The construction of diaphragm walls—some causes for failure and proposals for their avoidance

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THIS PAPER points out a number of basic causes for deficiency, which may be attributed almost exclusively to the fact that some contractors, tempted by what at first sight seems a relatively simple construction method, take on the construction of diaphragm walls without having sound technical knowledge. It describes how careful interaction between management and construction team can ensure the technically perfect construction of diaphragm walls, even under the most difficult subsoil conditions. In the final section (5) some ideas and findings regarding soil mechanics processes during excavation work are explained.

1. Introduction
FROM THE earliest days of the diaphragm wall technique and its outstanding success, all sorts of deficiencies developed as this type of wall came into wider use. This Paper has been written with the intention of pinpointing some of the main causes leading to the difficulties experienced with this construction method.

Some contractors, deceived by the fact that at first sight it appears simple, were tempted to take on what is actually quite a difficult job without sufficient expertise. Evidently they were of the opinion that buying the special construction equipment ensured success, without realising that good machinery alone is insufficient in producing a perfect job.

As has been proved by experience, in construction the more or less efficient interaction between the following three components determines success or failure— the design engineers, the management, and the construction team. If only one link in this chain fails, the whole construction project will suffer considerable technical and economic consequences.

In the following presentation, the author attempts to provide a systematically grouped review of the recurring and to the expert well-known causes for failure, supplemented in the last section (5) by a number of new concepts and judgements. It is hoped that this will serve to encourage geotechnical engineers to choose the construction method that will be most suited to the prevailing conditions and will serve the purpose best.

2 The design
The design must aim at transmitting the load of the construction as well as the soil and groundwater pressures safely to the diaphragm wall, with the creation of the minimum possible deformations. In this respect the main factors are the thickness of the wall, the depth to which it extends and whether its base is fixed into a solid layer or rock, what reinforcement is required, and the points of application of any foreseen anchoring.

2.1 Interaction between design engineer and construction team
The whole course of the construction work must be carefully reviewed in advance, and during construction operations any adjoining buildings must be monitored to establish whether and to what extent they are affected. Subsequent changes in the design are often not possible at all or entail high additional costs. Some examples will emphasise this:

- Due to a lack of, or inaccurate, soil exploration and trial loadings unexpectedly larger wall dimensions may become necessary in the course of construction operations, causing in turn higher costs and a delay to completion.
- The above point is especially valid if, due to inadequate preparatory investigations, very soft or very hard layers, water-bearing layers, boulders or old constructions are unexpectedly encountered.
- Where construction pits are secured by anchors, an erroneous assessment of the bearing capacity of the subsoil, which may vary greatly in strength within the construction site, or an unexpected rise in the groundwater table may lead to the sudden failure of anchors, thus endangering the construction pit lining.
- During the excavation of a construction pit enclosed by diaphragm walls, the unforeseen inflow of water or movements of walls or soil may, even if rarely, occur. Appropriate retaining measures must be foreseen for such cases—for example, sealing with sheet piled walls, backfilling with sand and gravel, or a temporary flooding of the construction pit.
- A lack of attention to adjoining buildings may lead to settlement damages (e.g. development of cracks) or the bentonite suspension may enter unprotected cellars—a particular nuisance when it occurs. All these can be avoided by timely provisions on the construction site, such as strutting, perhaps with hydraulic jacks, shortening the panel width, increasing in certain sections the depth to which the diaphragm wall extends, and by sealing cellar walls beforehand. It is important to find out in advance how the surrounding buildings have behaved during similar construction activities carried out previously in their vicinity.
- The forming of unbraced, cantilevered diaphragm walls directly adjacent to existing buildings or near sensitive transportation-route constructions must be avoided, since the elastic deformation of the wall after excavation of the construction pit may cause damage in adjoining areas.
- The construction level must be chosen bearing in mind the foundations of the other nearby buildings and the level of the groundwater table.
- Disturbance by noise and dust can be prevented by initially constructing protective walls.

3 The management
3.1 Interaction between management and construction team
In the introduction, the significance of the interaction between management and construction team has been mentioned. It is of greatest importance that the responsible engineers of the contractor, who together with the client represent the management, take care that only carefully trained skilled workers are put to work on the construction site, and, of course, that the required machinery is also available.

