Deep Diaphragm Wall Activities at RandstadRail Project in Rotterdam, The Netherlands

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The Netherlands RandstadRail project makes use of a large range of sophisticated geotechnical techniques to allow a shield driven tunnel to approach the central station of Rotterdam. This paper describes the construction of three deep excavation pits constructed with 1.2 m and 1.5 m thick diaphragm walls. Besides the presentation of the actual diaphragm wall activities special consideration is given to the break-in and break-out situations of the Tunnel Boring Machine (TBM) into the deep excavations pits using sealing blocks and partly glass fibre reinforcement in the diaphragm walls.

The Project

The project RandstadRail in the Dutch province of South Holland will provide a new light rail train connection between the cities of Den Haag and Rotterdam. While the project makes extensive use of the existing track from Den Haag to Rotterdam, it is necessary to construct a nearly 3 km-long tunnelled section for a direct connection to the central station of Rotterdam, where by another contract an interchange station to the Rotterdam's Metro system will be established. The tunnel below Rotterdam represents, from an engineering perspective, the most challenging part of the whole RandstadRail project and is let as a Euro 178M contract known as The Statenwegtracé contract.

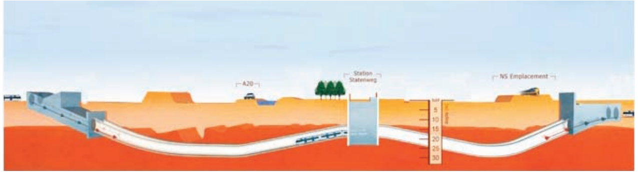
The tunnel will be made up of two 2.4 km-long single-track shield driven tunnel tubes, the first bored tunnel below an urban area in The Netherlands, with an outer diameter of 6.5 m. The tunnel will be driven using a hydro shield tunnel boring machine (TBM) with a diameter of 6.78 m. The remaining 600 m will be constructed as a cut and cover tunnel, mainly using construction pits with retaining sheet pile walls and combi walls. The launch shaft, the construction pit for the new underground station Blijdorp in the middle of the bored tunnel track, and the arrival shaft will be realised applying diaphragm walls.

The project contractor SATURN v.o.f. (Samenwerking Tunnelrealisatie Nederland) is a joint venture of two contractors, namely Ed. Züblin AG from Germany and The Netherlands firm Dura Vermeer Group N.V. The client for the project is the public transport company of Rotterdam RET (Rotterdamse Electrische Tram).

The project management in the tender and construction phase, including the principle design and the site supervision is carried out by the engineering office of the municipality of Rotterdam (Ingenieursbureau Gemeentewerke Rotterdam). Ed. Züblin's subsidiary Züblin Spezialtiefbau GmbH (Züblin Ground Engineering) is in charge of all geotechnical and foundation works on the Statenwegtracé contract. The project was contracted in April 2004 and is scheduled for completion end of 2008.

[Fig. 1] Aerial View on Tunnel Track in Rotterdam

Particularly complex foundation and geotechnical work is needed for the tunnel launch and reception shafts, the new cut and cover station midway along the tunnel section, and retaining support for the cut and cover tunnel. At the starting and arrival situation of the TBM different types of soil improvement activities such as lime-cement columns, permeation grouting and jet grouting are required to allow the tunnelling.

