High Speed Railway Link South: on the horizontal move

Horizontal displacements of a concrete U-shaped cutting near Rotterdam

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Summary

Due to the deformations of the subsoil caused by an embankment, a concrete U-shaped cutting for the high speed railway link, which is founded on piles, will displace horizontally. To ensure that the structure will remain within the tight deformation requirements defined by the HSL organisation, a calculation procedure was developed using 2D and 3D F.E.M. calculations.

Keywords: settlement, F.E.M. method, horizontal displacements, bending moments, soft soil, cutting

1. Introduction

In the area north of Rotterdam over a distance of 3 km, the High Speed Railway Link (HSL) Amsterdam – Antwerp is built in a reinforced concrete U-shaped cutting or channel structure at 3 m below groundlevel (figure 1). Horizontal movements of the structure, due to vertical and horizontal deformations of the subsoil below an embankment near the structure might be in conflict with the tight deformation restrictions for the HSL.

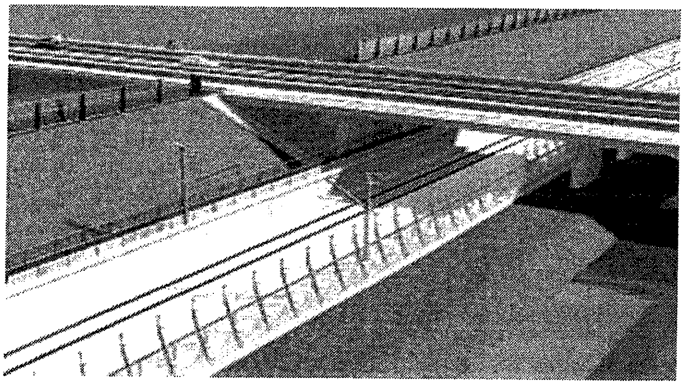

Fig. 1 Artist impression of the U-shaped cutting

2. Situation

The cutting, with a total length of 3 km and an internal width of 11.7 m, consists of two parts. The main part of the cutting is built at 3 m below groundlevel; the rest of it is built at 6 m below groundlevel. The structure will be founded on prefab concrete piles ø450 mm piles with pile tip elevations at 20 to 25 m below groundlevel. The total structure is divided into coupled sections of 35 m between the expansion joints.

At a distance of 3 m from the structure, an embankment is constructed as a noise barrier and as a landmark (figure 2). The embankment will be built up in four phases to a height of 7 m. After consolidation, the front slope of the embankment is designed 1:2. The back slope of the embankment will be placed after finishing the concrete structure of the cutting.

The subsoil varies along the structure and generally consists of 9 m soft clays and peat overlying Pleistocene sands.

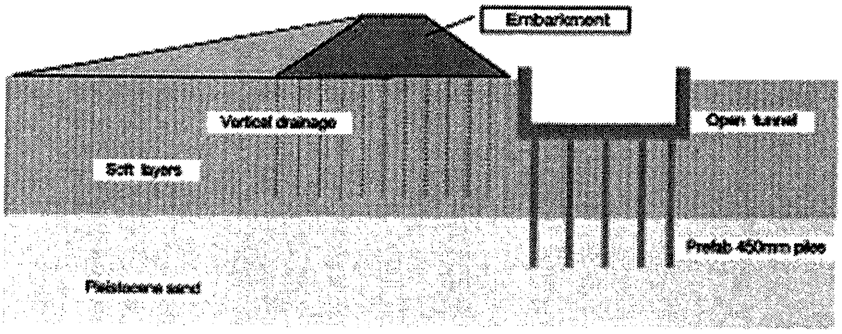

Fig. 2 Cross section of the cutting and embankment

3. Horizontal deformation criteria

The HSL organisation [the client] has defined very strict requirements for the horizontal movements of the structure and the track, which are fixed to the cutting floor because of the comfort of the passengers and to limit the maintenance of the track. The requirements are as follows:

- a maximum deformation of 10 mm over 100 years or
- a very small rotation of less than 1 in 2000, which allows 17,5 mm displacement over a 35 m section.

4. Problem definition

The construction sequence and the stratigrafy of the subsoil will have consequences for the cutting. Horizontal deformations due to primary and secondary settlements below the embankment will occur, causing:

- horizontal deformations of the structure and the track
- high horizontal groundpressures on the wall near the embankment (not included in this article)
- bending moments in the piles
- forces in the coupling elements between the sections

Because of the complex situation (an embankment next to the concrete structure, the construction sequence and the strict requirements), a correct understanding of the above phenomena is very important.