3.2 Essential preparatory activities
It is the responsibility of the contractor's head office that the following aspects of the construction project are fully clarified well before work on the diaphragm wall is started:

- The course and duration of the construction work; assignment of personnel and machinery.
- Quality of the bentonite and estimated swelling period after mixing bentonite and water, taking into consideration the soil properties and the quality and level of the groundwater. For example, in very permeable soils and if there is a flow of artesian water, the suspension may be diluted during excavation work. On the other hand, groundwater will reduce the loss of suspension as it reduces penetration depth.
- Consistency of the concrete, i.e. to give the required smoothness, and the most efficient pouring method; the pouring tube must reach to the correct depth and must be properly operated if cavities in the concrete wall are to be avoided (Section 4.2.1).
- Assessment of the tendency of the bentonite suspension to absorb fine
4.2 Interaction between the engineer in charge and the operator

Failure is unavoidable if the following working steps are not carried out with the closest cooperation between the engineer in charge and operator:

4.2.1 Quality of the bentonite suspension

The bentonite suspension must be kept at a level of quality that ensures maximum efficiency, since this is the most important material in the construction of diaphragm walls. The bentonite supplied today, also for gas and oil drilling, by well-known reliable companies (e.g. Sud-Chemie Munchen Erböl & Co., Gesenheimer Kaolinwerke, Valdol, Switzerland), as a rule has a uniform, practically standard quality. Its coefficients must be tested in the contractor's laboratory to determine which bentonite is suited best for the specific project; detailed literature is available on the subject.

On the construction site the bentonite suspension must be inspected periodically and the following measures taken to maintain its effectiveness:

- Determination of the dry bentonite/water ratio, and duration and intensity of the mixing process, as too long and intensive a mixing may be as harmful as the use of a suspension that is too thick in finely grained soils or one that is too thin in coarse-grained soils. The consistency of the suspension must be examined, at least approximately, with a shearerometer.

- Determination of the swelling period, i.e. the time elapsing between completion of the mixing process and the use of the suspension for the trench excavation. For example, if the soil is strongly permeable, this period will be shorter so that the suspension continues to swell in the soil, thus preventing its penetration deep into the soil with a high loss of bentonite.

- Testing of the bentonite suspension with regard to its fine particle content as, in the course of excavation work, it tends to absorb soil particles and cutting sludge. This content must be constantly monitored with a graduated measuring glass. A proportion of about 5% of fine particles does not impair the effectiveness of the bentonite suspension, but a higher percentage may lead to the following deficiencies:
  - The excavation tool encounters in the suspension an uneconomically high resistance and excavation progress is slowed.
  - The perfect formation of the cake is disturbed.
  - Displacement of the bentonite suspension by the concrete is obstructed; this may cause the formation of much feared cavities sometimes several square metres in extent, in the concrete wall, possibly leading to inrushes of water and sand.
  - The used suspension must be replaced by fresh material as soon as excavation progress slows down noticeably, but in any case before the reinforcement is inserted and the concrete poured. Devices are available for cleaning a used suspension of absorbed fine particles. After cleaning the suspension may be reused like a fresh one; however, it needs to be determined how often a suspension may be reused without detrimental technical and economic effects for the construction project.

4.2.2 Countermeasures in case of loss of suspension

An abrupt loss of bentonite suspension may occur as it enters the pores of the adjacent soil, and countermeasures need to be foreseen for this circumstance. Disregarding the loss of suspension when excavation works cuts into large cavities (abandoned cellars, fortifications, channels), such losses are naturally the larger the more coarse grained and permeable the surrounding soil. The operator will register a relatively higher loss of bentonite from a rapid sinking of the suspension in the trench. In consultation with the engineer in charge the following measures may be taken:

- Thickening the suspension by changing the bentonite/water ratio.
- In certain cases, the addition of cement or other thickening agent available on the market.
- Backfilling the trench with lean concrete, which has to be re-excavated.
shortly after it has started to set. These measures must be taken immediately, since the trench will cave in as the level of the bentonite suspension exists.

4.2.3 Inspection of excavation work

The trench must be periodically inspected by the engineer in charge—if possible without interrupting excavation work—to make sure that its sides are vertical and that its position corresponds to the design. There are well-known devices for this inspection, such as measuring cages and sensors (Fig. 1), that have proved efficient. However, one detail is often overlooked and leads to faulty measurements; the cables of the measuring cage must be as thin as possible (e.g. piano wires) and should be tensioned and relaxed several times to make sure that they “saw” themselves into an absolutely vertical position in the bentonite suspension.

