THREE DIMENSIONAL GROUND DEFORMATION ANALYSIS OF DEEP EXCAVATION ADJACENT TO RAILWAY EMBANKMENT IN THE CITY OF ROTTERDAM

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ABSTRACT

In Rotterdam, the Netherlands, the new RandstadRail underground line is going to be built in the period 2004 - 2008. Approximately two-third of the 3.0 km long Statenweg route will be constructed using tunnel-boring techniques. The remaining part is built in deep conventional excavations (depth around 20 m), which are also used for line-up and dismantling of the tunnelling equipment. This paper highlights some of the geotechnical calculations as performed during the engineering of the excavations near the Rotterdam Centraal station railway yard. Special attention has been paid to the ground deformations of the railway yard embankment that are expected to occur during the excavation works, as very strict tolerances apply to railtrack position and elevation.
Modelling of the excavation geometry for one- and two-dimensional geotechnical calculations revealed that quite a number of simplifications had to be made on following aspects: surface profile (embankment vs. street elevation), varying distance between excavation and embankment, supporting effect of perpendicular diaphragm walls, more or less independent behaviour of diaphragm wall sections, etc.. It has therefore been decided to perform additional three-dimensional computations. The selected software (Plaxis 3D) provided sufficient possibilities to account for all kinds of asymmetry within the geometry. Verification of the Plaxis 3D results was done through evaluation of the calculation results for a one-dimensional geometry by 1D-, 2D- and 3D calculation tools. The results from the 3D calculations show some typical features of soil behaviour, such as arching effects. The ground deformations on the railway embankment as derived from the output data have been used in the official procedures for obtaining permission for working close to, and partly on, terrain owned by railway company ProRail.

RANDSTADRAIL IN ROTTERDAM

In Rotterdam, the Netherlands, the new RandstadRail underground line is going to be built in the period 2004 - 2008. After completion it will provide connections from the centre of Rotterdam to the towns and cities in northern direction: a.o. Den Haag and Zoetermeer. RandstadRail will be linked to the terminal station of the existing Erasmus underground line, which is located in the vicinity of the Rotterdam Centraal railway station. On October 28, 1999, local authorities have decided on the preferred routing of the RandstadRail line on Rotterdam territory, known as the "Statenwegtracé, variant 2". Approximately two-third of the 3.0 km long Statenweg route will be constructed using tunnel-boring techniques. The remaining part is built in deep conventional excavations (depth around 20 m), which are also used for line-up and dismantling of the tunnelling equipment. This paper highlights some of the geotechnical aspects involved in the design of the excavations near the Rotterdam Centraal station railway yard.

EXCAVATIONS NEXT TO RAILWAY EMBANKMENT

Relatively deep excavations are required at the Conradstraat, near Rotterdam Centraal railway station. Here, the arrival of the tunnel boring machine (TBM) is planned. The location and dimensions of the excavations are mainly determined by limitations related to tunnelling in soft soil conditions, existing buildings and infrastructure, future connection to Erasmus underground line, and general specifications for underground railway design (a.o. slope inclination). As illustrated on Figure 1, the excavations will be located very close to the railway yard. At some points the distance to the nearest railway track is about 5 meters only. Terrain conditions are: Conradstraat street level at NAP -0.3 m, railway yard elevation at NAP +3.0 m. An impression of the local site conditions is shown on Figure 2 (camera positions as indicated on Figure 1).

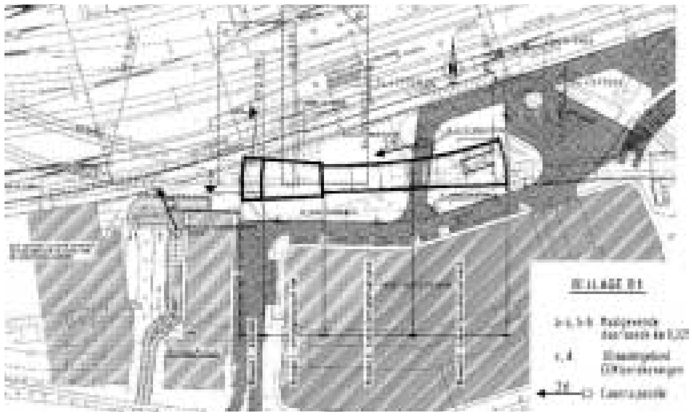

Figure 1: General location plan.

