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Engineering highlights of RandstadRail in Rotterdam, The Netherlands

Abstract

RandstadRail is a new lightrail connection between the cities of Rotterdam, The Hague and Zoetermeer (The Netherlands). A tunnel of three kilometres length is being built at present to realize RandstadRail in Rotterdam. The project contains building of one new station (Blijdorp) and re-building of an existing underground station (Rotterdam CS). Latter station will be transformed into a three-track configuration with two platforms while regular traffic is not to be interrupted by building activities.
Within this project a number of special techniques have been used aiming at minimizing the effect of the building activities on every day life within the city of Rotterdam. This paper gives a quick-scan of the engineering highlights of the project. Special attention is paid to the shield-tunnelling in soft clay as well as the design of the building pit of Central Station in which ground freezing techniques are applied.

***Figure 1** Bore tunnel*

Introduction

The four major cities of The Netherlands, Amsterdam, Rotterdam, The Hague and Utrecht, are situated in the western part of the country. Within this densely populated area, there is an increasing demand for public transport on a high service level. One of the key-projects in this context is RandstadRail. RandstadRail is a lightrail line, by which it will be possible to travel from the centre of Rotterdam to the towns and cities in northern direction without transfer. In Rotterdam, RandstadRail will be linked to the existing metro line (Erasmus line) at its terminal station Rotterdam CS, which has to be enlarged to provide sufficient passenger transfer capacity. Re-building of the underground station Rotterdam CS as part of the RandstadRail project is closely related to the overall project Rotterdam Centraal. This major project comprises the building of a large OV (public transport) terminal in the centre of Rotterdam, in the vicinity of the Rotterdam Centraal railway station. It is designed to facilitate passenger transfer between (inter)national trains including High Speed Line (HSL) and local public transport like trams, buses and metro/lightrail.

Inside Rotterdam urban area, a new tunnel has been built since 2004 to create the connection between RandstadRail and the existing Erasmus line. Subject tunnel is approximately three kilometres in length, and has one underground station (called Blijdorp) halfway *(figure 2)*.
Due to the fact that several infrastructure (railway, highway as well as waterway) and the inner city of Rotterdam had to be crossed, 80% of the tunnel length is built by means of shield tunnelling technique. The remaining part is constructed through conventional cut and cover method. RandstadRail Rotterdam is the first tunnelling project in The Netherlands that has been executed in soft soils conditions and in densely populated urban area. This paper presents a quick-scan on some of the engineering aspects of the bored tunnel and the new underground station Rotterdam CS.

Soil Conditions

The general subsurface conditions, which are typical for the Rotterdam region, are summarized in *Table 1*.
The ground water level along the line is approximately 2.5 metres below reference level (NAP).

Bored tunnels main design considerations

An extensive study regarding the options of one double track tunnel (1*Ø11.2m) versus two single

Photo: D. Sellenraad; Aeroview

***Figure 2** Alignment of RandstadRail in Rotterdam.*

	Elevation NAP m	γ_{sat} kN/m³	W %	PI	c_u kPa	K_0	OCR
Man made soil (sand fill)	-0.3 (surface)	18	-	-	-	-	-
Clay type a	-5.0	13.5	87	47	41	0.5	1.3
Peat	-7.5	10.5	457	-	41	0.4	1.2
Clay type a	-10.0	13.5	87	47	41	0.5	1.3
Clay type b	-12.5	16.5	56	37	30	0.5	1.3
Pleistocene sand	-16.0	20	-	-	-	0.5	1.0
Kedichem clay	-35.0	20	24	24	86	0.8	1.7
Kedichem sand	-37.5	20	-	-	-	0.8	1.7

***Table 1** Average soil parameters.*

track tunnels (2* Ø6.5m) led to the recommendation to use a configuration of two single track tunnels. This recommendation was based on (i) lower estimated building costs and (ii) lower risk profile of the project due to the greater influence on infrastructure when crossing with a larger TBM. It is noted that the sharp horizontal curves of the tunnel alignment (radius 240 metres) gave an additional technical reason for choosing two single track tunnels.

Passenger safety is incorporated in the overall design of the tunnel through the safe haven concept. All underground stations are designed to be safe haven. In case of an emergency situation, standard procedure will be that trains run to one of these safe havens. In the unlikely event that this procedure fails and a train stops somewhere in the tunnel, additional cross connections (each 350 metres) are available for escape to the other (safe) tunnel. The cross connections are built using ground freezing technology (brine coolant), to allow for excavating from one tunnel to another. Shotcrete with thickness 300 mm is applied for stabilising the excavation.

