A Study of Different Aspects of Diaphragm Walls

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Abstract—This paper traces the highlights of different aspects of diaphragm walls with regard to their design and methods of construction. Special attention is given to some practical points that need consideration, discussion or further research. First, the principles of the construction technique, methods of trenching, tools and tolerance for cast-in-place concrete diaphragm walls are introduced. The behaviour and control of bentonite suspension are also indicated. Finally, the paper treats the use of diaphragm walls as load-bearing foundations in comparison with piles, from the point of view of base resistance and skin friction.

Introduction

For the purposes of this paper, the term “diaphragm wall” is understood to mean an artificial membrane of finite thickness and depth, constructed in the ground by means of a process of trenching, with the aid of a fluid support.

This paper deals with three different aspects of diaphragm walls:

1. Basic requirements of trenching tools and tolerances.
2. The role of bentonite slurries used in diaphragm walls and their control.
3. How diaphragm walls can work as load-bearing foundations.

The conclusion of the paper deals with the scope of possible future study in this field.

Principles of Construction Techniques

Construction of diaphragm walls is carried out from the ground surface by means of various kinds of mechanical devices that permit the progressive excavation of a relatively narrow trench in the ground in such a way that the stabilizing fluid is introduced simultaneously as the trenching operation proceeds.

Furthermore, the trench will be filled with concrete or other backfill material, thereby displacing the trench-supporting fluid from the bottom up.

Trenching

Trenching Method

In theory, any technique for achieving a vertical cut in the soil can be used for the trenching operation.

The basic requirements, however, are minimal disturbance of the soil at the cutting face, combined with a trenching rate that is slow enough to permit the build-up and maintenance of the membrane or filter cake at the soil/stabilizing fluid interface.

The type of subsoil, the ground water, the properties of the stabilizing fluid, and the characteristics of the trenching equipment are all important factors that must be taken into consideration in the determination of the trenching method.

Trenching Tools

Three basic types of trenching tools are commonly used, either individually or in combination:

1. Percussive tools;
2. Rotary tools; and
3. Excavating tools.

Only percussive and rotary tools are effective in rock. It is important to select a moderate and controllable cutting speed, with a rate appropriate for the removal of cuttings, in order to avoid violent disturbances at the cutting face and excessive turbulence in the stabilizing material, both of which can cause localised collapses ("cavitation") of the sides of the trench.

Percussive and rotary tools loosen the soil and break it into relatively small particles; they mix the cutting with the stability suspension at the cutting face. The suspension, laden with soil cuttings, is then transported to ground level by either direct or reverse circulation of the drilling mud.

The grabbing tool operated on either a rope or a kelly bar seems to fulfill the basic requirements of trenching and is the most successful and most commonly used tool for this operation.

The success of the grabbing tool may also be attributed to its great efficiency as a tool for bulk excavation in average soil, and, in particular, to its effective and easily controllable shearing operation when cutting the soil. Combined with a suitable lifting and lowering rate, this avoids undue disturbance at the soil cutting face and in the supporting stabilizing suspension.

Trenching Tolerance

Three principle trenching tolerances must be considered:

1. Deviations from the true vertical alignment.
2. Deviations from the true horizontal alignment.
3. Deviations from the average trench face.

The incidence of these deviations depends on the characteristics of the
trenching tool—its shape, size and weight, support and control mechanism—as well as on the type of subsoil encountered.

Because only vertical trenches can be cut effectively, it is logical that the cutting tool should be primarily controlled for verticality by gravity. In this context, a heavy tool performs better than a light one, and the system of suspension of the tool from the winching rig should preferably utilize the continuous influence of gravity during the trenching process.

In fact, a repeated lifting and lowering of the tool under gravity has a rectifying influence on deviations from verticality. A check on verticality with increasing depth may be required more frequently for a rigid suspension than for a digging tool suspended freely.

The grabbing tool, with its repetitive raising and lowering from its point of suspension, seems to have an advantage over tools advancing in situ, which may require the assistance of a feedback device because their verticality of advance may be significantly influenced by varying soil strata of differing penetrability, especially if they are not horizontal.

Horizontal deviations are mainly caused by rotation of the trenching tool about its axis of suspension. In this respect, a big tool with rigid suspension has advantages over a small one, unless special guides or restraints are provided to minimize horizontal rotation of the tool during the trenching operation. If such restraints are not provided, a "wavy" alignment of the trench may result. This tendency increases with depth.

Local deviations of the trench face are closely related to the general stability of the trench. They are the least predictable of all deviations because the factors that influence them are many and generally occur in combination. These factors include:

- The subsoil—e.g., whether or not it is cohesive; its adverse effects on the stabilizing suspension.
- The granularity of the soil, and whether it contains boulders or artificial obstructions.
- The excess head over ground water of the stabilising suspension, and its density.
- The head of the ground water, whether flowing or static, and the likelihood that it may contaminate the stabilising suspension.
- The type of tool used for the trenching process, the trenching speed, and the method of soil removal.

