# Specialist foundation construction for large deep open excavations in Berlin, Germany

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ABSTRACT
The centre of Berlin has been one huge construction site, where international architects, consultants, geotechnical engineers and investors faced the challenge of the largest and probably most complicated projects in Europe in terms of soil conditions. The Berlin sand is generally suitable for foundation measures, but can be very problematic for deep excavations below the high groundwater table due to of its rounded grain, uniform grading, medium dense compaction and lack of cohesion.

RÉSUMÉ
Le centre de Berlin était un gigantesque chantier ou architectes, conseillers, ingénieurs géotechniciens et investisseurs ont relevé le défi des plus grands projets et probablement les plus compliqués en Europe concernant les conditions du sol. Le sable de Berlin est en général propice aux fondations mais peut devenir problématique pour des excavations profondes au-dessous de la nappe phréatique dû à son grain rond et uniforme ainsi qu'à sa structure mi-compacte et sans cohésion.

## 1 INTRODUCTION

Berlin, Germany's old and its new capital of almost four million peoples, has been constructed on difficult ground conditions. Many historic buildings were founded on timber piles - generally pine - to carry their loads and prevent settlements. Since the fall of the Berlin wall, the city has been and is still witnessing the largest open excavations in Germany's recent history in terms of plan area and depth below the high natural ground water table. Individual construction projects had to be completed within pressing deadlines and at rock-bottom prices under the influence of the general market situation (Figure 12.).

The characteristic parameters of these large and deep open excavations are:

- overall plan areas of up to 200 000 m²
- excavation depths up to 22 m below groundwater table
- absence of dense horizontal geological layers
- no permission for lowering ground water tables
- Europe's toughest ever competition in construction.

Sheet pile walls, sheet piles set into slurry walls, secant pile walls, diaphragm walls, all with tie backs under high hydrostatic pressure, are used as excavation retention systems. The excavation pits are sealed at their base against ingress of water either by low-level grouted cut-offs, anchored down high-level jet-grouted cut-offs or under water concrete slabs. The huge dimensions of these open excavations presented a new challenge for geotechnical engineers and resulted in new experience.

## 2 SOIL CONDITIONS

Berlin sand is generally suitable for foundation constructions, but can be very problematic for deep open excavations below the high natural ground water table. The reasons for this are its rounded grain, uniform grading, medium dense state of compaction and its lack of cohesion. Berlin sand consists of Pleistocene fine to medium sand which is generally in a medium dense state of compaction in its upper layers, and more dense at greater depths (Figure 1.).

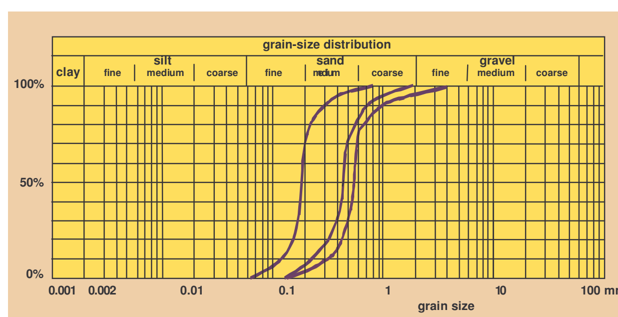


Figure 1. Typical grading curves of Berlin sand at Potsdamer Platz

Berlin sand is interbedded with discontinuous layers of boulder clay consisting of sandy clay to silty sand, which may also be overlain by cobbles and glacial boulders.

