonite slurry
- Concrete bentonite basin - buffer for exchanging slurry prior to concreting
- Working bentonite basin - for slurry circulation during excavation
- Waste bentonite basin

The storage unit can be made up of a series of ponds excavated in the ground, steel tanks (Figure 8 left) stacked parallel or on top of one other or, if space is at a premium, a series of silos (Figure 8 right). The layout can have different configurations to best suit the geometry of the site but it is important, in order to guarantee continuity in the work that the total capacity of the storage by unit is at least 3 times the volume of one panel trench.

Figure 8. Bentonite storage in tanks (left); Desanding plant and bentonite storage in silos (right)

In the design of storage capacity, consideration should be given to the local geology. If there are indications of the presence of formations that could lead to a sudden loss of bentonite during excavation and that could thereby compromise the stability of the trench. The size of the storage basins should take into account a surplus supply that needs to be used in these emergency situations.

3 The Installation Procedure

3.1 Working sequence

The typical working sequence for the construction of a diaphragm wall comprises the following key steps:

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

3.1.1 Guide wall

For the installation of the diaphragm wall guide walls need to be constructed prior to the diaphragm wall to provide:

- Guidance to ensure the correct alignment of the excavation.
- Stability of the upper trench that could be affected by the vertical surcharge induced by the excavation equipment and other heavy jobsite traffic adjacent to the trench.
- Protection against instability of the uppermost layers of soil caused by washing and fluctuating levels of stabilization slurry during excavation.
- Prevent collapse of the top of the trench due to equipment loads close to the trench.
- Support for the vertical loads imposed by the reinforcement cages that are suspended off the top of the guide wall. Abstract frame

3.1.2 Pre-excavation (required for trench cutter use)

For the cutter to operate properly the circulation of bentonite must be established before the machine starts to excavate the trench.

The cutter’s mud pump is located above the cutting wheels and in order to prime this pump it should be fully submersed in the bentonite fluid. Some pre-excavation of the trench must be carried out therefore, using other tools, to facilitate priming of the mud pump.

3.1.3 Excavation

Following preparation of the site and construction of the guide walls, excavation of the diaphragm wall can begin. Diaphragm wall construction begins with the trench being excavated in discontinuous sections or “panels”. Depending on the used equipment, either grab or cutter, the sequence vary slightly.

Figure 9 for instance shows a typical sequence for the installation of a diaphragm wall using a grab when using a joint element in form of a Continuous Water Stop (CWS). After a primary panel is installed, here shown as a multiple bite panel, the adjacent panel will be installed without leaving a gap.

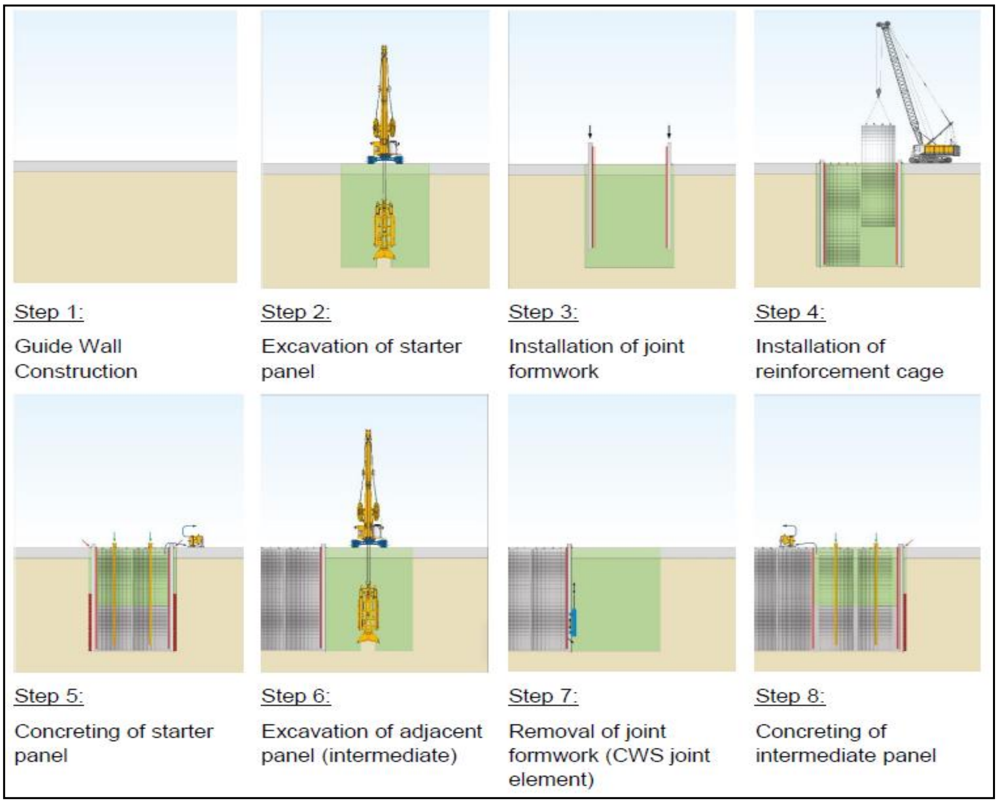

Figure 9. Triple bite sequence with CWS joint element (exemplary)

Compared to that, the cutter installation process is typically carried out in a predefined sequence to enable the construction of clear joints. This is achieved by constructing alternate "primary" panels first, followed by the excavation of the intermediate "secondary" or "closing" panels Figure 10).