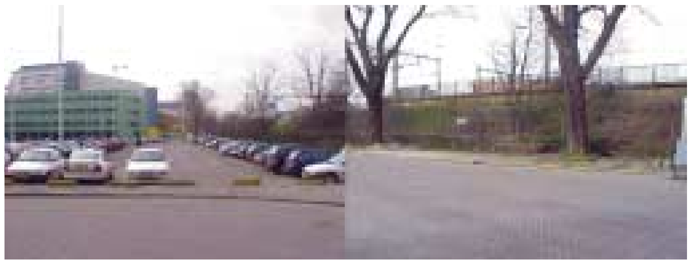

Figure 2: Site impression photographs.

Following excavations are described in detail in this paper:

Excavation (reference coordinates)	Length x Width	Excavation depth (*)	Struts	Remarks
I-west (km 0.220 to km 0.230)	10.0 m x 20.0 m	NAP -19.1 m	NAP -2.0 m	Submerged excavation; water level @ NAP -0.5 m
I-east (km 0.188 to km 0.220)	30.0 m x 17.5 m	NAP -16.8 m to NAP -18.3 m	NAP -1.0 m NAP -7.5 m NAP -13.5 m	Dry excavation

(*) NAP: reference elevation

The retaining wall has been designed as a reinforced concrete diaphragm wall down to NAP -42.5 m with thickness 1.50 m. Additional anchoring is used on the railway embankment side in order to counteract the ground pressure driving force. Cross section drawings of the excavations are presented on Figures 3a and 3b.

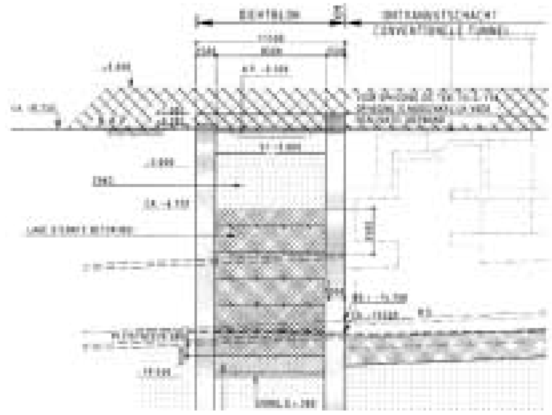

Figure 3a: Cross section a-a.

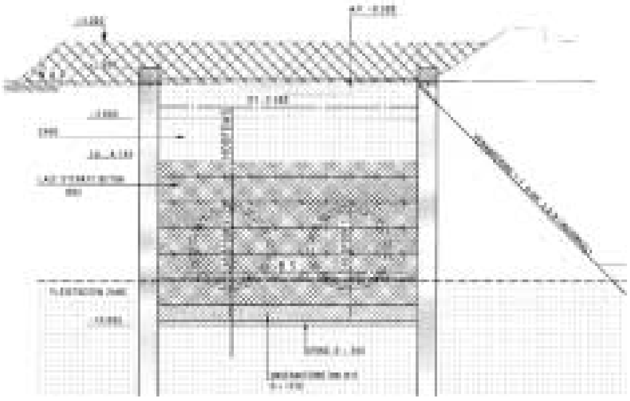

Figure 3b: Cross section b-b.

GEOTECHNICAL ANALYSES REQUIRED

Special attention has been paid to the ground deformations of the railway yard embankment that are expected to occur during the excavation works, for following reasons:

1. Obtaining permission for working close to, and partly on, terrain owned by railway company ProRail;
2. Anticipating on remedial levelling activities on the railway yard, as very strict tolerances apply to railtrack position and elevation.

