Technical challenges in immersed tunnelling and pneumatic caissons in the North/South Metroline in Amsterdam

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ABSTRACT

The new North/South Metro line in Amsterdam is currently under construction. The 9km line runs from the northern ring road to the southern ring road and passes the historic and very vulnerable city centre. For the part in the city centre special tunnel techniques are applied to limit the impact on both the historic buildings and the disruption on the city life.

One special technique that is applied is the immersed tunnel technique. This technique has been used for the crossing of the IJ-river under very soft soil conditions and for the crossing of the historic Amsterdam Central Railway Station. The application of the immersed tunnel technique underneath a historic building has never been applied in the world and was a true challenge considering the special immersion trench that had to be created underneath the building. The tunnel has been successfully immersed under the Central Station in the summer of 2011.

Another special technique that has been applied was the pneumatic caisson technique. This technique was selected to be the most preferred option considering the environmental impact (to buildings and city life) and construction costs. Two of the three caissons have already been sunken into the ground successfully and the last one is supposed to be sunk in 2012.

This paper will focus on the technical challenges of both techniques applied in a complicated and busy urban environment.

1 INTRODUCTION

The North/South Metro Line in Amsterdam, containing eight stations and measuring 9-km in length, will connect the northern and southern suburbs with the city centre (figure 1).

Figure 1 Alignment North/South Line

The northern part of the line will be mainly on surface level; as the line approaches the IJ river, the line goes underground using traditional cut and cover techniques. An immersed
tunnel will be applied for the crossing of the river. The southern part of the line will be just below surface level, also applying the traditional cut and cover techniques.

For the metro sections running under the city centre, construction is treated quite differently. As a requirement, the city centre’s design solutions were specifically tailored to protect the historic structures and limit disruptions. The design of the underground station at Amsterdam’s Central Railway Station (CS) and the adjacent sections were largely determined by local environmental constraints. Damage to the listed station building and obstruction of the existing traffic and passengers flows were not acceptable. Additional complications were the soft and highly variable subsoil conditions and the high ground water table.

**Part 1: Expanding possibilities for immersed tunnelling in the new Amsterdam Metro Line**

**2 METRO STATION CENTRAL STATION**

The underground station Central Station of the North/South Line is located on Station Island (figure 2). Station Island is an artificial island (land reclamation) that was created at the end of the nineteenth century in order to build the new Main Railway Station for Dutch Rail (Amsterdam CS). The island was formed by filling in a channel area in the River IJ with sand. At the Station Island location, the first Amsterdam sand layer is completely missing and the second sand layer is only partially present; the subsoil can be classified as poor to very poor

The new metro station will be an integral part of the biggest public transport hub in the Netherlands and will provide transfer facilities between local, regional and international public transport systems. Currently over 200,000 passengers per day use the present transport amenities. Building an underground station at such a location can be seen as one of the greatest challenges of the construction of the North/South Line. The underground station consists of three parts (see figure 2, 3):

1. Southern entrance under the Square “Voorplein” in front of Amsterdam CS
2. Northern entrance under De Ruijterkade
3. Platform part underneath the railway station Amsterdam CS

The top track level of the station is NAP -15.2 m (Amsterdam Ordinance Datum).
On the south side, a spacious concourse as well as entrances will be constructed underneath the Station Square, one of the busiest squares in Amsterdam. The building pit of this part of the station consists of 1.2 m-thick braced diaphragm walls with lengths varying from 30 (building pit wall) to 60-m (building pit wall and foundation element). To limit the disturbance to city life a building pit cover will be installed in different stages. This deck will be founded on bored piles and diaphragm wall panels with a length of 60-m. A jet grout prop is installed underneath the final excavation level. When the building pit has been excavated in the dry (underneath the deck) to the required depth of 22-m, the concrete structure can be built and the diaphragm walls will be integrated into the permanent body.

On the north side, a concourse as well as metro entrances will be built. The construction of this part is combined with the construction of a 2x2 lane traffic tunnel (passing over the metro) and a bus station platform at level +1. The building pit consists of braced combi pile walls and an underwater concrete slab acting as strut (excavation will be carried out in the wet). After the excavation is completed the concrete structure, founded on bored piles (60-m), can be built. In the construction phase the main building pit will also serve as a lock pit (in
connection to the IJ river) for the floating transportation of a tunnel element (platform part) that is immersed underneath the railway station.