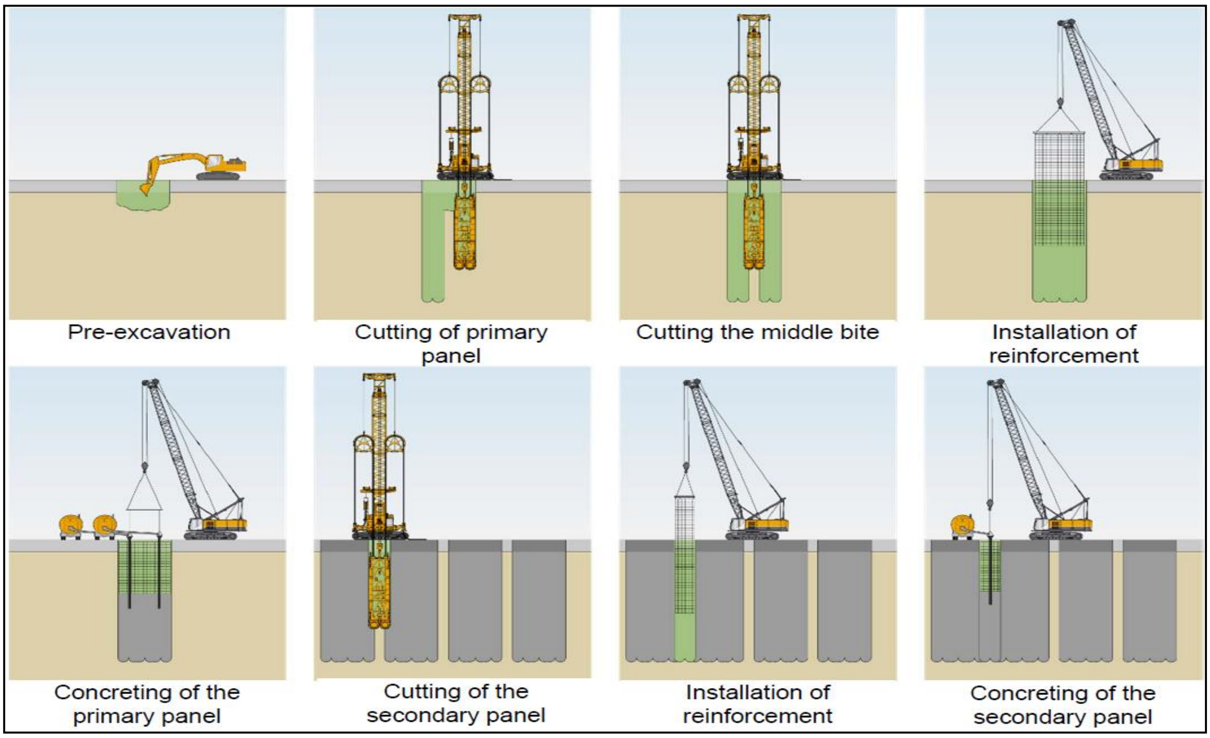

Figure 10. Construction process, exemplary for Diaphragm wall process using trench cutter

In order to ensure trouble-free excavation and that the required alignment of the trench is maintained, the excavation tool should always work within similar boundaries. The following sketches shown in Figure 11 illustrate typical applications.

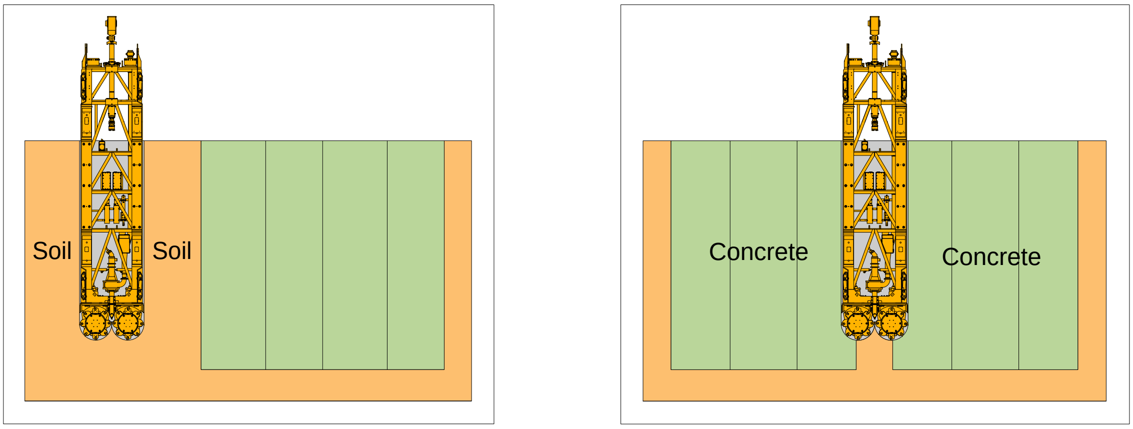

Figure 11. Excavation in soil - soil boundaries (left); Excavation in concrete- concrete boundaries (right)

Logistic of slurry and spoil handling during excavation

During the excavation of the trench, two main tasks have to be fulfilled. At first, slurry needs to be transported to the trench to ensure trench stability during excavation. Second, the excavated material needs to be disposed.
At this point, we have to distinguish the two common excavation methods, the use of a grab and the use of the cutter.

The use of the grab requires a high logistic effort for handling the disposal, as the grab will typically load the excavated material directly at the trench into a truck (Figure 12 left). This requires access and working space for the truck, which might be complicate in inner city sites with limited space. In addition, the loading process typically will generate also some pollution on the working platform. Compared to that, the cutting process will require less space for the handling of the excavated material, as the loosened soil will be transported via a second slurry line to a slurry treatment plant, which can be positioned e.g. some hundred meter away. The closed bentonite slurry circulation (Figure 12 right) therefore causes only low-level pollution during the construction process. Due to the removal of solid particles from the support fluid in the slurry treatment plant, the excavated material can also simply be moved off site and disposed.