Initially, one-dimensional calculations were performed for the structural design of the diaphragm wall. These analyses are not sufficient to determine ground deformations at the railway tracks on the embankment. Therefore, two-dimensional finite element calculations are required to find the ground deformations at varying distance from the retaining wall. In this particular case, additional three-dimensional finite element calculations were executed to account for all kinds of asymmetry.

MODELLING OF GEOMETRY

Modelling of the excavation geometry for one- and two-dimensional geotechnical calculations revealed that quite a number of simplifications had to be made on following aspects: surface profile (embankment vs. street level), varying distance between excavation and embankment, supporting effect of perpendicular diaphragm walls, more or less independent behaviour of diaphragm wall sections, interaction between excavations, etc.. It has been decided to use three-dimensional computations to account for these features. The selected software (Plaxis 3D) provided sufficient possibilities for modelling of the geometry; building the model and performing the analyses appeared to be rather time consuming, however. The 3D analysis has been split into two parts denoted 'c' and 'd' for practical reasons (hardware limitations), as shown on Figure 4. The diaphragm wall is assumed to be in place at start of the calculations. Length of the diaphragm wall sections are 2.9 m and 0.1 m. The 0.1 m sections, having very low strength properties, are located between each pair of 2.9 m sections to simulate the reduced interaction effect between the longer elements.

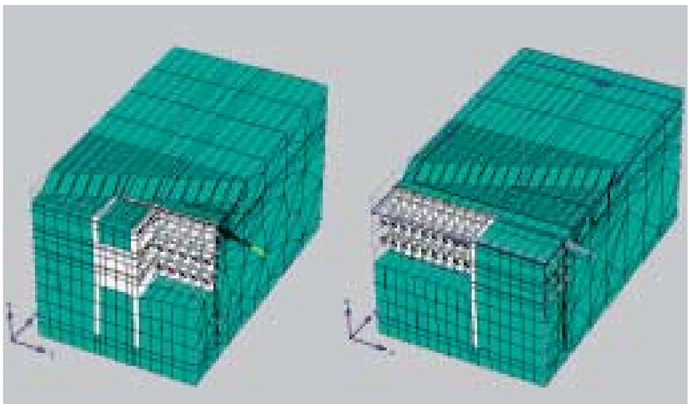

Figure 4: 3D finite element analyses model geometry.

ROTTERDAM SOIL DATA

General soil conditions at the site, which are typical for the Rotterdam region, are as follows:

Elevation (NAP m)					Water pressure
from:	to:	Origin - Type of soil	ϕ' (deg)	c' (kPa)	head (NAP m)
-0.3 (surface)	-4.5	fill - sand	25.0	0.0	-1.6
-4.5	-5.5	Holocene - clay	18.0	8.0	
-5.5	-8.0	Holocene - peat	12.4	10.0	
-8.0	-17.0	Holocene - clay	16.6	10.0	
-17.0	-35.0	Pleistocene - sand	27.2	0.0	-2.4
-35.0	-37.5	Kedichem - clay	18.0	8.0	
-37.5	-40.0	Kedichem - sand	26.4	0.0	-2.4
-40.0	-41.0	Kedichem - peat	13.0	3.5	
-41.0	-44.5	Kedichem - loam	24.5	4.0	
-44.5	-45.0	Kedichem - sand	26.4	0.0	-2.4
-45.0	-50.0	Kedichem - loam	24.5	4.0	
-50.0	....	Kedichem - sand	26.4	0.0	-2.9

The data coming out of the extensive RandstadRail laboratory testing programme have been used to determine the required input parameters for the geotechnical calculations.