The 6.5 m external diameter bored tunnels have a concrete lining of 0.35 metres thickness. Concrete design strength is 55 N/mm^2 (B55). Each tunnel ring is 1.5 metres in width. The tunnel rings have a conicity of 5 centimetres for realising the horizontal and vertical curves. Every ring consists of eight (including one key-stone) pre-cast concrete segments. The tunnel rings are placed in stretching bond and are connected by specially designed concrete dowels.

The bored tunnels are placed mainly into the Pleistocene sand layers, which provide suitable soil conditions for this type of tunnel structure *(figure 3)*. However, near the starting shaft in the Northern part of Rotterdam as well the receiving shaft near the existing underground station Rotterdam CS, the tunnel had to be placed in the soft Holocene clay. Reason for this are the fixed connections of RandstadRail to the already present rail infrastructure. The soft clay does not provide sufficient support to the concrete lining. Also, continuously developing settlement of the Holocene clay (~1 cm/year on surface elevation) will result in additional time dependent forces on the tunnel. These two problems have been solved by use of ground improvement techniques for the shallow parts of the tunnel alignment. Several ground improvement techniques have been used, considering the typical conditions and circumstances at each individual location. Soil deep mixing and soil replacement

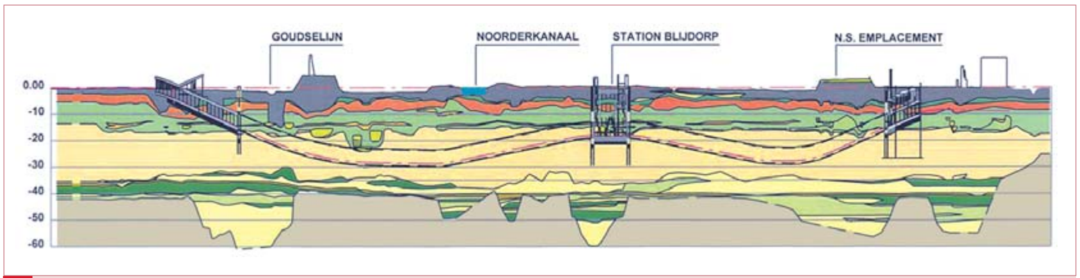

Figure 3 *Vertical alignment of bored tunnels; distance start tunnel – Blijdorp station – Rotterdam CS station ca. 2,0 & 1,2 km.*

Figure 4 *Jet grouting near the receiving shaft.*

have been executed near the starting shaft. Jet grouting has been applied near the receiving shaft *(figure 4)*. It was observed that, when realising the ground improvement techniques of jet grouting and soil deep mixing, substantial horizontal deformations occurred (several centimetres), but this did not cause any damage. However, when using these techniques in densely built areas, these deformations should be anticipated for in the design.

Ground improvement techniques could not be applied at all desired locations, for example near the receiving shaft which is located underneath the Rotterdam main railway station embankment consisting of 16 railway tracks, and near future station Blijdorp where the tunnels are located under a road. Using ground improvement techniques at these locations was not advisable as this would lead into influencing rail and road traffic. At these locations a steel tunnel lining is used, for a total of ca. 5% of the bored tunnel length. However, for this type of lining it is required to consider the possibility of stray currents originating from nearby railway tracks. Corrosion of the steel lining as induced by stray currents had to be avoided, which resulted in application of a steel lining with special coating and cathodic protection.

Tunnel boring process

The boring process was done using a TBM with a slurry shield *(figure 5, next page)*. The length of the TBM was 68 metres. The length of the shield was 9.8 metres. The machine had a diameter of 6.78 metres and contained a 5-arm cutting wheel. A pivoting joint between middle and tail shield was built-in to make passage of the tunnel curves having relatively small radii possible.

The tunnel boring process started in December 2005. When crossing the sealing block, consisting of low strength concrete (expected strength ~15 MPa) and a diaphragm wall (expected strength ~45 MPa), substantial wear of the cutters was noticed. Here, the cutting wheels had to be changed several times. When boring in the original soil conditions (sand, clay) no significant wear of the cutters was noticed. The boring speed was ~40 mm/minute. When crossing the ground improvement areas (jet grouting, soil deep mixing) the boring speed was reduced (~20 mm/minute). Crossing the diaphragm wall the boring speed was even lower (~1 mm/minute), so passing the diaphragm walls (thickness of 1,5 metres) took several days. The influence of the boring process to the environment was relatively small. At surface level settlement of 10-15 mm was encountered when crossing the railway tracks. In the design phase of the project these settlement have been determined using the simple formula of Peck (1969), as well as a finite element calculations (Zanten, 2002). The actual surface settlement was small, but larger than expected. Post-diction of the settlement along the line resulted in a higher volume loss than initially expected *(table 2)*.