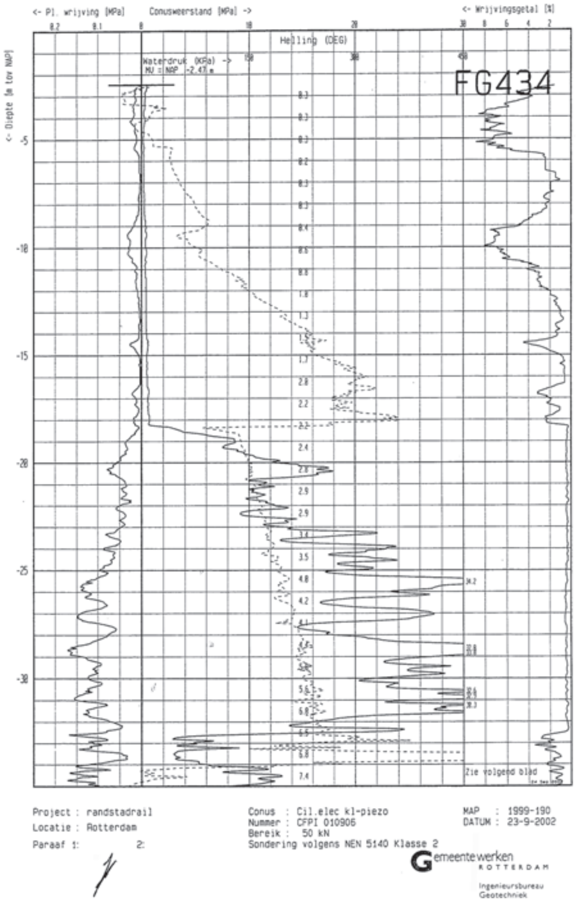


[Fig. 2] Cross Section Through Tunnel Track

Ground conditions

Ground conditions, although typical for Southern Holland, are particularly difficult for tunnelling and deep excavations. They include deep deposits of soft clay and peat and with the groundwater level just below ground surface, retaining elements need to extend to at least 35 m to reach an impermeable cut-off.

The soil investigation carried out by the client before the tender included around 600 cone penetration tests (CPT) and around 60 borings across the whole tunnel track. Fig. 3 shows a typical CPT at the start situation of the tunnel.



[Fig. 3] Cone Penetration Test (CPT)

In detail the soil profile consists of between 2 to 5 m of refilled sand overlying geologically young Holocene soils. These are made up of alternating layers and lenses of soft clay and peat to a depth of between 15 to 18 m. These in turn overly denser Pleistocene sand to depths of between 35 to 38 m. The soil characteristics of the Holocene and Pleistocene are shown in Table 1. The water table in the Pleistocene is pressurised and any exchange with the free water table in the refilled upper sand layers due to building activities has to be avoided. Below this is the impermeable layer of Kedichem, an over consolidated sand, clay and peat, which provides the target layer for retaining elements to achieve a natural seal and prevent the inflow of groundwater into the deep excavations.

[Table 1] Soil Characteristics

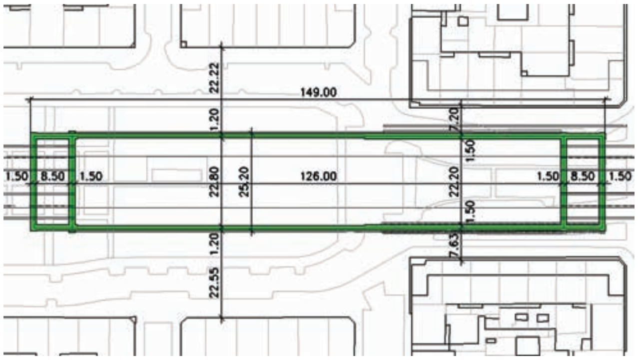
	Holocene		Pleistocene
	clay	peat	sand
γ / γ_r **[kN/m³]**	14 – 16	10 – 14	18 / 20
c [kN/m²]	10	10	0
ϕ [˚]	13 – 20	10 – 18	27 – 35
k [MN/m³]	3.0 – 3.75	2.0 – 3.0	20.0 – 30.0

The vertical alignment of the tunnel as can be seen in Fig. 2 was designed to situate the major part of the tunnel in the Pleistocene sand layer, which is advantageous for the tunnel drive and the permanent stability of the tunnel linings.

Deep Excavation Pits

Three deep excavation pits have to be constructed for this project: the launch shaft, the cut and cover pit for a new underground station and the arrival shaft. The retaining walls for all three excavation pits are carried out with diaphragm walls up to a depth of 42 m and a thickness of 1.2 m and 1.5 m.

The largest of these three excavation pits is the mid-way along the twin 2.4 km long tunnel drives positioned pit for the new Blijdorp Station, that will be excavated before the TBM passes through. Including the sealing blocks the excavation pit has a length of nearly 150 m and a width of around 25 m. The plan view of the pit with the surrounding buildings is shown in Fig. 4. The excavation depth of the pit is 22 m below ground level and the diaphragm walls reach to a depth of 42 m giving an embedded length of around 4 m in the impermeable layer of Kedichem. This way the pit is sealed against inflow of groundwater from beneath.