1D VERSUS 2D VERSUS 3D ANALYSIS - VERIFICATION OF RESULTS

The one-dimensional analyses as used for the structural design of the diaphragm wall have been performed using MSheet software. An iterative solution procedure was followed to account for the dependency of the wall stiffness (reinforced concrete) on the bending moment. For verification of the calculation models, the same one-dimensional geometry has been analysed using both Plaxis 2D and Plaxis 3D software. For comparison, the horizontal displacements as derived from the MSheet analysis are shown next to the Plaxis output data in Figure 5a (Plaxis 2D) and Figure 5b (Plaxis 3D). The maximum values as determined from the analyses are as follows:

Analysis	Location (ref. Fig. 1)	u_{max} (@ elevation)	Soil model	Software (version)
1-D	b - b	63 mm (NAP -13.6 m)	Mohr-Coulomb bi-linear springs	MSheet (5.4.8.2)
2-D	b - b	89 mm (NAP -13 m)	'Hardening Soil'	Plaxis 2D (8.1.2.109)
2-D	b - b	64 mm (NAP -13 m)	'Hardening Soil'	Plaxis 3D Tunnel (1.2.1.211)

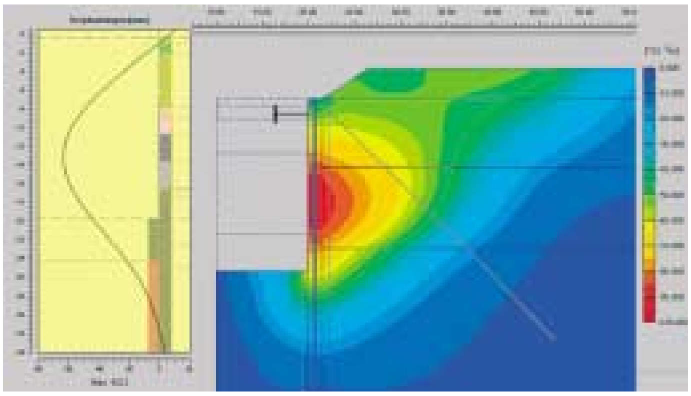

Figure 5a: Model verification - One-dimensional geometry analysis MSheet (1D) vs. Plaxis 2D.

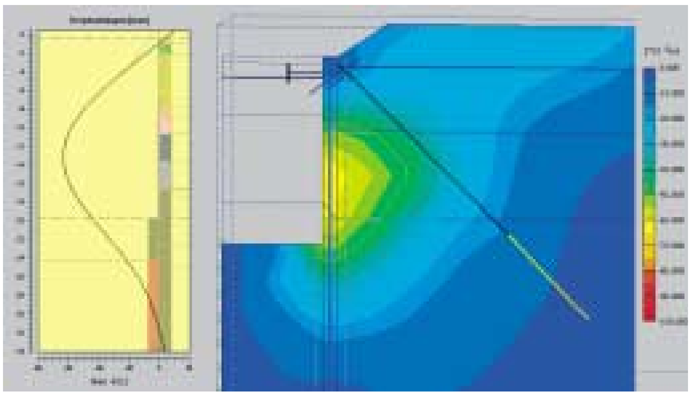

Figure 5b: Model verification - One-dimensional geometry analysis MSheet (1D) vs. Plaxis 3D.

The two-dimensional analyses result in horizontal ground deformations at location b - b (Plaxis 2D: 89 mm and Plaxis 3D: 64 mm) which are in the same order of magnitude compared to the one-dimensional analysis (MSheet: 63 mm). This gave sufficient confidence to proceed with full 3D analysis of the complex asymmetrical geometry. Further interpretation of the three-dimensional analysis results is discussed below.

FULL 3D CALCULATION RESULTS - SPECIAL FEATURES

The horizontal displacements in model x-direction as calculated by the three-dimensional Plaxis 3D analyses are shown on Figure 6. Following aspects from the full 3D analysis results are highlighted:

- Consequences of analysis split into part 'c' and 'd'.
  It is noted that the displacements towards the edge of the model are affected by the boundary conditions. The influence area of the boundary conditions appears to be different for each analysis, due to the variation of excavation geometry. Careful evaluation and interpretation of this aspect is very important, as to obtain a reasonable combination of output data coming from both analysis parts.
- Diaphragm wall behaviour.
  As intended, each diaphragm wall section along the railway yard is supported only by anchors and struts, and does not get any significant support from adjacent sections. As a result, direct support due to presence of the perpendicular wall is limited to just one diaphragm wall section only.
- Arching effect.
  The arching effect around the excavations is clearly visible on the displacements plots. Locally, the supporting effect due to the perpendicular diaphragm walls has a major influence as well.
- Horizontal displacements of diaphragm wall.
  For comparison, the maximum values as determined from the Plaxis analyses of the 2D- and 3D-geometry are as follows:

Analysis	Location (ref. Fig. 1)	u_{max} (@ elevation)	Soil model	Software (version)
2-D	b - b	64 mm (NAP -13 m)	'Hardening Soil'	Plaxis 3D Tunnel (1.2.1.211)
3-D	b - b	21 mm (NAP -12 m)	'Hardening Soil'	Plaxis 3D Tunnel (1.2.1.211)

  The arching effect is considered to be the main reason for the large reduction of the calculated horizontal displacements when comparing the outcome of the 2D- and 3D-geometry analysis. The three-dimensional analysis of the geometry at location b - b results in horizontal deformations which are 65% less (21 mm vs. 64 mm) than the two-dimensional analysis.
- Railtrack deformations.
  The deformations of the railtrack on the embankment have been derived through processing of all (!) data points of the Plaxis geometry. The relevant points were found by selecting those with y-coordinate +3,0 m (embankement surface elevation). The vertical displacements of these data points have been put on drawing as presented in Figure 7. Another selection has been made where x-, y- and z-coordinate had to match with the railtrack line coordinates. The horizontal deformations perpendicular to the railtrack were calculated from these points as presented on Figure 8.

EPILOGUE

Dutch railway company ProRail is expected to provide a formal statement of no objection to the planned excavation works at the Conradstraat site by november 2003, after evaluation of technical information including the railway yard embankment deformations as described in this paper. The results of the described geotechnical analyses have also been used to optimise the funds reservation for the anticipated remedial railtrack levelling works. Start of the building activities is expected before end 2003. Extensive monitoring of railtrack and ground deformations in the vicinity of the building pit will be performed during the excavation works.