If a deviation of the diaphragm-wall trench beyond the permissible limit is registered, the situation must be corrected, usually by backfilling with lean concrete and re-excavation.

The experienced operator will have already noticed any such major deviations during the excavation work (see 4.1).

4.2.4 Formation of the joints

The proper formation of the joints is without doubt the most difficult detail of diaphragm wall construction.

If a wall is only to serve as an impermeable membrane, i.e. it will not be excavated, the joints can be simply formed by overcutting the completed panels with the excavation tool. However, if, in addition to an impermeability role the wall must also accommodate vertical and horizontal loads (earth and water pressures), as in the case of construction pit linings, the greatest attention must be paid to the formation of the joints.

The joint is where the “old” diaphragm wall panel, concreted some time previously, abuts the “new”, recently concreted panel; in this area no gap must remain that could allow water and fine soil particles to enter the construction pit. There exists such a large variety of methods for forming the joint that it is possible to achieve a perfect one under any conditions; it should be as vertical as possible and its face towards the “new” panels must be smooth and absolutely free of adhering bits of soil and concrete.

Fig. 2 illustrates the difficulties:
(1) Theoretical excavation for the left section of the diaphragm wall — “old” panel
(2) Theoretical excavation for the right diaphragm wall section — “new” panel
(3) Actual over-excavation, backfilled with concrete
(4) Over-width concrete around stop-end tube (5), which is pulled out again after concrete has set; if precast joint elements are used, these remain in the concrete but the problem of over-width concrete as such, however, still exists
(5) Hole after stop-end tube has been extracted
(6) Twisting of excavating tool if the remains of over-width concrete are not properly removed
(7) Deflection of excavation tool from the vertical caused by remains of over-width concrete (4)
(8) In this area inrushes of water and soil will occur
(9) Proper position of the excavation tool.

There are several methods for achieving a perfect joint:

Stop-end tubes of steel

Round or rectangular stop-end tubes (with or without teeth) may be inserted. The tubes are extracted after the concrete has fully set. Any over-width concrete is chiselled off with a suitable tool (e.g. eccentric bit) and the face of the joint is cleaned of adhering bits of concrete and soil. If this is not done, it is inevitable that the excavation tool will be deflected during work for the “new” diaphragm wall panel. Only after it has been ascertained by control measurements that the position of the joint is correct and the surface clean may the “new” right panel be concreted.

Precast joint elements of concrete
Precast elements, with or without gravel backfill, may also be used. There are no objections to this method, which will not normally create problems provided that the basic rules for diaphragm wall construction are observed. At the end of the newly excavated trench section, the precast element is inserted vertically and the concrete then poured. The trench is usually wider than the precast joint so that the concrete surrounds it. The volume of this over-width concrete varies with the amount of the over-excavation resulting from caving-in of the soil.

The use of precast concrete joints requires special detailing and considerate craftsmanship, as it entails more technical problems than the use of extractable stop-end tubes of steel:

- The over-width concrete forms relatively blunt bulges around the precast element which are appreciably more difficult to remove (e.g. chisel off) than the sharp-edged concrete adhering to the joint face after a stop-end tube is pulled out.

- The situation can be improved by filling gravel between above the end of the trench and the precast joint; however, care must be taken that the gravel and concrete do not mix and that no gravel "nests" form. The gravel must, of course, be removed completely before concreting the new diaphragm wall panel.

- Usually the precast joint is installed in the bentonite-filled trench in a dry state. The dry concrete will absorb water from the suspension and its solids will quickly form a considerable cake on the surface of the concrete joints. If concreting work is not carried out immediately, this cake can no longer be removed by the rising concrete and porous conditions will be formed in these zones.

To repeat, if the jointing operation is not carried out properly, and remains of soil and concrete are left between the "old" (left) and the "new" (right) panel, disturbing the smooth gravel of the joint faces and preventing a flush contact between concrete and concrete, this will cause the dreaded inrushes of water and/or soil. Fig. 3 shows the gap between the left diaphragm wall panel, faced by a precast joint, and the concrete of the right panel, caused by the deflection of the excavation tool due to over-width concrete not being properly removed. This gap was first provisionally closed with wooden wedges and by using freezing, to stop the inrush of the water/sand mixture; it was then permanently closed with a concrete plug. Generally, if such inrushes occur, the affected area must be sealed or strengthened by suitable means, such as sheet-pile walls, grouting, or freezing.

