Diaphragm Wall Technique – Planning, Execution and Development over the Last 65 Years

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Abstract. The development of diaphragm wall technology in Europe began at the beginning of the 1950s with the work of Christian Veder and Hans Lorenz. The advantages of this special civil engineering method quickly became apparent in the construction of inner-city excavation pits and infra-structural measures in the form of low-deformation, water-impermeable reinforced concrete walls, as well as in the use of sealing walls in earth dam and landfill construction.

In the beginning, the focus was on the investigation of the supporting effect of bentonite suspension in the open slot, but soon the technical developments of the excavation tools followed. After setbacks in the quality of the walls, the pioneers of the method tried to identify the sources of error and to avoid them by consistently adhering to the self-imposed specifications. To this day, the process is a speciality in terms of planning and execution and requires a great deal of experience on the part of those involved. The project-specific quality assurance of diaphragm wall construction sites is a decisive aspect for the safe and economical execution of the work.

1 Basics

A diaphragm wall usually has 2 functions. On the one hand, the static function serves to absorb the loads from the neighbouring buildings and the earth and water pressure. Secondly, it has a waterproofing function. This combination of functions is particularly evident in inner-city construction pits. From the upper edge of the diaphragm wall to a few metres below the construction pit floor, the wall has to assume the sealing function in addition to the static effects, and deeper down it actually only serves to shut off the water. Trough pits with a sealing base are constructed to avoid lowering the groundwater level. This is achieved either by incorporating the walls in a soil layer with low water permeability or, for example, by means of a grouting or jet grouting slab.

With the diaphragm wall construction procedure, a construction pit enclosure can be planned directly at the property boundary for optimum utilisation of the area. Compared to a sheet pile wall, there are hardly any vibrations or noise disturbances in the direct vicinity. The depth of the wall is freely selectable under consideration of the boundary conditions (number of basements, load, geology, etc.) and is only limited to a limited extent by technical equipment restrictions. In the 70 s, wall depths of 25 to 30 m were already a special feature. In recent years, diaphragm walls for inner-city

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excavation pits with a depth of 40 to 50 m have been constructed. In Hamburg, a diaphragm wall with a depth of up to 72 m was constructed in 2017 at the Olympus Campus pit.

The wall thicknesses have increased in recent years. Today, wall thicknesses of 1.0 m with deep excavation pits are no longer a special feature. Walls with a thickness of 1.5 m are planned for the construction pits for the new metro main line in Munich.

2 Development of Equipment and Tools for Diaphragm Wall Execution

The equipment and tools used in Milan subway construction in the 1950s can no longer be compared with those used today. Christian Veder patented a process for the production of a watertight wall, which was characterized by the stringing together of uncased bores, which were produced with a free-fall chisel in a flushing stream from clay suspension. This continuous wall surface was then concreted using the tremie concrete method (Fig. 1).

Fig. 1. Diaphragm wall works in Milan from 1956 (Quelle: Wikipedia)

In the early 1960s, the first excavation methods with continuous soil excavation by means of indirect flushing with bentonite suspension were developed in Japan by the companies Tone Boring and Okumura. Soletanche brought a further development of this excavation technology onto the market in the 1970s. Menck & Hambrock started building the first series-produced diaphragm wall grabs in 1966. At the end of the

1960s, STEIN began working with diaphragm walls and initially designed its well-known rope grab for its own use. Later, STEIN also built the grabs for its competitors (Fig. 2).

Fig. 2. Construction site with 3 cutters for the construction of a shaft in the UK (Quelle: BAUER)

BAUER is the only manufacturer of diaphragm wall cutters in Germany. BAUER has been building its various cutters for the world market since 1984. The use of these cutters enables them to be integrated into rock formations and to reach great depths with minimal deviation in verticality. The cutter wheels can be adapted to the geological conditions with an appropriate choice of loosening tools. Verticality is continuously measured by means of an integrated inclinometer and counter-controlled by flap controls in the event of deviations from the nominal position. An additional control of the position of the cutter is carried out at BAUER with the specially developed "Cutter Inclination System", CIS for short. This system uses a tachymeter to record the above-ground position of the retaining ropes of the cutter three-dimensionally and extrapolates it to the cutter body, thus determining the position of the cutter.