$$\delta_{s;x} = \delta_{\max} \cdot e^{-\frac{x^2}{(2*i^2)}}$$

$$\delta_{\max} = \frac{V}{i \cdot \sqrt{2 \cdot \pi}}$$

$\delta_{s;x}$ *surface settlement at distance x from tunnel;*
δ_{max} *maximum settlement;*
V *volume of settlement through;*
x *horizontal distance from tunnel axis;*
i *horizontal distance of tunnel axis to point of inflection;*
k *indicator for stiffness trough;*
z *depth tunnel axis.*

Also, settlements in the vicinity of the tunnel have been measured. This is shown in figure 6 for one location. From this graph, it can be seen that settlement near the tunnel is twice as high as settlement at surface level. This effect has to be accounted for in projects containing tunnelling underneath pile foundation structures. Within the RandstadRail project, no such structures are located directly above the tunnel.

Other obstacles have been encountered, such as remnants of wooden pile foundations. The design philosophy of the project is to retract these piles if possible. However, at some locations retracting of the piles was very difficult (e.g. under the embankment for the railway tracks). At these locations the TBM had to pass through the piles. The RandstadRail project experience on boring through wooden piles is good. No influence on TBM face stability was encountered, just some minor effect on the bentonite cycle was noted. In February of 2008 the tunnel boring process was succesfully completed.

Underground station Rotterdam CS

The existing 'Erasmus' underground tunnel, of which underground station Rotterdam CS is the end stop, was built in the period 1962-1967. The tunnel was assembled from prefabricated segments, which were built in dry docks. The tunnel segments were floated to their final - destination through a canal (sunken tubes). Once arrived on the spot, the segments were sunk onto their permanent foundation which consists of pre-installed concrete 'oppers'-piles.

The present underground station Rotterdam CS having a two-track lay-out and single platform will be transformed into a three-track configuration with two platforms. The building pit as required for the reconstruction works of underground station Rotterdam CS covers ca. 7500 m² *(figure 7a, b)*. Governing design condition is that regular underground traffic and passenger transfer at the existing underground station is not to be affected during the construction works, thus no damage (e.g. cracks, water leakage) to the tunnel due to the works is allowed.

The existing underground tunnel reaches to depth 10 m below surface. Excavating is done to 14 m depth to allow for installation of new foundation piles underneath the tunnel. Therefore, the surrounding soil around the existing tunnel had to be removed completely. Consequently, as the tunnel elements have not been designed to carry any horizontal loads under these circumstances, special supporting frames have been put in place *(figure 8a, b)*.

The excavating method itself is based on isolating the water carrying Pleistocene sand layers inside the building pit by means of a diaphragm wall to a depth of 38.0 m below reference level (NAP). This so-called "Kedichem"-method provides a water regime inside the building pit which can easily be maintained, as only a very limited amount of water is expected to pass through the diaphragm wall and the low permeability clay/peat/loam layers of the Kedichem formation below depths NAP -35 m.

The existing underground tunnel enters the building pit at the east side of the construction site *(figure 7)*. Closing the building pit at this location requires a watertight solution, especially at shallow depths. Final design for closing the gap in the cut-off wall at this location by means of a collar construction around the underground tunnel comprises application of ground freezing technology *(figures 9,10)*.

The collar construction consists of a frozen soil body, thus creating an arch-shape collar construction supported by long diaphragm wall sections to carry the hoop forces as induced by