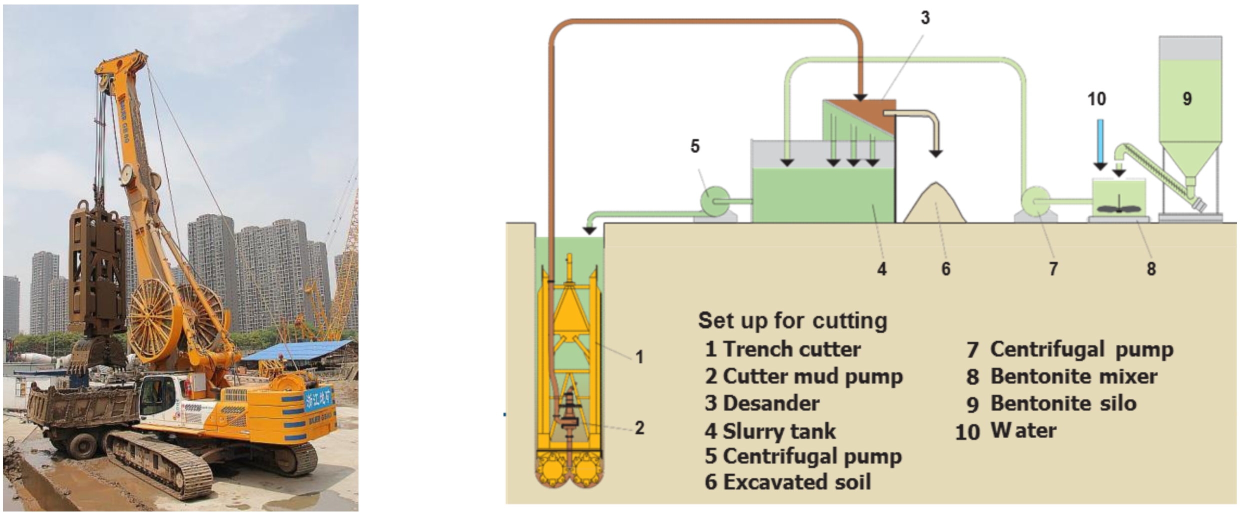

Figure 12. Loading process for grab (left), Slurry circuit for trench cutter (right)

The two slurry lines for the cutter process, the so called conveying unit, is made up of a series of pumps, pipes, valves and controls designed to facilitate conveying bentonite to and from the trench. In the design of the conveying unit account must be taken the high volume of flow of bentonite to and from the trench. It can be as high as 500 m³/h.

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.

3.1.4 Installation of Joint element (if required)

Various types of joint systems have been used in the past. One of the most common system in the early days was the construction of joints with stop end pipes as shown in Figure 13.

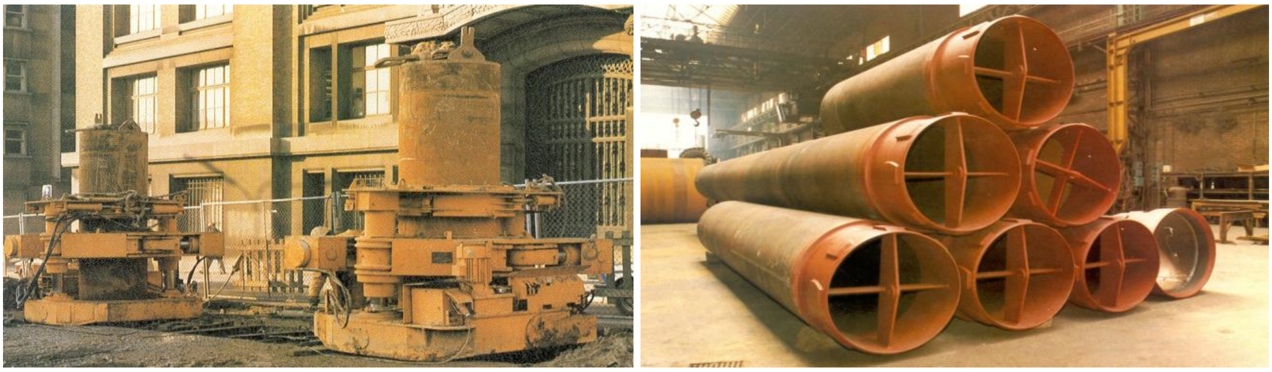

Figure 13. Stop- end pipe extractor (left), Stop- end pipes with coupling (right)

Nowadays, it is more common to use joint formwork, e.g. prefabricated reinforced concrete or steel elements can be used (Figure 14). The elements can be linked together to form a continuous vertical string. The enhancement of their water tightness is possible by fitting rubber water bars into the elements.

Figure 14. Prefabricated Concrete Elements (left), Steel forms for CWS system (middle), Exposed CWS joint (right)

Prefabricated concrete elements can be permanent construction elements that remain in the ground as integral parts of the completed wall, whereby the CWS steel elements need to be removed prior to concreting the adjacent panel.

Prefabricated joints as well as CWS joint systems can be used either for the use with grab or trench cutter. Unfortunately, they are limited in depth.

Therefore, the trench cutter offers an alternative solution. The design of the cutter allows to cut into the concrete of adjacent panels. The so called "Overcut Joint (OCJ)" system is the most common way for construction of joints using the trench cutter, especially for greater depth.
When the Primary/Secondary sequence is used, the "overcut" into a primary panel generates a clear and watertight joint (Figure 15).

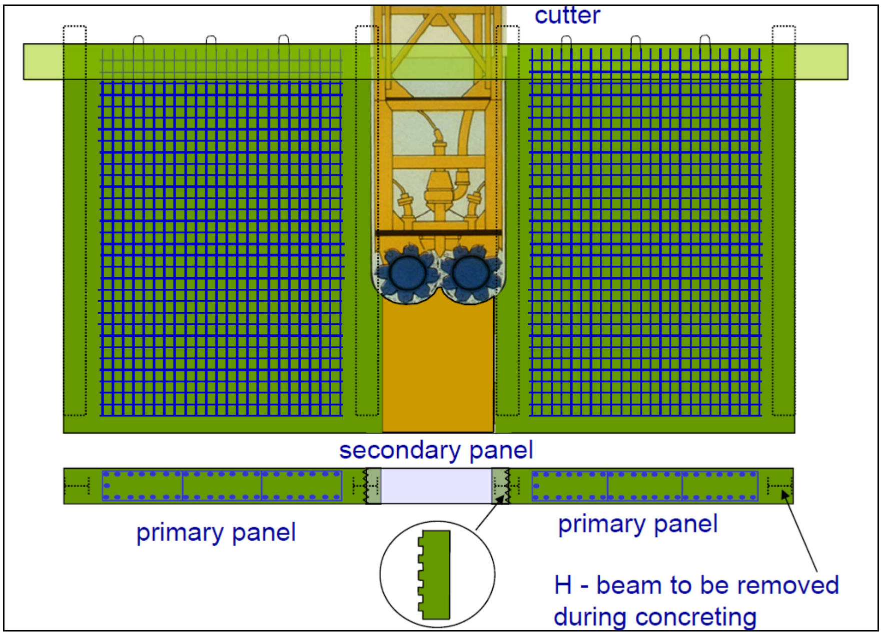

Figure 15. Principle Overcut Joint system

3.1.5 Installation of Reinforcement (for retaining walls)

Once the excavation of a panel is complete, a prefabricated reinforcement cage is lowered into the trench to the depth required by the specifications.
In case of using a trench cutter, the system of overcutting adjacent panels with the trench cutter to form good joint, requires special caution for the dimensioning and placing of the cages.
A sufficient cover must be provided to prevent the machine from accidental cutting into the reinforcement of an adjacent primary panel.
In the design of the reinforcement cage, free slots must be provided for passage of the tremie pipes (app. 50 x 50 cm) and the cages must be well cross-braced on all faces for rigidity.

