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An underground tunnel beneath Amsterdam Central Station

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Abstract

The public transport authority of Amsterdam has drawn up a plan to build an underground subway connection between Amsterdam North and Amsterdam South. The route of this line will pass under Amsterdam Central Station.
There will be a total of 9 km of underground line. Bored tunnels will in principle be used in the centre of the city. For the design of the route through Amsterdam Central Station a conventional building method has, however, been chosen. The geotechnical aspects typical of such a project are contained in this publication.

Introduction

Built at the end of the 1880's, Amsterdam Central Station comprises a main building at the front, a building on the De Ruyterkade at the back and five platforms and various tracks in-between. Under this, from front to back, there is the centre tunnel introduced in 1980. The construction level of this tunnel is approx. 0.5 m above Normal Amsterdam Level (NAL) and it has a width of 30 m. The De Ruyterkade has been integrated with the northern platform roof (Figure 1).

The main building and the De Ruyterkade building are built on wooden piles with the point levels at approx. NAL -17 m and NAL -22 m respectively. The centre tunnel is built on a shallow foundation.

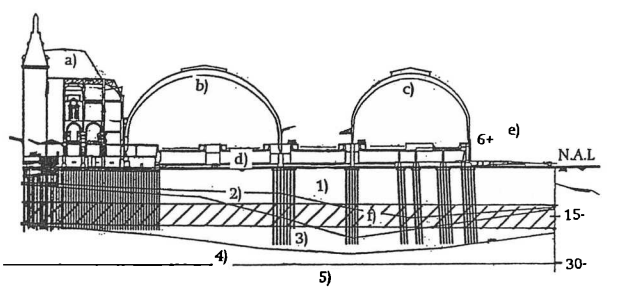
The station is currently a listed building. A key requirement during the tunnelling is that little or no damage may occur to the building. Another requirement is that there may be little or no effect on the running of the trains and the flow of passengers. This also applies to the shops and offices located in the station. Nuisance due to noise and vibrations must therefore also be kept to a minimum.

Since it was not fully known at the time of the recommendations how the tunnel for the underground line might turn out, the construction of a concrete tunnel with a width of 35 m and a construction level for the underside of the tunnel of NAL -18 m under the centre tunnel was assumed for the recommendations concerned. The total length of the tunnel will be approx. 150 m. To construct the tunnel, a high proportion of the wooden piles will have to be removed under both the main building and the De Ruyterkade building.

Supporting structures must therefore be installed for this which will be placed on a temporary or final pile structure. Support also needs to be given to the centre tunnel on shallow foundations.
The overall order of construction should be such that first the supporting structure is installed then the construction pit wall is built, after which any loads are transferred to the walls. The pit will then be excavated.

Ground investigation undertaken

For the overall exploration of the subsoil, four cpt's were



A) station building
b) southern platform roof
c) northern platform roof
d) pedestrian tunnel
e) De Ruijterkade
f) underground tunnel

1) sand
2) Y-clay
3) sandy clay
4) clayey sand
5) Eemclay

Figure 1: Longitudinal section

made just outside the station complex to an average depth of NAL -67 m. Two borings were also made to a depth of NAL -32 m. Two observation wells were placed in the bore holes with a filter at NAL -20 m.

Ground composition

Central Station is situated on the 'station island'. This artificially constructed island was built in the period 1870 - 1880 on the formerly open harbour front by dredging, laying slurry walls, filling in with sand and raising to dry level to approx. NAL +5 m at the platforms, to approx. NAL +3 m at the front square and on the De Ruyterkade to approx. NAL +0.7 m.

A characteristic of the area in which Central Station is situated is that it is a trench area. This manifests itself in the complete lack of the first layer of sand and also the second layer in places.
The overall composition of the soil can be described as follows:

The ground composition at the location of the main building is materially different to the ground at the De Ruyterkade. On the front side, elevating sand is encountered from ground level to NAL -6 m. From NAL -6 m to NAL -7 m there is a thin layer of clay from the river IJ.

Under this, a very thick pack of sand-bearing clay is found down to NAL -18 m. From this level to approx. NAL -28 m the second sand layer is encountered. Under this, down to approx. NAL -56 m, there is a relatively stiff clay called 'Eem clay'. The third sand layer is encountered from approx. NAL -56 m. At the location of the De Ruyterkade, the strong, supporting second sand layer is not present.