[Fig. 4] Ground Plan of Excavation Pit Blijdorp Station

The thickness of the diaphragm walls varies between 1.2 m and 1.5 m, depending on the distance to the surrounding pile founded buildings. In the smaller part of the pit, where the adjacent buildings are only 7.2 m from the construction pit, the client applied the 1.5 m thick diaphragm walls, to reduce the bending of the retaining walls and the influence on the foundation piles of the close building. In this part of the construction pit the panel length was also restricted to 3.0 m by the client. For the rest of the diaphragm walls the structural analysis of the trench stability carried out by Züblin's geotechnical design office allowed a panel length of 8.0 m. This calculation had to be carried out according to the German standard DIN 4126 with an increased safety factor of 1.3 instead of 1.1 and by close adjacent buildings 1.5 instead of 1.3. This regulation was resulting in L-shaped guide walls for the trench excavation that had to reach 1.0 m above ground level.

[Fig. 5] Diaphragm Wall Activities at Blijdorp Station

The joints between adjacent diaphragm wall panels are provided by recoverable steel elements with a trapezoid form as shown in Fig. 6. Before the installation of the reinforcement cages these steel joint elements are inserted into the open trench and hang up on the leading walls. They reach over the whole depth of the trench panels. After the installation of the reinforcement cage and the casting of the concrete the excavation of the adjacent panel can continue. Just after the excavation of the secondary panel reaches the final depth the steel joint element can be detached from the concrete of the primary panel and can be lifted out of the trench. After cleaning the steel element it will be used for the following panels.

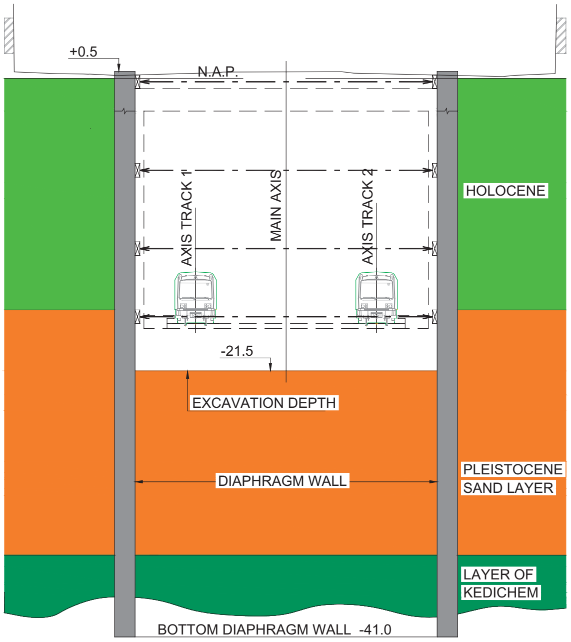
This technique has never before been used on panels with such a depth and width.

[Fig. 6] Recoverable Steel Joint Element

For the improvement of the impermeability the steel joint elements will be provided with rubber waterproof sealing strips, that will stay in the concrete of the primary panel while detaching the steel element.

As the station is excavated, internal support will be provided by massive tubular struts and walings in four layers. The diaphragm walls will be part of the final structure of the station and are used as foundation elements of the station. They will form together with a second reinforced concrete wall, which will be cast after the TBM passes through the final walls of the station. After removal of the steel struts and walings the station walls will be supported permanently just by the concrete base slab and roof slab. The thickness of this combined final station wall will be 2.15 m. This allows a maximum span of 16 m between the base and roof slab.

This design resulted in unusually heavy reinforcing cages reaching the full depth of the diaphragm walls. The cages have two layers of



[Fig. 7] Cross Section through Excavation Pit Blijdorp Station

40 mm reinforcement bars at 175 mm centres on both faces over nearly the full length of the cages. Additional screw joints had to be installed in the reinforcing cages to connect the diaphragm walls with the internal walls. Because of space limitations of the inner city construction site, the cages are fabricated off-site in three sections, transported to the site and joined together as they are installed in the trench panel. Once assembled each cage for a 42 m-deep by 3 m-wide panel weighs up to 45 tons. The overlap of the reinforcing bars for the two layer reinforcement had to be shifted, resulting in a total overlap length of 3.5 m. To be able to connect the three parts of the heavily reinforced cages without difficulty, it was necessary to crank the overlapping bars.