5 Points on significant soil-mechanics processes during diaphragm wall construction

5.1 Significance of the free-standing height

In the construction of diaphragm walls failure may occur even though the problems described in sections 2, 3, and 4 have been avoided, if the following soil mechanics processes are not taken into account. The key concern is the need to obtain a free-standing height of the trench sides during excavation works.

The following also describes how, under certain conditions, the free-standing height can be increased by improving the soil properties.

5.2 Free-standing height related to the excavation process

Fig. 4 illustrates the three main phases of sinking a trench protected by bentonite suspension. Phase (a) shows the bentonite-filled trench; excavation depth is indicated by I-I'. The bentonite cake (2) has formed and supports the sides (2). Phase (b) shows the excavation from I-I' to II-II'. The excavation tool (5) loosens, grabs and hoists the soil (5a). During this process the soil, even if over only a short period, must remain free-standing, without the support of bentonite, between level I-I' and level II-II' (the most recent excavation), because the bentonite cake has not yet had time to take effect. The equation for free-standing height without load,

\[ h_n = \frac{4c}{\gamma V/K_r} \]

shows that no free-standing height is possible without cohesion c.

5.3 Sources of strength in cohesionless soils

The so-called cohesive soils (clay, silty clay, clayey silt and partly also silts) mostly have what is termed cohesion to a sufficient degree. In the so-called cohesionless soils (silt, sand, gravel) two other types of cohesion are present which the cohesive soils do not have. These are described in the following.

5.3.1 Interlocking cohesion

Interlocking cohesion means that adjacent soil grains interlock with their jagged surface roughness. Fig. 5 shows the interlocking effect of the effective surface roughness of soil grains (1) and (2) termed Ra, which may be measured by Perthometer; it is the mean value of all distances between the roughness profile and the centre line. Ra is approximately 2-10μm.

Interlocking cohesion may reach considerable values, especially in densely deposited sand-gravel soils, as demonstrated, for example, in gravel pits, where the construction of slopes where very steep cutting slopes often occurs.

5.3.2 Meniscus cohesion

The so-called meniscus cohesion existing above the groundwater table results, as a rule, from the effect of the menisc created at the boundaries of the soil particles by the surface tension of the water. These menisci exert a two-way pressure upon the adjoining soil particles and thereby generate a frictional stress that is independent of load pressure. As is well-known, fine sand, as long as it is moist, will form a free-standing over a height of several decimetres, with or without interlocking cohesion, while dry sand cannot achieve any free-standing height. For example, for a soil consisting of uniform sand grains with D = 1 mm, at a unit weight of soil ρ = 18.5KN/m³ and an internal friction angle ɣ = 30°, the calculated free-standing height is 0.45m.

5.4 Osmotic forces

Observations indicate that a free-standing height is also achieved by osmotic forces that become active between the bentonite suspension and some body water-saturated soils even before the bentonite cake forms. At the

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**Table I: FORMATION OF FREE-STANDING HEIGHT AS A FUNCTION OF THE SOIL PROPERTIES OF COHESIONLESS SOILS**

<table>
<thead>
<tr>
<th>Cohesionless soils</th>
<th>Water content</th>
<th>Interlocking cohesion present</th>
<th>Forms during excavation operations</th>
<th>Delayed formation after excavation operations – consequently excavation to be carried out slowly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Yes</td>
<td>No</td>
<td>C A S E</td>
</tr>
<tr>
<td>Dry</td>
<td>X</td>
<td>X</td>
<td>X X</td>
<td>CASE</td>
</tr>
<tr>
<td>Moist</td>
<td></td>
<td>X</td>
<td>X</td>
<td>CASE</td>
</tr>
<tr>
<td>Saturated</td>
<td></td>
<td>X</td>
<td>X</td>
<td>CASE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meniscus cohesion impossible (Coarse grain)</th>
<th>Yes</th>
<th>No</th>
<th>CASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Moist</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Saturated</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Formation of free-standing height: X—no; O—yes

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*—Required cohesion to be created, e.g. by grouting, vibroflotation, loading, etc.

In—Creation of sufficient cohesion might be required, as above
Graz Technical University precise investigations are currently under way in the course of a research project.