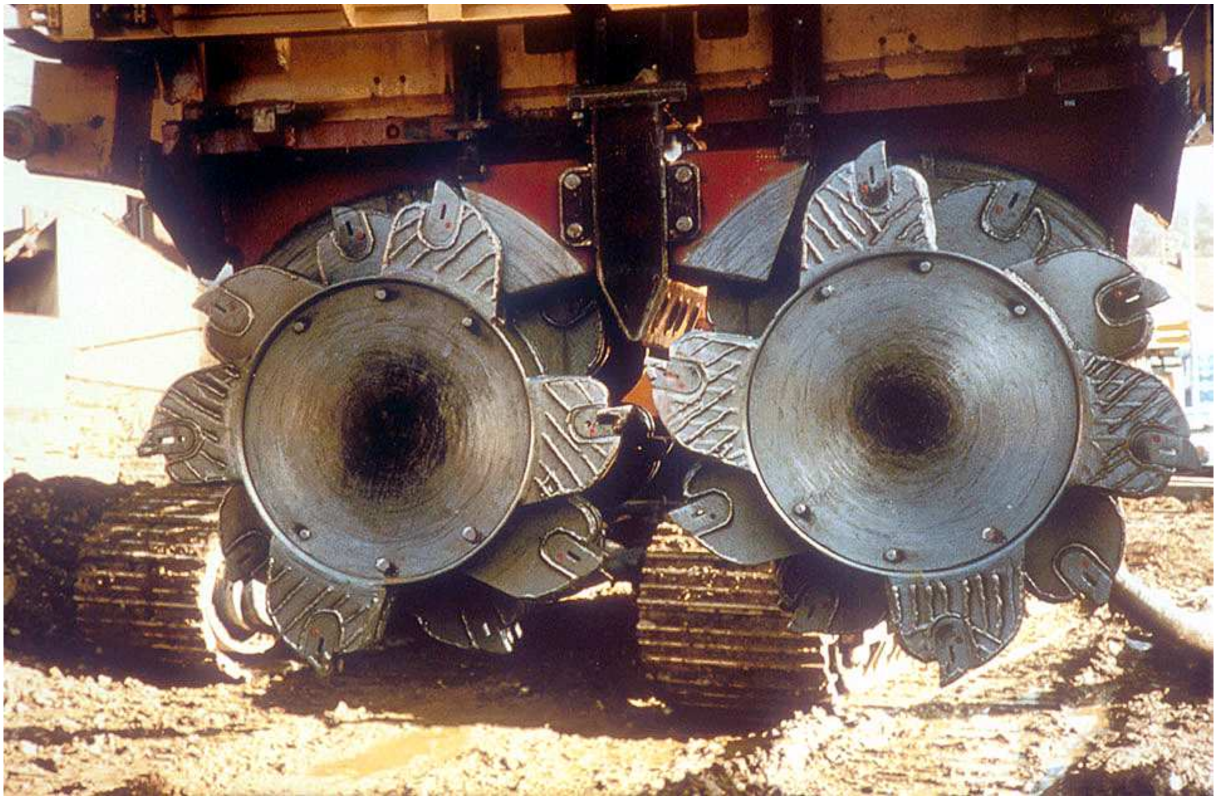

Figure 2. BAUER BC cutter wheels

The groundwater table is generally 2 to 3 m below ground level. Groundwater flow rates amount to only a few centimetres per day; the coefficient of permeability ranges from $10^{-3}$ to $10^{-4}$ m/sec.

Prior to the post-reunification construction boom, excavations were constructed to depths of up to 15 m, i.e. about 12.5 m below ground water table. At present, large open excavations are under construction to depths of up to 25 m, which is 22.5 m below the existing groundwater table.

For both technical and ecological reasons, groundwater lowering is no longer permitted in Berlin. Natural dense geological strata cannot be found even at greater depth. But even if it were possible to seal open excavations by the construction of extra deep cut-off walls penetrating into natural dense strata, it is unlikely that such solutions would be chosen, since the groundwater flow would be severely interrupted by such large barrier walls. Trough-like watertight structures are, therefore, formed by artificial horizontal base cut-offs in combination with watertight retention systems.

## 3 RETAINING WALLS

The following types of retaining wall systems have proven to be suitable for watertight excavations:

- sheet pile walls secant pile walls
- sheet piles set into slurry walls diaphragm walls

Today, sheet pile walls are highly advanced in terms of their interlocks, particularly with regard to sealing each joint reliably, thus achieving a relatively high degree of watertightness. This method is also very economical since the sheet piles can generally be recovered. To guarantee watertightness and for practical reasons of driving sheet piles, the depth of sheet pile walls is limited to around 25 m. Today, sheet piles are generally installed by top vibrators with adjustable frequency to prevent damage to neighbouring buildings. Obstructions in the ground, such as cobbles or boulders, can cause serious difficulties for the system. The interlocks may easily split open and the sheet piles may not be driven to their full design depth.

The disadvantages of the sheet pile system can be overcome by a composite construction technique applied successfully over recent years: sheet piles set into a slurry wall. A so-called single-phase slurry wall is first constructed by means of a grab or a cutter. Sheet piles are then inserted into the fresh cement-bentonite slurry or suspended in it. After the slurry has fully hardened, the sheet piles become the structural members, the slurry ensures that the wall is watertight. Walls which are subjected to structural forces at the top only become particularly cost-effective. With this type of wall the sheet piles cannot be recovered. The exposed side of the sheet piles can easily be cleaned. The slurry material within the “valleys“ of the sheet piles must be removed for safety reasons, as it would otherwise drop out as a result of drying.

Alternatively the valleys could be covered over by thin steel plates to give the retaining wall a smooth finish.

Secant pile walls of 880 mm diameter piles, for example, offer a well proven method. The system is, however, less suitable for depths of 20 m and below, as it is difficult to guarantee the verticality and overlap between the piles at such depths and water or sand may flow through any gaps as a result.