[Fig. 8] Installation of a Reinforcement Cage for a 1.5 m Diaphragm Wall

To form the box structure of the station and the sealing blocks L-shaped and T-shaped panels were used. Also the reinforcement cages had to follow the form of these panels in one piece in their horizontal layout. These special panel cages weighed over 50 tons.

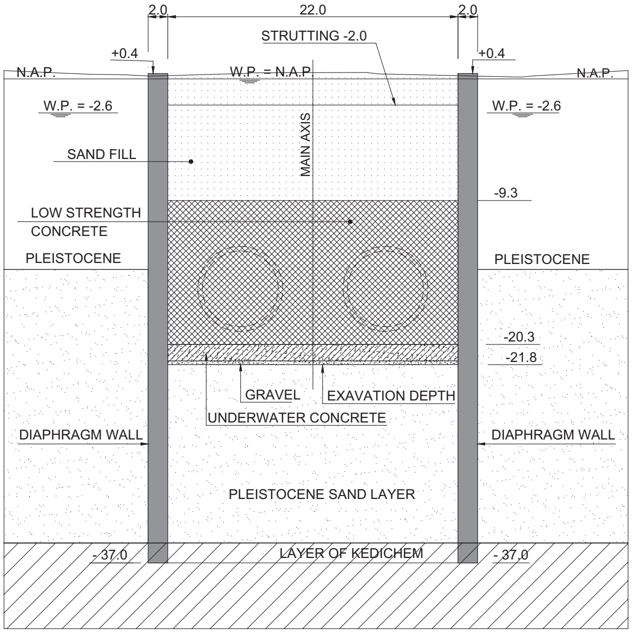
For the construction pit of the Blijdorp Station a total of 4,500 tons of reinforcement for a diaphragm wall area of 15,000 m² had to be installed. For all three deep excavation pits in total around 7,500 tons of reinforcement is installed into the diaphragm walls.

[Fig. 9] Joint of Two Reinforcement Cages for 1.2 m Diaphragm wall

Sealing blocks

For the three deep excavation pits the break-in and break-out situation of the TBM is handled by creating sealing blocks in the underwater concrete construction method. The underwater excavation is carried out, after pits of about 9 m length and 22 m width are constructed using 1.2 m or 1.5 m thick diaphragm walls. During the excavation the water table is not lowered and after reaching the final excavation depth the sealing blocks receive an underwater concrete slap of 1.2 m thickness. Above that the sealing block pits are filled with unreinforced low strength concrete about 3.5 m above the later tunnel drive. The remaining pit until the ground level will be filled with sand.

Because the cutting wheel tools of the TBM cannot cut through reinforcement bars in concrete structures, the area through which the machine has to pass must be cleared of any reinforcement before the start of the TBM drive (Fig. 11). The sealing block will prevent water and soil entering the excavation pit while creating the opening in the diaphragm walls for the shield passage. For the circular openings,



[Fig. 10] Cross Section through Low Strength Concrete Sealing Block at Blijdorp Station with Indicated Tunnel Tubes

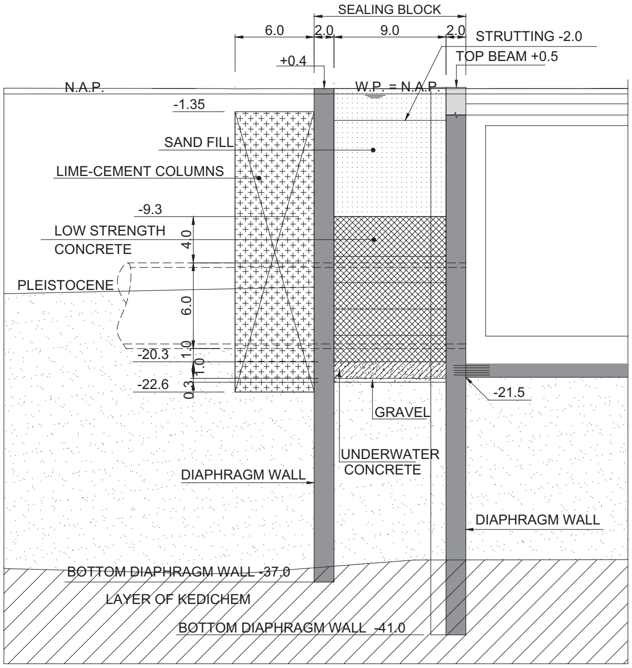
that are made out of the excavated construction pits, the concrete and the reinforcement bars of the diaphragm walls will be demolished within a distance of 500 mm around the tunnel diameter. In front of the diaphragm wall then a precast rc-wall will be installed, on which the starting seal construction is fixed (Fig. 12).