5.5 Free-standing height in cohesion-less soils

Table I shows the possibilities of achieving a free-standing height in cohesionless soils, taking into account these osmotic forces; it lists 12 cases, grouped by coarse-grained and fine-grained soils and subdivided into dry, moist, and water-saturated.

As the table shows, it is only in Case 1 (dry, coarse-grained, without interlocking or meniscus cohesion, no osmotic force) that it is impossible to achieve a free-standing height. In all of the other eleven cases a free-standing height may be assumed, either owing to an effective interlocking or meniscus cohesion, or from an osmotic strength.

This raises the question of how to deal with Case 1 when constructing a diaphragm wall.

5.5.1 Measures to solidify cohesionless soils

To create the desired cohesion, an interlocking of the soil particles may be caused either by pressing the soil grains together, e.g. by vibroflotation or by superimposed layers of sand and gravel, or the superimposed particles may be cemented by grouting, using gel or cement. This latter alternative means that colloids (Greek, glue-like) are artificially introduced. The above methods have proven effective in many cases, especially for example in the construction of subway tunnels.

5.5.2 Solution to problems encountered in the construction of guide walls

Similar considerations are valid for the solution of the problems illustrated by Figs. 6, 7, and 8, which are encountered during the excavation of guide walls and the sinking of trenches, usually immediately under or at shallow depth below the guide wall.

Fig. 6 shows how the side of the guide wall (7) remains standing upright in cohesive soils (2) without bracing. The same is valid for cohesionless soils, with the exception of Cases 1, 3, and 7 (Table I). In Fig. 6b it is necessary to brace (3) the side of the guide wall (7), e.g. with a sheet-pile wall, or to solidify the soil, e.g. by vibration, grouting, etc.; this is valid for the Cases:

1. dry, cohesionless, coarse-grained soils without interlocking or meniscus cohesion, 3, as in 1, with moist soils, and 7, as in 1, with fine-grained soils, or the side of the trench excavation is sloped (4).

If excavation work is not carried out properly (Fig. 7), then soil movements may set in around the trench, especially in soils of Cases 1, 3, 5, 7, and 11 (Table I), causing the damage described below. This damage may be mainly attributed to the factor that owing to a lack of cohesion no free-standing height is present.

This is the process shown in Fig. 7:
- a slide movement sets in, for example, with the development of a slide joint (2),
- consequently, a subsidence develops on the surface (3),
- the trench side caves in (4), and
- further:

The guide wall (7) slumps.

Soil movements, which as a rule occur in soils of Cases 1, 3, 5, 7, and 11 if excavation work is not carried out properly, may be avoided by the following measures:

Case 1: Soil coarse-grained, dry. Avoid by creating cohesion by grouting or compacting (e.g. by vibration) the endangered area.

Case 3: Soil as in 1, but moist. Avoid by gradual formation of the bentonite cake which supports the sides of the diaphragm wall trench; therefore excavation work must be slowed down.

Case 5: As in Case 3, but below groundwater. Avoidance as in Case 3.

Case 7: As in Case 1, but fine-grained. Avoidance by formation of menisci at the sides of the excavation, as the water is drawn from the bentonite suspension by the surrounding soil.

Case 11: As in Case 7, in fine-grained soils, below groundwater. Avoidance as in Case 3.

Fig. 8 shows the caving-in of a diaphragm wall trench, as presented in Fig. 7, in more detail. In the course of constructing the diaphragm wall for a load-bearing element, the box-shaped guidewall was made of cast-in-place concrete (1); the subsoil consisted of coarse loamy gravel (2), over an underlying layer of silt (3) at a depth of about 3m. The groundwater table was 1.5m below the bottom edge of the guidewall box.

Excavation work was carried out under bentonite suspension (3); when it reached a depth of about 1m below the bottom of the guidewall box, a subsidence, as shown in Fig. 8, occurred. The surface suddenly slumped (6) and, as a consequence, also the guidewall box (7). The machinery standing nearby was greatly endangered by the subsidence (6).

6 Conclusions

The author can now look back on more than 30 years of experience with diaphragm wall construction throughout the world. Based upon this experience he is fully convinced that, with the methods available at the present time and providing mistakes are avoided, it is perfectly feasible to construct watertight and load-bearing diaphragm walls in any type of soil, with or without fixing it into an underlying solid layer.

References


Onorm B 4455, Schutzwände.