Diaphragm walls offer the most universally applicable deep watertight retaining wall system. They can be used in almost any type of soil and subjected to any kind of stress. Diaphragm walls have been installed all over the world as cut-off walls to depths of 150 m and as structural reinforced concrete retaining walls up to 3 m thick to depths of 120 m. Diaphragm walls with waterstop systems are used to depths of up to 50 m. For greater depths the diaphragm wall cutter is superior to the grab with regard to verticality, productivity and watertight joints between individual panels by cutting back the fresh concrete of the primary panels (Figure 2.). Another advantage of the cutter technique is the possibility of cleaning the slurry in modern separation plants, such as desanders, desilters and decanters. Excavated soil material can be removed off site almost completely dry resulting in a clean site free from mud.

## 4 HORIZONTAL BASE CUT-OFFS

Three different structural systems can be employed: low-level grouted cut-offs (Figure 4.), high-level jet-grouted cut-offs and underwater concrete slabs (Figure 5.); the last two must be anchored down against hydraulic uplift.

Horizontal low-level grouted base cut-offs have been installed on numerous sites throughout Berlin and have proved very successful. The degree of watertightness achieved was significant with the total quantity of water seepage amounting to just 0.5 to 1.5 l/sec per 1000 m² of the trough surface area immersed in the ground water. Low-level cut-offs are installed from a working platform above the groundwater level with the use of the grouting technique generally in the form of 1 to 2 m thick grouted base slabs. Spacings between grout tubes also range between 1 and 2 m (Figure 6.).

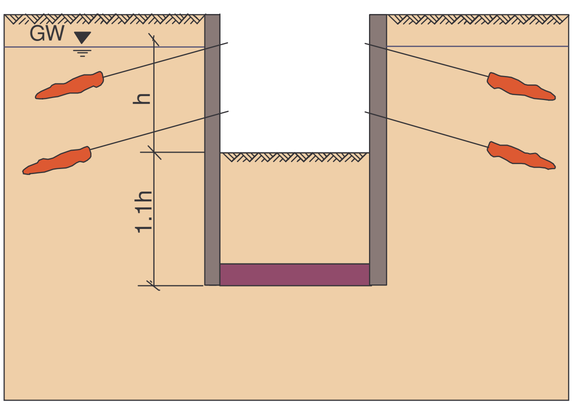


Figure 4. Low level grouted cut-off

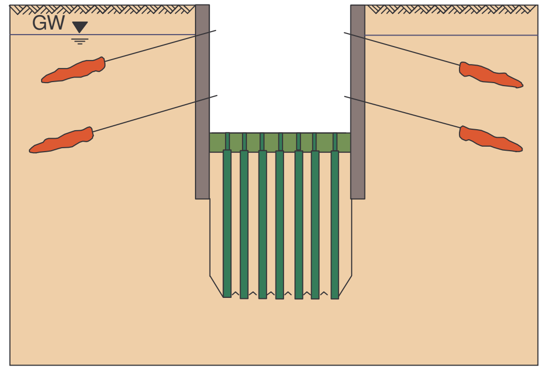


Figure 5. High level jet-grouted cut-off

The formation level of a low-level cut-off is designed with a safety factor of 1.1 against hydraulic uplift. The weight of the soil between the cut-off and the base of the excavation acts as a counterweight (Figure 4.).

After the low-level cut-off has been installed and the water inside the trough has been pumped out, bulk excavation can proceed in dry conditions, which is of great technical and economic advantage. Any major leak in the base cut-off can be detected during the water lowering process before commencing the actual excavation, which can proceed without the risk of failure. A further advantage is the fact that during the excavation in dry conditions, rows of anchors can be installed which reduce the wall displacement due to bending.

Figure 6. Soft gel grouting

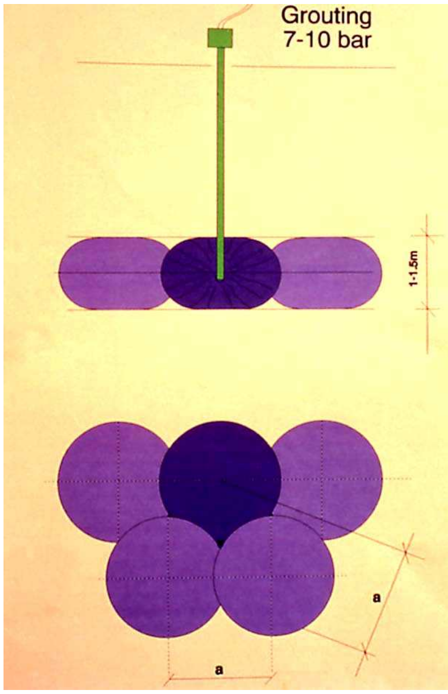


Figure 7. Jet-grouting

Relatively large horizontal deformations of the walls below the base of the excavation may occur due to the high hydrostatic pressure and the fact that the grouted cut-off slab does not act like a stiff prop.