	Average volume loss %	k
Prediction	0,5	0,4
Post diction	1,1	0,35

Table 2 *Parameters for formula Peck.*

Figure 5 *RandstadRail Tunnel Boring Machine (TBM).*

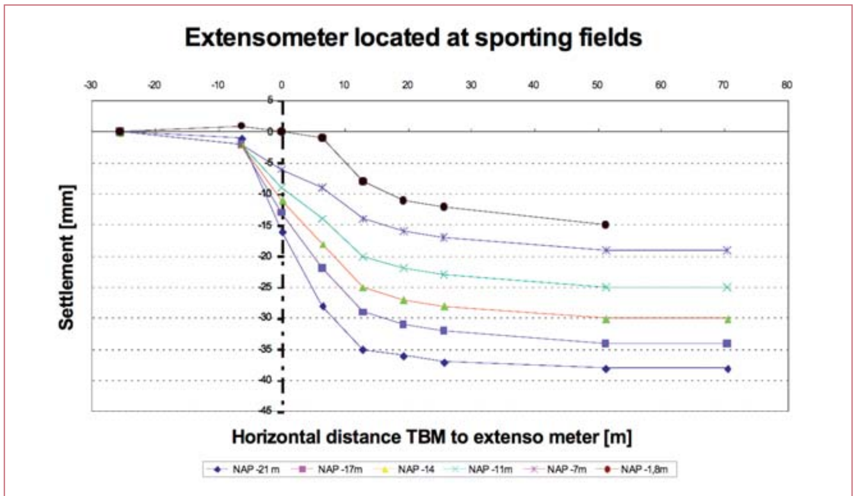

Figure 6 *Settlement in time above tunnel*

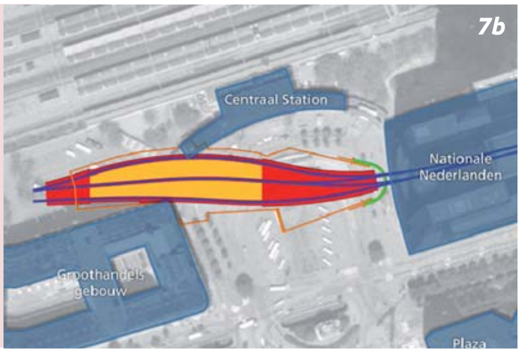

Figure 7a Picture of the building site.

7b Top view of Stationsplein. contour lines of excavation (diapragm walls, yellow) and re-built underground station are shown. On the right: location of collar construction (green).

Figure 8a Fixation frame for stabilising horizontal position of station.

8b Piling equipment working on installation of new pile foundation below existing tunnel.

excavating. The frozen soil body is generated through two parallel rows of vertical freeze pipes to 40 m depth. Freeze-up is done using combined brine (inner row) and liquid nitrogen (LN_2, outer row) freezing. During maintenance, freezing is done using the brine pipes only. The LN_2 facilities remain standby on site for back-up reasons.

Some key-data are as follows:

- Collar construction retaining height ~14 m (incl. hydrostatic water pressures).
- Minimum thickness 2.5 m (i.e. frozen soil volume at least ~4000 m^3).
- Approximately 100 tubulars installed: 50% brine freeze pipes, 30 % LN_2 freeze pipes and 20% temperature monitoring pipes.
- Additional temperature monitoring of connection between tunnel structure and frozen soil.
- Distance between freeze pipes ca. 0.9 m (also inside existing tunnel and in between rail tracks).
- Freezing operation for at least one year.

Conclusion

Building the tunnel for RandstadRail to the existing underground infrastructure has been done under very strict design conditions, aiming at minimizing the effect of the building activities on every day life within the city of Rotterdam. For this reason, some special techniques a.o. shield tunnelling in soft clays and combined brine and LN_2 ground freezing, have been applied on unprecedented scale within urban area in The Netherlands. The connection between RandstadRail and the existing underground station Rotterdam CS is expected to be in service by end of 2009. ■

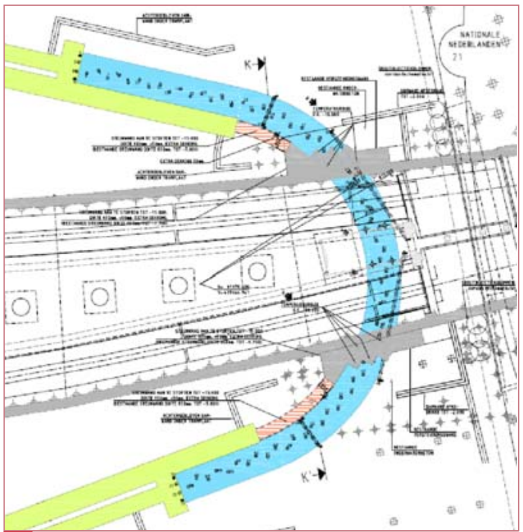

Figure 9 Plan of designed collar construction around the tunnel at station platform elevation, showing frozen soil area (blue) and supporting diaphragm walls (green).

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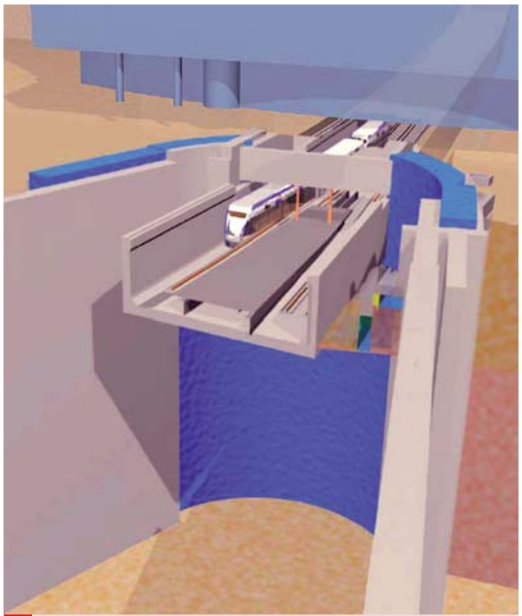

Figure 10 Artist impression of collar construction.