3.1.6 Desanding

Prior to concreting, bentonite in the trench is circulated through the desanding plant; alternatively, it may be partly or completely replaced by fresh bentonite so that its characteristics satisfy the contract requirements.

3.1.7 Concreting

Concreting a fluid filled trench is carried out using a "Tremie pipe" that introduces fresh concrete to the bottom of the trench and allows it to rise upwards displacing the fluid in the trench. Concrete will be supplied to the trench locations by concrete trucks at a rate sufficient to ensure a pouring rate of about 45 m^3 per hour, using the tremie pipe method.

The number of tremie pipes will be determined primarily based on the length of the individual panel to be concreted. For panels up to 4 m length one tremie, for 4 to 7 m two tremie should be used.

Concreting a fluid filled trench requires a good knowledge about concrete. Concrete for special foundation works continues to advance rapidly. Recent trends have favoured higher strength classes and lower water/cement ratios, resulting in greater dependence on admixtures to compensate for reduced workability and to meet the demands for workability in the fresh state and setting time. Seeing the problems in the field, a joint research using tremie methods by both the European Federation of Foundation Contractors (EFFC) and the Deep Foundations Institute in the United States (DFI) was carried out which leads to the decision to prepare and introduce a guideline for the use of tremie concrete, "The Guide to Tremie Concrete for Deep Foundations". One purpose of this guide is to give guidance on fresh concrete characterisation, the mix design process, and the methods used to test the fresh concrete. The guide addresses design considerations including concrete rheology, mix design, reinforcement detailing, concrete cover and good practice rules for placement. The guide can be downloaded free of charge e.g. at DFI.org.

4. QA/QC

Quality assurance and quality control starts already prior to the start of the excavation process. The first step in terms of QA therefore is the installation of a guide wall.

Guide wall

Guide Walls need to be constructed prior to the diaphragm wall to provide:

- Guidance to ensure the correct alignment of the pre-excavation.
- Stability of the upper trench that could be affected by the vertical surcharge induced by the Cutter and other heavy jobsite traffic adjacent to the trench.
- Protection against instability of the uppermost layers of soil caused by washing and fluctuating levels of bentonite slurry during excavation.
- Prevent collapse of the top of the trench due to equipment loads close to the trench.
- Support for the vertical loads imposed by the reinforcement cages that are suspended off the top of the guide wall.

The guide walls are normally constructed as a cast-in-situ reinforced concrete unit. Figure 16 shows exemplary dimensions, which have to be verified according to the actual site conditions.

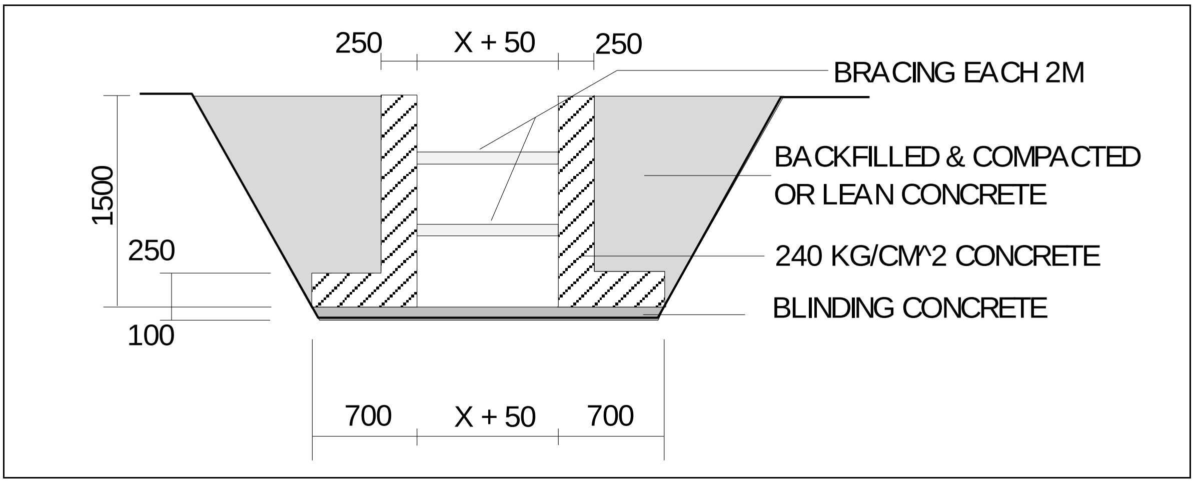

Figure 16. Typical guide wall section

Support Slurry

The trench support slurry is typically a mixture of bentonite, polymer or a combination of both with water. Admixtures such as soda may also be included in the mix design to prevent, for example, cement contamination or flocculation due to salinity of water. The slurry mix design will be finalized on site following the results obtained from trial mixes, in order to fulfil the main duty of the support slurry, to guarantee the trench stability and avoid collapse of the trench.

A typical bentonite concentration will be 30 - 40 kg of dry bentonite per 1 m^3 of slurry. Dry bentonite or Polymer powder is stored on site. After mixing it thoroughly with water, it is pumped to a hydration tank where the slurry is kept in motion and aerated for 12 hours. This process is necessary for the bentonite to fully develop its properties of viscosity and thixotropy. Using colloidal mixer may reduce the hydration time to a minimum.

It is then pumped to the main storage tanks for use. During the excavation process the fluid may become diluted or contaminated, it is important therefore that its properties be checked at regular intervals to ensure consistency in its quality.
The source and properties of the bentonite or polymer to be used shall be provided in the form of supplier certificates. The certificates will be submitted prior to the commencement of the works for approval.
The properties of the bentonite should be checked at regular intervals at the trench to ensure consistent quality of the slurry. For checking the quality of the slurry the following equipment shall be used:

- Marsh funnel
- Mud balance
- Sand content measuring kit
- Filter Press
- Fann Viscometer (or similar)

The following table lists a range of properties of typical bentonite slurry. The values are empirical and can be used unless different values are given in the project specifications.