Although some of these factors can be assessed in advance and kept under control reasonably well, broad practical experience is required to understand and foresee what is likely to happen during the trenching operation, and thereby permit remedial measures to be taken when necessary.

**Bentonite Slurry**

**Effect of Slurry Properties on Required Functions**

Bentonite slurries used in constructing diaphragm walls have to carry out a wide variety of functions, some of which place conflicting requirements upon their properties.

For example, a slurry that forms a good filter cake upon the wall of an excavation, and thus enables the hydraulic pressure of the mud to be exerted for stabilization of the face, may well be too resistant to flow to permit it to be displaced cleanly from reinforced bars by concrete. On the other hand, a slurry that is easily displaced may not build up a suitable filter cake.

Similarly, a slurry that is dense, and which thereby exerts a large hydrostatic head for stabilization purposes, may become trapped in the bottom of the trench during displacement because of its density.

With regard to freshly prepared and hydrated bentonite, there is a fairly well defined concentration limit below which the rate of filter cake build-up is very slow, and an upper limit above which the slurry is very difficult to handle. In addition, contamination by detritus, ground water or cement can completely alter the relevant properties of slurries.

Bentonite slurries can vary widely in properties, both physical and chemical. However, all such slurries must:

- Support the excavation by exerting hydrostatic pressure on the excavation walls.
- Remain in the excavation, and not flow into the soil.
- Suspend detritus, to avoid a build-up of sludgy layers at the excavation base.

In addition, these slurries must allow for:

- Clean displacement by concrete, with no subsequent interference with the bond between reinforcement and set concrete.
- Screening or hydrocycloning, to remove detritus and permit recycling.
- Ease of pumping.

**Excavation Support**

In order to exert a stabilizing pressure on permeable walls of an excavation, the bentonite slurry must form a seal on the surfaces with which it comes into contact.

This seal avoids both loss of slurry into the soil, with consequent reduction in angle of friction, and rise in pre-water pressure. In addition, the mud can provide a maximum stabilizing effect.

Three different mechanisms can occur under various conditions during the formation of the seal.

**Surface filtration** occurs when a classic filter cake is initiated by the bridging of hydrated bentonite particles at the entrance to pores in the soil, with negligible penetration of bentonite. During and after formation of the filter cake, water continues to percolate through it from the slurry into the soil water. This type of fluid loss can be divided into two quite distinct parts (see Fig. 1):

1. *Initial fluid loss*, which occurs during filter formation.
2. *Subsequent fluid loss*, which obeys the usual law:

\[ q = M \cdot T^{-\frac{1}{2}} \]

where

- \( q \) = Flow rate
- \( T \) = Time after filter formation
- \( M \) = Constant

**Deep filtration** occurs when slurry penetrates into the soil, slowly clogging the pores and building up a filter cake within them. In this case, the seal may extend several centimetres into the soil.

In both surface and deep filtration, the bentonite concentration in the filter cake is greater than its concentration in the slurry. **Rheological blocking** occurs when slurry flows into the ground until restrained by its shear strength. This is the mechanism operating when bentonite is found away from the excavation wall.

Of these three mechanisms, surface filtration is much to be preferred, since the seal is formed the most rapidly, with no penetration of bentonite into the soil.

The presence of small quantities of fine sand in the slurry can change the sealing mechanism in open ground from deep to surface filtration (see Fig. 2), with a consequent dramatic reduction in initial fluid loss.

**Excavation Sealing**

The ground is envisaged as a reasonably homogeneous granular medium with no gross voids or fissures.

Consequently, if a slurry forms a surface filter cake, then it will also form an effective seal against loose slurry from the excavation.

In addition, even slow loss of water (rather than slurry) from the excavation must be considered, as this can lead to an increase in bentonite concentration.

**Suspension of Detritus**

During the excavation process, it is inevitable that detritus will become mixed with the slurry. In addition to raising the average density of the
slurry, this situation can give rise to slowly setting layers of sand and silt, which can cause density gradients in the slurry and a build-up of sludge at the excavation base. This is precisely the situation that will cause displacement difficulties, when the tremed concrete is unable to push the slurry clearly from the bottom of the excavation. Thus, it is advantageous to allow the minimum of setting of detritus in the slurry, even if this means that the slurry is, on average, denser than it would otherwise be.

