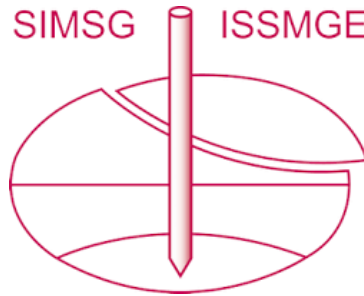


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IMPROVEMENTS IN DIAPHRAGM WALL EXECUTION – POSSIBLE DEFECTS AND THEIR CONTROL

AMELIORATION DE LA REALISATION DE RIDEAUX SOUTERRAINS D'EAUTS EVENTUELS ET LEUR CONTROLE

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INTRODUCTION

Hardly any other technique had such a profound influence on modern foundation engineering than the use of fluids to support excavations in the ground. In particular the method of diaphragm wall (in the U.S. called slurry trench wall) has undergone a continuous development through progressive improvement of the technique and its adaptation to specific engineering needs since its first use some 40 years ago. Since then their use on a world-wide scale has grown with an almost spectacular expansion in recent years.

The essential feature of the method of diaphragm wall construction is the excavation of a deep narrow trench in the ground with the aid of a purpose - designed excavation tool, introducing a stabilizing fluid which replaces the soil removed by the excavating tool. On completion of the excavation the trench is filled with concrete or other backfill material by tremie thereby displacing the supporting fluid.

New developments in diaphragm wall execution can be related to any of the following:

- Mechanical tools and equipment
- Materials and products
- Design

TOOLS AND EQUIPMENT

Most notable is the development in recent years of the mechanical equipment for the trenching operation. To excavate a trench for diaphragm walls any of the following trenching tools are nowadays used:

- Bulk excavating tools (grabs, buckets, back-hoe)
- Percussion tools (chisels)
- Rotary tools (drills, milling cutters [Fraise], Auger)

The most commonly excavation tools are specially designed grabs, either rope suspended or mounted on the end of a rigid guided Kelly-bar. The opening and closing of the grab can be achieved by a rope mechanism or hydraulic pistons. Essential for efficient digging, apart from the mechanism of the grab itself is the total weight and the guidance of the grab. Present developments tend towards heavy hydraulic grabs of up to 20 tons with large jaw opening (4 m and more) and a single or telescoping Kelly-bar for added weight and guidance mounted on heavy crawler base.

The improved rate of digging by these grabs resulted in a significant increase in production rate in wall construction. This improved digging rate should, however, not be used indiscriminately in any kind of ground condition, as in loose cohesionless soil, especially with a high groundwater table, this can lead to scouring actions at the digging face.

The guidance for verticality of the rope suspended grab is mainly gravity. Boxlike frames above the grab jaws improves the guidance. A new development are special long frames with hydraulically controlled movable plates which permit a correction of the alignment whilst digging.

Normally a grab has two jaws for digging a prismatic section. A more recent development are grabs with three or four jaws which allow to excavate in special cases π or $\frac{\pi}{2}$ sections in one digging operation. The increased force exerted at digging face by modern heavy grab rigs permit them to be used with special attachments as percussive tools for breaking up obstructions in the ground.

PERCUSSIVE AND ROTARY TOOLS

Bulk excavating tools, like grabs have to be brought up above ground level for discharge of the spoil.

In contrast, percussive and rotary tools loosen and break up the soil into small particles and mix the cuttings with the supporting fluid at the digging face. The fluid, laden with soil cuttings, is then pumped to the surface, where the soil cuttings are separated from the drilling mud. These tools advance in situ and remain at the cutting face until the excavation is complete.

Percussive tools or chisels can penetrate any type of soil, even soils containing a high proportion of large boulders, and can effectively cut into bedrock.