With the development of the hydraulic diaphragm wall grabs, the mechanical rope grabs were partially replaced. The hydraulic grab does not require such high demands on the machine operator and can optionally correct the vertical position of the trench during excavation by means of control plates. In France, SOLETANCHE had already adapted hydraulic grabs to Kelly bars in the 1970s and thus reached depths of between 50 and 60 m. In 1993, BAUER developed a hydraulic grab with a width of 35 cm for use with sealing walls.

The mechanical grab achieves its high closing forces by the closing cable guide via deflection pulleys. For operation with the mechanical rope grab, a rope excavator requires free fall winches. As a rule, the grab is lowered to the bottom of the excavation, lifted up again a little and then dropped onto the bottom. This strengthens the penetration of the grab teeth into the soil and increases the digging capacity. In contrast to this, the hydraulic grab is simply placed on the excavation base when open and the grab shells are closed hydraulically. The “chiselling” or “stabbing” of the grab is not carried out with the hydraulic grabs.

The first rope crawler crane for diaphragm wall work, which were used area-wide in Germany for use with mechanical rope grabs, were MENCK cranes. After the insolvency of the MENCK company in 1978, LIEBHERR began building crawler cranes with free fall winches.

3 Supporting Fluids

The use of bentonite suspension was a major mystery in the early years of diaphragm wall technology. Only the consequent research of the properties and modes of action of thixotropic clay suspensions by Hans Lorenz, Fritz Weiss and Hanno Müller-Kirchenbauer enabled the well-founded handling and calculation of the stability of the “open, suspension-supported trench”. With the publication of the dissertation by Fritz Weiss in 1964, the total stability of the panel and the single grain in the diaphragm wall could be calculated for the first time. Fritz Weiss introduced the concept of flow limit to understand the suspension properties, and his pendulum device for determining the shear strength was initiated by standards. With the development of the ball harp (german: Kugelharfe) in 1974, Paul von Soos brought a measuring instrument onto the market that can still be found on all diaphragm wall construction sites today.

Two phenomena are described with the mode of action of a bentonite suspension. In cohesive and fine sandy soils a filter cake is formed. The water in the suspension is partially filtered out at the interface of the soil layer and the hydrostatic pressure acts on that of the suspension and is transferred to the soil. In the case of coarse sand and gravel without sufficient fines, the bentonite suspension penetrates the soil to a certain depth. Although there is no filter cake formation, stabilisation is nevertheless effective on the soil. This stabilizing effect is described by the term flow limit (shear strength of the suspension).

The use of polymers as additives for a hybrid suspension has become increasingly common in recent years. For example, a bentonite suspension is enriched with the addition of polymers especially for special applications or properties. In Germany, the use of a pure polymer suspension is not as common as in Asia, for example. In France, diaphragm walls with pure polymer suspensions were already successfully manufactured in the 1990s. BAUER switched from a bentonite suspension to a pure polymer suspension at a milling construction site in the Middle East because the milling wheels bonded due to the geological conditions and this phenomenon no longer occurred due to the change in the supporting fluid.

In March 2019, the European Foundation Engineering Federation (EFFC), in cooperation with the American Foundation Engineering Federation (DFI), published a guideline entitled “Guide to support fluids for deep foundations”, describing the source materials for support fluids and explaining how to handle them on the construction site with practical test options.

4 Formation of Joints

The formation of joints is a fundamental issue in the construction of diaphragm walls. The selected joint system must be known as early as the planning and design of the diaphragm wall reinforcement. The different types of joint formation have an influence on the geometry of the panels and the reinforcement steel cages.

In the last 20 years, the use of round joint tubes to limit the panel has been reduced in favour of flat joint elements. The depth of use of the recoverable formwork elements is 35 to 40 m for standard tasks. For deeper trenches, lost joint elements are used.

Prefabricated formwork elements are a somewhat more expensive but high-quality alternative among the lost formwork elements. Due to the stable design of the concrete elements, there are actually no distortions or solder deviations. However, they are very heavy and their use is limited by depth.

The proper and complete removal of the circulated concrete and bentonite residues around the formwork element is very important for a watertight execution.