3 IMMERSED TUNNEL UNDERNEATH RAILWAY STATION

The platforms of the underground metro station are located underneath the railway station. The major challenges were the protection of the historic and listed structures of the station buildings together with requirements of not disturbing the operation of the railway station and to keep the inconvenience for the passenger to a minimum. The station building was built around 1880 on an artificial island in poor soil conditions. The building is supported on some 9,000 wooden piles and considered to be highly sensitive.
After extensive studies it was concluded that a platform tunnel immersed in an artificial canal underneath under the railway station was the preferred option. The main reasons for selecting this option were:

- Since the platform tunnel is constructed at another location it limits the extent of construction activities on the railway station and it results in a shorter construction schedule since construction can take place on two locations.
- For the immersed tunnel option only a limited lowering of the water table inside the artificial canal was required. This was regarded as a significant advantage since the risk of influencing the water table outside and consequently the sensitive wooden pile foundations under the buildings was minimal.

Although the design was challenging it appeared to meet the requirements in the best way.

The platform part underneath the railway station consists of the following two main parts:
- An artificial canal (immersion pit) underneath the railway station including auxiliary support structures for the buildings and supplementary relief measures to protect the structures.
- Platform tunnel, built on another location and that is immersed in the artificial canal

The artificial canal (immersion pit)
For the formation of the artificial canal special tailor made types of building pit walls are developed:

- Underneath the masonry station building a composite building pit wall, the so-called “sandwich wall” was constructed, providing strength and water and ground tightness. This wall consists of two rows of steel tubex piles of φ457/16, with the space between the pile rows being grouted, thus creating a wall with a thickness of about 2.5-m, suitable for absorbing both horizontal and vertical loads (figures 7 and 9). One steel tubex pile is assembled with lengths of about 2 to 5 m (total length 30 to 60 m).

- The building pit wall underneath the platforms consists of tubular piles (diameter 1.82 m) connected together with watertight interlocks. The piles with lengths of 30 to 60 m are installed with a limited head room (2.80-m) using a vertical micro tunnelling method. This method is proposed by the contractor and worked out in an alliance with the contractor and the clients’ advisor. Special equipment (TBM, press frame, service crane) is developed (see figures 8 and 9).

Before the building pit walls were installed a number of supplementary measures were taken, such as reinforcing existing pile foundations, to limit the effects of the construction of the walls on the surrounding station structures. When the building pit walls were put in place, the support structures over the pit will be made; these were installed on a capping beam over the
building pit walls in order to support the station components above the building pit. The building pit wall will be braced at the top by the support structures and at the bottom by an underwater concrete strut underneath the excavation level. The first part of the excavation was carried out in the dry in order to install the first intermediate strut level. This allowed for a visual inspection of the building pit walls (figure 9). Subsequently, the building pit was excavated wet. During the excavation the walls are supported by temporary intermediate struts, that were removed once the under water concrete strut was in place. Only the first intermediate strut layer (4.5-m) for the sandwich wall part remained (southern 40 m).

Since the historic structures were sensitive to effects caused by the execution of the works an extensive monitoring program, comprising three independent systems, was implemented. Potential mitigating measures were identified and prepared in case the impact including the predicted effects of the remaining of the works exceeded the allowable impact.

The platform tunnel
The platform tunnel was designed as an immersed tunnel element and constructed on the north bank of the IJ-river. As construction dock the northern approach of the North/South Line IJ-river crossing was used. In this approach also the three tunnel elements for the crossing of the IJ-river were built.
The platform tunnel is 130 m long, 21 m wide and 8 m in height. In the final situation the tunnel is subjected to a ground cover of approx. 9 m. The tunnel is designed as a segmental tunnel, consisting of 7 segments with lengths varying from 14.5 to 21 m. The centre support of the tunnel cross section is designed as a row of columns with heavy longitudinal beams at roof and floor slab level. A continuous wall was not accepted because of social safety and surveillance during operation.