Property to be measured	**Test method and apparatus**	**API RPI3 Section**	**Recommended values**	
			slurry pumped to the trench	**slurry in the trench prior to concreting**
Density	Mud balance	1	< 1.30 g/ml	< 1.15 g/ml
Viscosity	Marsh cone	2	30 - 70 seconds	< 90 seconds
Sand content	Sand screen set	4	unlimited (high content is advantageous in permeable layers)	< 5 %
pH	Electrical pH meter range pH 7 to 14	-	9.5 to 12	9.5 to 12

Table 1. Typical bentonite properties

Prior to the concreting process it is essential to adjust the slurry properties to ensure proper concreting. Using a trench cutter, it is common practice to use the trench cutter itself to replace or recycle the trench slurry. The machine is kept just off the bottom of the trench and its centrifugal pump is used to pump the slurry to the treatment plant. Alternatively, a heavy duty submersible pump may be lowered to the bottom of the trench in lieu of the cutter.

Controlling the excavation process

Electronic support system developed are typically integrated for controlling all equipment operations and visualizing actual operating parameters in real-time on a large interactive touch-screen monitor. The following operating parameters are displayed and controlled e.g.when using a trench cutter (Figure 17):

- Actual cutter depth
- Speed of rotation and hydraulic oil pressure of each cutter gearbox
- Speed of rotation and hydraulic oil pressure of mud pump Delivery volume of mud pump
- Crowd pressure of cutter teeth Penetration rate
- Inclination of trench cutter and computed deviations in x- and y-axes (digital and graphic)
- Internal gearbox pressure Gearbox temperature
- Residual pull on crowd winch (surcharge)

Of highest importance is the inclination control of the tool in the trench. The information as displayed in real time on the screen assists the operator in maintaining the verticality of the trench excavation, but does not show the final alignment of trench. Therefore, after finishing the excavation, the use of an independent measuring device like an ultrasonic measurement is recommended.

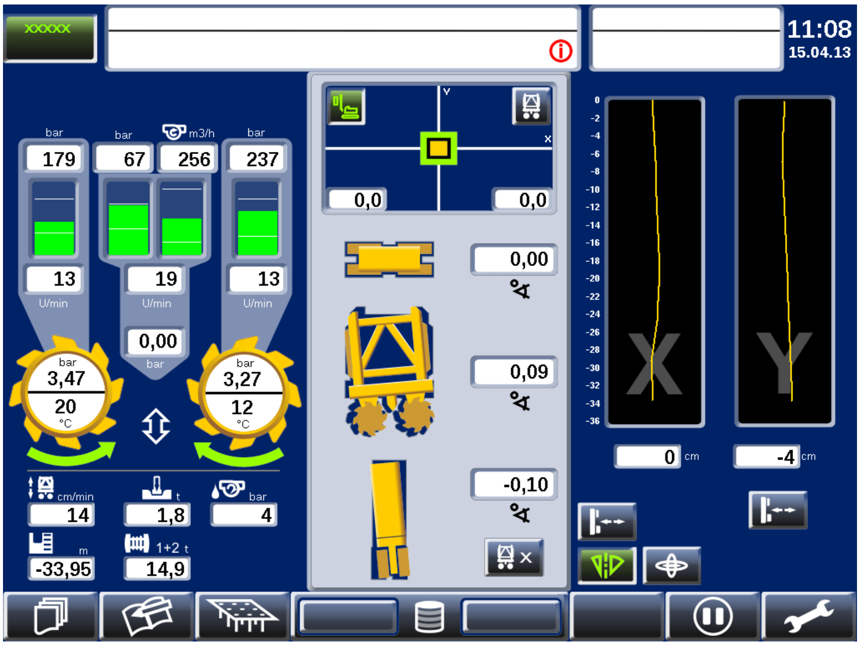

Figure 17. Example for a monitor in the operators cabin

In addition to these basic operational data, general machine operating parameters (e.g. engine data) are also acquired and monitored. The display of current machine operating states and error messages is a valuable aid for targeted and effective fault finding by service personnel on site, but also by specialists based at the offices, as data can be transferred real time via internet connection. This does not only allow the control of equipment and installation process including relevant reporting, it also allows comparing “virtual reality” and “reality”, hence planned and actual execution, which enables the project manager to control not only the schedule, but also the use of budget.

Ultrasonic Measurement (Koden Measurement)

As an independent measuring device, the ultrasonic measurement is frequently used for verticality measurements of diaphragm wall trenches.

The use of ultrasound technology allows measurements to be taken in water or bentonite slurry. The density of the slurry must not exceed 1.15 g/cm³. The deviation of the trench from the perpendicular and any surface cavities in the trench surface are measured. The ultrasonic measurement probe (Figure 18) is suspended vertically by a cable and lowered into the trench to be surveyed. Simultaneously, orthogonal waves are continuously emitted by the device and reflected from the walls. The reflected waves are registered by measurement sensors. The distances, calculated as a function of wave speed and reflection time, are presented in graphic form (Figure 18 right.) The printout shows the distance between the probe and the wall in function of depth.

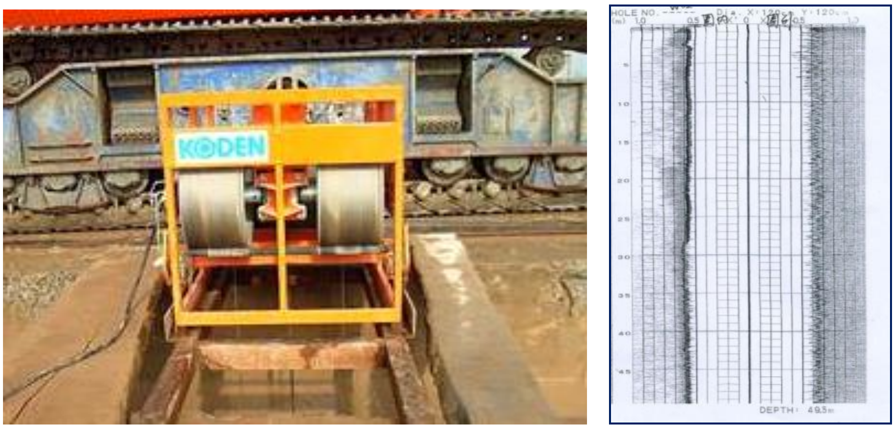

Figure 18: Koden device and measurement log

4 Where we are now?

Finally, a few reference projects should give an idea of the capability for the use of diaphragm walls.