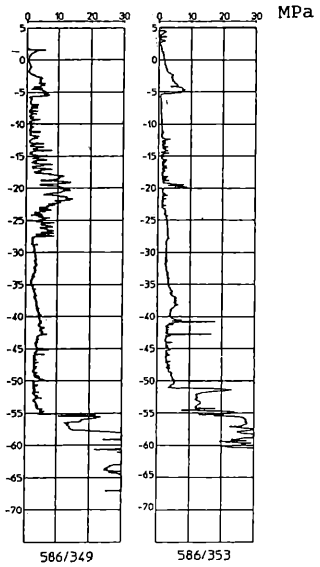


Figure 2: Characteristic foundations

The characteristic difference in foundations is shown in Figure 2.

The groundwater position and elevation are as follows:

- Groundwater level : NAL -0.40 m.
- Piezometric surfase of 2nd sand layer : NAL -1.50 m.
- Piezometric surfase of 3rd sand layer NAL -3.00 m.

Design:

The station building, the centre tunnel and the De Ruyterkade building must be supported. During the construction of the underground tunnel this supporting construction should be formed by the construction pit walls and a tunnel roof and possibly a mid-support point. At the location of the station building this is shown in Figure 3.
In the construction thus formed, excavation should take place to approx. NAL -18 m. The water level in the construction pit should be lowered to at least this level.
It is recommended that in this case the construction pit wall be given an earth and water retaining function as well as a supporting function. To provide sufficient supporting strength, the wall must be underpinned in the 3rd sand layer (approx. NAL -65 m). To make the wall watertight, the wall must be installed to a minimum depth of NAL -32 m.
Due to the great stability desired and the high supporting strength required, a construction pit wall formed by a wall in trench or a steel pipe pile wall was assumed for the time being in the pre-design.

Vertically balanced construction pit base

The construction pit walls should go down to approx.

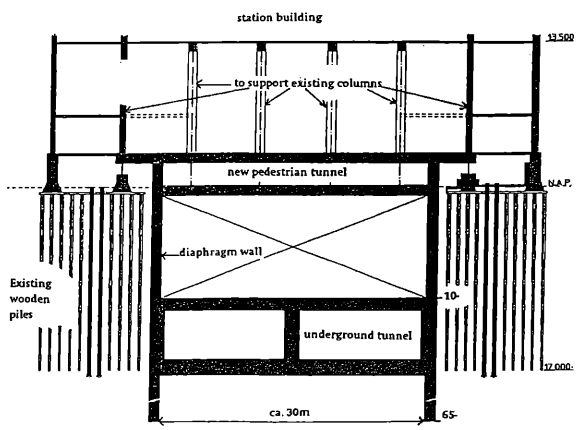


Figure 3: Principle construction pit/support construction

NAL -32 m. The Eem clay layer from NAL -28 m to NAL -56 m is relatively impermeable.
The vertical permeability is anticipated to be approx. $k_v = 10^{-10}$ m/s. This layer therefore forms a tight, natural seal for the construction pit base. The piezometric surfase in the 3rd sand layer can be up to a maximum of NAL -3.0 m. In view of the salt content of the water, this is estimated at $\gamma_w = 10.1$ kN/m^3.
The water pressure against the underside of the Eem clay layer at NAL -56 m is therefore 535 kN/m^2. For a maximum excavation to NAL -18 m, the vertical ground pressure at a depth of NAL -56 m will be approx. 652 kN/m^2 at the main entrance and approx. 637 kN/m^2 at the De Ruyterkade. The safety factor against excess pressure must, assuming partial materials factors, be a minimum of 1.0. In the case in question, a minimum safety factor against breach of the construction pit wall of n = 1.08 therefore applies, this being more than sufficient.

Supporting strength of wall and pile foundations

General

The loads on the wall and pile foundations arise from the fact that parts of the buildings and the whole of the centre tunnel must be supported. A mid-support point can be used at the location of the centre tunnel. The loads (calculation values) for the support have been given as overall figures in Figure 4. It may be noted that the difference in loading between the construction phase and the final phase is negligible.

Location	Permanent	Variable	Total
Centre tunnel	650	450	1100
Main building	1800	300	2100
De Ruyterkade building	1200	900	2100

Figure 4: Estimated values of load on the construction pit wall in kN/m .

Here no account has yet been taken of the wall's own weight.
A load of 2900 kN (1500 kN permanent and 1400 kN variable) is imposed on the support points.