After completion of the tunnel elements the construction dock was filled with water and the elements were floated up. Thereafter they were towed out of the construction dock and transported to and moored temporarily at a quay in the western Amsterdam Port area (figure 11). Once the immersion pit underneath the railway station is completed an open connection has to be made with the IJ-river in the north in order to be able to transport the tunnel element under the railway station. This connection is made through the deep building pit for the northern part of the metro station. The transport and immersion process (figure 12 and 13) had to deal with some particular circumstances:

- the structures over the building pit that were supporting the parts of the station above the building pit were just above the groundwater table. To enable transport and immersion underneath these structures, the water table in the immersion pit had to be lowered approx. 2.5m. For that reason a so called lock-pit had to be applied in line with the immersion pit and extending into the IJ-river. After the lock pit is closed off with a separation wall the water table within the immersion pit can be lowered. (figure 12, 13).
- The sandwich wall at the Station Building (southern 40m) is supported by strut layers at 4.5-m. This strut layer is an obstruction to the floating tunnel element and implies a staged immersion process as described below.

After the lock pit has been closed off, the water level in the lock pit / immersion pit can be lowered to about 3-m and the element can be pulled towards the station building of Amsterdam CS and the under water struts at 4.5-m. The element, hanging from flat pontoons, will be immersed to a level such that the upper side of the element is marginally below the strut framework. The element can now be shifted horizontally underwater over a distance of about 40 m in a southern direction. Then it will be immersed deeper until it reaches its' final position. At this stage the tunnel element will be secured with hanging beams attached to the support structures over the immersion pit. After the separation wall between the immersion pit and the building pit for the north entrance has been installed, the gap between the tunnel base slab and the under water concrete slab (strut), which is approx. 0.6 m, is filled with sand, using the sand flow method. Pre installed pipes (0.3 m diameter) inside the tunnel element are used for this purpose. Finally the ground fill on top of the tunnel is installed. At the same time the concrete structure at the northern entrance is
executed. When adjacent structures are completed the connections with the platform tunnel can be constructed using freezing techniques for temporary water tightness purposes.

1. floating transport of tunnel trough lock pit and building pit “De Ruijterkade”

2. shift element underneath railway station at a lowered water table (2.5 m) up to struts sand which wall underneath station building

3. immersion phase 1 below level struts station building and shift to the far south end

4. immersion phase 2 (to its final position)

Figure 12: Immersion process in four stages

Finally
To increase flexibility towards the construction program of the adjacent Station parts the tunnel element was accommodated with two closure joints. A traditional immersion joint at one end would mean that one adjacent structure had to be completely finished to receive the tunnel element. In the current layout this was not necessary. The tunnel element could be immersed anyway and the connecting joints could be realized in a later stage. This would enable earlier immersion and start up the concreting works for the northern entrance.

Figure 13: Transport of the tunnel element in the lock pit

Colophon:
Client : Dienst Noord/Zuidlijn (Municipality of Amsterdam)
Designers : North/South Line Consultants (JV Royal Haskoning and Witteveen+Bos)
            VOF Stationseiland (JV Arcadis and Movares)
Contractor : CSO (JV Strukton Betonbouw and Van Oord)
            Mergor Under Water Construction (Sub contractor Transport and Immersion)
Part 2: North/South Line Amsterdam, Pneumatic caissons to solve particular design problems

4. BOUNDARY CONDITIONS FOR THE DESIGN

Pneumatic caissons are being used for the underground section at the Open Havenfront and the Natte Damrak between the CS underground station and the bored tunnel (figure 14). This technology has been used before, during the construction of the East Line of the Amsterdam underground system in the nineteen-seventies.

![Figure 14. Overview of construction southernmost caisson ready to sink – September 2005](image)

The route of this underground section of the new metro line goes from the south end of the main square in front of Amsterdam CS (central railway station) to the east of bridge 306, crosses bridges 326 and 303, (the Nieuwe Brug – already demolished in figure 14) and ends about 30 m to the south of this last bridge in the Natte Damrak. The level of the top of the track drops from north to south, from NAP (Amsterdam ordinance datum) –15.4 m to NAP – 18.9 m. The length of this section is about 150 m. The southern part of this underground section also acts as the launching shaft of the tunnel boring machines.