High-level cut-offs are installed by the jet-grouting process immediately below the base of the excavation (Figure 7.). This method offers the advantage of shorter retaining walls when compared to deep cut-offs. In addition, high-level cut-offs provide a much stiffer prop than grouted slabs. However, high-level cut-offs do have to be anchored down against hydraulic uplift by way of ground anchors or anchor piles.

High-level jet-grouted cut-offs are also installed prior to the excavation (Figure 8.). A pumping test will is carried out to establish whether the system is watertight. Bulk excavation can again be carried out in dry conditions and additional rows of anchors can also be installed during the excavation. The uplift anchors, such as ground anchors or piles, must be designed to protect against hydraulic uplift failure (Figure 5.).

Figure 8. Deep excavation construction site with jet-grouted cut-off

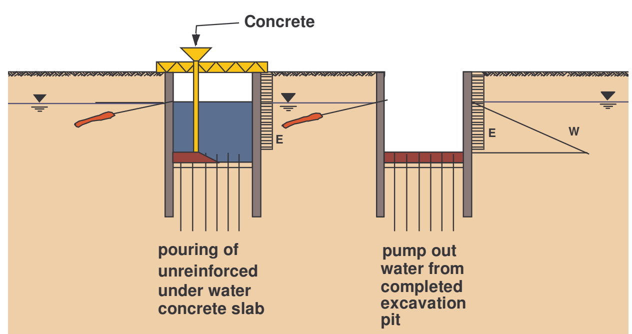


Figure 9. Under water concrete slab

Underwater concrete slabs are poured after the excavation has been completed. If the underwater concrete method is used, it is generally only possible for a single row of anchors to be installed above the water level (Figure 9. and 11.). In the absence of any additional rows of anchors, an excavation extending to a depth of 20 m below ground water means a span of 20 m between ground anchor and concrete slab. This will result in fairly large deformations even for a 1.2 or 1.5 m thick diaphragm wall. The design has to take into account the stresses occurring at the connection between diaphragm wall and concrete slab.


Figure 10. Ground anchor installation into diaphragm wall

Figure 11. Excavation under water at Potsdamer Platz

The ground anchors installed at Lehrter Bahnhof for example are with 50 to 85 m length the longest tiebacks in Europe. The reason for this comes from the under water concrete system which allows only one layer of anchors at the top of the walls and some geological disturbances in the Berlin sand like mud and organic layers in greater depth.

Figure 12. Areal view of Berlin's city centre construction site

## 5 SUMMARY OF EXPERIENCES AND CONCLUSIONS

- No fundamentally new construction techniques, retaining wall or base slab systems have been employed during the boom in specialist foundation construction. However, numerous improvements have in fact been carried out on all wall and base slab systems with regard to detail design, quality and productivity. Significant progress has also been made in measuring and monitoring technology. Deformations in the ground very often reach far below the structural walls or behind the ground anchors. Inclinometers and extensometers should, therefore, always be installed to an adequate depth. The designer should measure and monitor on site as much as possible.
- Various design detail modifications have been introduced in the retaining wall sector, such as the inclusion of tubes for subsequent anchor installation and an improvement in the erosion resistance of high-level jet-grouted base slabs by an additional surcharge of sand.
- Sheet piles set into a slurry wall offer a retention system of the highest integrity due to its dual seal, whilst bored pile walls must be rated rather less reliable as in contrast to diaphragm walls they do not allow waterstops to be installed in the joints between the piles.
- The smallest construction-based wall deformations in Berlin sand are being recorded on diaphragm walls, in particular when constructed by the cutter technique. Bored pile walls represent the least favourable solution.
- With regard to the construction period, sheet pile walls installed by vibrator - possibly in combination with Mixed-in-Place (MIP) piles to assist penetration - are advantageous. Bored pile walls are once again less favourable.
- Props or partial covers are the preferred method of wall support for deep excavations which are affected by adjacent buildings, provided this is technically feasible. Otherwise, the number of anchors should be reduced to a minimum. Less favourable are multiple rows of closely spaced anchors.

- Soft-gel grouted base slabs provide the highest degree of structural integrity. Jet-grouted base slabs offer the least favourable system.
- A jet-grouted base slab constructed just below the base of the excavation and acting as a prop provides the most favourable conditions imaginable for limiting the deformations of the retaining wall system. The least favourable solution is a free earth support wall in conjunction with a grouted soft-gel base cut-off with a marginal safety against hydraulic uplift.
- In terms of the construction period, a low-level grouted soft-gel cut-off is preferable to solid base slab designs.

This summary shows that in Berlin's prevailing ground conditions, bored pile walls are generally avoided for good reasons as retaining walls for deep watertight excavations. All other process and design related decisions should be considered and made on a case-by-case basis.

Figure 13. Removal of historic concrete structures with BAUER BG's by Bilfinger Berger AG