Supporting strength of final piles and walls

To provide supporting strength in the final situation, three types of foundation elements have been assumed for the time being. These are given in Figure 5 along with their calculated maximum supporting strengths.
For the values given in the table, account has already been taken of the foundation elements' own weights.
In the calculations, no account has been taken of a load occurring in the form of negative adhesion.
The stated displacements are in principle the

	$F_{r,d}$	δ point (cm)
Diaphragm wall = 1.30 m	2,600 kN/m	3.0
Steel pipe pile wall Ø 1.50 m; c.t.c. 2.0 m	2,250 kN/m	3.0
Tubex pile Ø 0.457 m (0.65 m); c.t.c. ≥ 2.5 m	2,400 kN	1.5

Figure 5 Overview of calculation values of maximum supporting strength for NAL -64 m

displacements from the point of the foundation element. Since a wall in trench and steel pipe pile wall both have major weight of their own, a major part of the displacement will already have taken place before the element fulfils a supporting function.

Construction pit wall with foundations in Eem clay

Due to the relatively high stiffness of the Eem clay (q_c = 3 MPa), it may be possible to position the foundation level for the construction pit wall in this layer. Both the balance and deformation supporting strength must then be checked.
To determine the minimum required length of the diaphragm wall, an average load (calculation value), including the wall's own weight, of 2900 kN/m' was assumed for both buildings and of 1900 kN/m' for the centre tunnel.
To be able to absorb the loads stated above, it is necessary for the wall to have a point level of NAP -38 m and NAP -45 m respectively.

Due to the contribution of shear stress along the wall and the point stress, the layer of Eem clay would undergo a deformation. The calculated final settlement and the settlement over time have been shown in Figure 6. A hydrodynamic period of 500 years and a ratio between the primary and secondary effect of 50 - 50% has been assumed here.

	Settlement arising after ... years (cm)						
	0.5	1	2	5	10	100	500
NAL -38 m	7	9	10	12	14	18	25
NAL -45 m	10	12	14	17	19	25	35

Figure 6: Overview of settlement arising over time.

It may be noted that the settlement for a steel pipe pile wall is expected to be of the same order of magnitude.

Effect on existing and temporary pile foundations

Disturbance will take place in the subsoil due to the insertion of the piles and the construction pit wall. Through this the bearing capacity of the piles already in place will decrease. The degree to which this disturbance

will occur depends on factors such as the way in which the foundation element is introduced, the distance relative to the threatened object and the depth of the new foundation level.
In this case the new foundation elements and the construction pit wall should in principle be given much deeper foundations than the wooden pile foundations that are present. With empirical figures from within Holland Railconsult and some measurements in the construction of a wall in trench for the Willemsspoor tunnel (Rotterdam) it is suggested in the assessment of the effect on the supporting strength of pile foundations already present to assume the changes in supporting strength as shown in figure 7.

It can be deduced from this that when, for example, constructing a wall in trench at a distance of 3 m from a wooden pile, no loss of bearing capacity occurs. If the distance is less, account must be taken of a reduction in bearing capacity.
For this project, it is thus also proposed that the function of every wooden pile within a distance of 3 m from the construction pit limits should be taken over by a new foundation element.

Deformation as a result of excavation

Swelling of the construction pit base

As a result of the disturbance to the subsoil caused by the excavation, the sand-containing clay layers and Eem clay layer still remaining under the construction pit base will want to swell. With the aid of the finite element program Plaxis the maximum swell in the centre of the construction pit has been calculated at 11 cm.
This is somewhat less at the edge of the pit.

Progression over time

In principle the progression of the swelling should occur according to a process of consolidation. Due to the subsoil excavation, the consolidation period is less than the hydrodynamic period which would in principle be assumed for loads. A different C_v value applies. The swelling or settlement of the layers under the construction pit base is determined by the sand-containing clay layer and the Eem clay layer.
When determining the progression over time it has been assumed that the consolidation period of the sand-containing clay layer is relatively short and that the settlement or swelling will occur virtually immediately. Due to its impermeability and great thickness, the hydrodynamic period in the Eem clay layer is very long. A period of T_e = 500 years has been taken for this situation.
For the consolidation process during relief a C_v value is taken which is twice as great as the C_v value for loading. The consolidation period for swelling is therefore half as great and is set at 250 years. The progression of the swelling over time is shown in Figure 8.

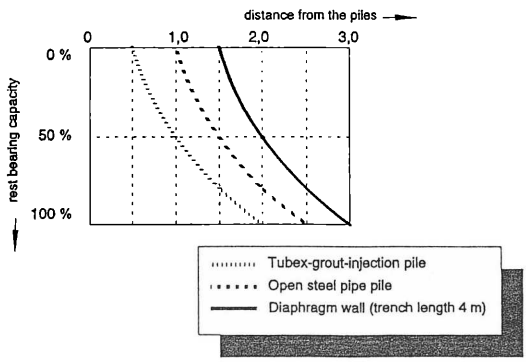


Figure 7: Changes to be assumed in supporting strength.