For the design of this section of the metro line account had to be made for amongst others the following boundary conditions:

- **Urban infrastructure**
  The construction of this part of the North/South Line is significantly influenced by the presence of adjacent structures (3 bridges), the many and complex flows of normal traffic (cars, cyclists, pedestrians) and public transport (buses, trams, water tour boats) and the requirements to be met applicable to the flood barrier in bridge 303.

- **Soil condition**
  The soil profile is highly variable because of the influence of former River IJ channels in this area. These former channels were filled in over time and have disrupted the top 15 to 20 m of the typical Amsterdam soil profile. A striking feature is that the top of the Eem clay layer is at about NAP -38 m, or in other words about 10 m deeper than in the other locations in the city centre.
- **Archaeological site**

The area between Amsterdam Central Station and the Damrak (the Nieuwe Brug) was once part of the roads of Amsterdam (figure 15). Whereas initially the bridge formed part of the city's defences, after a double row of piles had been driven into the IJ, it became an increasingly important meeting place. The activities in the lee between and behind the piles included the transhipment of goods from seagoing vessels to smaller craft and ship repairs. It is assumed that evidence of these activities will have been left behind in the soil. Traces of the foundations of the first bridges are being found at the Nieuwe Brug.

![Figure 15: 17-century print of the area](image)

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**5. DESIGN PNEUMATIC CAISSONS**

The design consists of three caissons that will be built on a temporary land fill between sheet piling (figures 16 and 17). The purpose of the sheet piling is to limit the size of the land fill and to limit the impact of the works on the vicinity. The sheet piling close to adjacent properties either stepped or not, will therefore be extended down to the second sand layer. After the sheet piling has been put in place, the canal bed will be cleaned up to a depth of NAP –4.5 m and the building pit will be filled with sand to a level of NAP, thus creating the temporary land fill.

![Figure 16. Plan and longitudinal section of caissons 1 to 3](image)
Existing structures present in the temporary landfill are removed; for example the masonry abutments and piers of bridge 303 and its’ timber foundation piles that are pulled out (as far as possible). A grid of sand piles will then be realised down to just above the second sand layer in order to accelerate the consolidation of the soft layers. The soil will also be improved because of the density of the grid, and there will be reduced settlement and more importantly, reduced differential settlements. An additional advantage is that the subsoil will be scanned to a certain degree for the presence of large obstacles so that account can be taken of these while sinking the caisson.

The caissons will be constructed in two main phases in order to minimize disruption to flows of through traffic. During phase 1 land fills 1 and 3 will be made and caissons 1 and 3 will be constructed and sank into them (fig. 17). During this phase traffic on Prins Hendrikkade will use the renovated bridge 326. In phase 2 land fill 2 will be produced, after the dismantling of bridge 326. Subsequently the caisson 2 will be made and sunk. At this point traffic on Prins Hendrikkade will be directed across the renovated and widened bridge 303.

![Figure 17. Phase 1 of the construction (landfills 1 and 3)](image)

The caisson method involves constructing a relatively rigid box structure at ground level that is lowered by excavating the soil underneath it. The excavation process takes place from the work chamber, which is made up of tapering walls 2 to 3 m high (so-called cutting edges) around the perimeter of the caisson base slab. When excavation takes place below the groundwater table, the work chamber is kept ‘dry’ by applying an air overpressure. The soil in the work chamber is loosened by water jets and removed hydraulically to a nearby basin. The caisson sinks into the ground because the soil underneath the cutting wall edge fails. For this to happen the sum of the downward loads (weight of the caisson and possibly temporary ballast) is greater than the sum of the resisting upward forces (cutting wall edge resistance, wall friction and water or air overpressure). In order to reduce the friction along the caisson a recess is made above the cutting edge that will be filled with bentonite. After it has been sunk, the work chamber will be filled with concrete so that the caisson can act as a (deep) footing (see phasing in figure 18).
Caissons 2 and 3 (12.4 to 14.3 m wide, 10.8 to 11.8 m high and 26.0 to 42.3 m long) have a relatively standard design and are more or less comparable with the track section caissons used to construct the existing underground East Line. Caisson 1 is substantially larger because of the fact that a number of temporary or permanent functions are combined in it:
- the actual tunnel for the North/South Line;
- service and operation facility areas for the underground system;
- launching shaft for the two tunnel boring machines (TBM) and their trains of supporting equipment. Two shafts will be kept open temporarily during the construction for the introduction of the TBM’s including supporting equipment, tunnel segments, grout etceteras and removal of soil;
- area for a flood barrier (segment barrier, see figure 16) and its operation;
- a stairwell and communal areas for access to the control rooms and the flood barrier;
- the western abutment for bridge 303 with facilities for a lock.