**Displacement by Concrete**

After the excavation has been made and any reinforcement necessary to the finished structure placed in it, concrete must be tremied into the trench to displace the slurry. The displacement is taking place in two distinct phases:

1. Displacement at the base of the excavation (mainly lateral displacement).
2. Displacement from the walls of the excavation and from the reinforcement bars (mostly vertical displacement).

**Diaphragm Walls as Load-Bearing Elements**

Through research on concrete technology and on bond stress between steel and concrete, the diaphragm wall has developed into a highly qualified reinforced concrete foundation element, which is most suitable for the construction of protection walls, subway tunnel walls and retaining walls. The main function of the diaphragm wall is to take up horizontal forces from earth and water pressures.

A new application for diaphragm wall elements is their use as load-bearing foundations, as an alternative to piles drilled by use of a steel casing. The use of a special grab permits the construction of piles of unconventional shape. The possibility of constructing such piles offers opportunities beyond the scope of typical cylindrical piles drilled by casing (see Fig. 3).

Because the cost for site installation and diaphragm wall construction is frequently about 5–15% less than for large bored piles, and the difference in design for the superstructure may save another 10–15%, it seems important to investigate the problems of load transfer by diaphragm wall elements.

As a general system of deep foundations, the diaphragm wall is applicable in principle wherever the use of cast-in-situ piles is advisable. Diaphragm walls offer special advantages:

- When very deep foundations are required, making the use of steel casing difficult or even impossible;
- When heavy vertical loads are combined with large horizontal forces and bending moments; and
- When special soil conditions are encountered.

**Comparison Between Piles And Diaphragm Walls For Load Transfer Into Soil**

**Horizontal Forces**

The load transfer for horizontal forces is achieved by lateral earth pressure, which depends on the soil properties (friction, cohesion, density), the shape and size of the elements, and the construction method. The computation of horizontal bearing is equal for piles and diaphragm walls.

**Base Resistance**

Load transfer by base resistance depends on the depth and size of the pile, the soil properties, disturbance of soil at the pile tip by the excavation method, and contact between the concrete and undisturbed soil.

Loosening of the soil, which may occur when piles are drilled by a casing in saturated soils, is unlikely to occur when the diaphragm wall technique is used because it always uses an excess hydraulic head which can easily be controlled.

In tests comparing two piles, with and without the presence of bentonite slurry, larger initial settlements were measured for the pile drilled with a steel casing. After compaction of the loosened soil by the first loading, the behaviour of both piles was the same under the second load cycle. It can therefore be stated that the diaphragm wall method, by achieving minimum soil disturbance even in saturated soils, offers good conditions for base resistance, but demands care and control in the construction process.

**Skin Friction**

Under the working load of structures, load transfer from piles into the soil is mainly achieved by skin friction. Skin friction depends mainly on the concrete surface (roughness) and on the soil properties (friction, cohesion, density), and secondarily on the contact between the soil and the concrete.

The basic questions concerning load transfer by skin friction are whether the bentonite mud can be completely replaced by the concrete, and whether, in which case, or to what amount the skin friction is affected by any bentonite filter cake remaining on the contact face between soil and concrete.

These questions can be answered only by testing and practical experi-

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**Figure 1. Fluid loss during filter cake formation.**

**Figure 2. Cross-sections of typical load-bearing elements.**

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ence. Laboratory tests were performed on skin friction under various confining stresses. In the case of test piles drilled with bentonite mud, a noticeable skin friction was found. For other in-situ tests, in a comparison between the diaphragm walls and piles, it was found that the skin friction was mobilized in the same way in the two cases, and was not influenced by the bentonite mud.

Conclusion

The technique of constructing diaphragm walls as an expedient in the field of civil engineering has been developed over a relatively long time, and to a great extent it still relies on the experience of a few established firms for its successful execution.

In spite of the most careful attention to detail in design and specification and the exercise of the greatest care in execution, the risks of faults occurring in work entrusted to the inexperienced are high. Even experienced firms will, if prudent, allow for a measure of remedial work to any exposed walls incorporated in permanent structures.

In order to eliminate these risks, much scope remains for further research and for development of improvements to the diaphragm wall construction technique. Furthermore, the control of bentonite slurries and the process of using it is enhanced by adhering to a recommended specification and carrying out a systematic schedule of tests to ensure that this is done. Clearly, the appropriate personnel must be available on site to perform the measurements on a routine basis. Further work in estimating the importance of fluid loss to the process, and in developing a site method of assessing it, may be of great importance.

Finally, by observing certain design principles and through careful and rapid construction, diaphragm walls as load-bearing foundations are at least as efficient in load-bearing capacity as in-situ concrete pile foundations, while from other points of view they have distinct advantages.

Summary

This paper has traced the highlights of different aspects of diaphragm walls with respect to their design and methods of construction. Attention has been drawn to some practical points that require consideration, discussion or further research.

References