4.1 The ONE Ho Chi Minh City, Vietnam

The First project to explain is a grab project, where the diaphragm wall technique is not only used for the excavation pit but also for the use of foundation elements with barrettes.

The ONE Ho Chi Minh City, as soon as it will be completed, will become a multi-use development complex in the heart of Ho Chi Minh City (Figure 19).

Figure 19. The ONE Ho Chi Minh City (© batdongsanexpress.vn)

The project contains two main towers, 48 and 55-storey high. It will include a hotel complex as well as luxury apartments, but also office facilities, retail shopping and restaurants.

As foundation concept the use of barrettes was established. Beside the installation of barrettes with thickness of 700 and 1.000mm to a depth of max 77 m, a diaphragm wall with thickness of 1.500 mm has been installed to an average depth of 50 m. Figure 20 shows the panel layout.

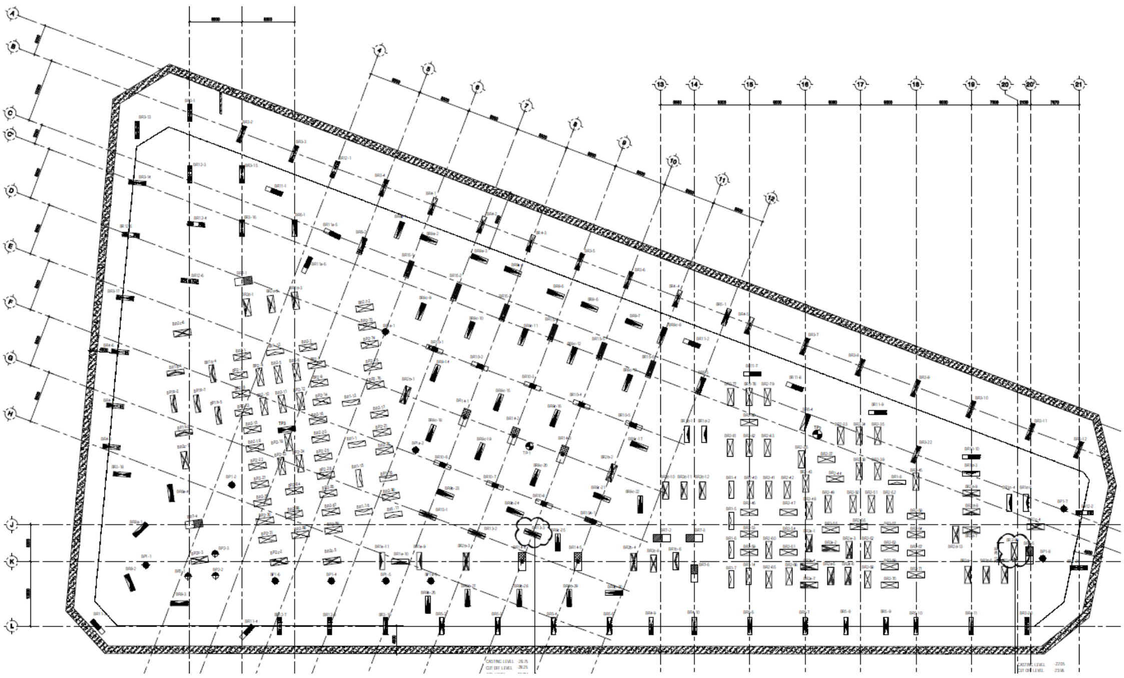

Figure 20. Barrette layout

The general soil conditions can be described as follows. Made ground is followed by a soft to medium dense sandy clay to approx. 10 m in depth. Afterwards a loose to medium dense clayey sand with a thickness of up to 40 m was found. This is followed by a very stiff to hard clay with a max thickness of approx. 14 m. Dense clayey sand is than encountered to final panel depth.
As no rock was encountered, the excavation was carried out using the grab system (see Figure 21).

Figure 21. Job site overview (left), GB 46 Grab at work (right)

The excavation, using the grab, was controlled as well by the installed grab control system (Figure 22 left) as an independent ultrasonic measurement (Figure 22 right).

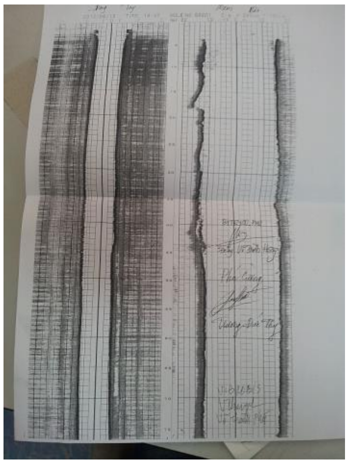

Figure 22. Job site overview (left), GB 46 Grab at work (right)

Both systems together ensured an accurate and successful installation of the barrettes.

4.2 Metro Sao Paulo, Line 5, five shaft Diaphragm wall for Brooklyn Station, Brazil

The Line 5 Extension, in the city of Sao Paulo/Brazil, is one of the most important investment in public transport by Sao Paulo state's government. It connects the south part of the city to the city center, crossing through four other major METRO lines and stations, all currently in operation. The extension includes a new parking yard for the trains and 11 new stations. The Brooklin Station is one of the new stations and has a unique geometry of five secant shafts.

The original design included constructing five secant shafts stabilized by two plastic slurry walls using conventional grab technology. One of them was to contain the contamination plumes in the neighborhood and the other for temporary support to enable the excavation of the shafts. The final retaining wall design was reviewed and changed to a concrete structural diaphragm wall. The reason of design change was as well the reduction of construction time of the shafts by half to meet the schedule as to avoid dewatering effects in a geological region characterized by Quaternary sediments and environmental contamination plumes. It was the first time that a trench cutter was used in such a situation in Brazil. The cutter increased the quality of the joints by overcutting, and decreased the probability of having seepage into the shafts. The cutter created a seepage barrier and avoided movement of contamination.

In general, the local geology is composed of a superficial Quaternary soil, basically soft organic clays, sands and gravels. From the depth of 8m until 18m, geology was composed by tertiary medium compact sand with thin silt-clay layers. From 18m down, there are alternating layers, compact silty sands and very hard clay layers, each approximately 5m to 10m thick.