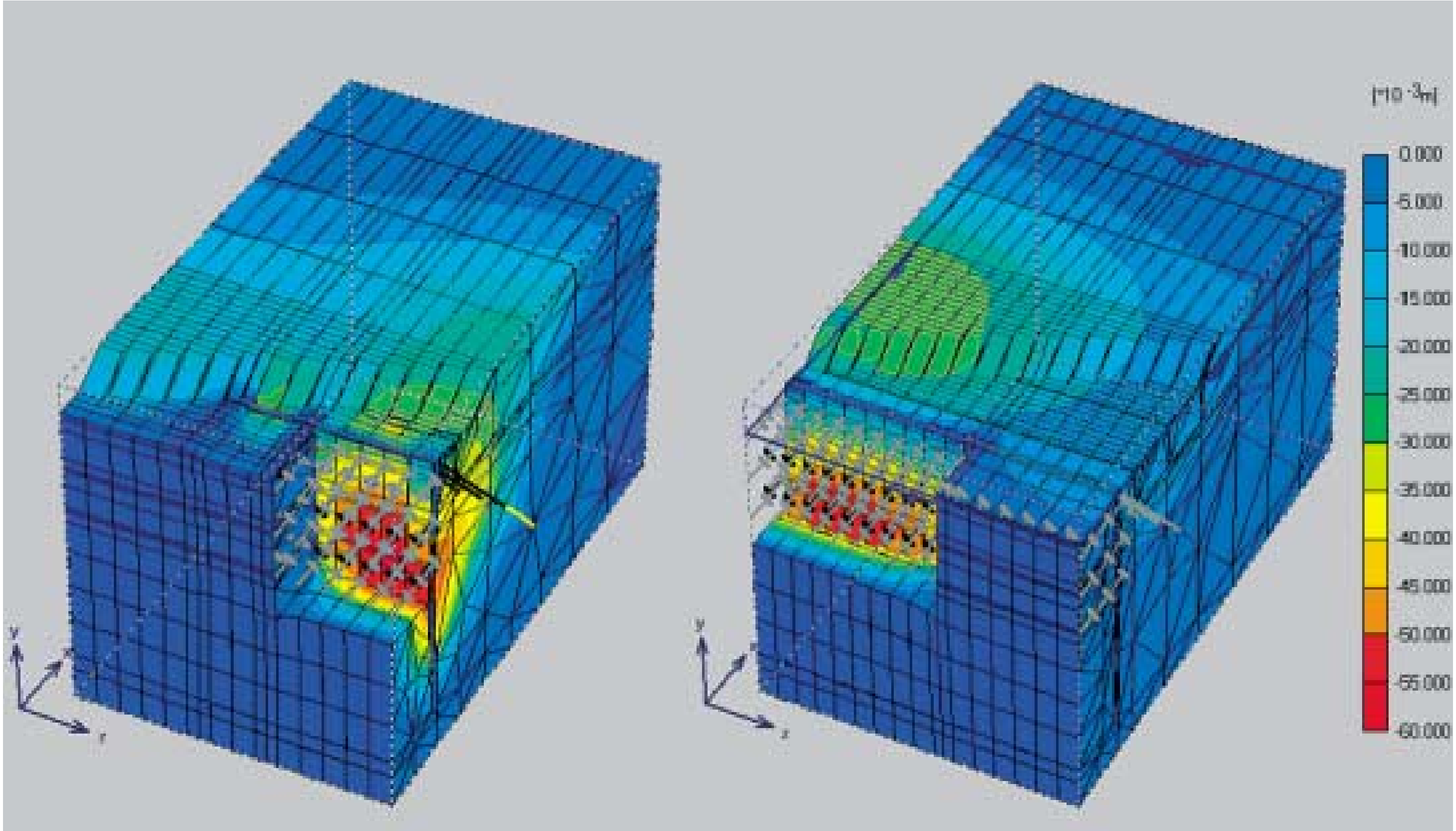

Figure 6: Horizontal deformations around excavation I-west and I-east (3D analysis results; model x-direction).

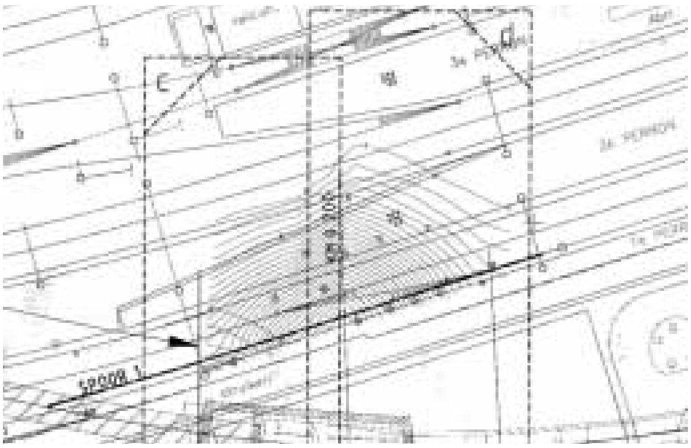

Figure 7: Vertical deformations on railway embankment (3D analysis results).

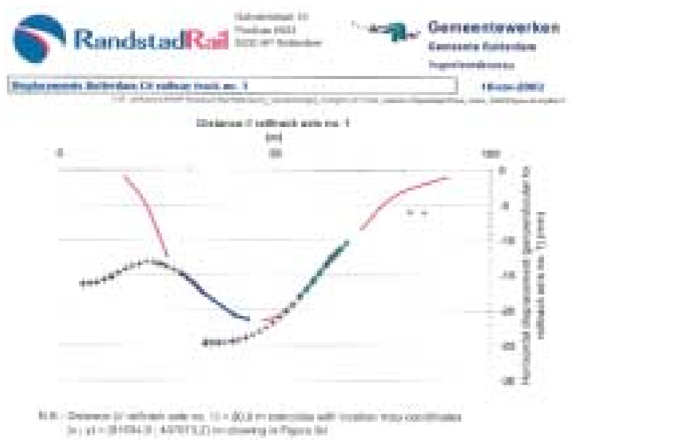

Figure 8: Horizontal railtrack deformations (perpendicular to railtrack axis).