For cuttered diaphragm wall lamellas, as a rule no stop-ends are required. The cutter cuts the previously concreted primary panel and the concrete of the secondary panel is seamlessly joined to the existing panel.

5 Execution

The essential success factor for proper execution is the competent and experienced team on the construction site.

In addition to knowledge of the geological composition of the soil, the on-site team also needs information on the groundwater situation. Careful adjustment of the bentonite suspension and storage in silos or reservoirs is one of the basics. In the event of a sudden loss in the suspension level in the trench, the team must immediately take countermeasures to prevent the trench from sinking further and to prevent it from collapsing.

The working platform should be sufficiently high in relation to the groundwater level in accordance with the boundary conditions. In this way, the stability of the excavation wall can be ensured by a sufficient pressure gradient.

Panel layout, joint formation and reinforcement design must be planned and determined in advance before execution. In the case of installations in the reinforcement cage, e.g. anchor ducts, care must be taken to ensure a flow-optimised shape. The rising concrete should be able to completely enclose the internals.

For the economical construction of a diaphragm wall, the execution sequence is also an important point. Unfortunately, malfunctions repeatedly lead to deviations from the ideal sequence. This has a strong influence on the daily output and logistics on the construction site (provision of reinforcement cages).

As early as the end of the 1960s, those responsible were intensively concerned with the damage that had occurred and developed instructions for action, which were included in the first diaphragm wall standard. Since then, numerous publications and lectures have reported on the proper execution

6 Quality Assurance

The diaphragm wall standard DIN EN 1538 and other regulations describe what has to be done on construction sites in terms of quality assurance. The topics exceeding the requirements of the standard are regulated in the contract and in the quality assurance plan of the construction site. After the collapse of the city archives in Cologne, the subject of quality assurance has become an even higher priority.

During the work preparation before excavation, special attention is paid to the geometric position of the wall, the building materials used and the reinforcement cages. During wall construction, the following partial steps are monitored and controlled: the excavation process, adherence to verticality and torsion, cleaning of the slots, joint formation, installation of reinforcement and concrete installation.

7 Outlook

Further developments in diaphragm wall technology will include not only developments in equipment but also the disposal of bentonite and polymer suspensions, wider use of polymer suspensions, quality improvement in joint formation, control of concrete paving and quality.

Over the next few years, we will be able to observe how diaphragm wall construction units are increasingly being equipped with data acquisition from production and various sensors for monitoring and quality assurance. Construction management will be able to concentrate on digital process management alongside execution technology.

8 Chronological Development of the Diaphragm Wall Technique

1912 Patent of the company Carl Brandt, Düsseldorf: Process for the manufacture of pillars, piles and the like for civil engineering purposes using the thick flushing process commonly used in mining

1950 Hans Lorenz: On the use of thixotropic liquids in foundation engineering

1950 Christian Veder: Patent for a process for producing watertight walls by stringing together uncased boreholes and using a thick flush stream

1956 Diaphragm wall work in Milan carried out by the company ICOS-Veder

1959 First diaphragm wall projects in Berlin and Munich carried out by the company Pollensky & Zoellner

1961 Development of the technology for the regeneration of bentonite suspension on a construction site in Belgrade/Petuelstraße, Munich

1962 Laboratory tests at Pollensky & Zoellner to investigate the support of earth walls by liquids

1964 Dissertation by Fritz Weiß: Theory of liquid-supported earthwalls and technology of supporting liquids. Introduction of the flow limit. Development of the pendulum device for determining the flow limit