For the final design several construction requirements were established; with the most important are listed as follows:

- Solutions to mitigate contamination found in the surrounding areas and prevent spreading.
- Construction systems and methods to accelerate station's excavation phase, in order to fulfill TBM schedule.
- Keep construction costs unaltered.

To address the challenges, a structural diaphragm wall was designed to provide peripheral containment for the station and to act as a seepage barrier wall. A 1 m thick structural diaphragm wall was proposed, based on the use of a trench cutter with no changes made in the final layout (Figure 23) of neither the shafts nor its architecture.

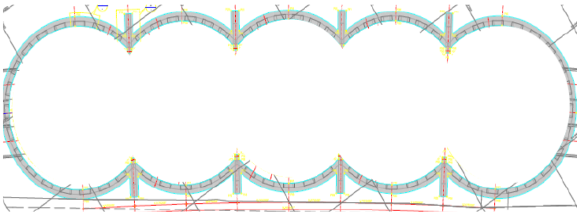

Figure 23. final design

The new solution avoided dewatering and all its related risks. Moreover, the diaphragm wall was considered to be a permanent structure whereas the slurry wall and the shotcrete support were both considered as temporary and disposable structures in the original solution. At the final design stage, 133 single bite panels, with dimensions of 1.0m x 2.80m and 30m deep were used to create the external circular geometry for the shafts.

At each of the five shaft intersections, four diaphragm panels 36m deep, forming the shape of an “arrow”, were constructed simultaneously aimed at “interlocking” the shafts. This solution offered a way to hold the arch effect of the shafts (in principle acting as big tieback) and avoid having to fully close the circles with panels, and then having to demolish these structures after the excavation.

As a specific solution, the installation of the diaphragm wall was carried out in a combination of using grab and trench cutter technology. The grab (Figure 24 left) was used to install the primary panels. Depth of the wall and soil conditions allowed the use of the grab without problems. The trench cutter technology (Figure 24 right) for the secondary panels was chosen for two specific reasons. One was to provide precise verticality control in the execution of the diaphragm wall panels critical for the panel overlap. The second reason was that due to the increased quality of joints between panels through overlap created at time of excavation of the secondary panel, a mitigated seepage was achieved.

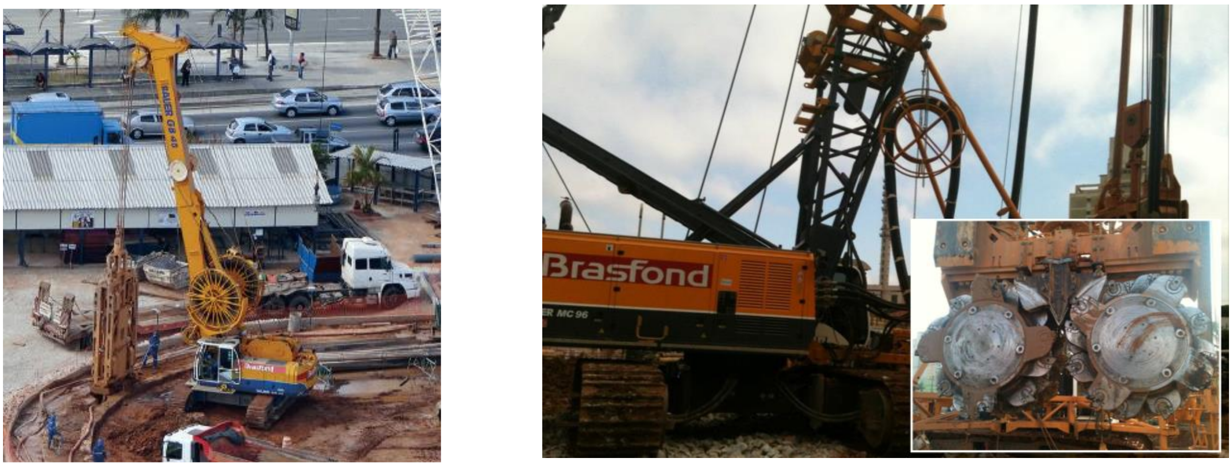

Figure 24. Hydraulic Grab GB 46 (left), Trench Cutter BC 40 on Crane MC 96 (right)

A specific challenge was the installation of the “arrows”. Panel verticality in the was of extreme importance. Any deviation in the excavation of one of the panels would have prevented the insertion of the reinforcement cage, as it would have gotten stuck on the walls of the excavation and would prevent it from reaching the full depth. Therefore, a combined excavation using as well the grab as the cutter was established for the eight arrows.

The arrow consists of four panels. The required amount of concrete for one arrow in total was about 430m³. Not only due to its three dimensional shape, but also to enable the installation of tremie pipes to ensure concreting, the reinforcement cage had to be built with the support of scaffolding in three 12m sections to achieve required verticality. Four tremie pipe gaps had to be foreseen as shown in Figure 25.