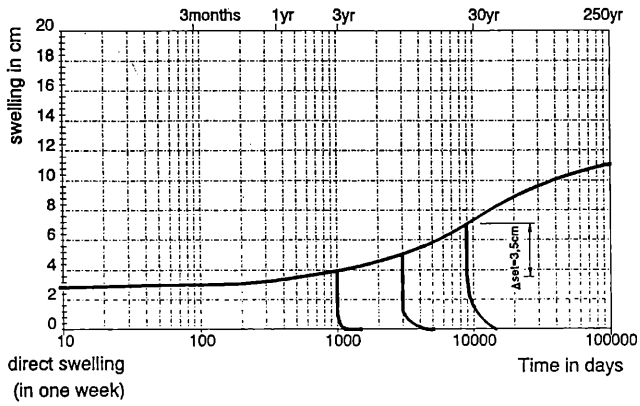


Figure 8: Progression of vertical deformation over time

Settlement of the construction pit base as a result of tunnel construction

After some swelling of the subsoil has occurred, at a certain time a load, in the form of the tunnel, will be reintroduced which will cause settlement to occur. The criterion in the recommendations concerned is for the time being that the loading should not be greater than the ground stress present before the excavation. The extent and the speed at which this settlement process occurs is dependent on the actual reloading moment.
This progression is shown in Figure 8.
From this progression it is apparent that overall account must be taken of a settlement of 3.5 cm which will occur virtually immediately.
As already stated, the whole station island is also still undergoing sagging of 1 to 2 cm every 100 years due to the continued occurrence of other effects as a result of the area being filled in in 1870.

Swelling forces on piles and walls

If piles pass through a swelling layer, this layer will, through its swelling, exert an upwards force on the piles. This swelling force must be regarded as a load on the pile.
The swelling force which occurs is calculated as follows:

$F_{swel:max} = \alpha . q_{c\ for} P.l$

in which:

$F_{swel:max}$	=	maximum swelling force
α	=	swelling factor, dependent on pile type and type of ground
$q_{c\ for}$	=	average cone resistance for excavation
P	=	pile profile
l	=	length over which swelling occurs

The criterion used in the calculations is that the swelling force is fully mobilised for a displacement of approx. 5 cm.
Since in the case in question the swelling which occurs is approx. 3.5 cm (see Figure 9), the maximum swelling force should not occur. The mobilised swelling force was determined with the use of Figure 9.

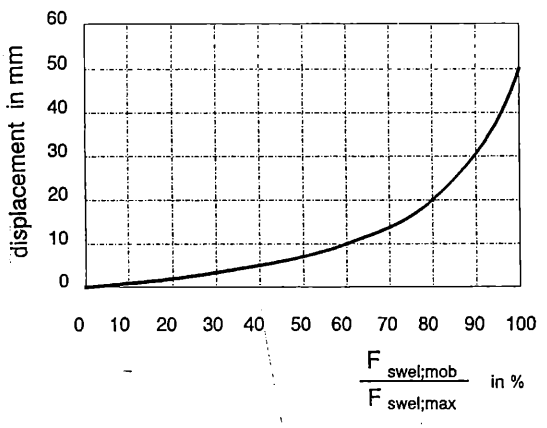


Figure 9: Mobilised swelling force as a function of displacement.

From this, the maximum occurring swelling forces on any mid-support point are estimated and given in Figure 10. For the piles a stand-alone pile is assumed for the time being. The swelling force which occurs for piles in a group may be less.

Pile type	F_{swel}
Tubex pile	2900 kN
Diaphragm wall	2500 kN/m'

Figure 10: Swelling forces arising at the mid- support point.

As already stated, these forces must be taken into account on the loading side. Assuming a partial loading factor of 1.0, the calculated F_{swel} is given as $F_{swel;calc}$. This leads to the following forces at the mid support points.

$F_{1,calc}$ = (pile own wt. + perm. load); $_{calc}$ = 1550 kN

$F_{2,calc} = F_{swel;calc}$ = 2900 kN

$F_{3,calc}$ = Pos. friction; $_{calc}$ = 750 kN

It may be concluded that for the mid-support points there is a resulting force on the pile directed upwards of 1350 kN. This must be absorbed through the positive friction developed in the sand, but this is not possible. The piles will therefore want to rise. This displacement will in principle be between 0 and 3.5 cm. The upwards displacement may possibly be compensated for by means of a screw jack construction on the head of the pile. If a diaphragm wall is used as mid-support point and at the location of the construction pit wall, the swelling force that occurs is less than the force directed downwards.