[Fig. 11] Opening of Diaphragm Wall

The diaphragm walls situated on the opposite side of the sealing block also have to be penetrated by the TBM and were therefore designed to be unreinforced in the area of the TBM passage. To prevent the earth pressure acting on this unreinforced diaphragm walls during the underwater excavation of the sealing blocks different means were taken at the three deep construction pits.

[Fig. 12] Sealing Construction

For the launch shaft the sealing block is excavated and refilled at the same time as an adjacent excavation pit. This excavation pit, surrounded by retaining sheet pile walls and tied back above groundwater level using single bar grout anchors, is needed to replace the soft Holocene layers by sand, because the soft layers would not provide sufficient stiffness to take the forces from the tunnel lining. After the sand refill has reached



[Fig. 13] Longitudinal Section through Sealing Block at Blijdorp Station with the Transition Zone that was Replaced by GFRP Reinforcement in the Left Sided Diaphragm Wall

above the groundwater table it is compacted using the deep vibro compaction method.

Just before the arrival shaft a monolithic block of jet grouting of about 15,000 m³ is installed beneath and next to the railway embankment of the central station. The jet grout block is reaching until the sealing block, protecting the unreinforced diaphragm wall against earth pressure during the underwater excavation of the sealing block.

The original proposal according to the client's design for the Blijdorp Station was to form additional transition zones of lime-cement columns, 4 and 6 m long, just before the two sealing blocks for the break-in and break-out of the TBM (shown in Fig. 13)

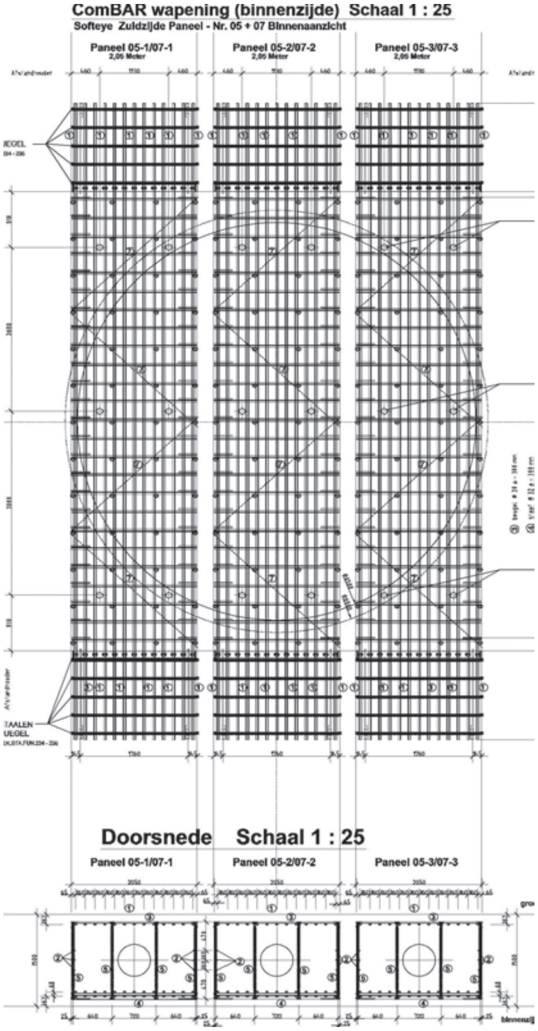
The method of lime-cement columns, also known as dry deep mixing, refers to in-situ mixing of soil with the addition of binders in a dry form. The mixing is carried out by means of mechanical equipment, typically using rotating single mixing tools. The mixing tool is first rotated into the soil down to the final depth of the column. The binder is fed through a nozzle in the mixing tool with compressed air from a separate binder tank and is then mixed with the soil during retraction of the mixing tool. The dry deep mixing method was developed in Scandinavia for the soil improvement of soft soil such as clay and peat. It is not suitable for the improvement of sand layers of larger extent, especially when the columns are applied in an overlapping grid. High strength of the lime-cement-columns in sand cause problems during intrusion and retraction of the mixing tool and bear the risk of loosing the mixing tool due to breakage.