Consequently the caisson has substantial dimensions: 57 m long, 18 m wide and 27 m high. Two ‘soft eyes’ will be applied in the southern wall. These are zones in the wall that have plastic reinforcement. This enables the TBM’s to drill out through the wall in order to be able to construct the bored tunnel. The northern end wall incorporates steel and concrete bulkheads. This is also the case for the end walls of the other two caissons. After completion of the sinking process, the joints between the caissons are made using freezing techniques, after which the end walls are broken out.

6. STRUCTURAL DESIGN PNEUMATIC CAISSONS

As described above, the dimensions of caisson 1 are quite substantial. This caisson will be built and sunk in two phases because of the resulting large construction loads on the subsoil and due to all the nuisances it would bring to the surrounding area if it were constructed in only one phase. The section with the work chamber and the underground metro tunnel is
implemented in the first phase and the remainder in the second. The design calculations revealed that two more inner load-bearing cutting edges were required in addition to the cutting edges. The load-bearing edges divide the work chamber into three compartments. The separate parts are connected by openings in the load-bearing edges. A 3-D finite element model with scale elements was used because of the complexity of the structure of caisson 1 and the phased construction (figures 19 and 20), whereby the effect of construction phasing was also taken into account.

Figure 19 : FE model of caisson 1  
Figure 20 : Results of FE analysis for caisson 1

Generally speaking it can be concluded that the loads during the sinking operation phases are determining the dimensions of this caisson. The caisson is supported by the cutting edges as the soil is undercut hydraulically. The reactions under the cutting edges are usually not evenly distributed because the ground under the work chamber is not removed evenly, the subsoil is not homogeneous or because there are obstacles in the subsoil. Consequently the support conditions of the caisson can only be approximated. A number of support scenarios were therefore defined for establishing the dimensions that represent a reflection of the conditions to be expected during the sinking. Some representative diagrams are shown in figure 21. Account is also being taken of horizontal soil stresses arising from tilting, as well as possible emergency situations caused by a sudden loss of air pressure in the work chamber.

Figure 21. Possible support conditions caisson 1

7. EXECUTION

Building in an urban environment like Amsterdam can be considered a challenge, dealing with all the technical and environmental constraints. This is certainly the case for constructing the caissons. Characteristic elements of implementation in a metropolitan city centre include complex phasing, limited access to construction sites, logistics problems and safety. The
limited size of the construction site is partially compensated by creating a sand fill and a number of platforms in the water. In spite of this, sophisticated logistics remain essential to the project. The type of surroundings also calls for limiting the nuisance, and this can be accommodated for example by having fixed periods outside rush hours for delivering and removing materials. Finally, the safety of the vicinity plays a significant role in the execution procedure and agreements have to be made with the competent authorities about stopping traffic temporarily for the purposes of the work and implementing additional safety measures. Currently, the caissons 1 and 3 are sunk successfully within predefined tight construction tolerances. Although large objects are encountered and removed (delaying the process) environment so far has hardly been effected. The in between caisson 2 is almost completed and the sinking process is about to start.

Figure 22: caisson 1 – construction phase
Figure 22: Hydraulic excavation process in working chamber underneath base slab caisson

Colophon:
Client: Dienst Noord/Zuidlijn (Municipality of Amsterdam)
Designers: North/South Line Consultants (JV Royal Haskoning and Witteveen+Bos)
Contractor: Heijmans Betonbouw Visser & Smit (Sub contractor Sink operations)