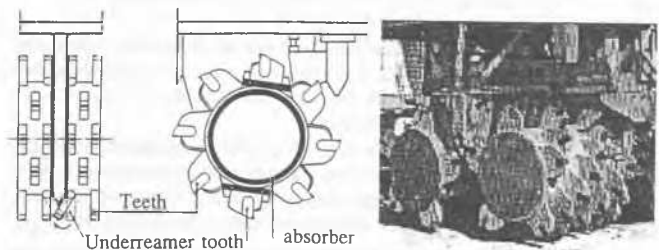
Recent developments include chisel attachments to grabbing rigs (see above) or tools which increase the chiselling force by automated hydraulic action (down-the-hole hammer).

By far the greatest advance in recent years is the development of rotary tools for excavation. Two Japanese companies introduced in the early 1960's heavy electro-mechanical drilling and milling machines with multiple rotary cutters about a vertical axis (Tone Boaring) or cutting wheels around a horizontal axis (Okumura). By employing high torque hydraulic motors instead of electric motors the machines improved drastically the penetration rate even in "heavy" soils.

The first milling cutter, capable of excavating through layers of calcareous rock in Paris was introduced by the French company Soletanche in 1975. Further improvements of the milling-cutter were made in Europe in the mid 1980 by the Italian company Casagrande and the Bauer company in W.-Germany the latter using elastic shock absorbers to protect the hydraulic drive when stones or rock fragments are crushed by the cutting teeth and using underreamer teeth to remove the soil between the cutting wheel.

The most notable advancement in the cutter technology by the Bauer Co. is the use of rock cutting wheels instead of tungsten teeth capable of penetrating very hard limestone and even granite.

Recent designs of giant cutters by European and Japanese companies permit the construction of walls 2,80 m thick to a depth of more than 150 meter.



Cutter with underreamer & shock absorber Cutter for 2,40 m wall (Bauer)

The continuous excavation process by the milling cutter requires also a continuous monitoring of the alignment and corrective measures in case of deviation. This is achieved by electronic sensors attached to the equipment recording to the operator the relevant data for manual or automatic control by changing the rate of rotation and the torque of cutting wheels.

SUPPORTING FLUIDS

The stability of the sides of the trench during excavation is due to the stabilization action of the supporting fluids. When using a bentonite suspension this action is due to the formation of a membrane or cake of low permeability by filtration at the contact zone of the soil-liquid interface provided the fluid pressure in the trench exceeds the external ground water pressure. This filter cake together with a limited penetration of the suspension into the pores of the soil, allows the full hydraulic pressure of the fluid to be exerted against the sides of the trench.

In recent years non-mineral liquid polymers without a notable shear strength are being used as a stabilizing fluid. The stabilizing action in this case is only due to the filtration of the fluid into the soil, the penetration distance depending on the permeability of the soil and the degree of colmatation i.e. deposits of suspended particles within the pores of the soil. In certain circumstances this may result in significant loss of fluid in the trench and requires regular topping up. Therefore a mixture of bentonite and polymers are preferred nowadays.

STABILITY

The main factors which affect the stability of a trench during excavation and need to be taken into account for a stability calculation are as follows:

- the stabilizing action of the supporting fluid
- the strength parameters of the soil including ground water condition
- the 3-dimensional geometry of the problem
- effects of loads adjacent to the trench

Some of the factors can be controlled during construction, namely

- the level quality of the supporting fluid
- the length of the panel (3-dimensional effect)
- the time during which the trench is left open (possible loss of shear strength)

A guide to the quality control of the supporting fluid is available through commonly accepted codes of practice. Some national codes provide standardized stability calculations taking all the above factors into account (Germany), others refer to comparable experience in similar geotechnical conditions. Localized overbreaks at the sides of the trench may develop during excavation at the transition zone between compact and loose layers of soil or by uncontrolled action of the digging tool (i.e. cavitation).

Should this be significant this may also be treated by backfilling with lean mix concrete and re-excavation.

To check the surface alignment of the trench sides an ultra-sonic monitoring device has been developed, which record on a continuous printout any variation of the width of the excavated trench.