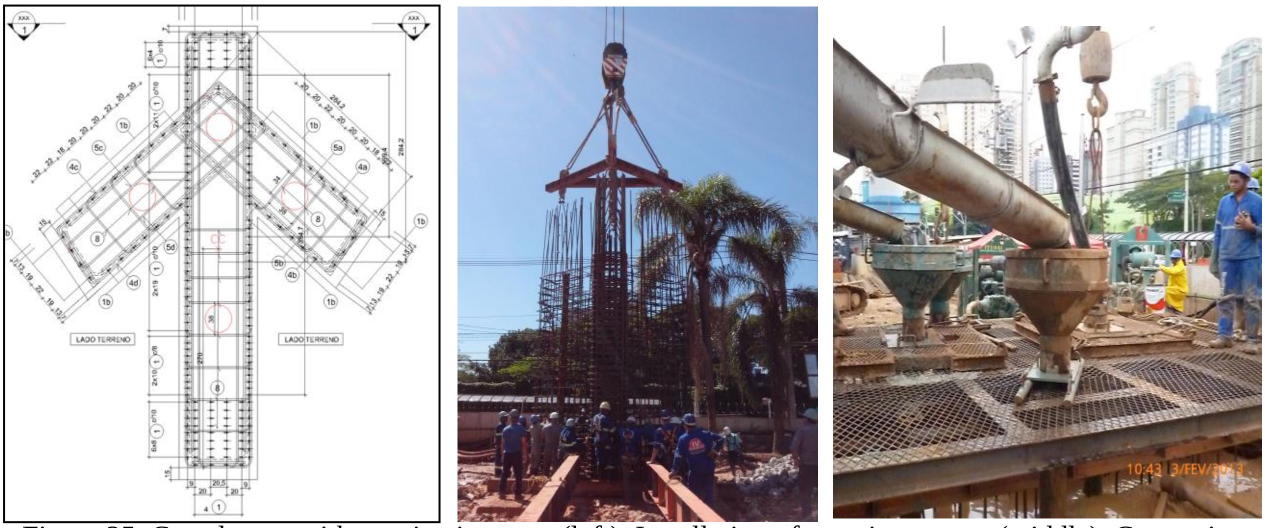

Figure 25. Cage layout with tremie pipe gaps (left), Installation of cage into arrow (middle), Concreting arrow (right)

The success of this project was based on the interaction between the Metro authority, the Construction JV, the designer, and the foundation contractor. This allowed establishing the best possible solution as well to reduce construction time. The final result can be seen in Figure 26.

Figure 26. Shafts after final excavation

4.3 **Yunlingxi Deep Shaft, Shanghai, China**

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. 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. the Layout is shown in Figure 27.

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 on a specific jobsite to 150 m by using the trench cutter only.

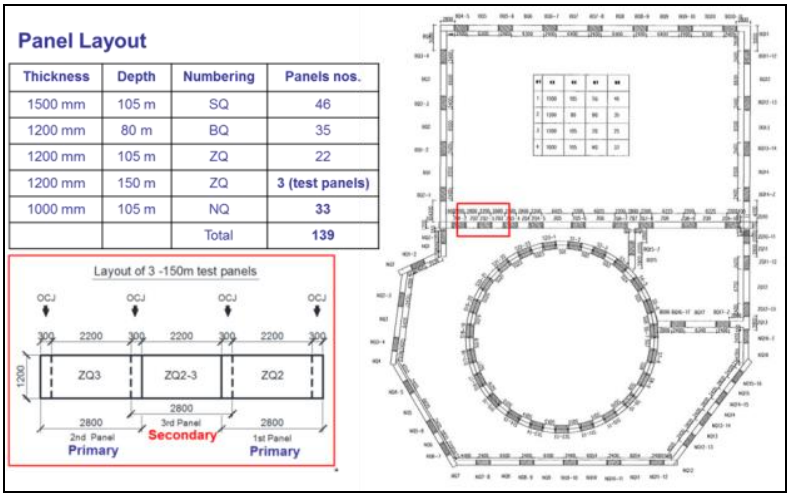

Figure 27. Site layout

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.

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, the construction of these three ultra-deep diaphragm wall panels were successfully completed in January 2018.

Figure 28: Cutter Configuration at final depth

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 (Figure 28) 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.

5 Summary and Outlook

The idea of the diaphragm wall technique is already more than 100 years old. But it took almost 50 years to get the system to a point until the market accepted this technology. Since then, huge effort has been undertaken by several companies to develop suitable and efficient equipment for various applications and soil conditions. The development of the trench cutter opens the door to work also in rock.

Installing continuous, water tide diaphragm walls required a solution for sealing the joints between adjacent panels. Temporary (e.g. CWS Joint) and permanent (e.g. prefabricated concrete) systems could and can be seen all over the world. Unfortunately, all these systems are limited in depth. Due to the capability of creating a joint using the "Overcut Joint (OCJ)" system with the use of a cutter, the depth is almost unlimited. Tests could proof the system, for a depth of 150 m.

With increasing demands on depth also the demands for the installation become stricter. There are for instance extremely strict requirements for trench verticality of 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. Accompanied with this also the specifications for the concrete will increase. The "Guide to Tremie Concrete for Deep Foundations" can be a good tool to help in that matter.

Looking to Figure 29, 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 the "Overcut Joint (OCJ)" system 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. It can be noticed and anticipated, that the request for deep and ultra-deep d-walls will increase in the future.

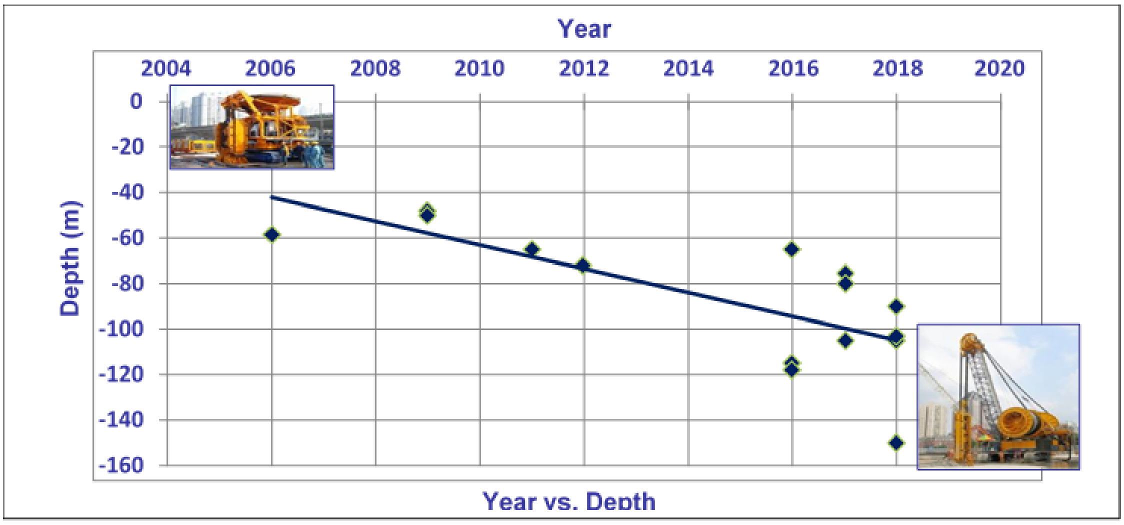

Figure 29: Selected cutter projects in Shanghai – Year vs. Depth

Finally, It can be summarized, that after a slow start the importance of diaphragm walls for various applications is increasing and will be an important technique for the future. Increasing demands for depth as well as for challenging ground conditions will drive further developments for equipment and materials.

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