The client's design asked for transition zones made of lime-cement columns that had to reach until 8 m into the Pleistocene sand.

Züblin came up with an alternative option, to apply glass fibre reinforcement in the diaphragm walls, which had originally been unreinforced and had to be driven through by the TBM. The glass fibre reinforcement (GFRP = glass fibre reinforced polymer) can easily be crushed by the cutting wheel tools of the TBM. The original transition zone of lime-cement columns could completely be abolished by applying the "soft eye" option.

Besides technical advantages it was a faster and cheaper option and was therefore accepted by the client.

[Fig. 14] Lifting of GFRP-cage



[Fig. 15] GFRP-cages in One Panel for Soft Eye

Glass fibre reinforcement is manufactured by a process whereby high-strength glass fibre is drawn through a form and immersed in synthetic resin. The impregnated fibres are then drawn through a mold and toughened. The result is a material with a very high tensile strength, even much higher than conventional steel. Perpendicular to the load carrying direction of the fibres it can be trimmed very easily, especially when it is embedded in concrete. Together with the concrete the GFRP bars will be crushed without major abrasion to the TBM cutting wheel tools.

For each of the in total four break-in and break-out situations at the Blijdorp Station a trench panel of 7.5 m length was located in the area of the later tunnel drive. In each of these panels three reinforcing cages were installed next to each other. To reduce the amount of the expensive glass fibre reinforcement, the height of the "soft eye" was just 7.5 m. That means that the area of the "soft eye" is just 350 mm larger than the TBM borehead. This measurement was determined by taking into account the tolerance of the TBM drive and the installation of the reinforcement cages.

[Fig. 16] Connection GFRP-Cage with Steel Reinforcement Cages

Above and below the GFRP-cages normal steel reinforcement cages were brought into the trench and joined with the GFRP-cages. Due to the subdivision into pure glass fibre and pure steel cages it was not necessary to use a temporary steel frame for lifting (see Fig. 14).

Each glass fibre cage was equipped with two layers of 32 mm GFRP-bars 160 mm centres at the earth side and one layer at the side of the sealing block. The shear forces in the diaphragm wall are taken by GFRP double-head anchor-bolts.

[Fig. 17] Installation of GFRP-Cage

Summary

The execution of the diaphragm walls for all three excavation pits was successfully finished in spite of difficult ground conditions and extraordinary dimensions. By now the launch shaft is excavated, the base slab is cast and the opening in the diaphragm wall and the installation of the sealing construction for the shield passage is completed. The TBM drive successfully started at the of end 2005.

Besides the large-scale diaphragm wall activities this project is very special in regard to the high concentration of different types of soil improvement works at the starting and arrival point of the TBM. At the starting point, where the tunnel is still mainly situated in soft Holocene clay and peat layers a monolithic block of more than 38,000 m³ of lime-cement columns has been created to increase the stiffness of the soil.

Permeation grouting has to be installed underneath a running railway line, where the tunnel crosses the loose packed sand embankment. Soft gel grouting is used at this position to prevent liquefaction of the sand and to prevent the communication of the ground water tables in the Pleistocene and in the sand deposit. Furthermore, a block of hard gel grouting has to be created in order to stabilise existing wooden piles that will be cut off during the tunnel boring process and to transfer the toe load of these piles to a higher level so they do not penetrate the tunnel lining.

Before the TBM reaches the arrival shaft next to the central station it has to cross the main railway embankment of the central station. Underneath and next to this embankment a monolithic block of jet grouting of around 15,000 m³ has to be installed. One third of these jet grout columns, that have to be installed below the embankment, will be produced with an inclination of less than 45° and a length of 24 m from besides the embankment.

Furthermore, gound freezing is going to be used to build in total five cross passages between the twin tunnel tubes.

This wide range of complex geotechnical methods at the RandstadRail project in Rotterdam leaves still a lot of interesting aspects to be presented in future.

[Fig. 18] TBM in Start Shaft

[Fig. 19] TBM in Start Seal

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