1964 TONE BORING company from Japan develops a tool for the continuous conveyance of soil by means of 3-cone chisels which rotate around their vertical axis.
1965 OKUMARA company from Japan develops the first diaphragm wall milling machine with horizontal milling wheels, which are moved by electrically driven chains
1966 First set of rules by Fritz Weiß for the Munich Federal Railway Authorities for the safe and damage-free manufacture of diaphragm walls
1966 First serially manufactured diaphragm wall grab from Menck & Hambrock, nominal thickness 60 cm and 80 cm with grab width of 2.6 m
1967 First training course conducted by Schönebecker Brunnenfilter GmbH: "Workshop on diaphragm wall construction", from 20 to 22 September 1967 in Munich in the meeting room of Munich Central Station with 126 participants
1969 SoOLETANCHE company builds first diaphragm wall with prefabricated parts
1969 The STEIN company builds the first diaphragm wall grab (K121) with oil-bearing rope pulleys and uses it on the Kaufhof construction site in Munich
1970 Start of production of single-phase diaphragm walls in Europe
1971 Foundation of the NABau "Working Committee II diaphragm walls" with 32 employees under the direction of Dr.-Ing. Bub, Institute for Civil Engineering, Berlin for the development of the later standards DIN 4126 and DIN 4127
1972 Calculation method for the "stability calculation of the open trench" by Hanno Müller-Kirchenbauer with introduction of the stagnation gradient
1973 First single-phase sealing wall in Germany at the Iffezheim barrage by the KELLER company
1975 SOLETANCHE company develops a slotted wall grab on a 60 m long Kelly bar
1975 SOLETANCHE company develops a cutter with horizontally mounted counter-rotating, hydraulically driven cutting wheels
1978 Development of the ball harp for determining the flow limit by Paul von Soos
1981 Publication of ATV 18313 "Schlitzwandarbeiten" (diaphragm wall works)
1982 CASAGRANDE launches a chain-driven cutting machine on the market
1982 First "earth concrete wall" manufactured in Germany at the Igelsbachsperre by BAUER company
1984 First sealing wall with adjusted HDE film at the Malsch landfill by the ZÜBLIN company
1984 Publication of the preliminary standards DIN 4126 "Diaphragm walls" and DIN 4127 "Clays for diaphragm walls"
1984 First German diaphragm wall cutter with direct hydraulic gear from BAUER, Schrobenhausen, Germany
1986 DIN 4126: "Diaphragm walls", version August 1986 and DIN 4127 "Diaphragm wall clays", version August 1986
1989 First cutter for rock works (rock strength up to 150 MPa), BAUER, Schrobenhausen
1989 First single-phase slurry wall with cutter in Ottmaringer Valley by Bilfinger + Berger

1990 Recommendations of the Working Committee "Ufereinfassungen": E 144 Application and design of diaphragm walls and E 156 Application and manufacture of sealing trench walls and sealing narrow walls
1990 DVWK Merkblatt 215 "Dichtungselemente im Wasserbau"
1991 Mini cutter MBC 30 (4.5 × 5 × 5 m) from BAUER with winding device for 150 m depth
1993 Construction of a BC 50 milling machine for off-shore work for diamond search at a depth of 150 m off the Atlantic coast of South Africa
1993 Hydraulic single rope grab for sealing walls with d = 35 cm from BAUER, Schrobenhausen, Germany
2000 First European standard for diaphragm wall work: EN 1538 "Diaphragm walls", version July 2000
2004 Theodoros Triantafyllidis, Planning and construction of a special foundation, Part 1: diaphragm wall and slurry wall technology, Ernst & Sohn Verlag
2005 Sealing wall for the Peribonka dam: Use of a cutter for rock strengths of up to 200 MPa with almost vertical rock flanks and a depth of 120 m. Carried out by BAUER Spezialtiefbau
2009 Use of a CBC25/MBC 50 low-headroom cutter at the Yeleh Water Power Station in China for the construction of a slurry wall from a 6.0 m wide × 6.5 m high tunnel: depth up to 75 m, width 1 m
2012 Center Hill Damm, USA: Thickest 2-phase slurry wall with d = 2.25 m manufactured with a cutter BC50. Depth up to 64 m (BAUER)
2012 Experimental field Gualdo Forli-Cesena for milling depth of 250 m (TREVI)
2015 Revised European standard EN 1538 "Diaphragm walls"
2016 EFFC/DFI Best Practice Guide to Tremie Concrete for Deep Foundations, 1st Edition
2017 The ZÜBLIN company uses the first rope grab with a nominal thickness of 2.0 m (MFS Maschinenfabrik GmbH & Co KG) for the EMSCHER BA60 project in Oberhausen
2018 EFFC/DFI Guide to Tremie Concrete for Deep Foundations, 2nd Edition
2019 EFFC/DFI Guide to Support Fluids for Deep Foundations
2019 Star-Orion South Diamond Project, Canada: Diamond exploration with a 3.2 m × 1.5 m milling machine for 250 m depth (Rio Tinto)