The most common deficiencies of completed diaphragm walls (mud inclusions, cold joints, silty/sandy deposits on reinforcement bars and inserts) can be traced back to inadequate cleaning of the supporting fluid and of the bottom of the trench before backfilling. Deficiencies provide generally pathways for water permeation through the wall.

PANEL JOINTS

There are various techniques of jointing adjacent wall panels. The most common form is still a butt joint formed by using steel or concrete stop-ends, which are extracted after the concrete or other material has hardened sufficiently, or are left in place as part of the wall.

With the milling-cutter technique, joints are formed by cutting into the concrete, or hardened material, of the previously cast panels. Although butt joints cannot be claimed to be waterproof they can be considered as being reasonably watertight for most practical applications.

There are now techniques available to physically connect adjacent panels with waterstops for improved watertightness, and with reinforcing bars to allow the transmission of structural forces and moments. This is of importance if permanent diaphragm walls have to be constructed in earthquake prone areas.

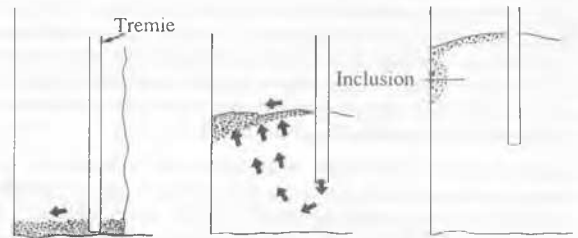
The contact surface of the joint, including any waterstops or continuity re-bars, must be freed of soil and debris immediately before concreting. This can be achieved by mechanical devices (scrapers or brushes) or by a high pressure waterjet sweeping along the joint.

REINFORCEMENT AND CONCRETING

When required, concrete diaphragm walls are reinforced. The reinforcement is prefabricated in cages horizontally on the ground surface and normally

hoisted into the vertical position by crane then lowered into the excavation. There can be considerable distortion and consequent damage to the cage especially of long cages under its own weight during this handling. Platforms for raising the cage in an undistorted manner have been developed which improves this operation considerably.

Concrete of high workability is placed in a continuous operation using one or more tremie pipes displacing the supporting fluid from the bottom upwards. It is the upward movement of the concrete with its sweeping action over the soil face and the reinforcement bars and inserts which achieves an intimate contact and bond so essential for the success of the diaphragm wall as a structural element. Most deficiencies can be attributed to insufficient attention to detailing and care and lack of understanding of the problems inherent in this important operation. Common deficiencies are cold joints, zones of segregation or contaminated concrete, and mud trappings or inclusions near the panel joints. The energy available for the sweeping action from the upward flow of the concrete is least at the greatest distance away from the tremie. It follows that at short panels with one tremie or with a tremie pipe nearer to the joint there is a lesser risk of mud trappings at the ends of a panel.



Formation of mud inclusion

WATERTIGHTNESS

Diaphragm walls constructed as an articulated wall with many joints and limited thickness cannot be considered as being completely watertight.

Although improvements have been made in the construction of joints and the design of concrete mixes some percolation of water through the concrete and fissures resulting from structural deflections are in practice unavoidable.

Some deposits, however minor, on reinforcing bars or inserts which are not completely swept clean by the concreting operation provide a potential pathway for water under a hydraulic head. Specifications for diaphragm wall should take this into account and make provisions for secondary measures (grouting, lining, cavity wall) to achieve a sufficiently dry exposed wall face.

DESIGN

Improvements of structural diaphragm wall execution related to pure design only have been described previously. They are:

- the prefabricated diaphragm wall (Panazol by Soletanche, Prefasif by Bachy)
- the pre-stressed diaphragm wall (Icos-Flex)

Most other improvements consist in the adaptation of the diaphragm wall construction method to specific and often novel applications on established principles and by using improved equipment and material.

As an example, the construction of a circular shaft at the Tokyo Bay Crossing 100 m in diameter, 135 m deep with a wall thickness of 2,80 m is only possible with the before mentioned Giant Cutter equipment.

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