5. Finite element analysis

The contractor has to demonstrate that the structure will remain within the requirements defined by the HSL organisation. Therefore, an analysis procedure was set up to calculate horizontal deformations over a period of 100 years.

To be able to determine the displacements of the soil and the structure and to take into account the interaction between the soil and the structure, the F.E.M. computer programme PLAXIS was used. Hence, it was possible to determine the time-dependent behaviour of the soil in terms of primary and secondary settlements by using the Soft Soil Creep model. Firstly, an analytical model with the well-known consolidation theory of Koppejan was used to determine vertical primary and secondary displacements caused by the embankment. This "Koppejan" settlement analysis was executed because of the large experience with the model and its parameters. Secondly, the results of this exercise were translated to parameters for the Soft Soil Creep model.

Within the 2D PLAXIS model, piles are simulated as walls of infinitive length. Therefore, to determine the deformation of the piles and the movement of soil between the piles, the PLAXIS 3D programme was used. Unfortunately, the 3D version cannot take into account the consolidation process, thus being restricted to drained analysis only.

The following steps have been performed to determine the horizontal deformation for each selected cross-section:

Step 1: Analysis of vertical primary and secondary settlements using conventional settlement analyses (no structure included). The soft soil creep parameters λ^*, κ^* en μ^* for the PLAXIS 2D and 3D model were derived by matching the PLAXIS 2D results with the "Koppejan" settlement analysis on the primary and secondary settlements.

Step 2: Drained analysis of the structure in the PLAXIS 3D model (figure 3). The 3D model was used to determine the horizontal movements of the cutting and the behaviour of soil around the piles, based on the calibrated parameters. The bending moments in the piles are also determined with the 3D model.

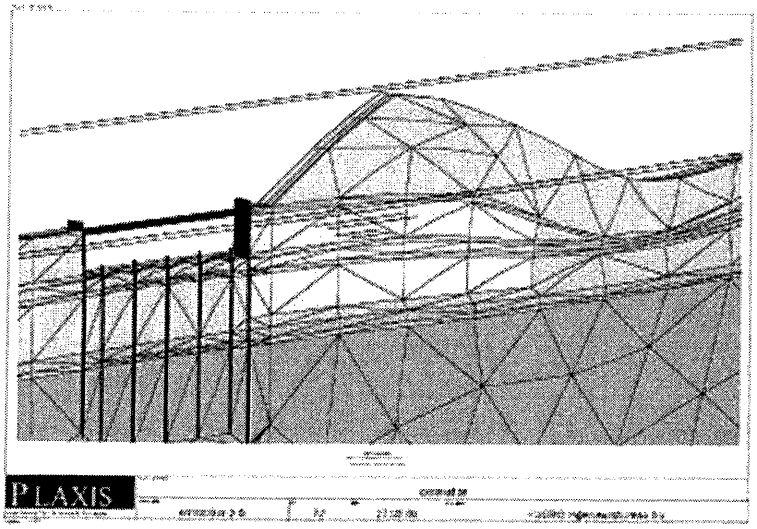

Fig. 3 PLAXIS 3D mesh

The PLAXIS 3D model takes into account the complex soil-structure interaction, which includes the mechanisms:

- Horizontal groundpressures on the walls of the concrete structure;
- Horizontal pressure on the piles;
- Flow of the soil between the piles.

It depends on the stratigrafy of the subsoil and geometry which of the above mentioned mechanisms is dominant.

Step 3: In the 2D simulation piles are modelled as walls of infinitive length. The stiffness of the piles is modelled in two ways (figure 4).

- Before building the concrete floor, piles are standing alone and are not coupled. The stiffness of the pile has to be spread out over the influence width. Within this area, interaction between pile and soil will appear. The influence width can be calculated as a multiplication of the pile diameter and the so-called "shell-factor". For this factor (Menard) a value of 1.8 was adopted.
- After building the concrete floor, the piles are coupled and behave as one structure. The stiffness of the piles in this situation normally is calculated by dividing the stiffness by the distance between the piles. However, when this procedure is followed during a 2D drained analysis, the results of the 2D drained simulation differ significantly from the results of the 3D drained analysis. The stiffness of the piles in the 3D simulation seemed to be less than the piles in the 2D calculation. To fit the horizontal displacement in the 2D drained to the 3D drained calculation, a so-called model factor was introduced. This factor was subsequently used in the undrained analysis. Thus, the stiffness of the "wall" in the 2D calculation was determined by dividing the stiffness of an individual pile by this model factor.

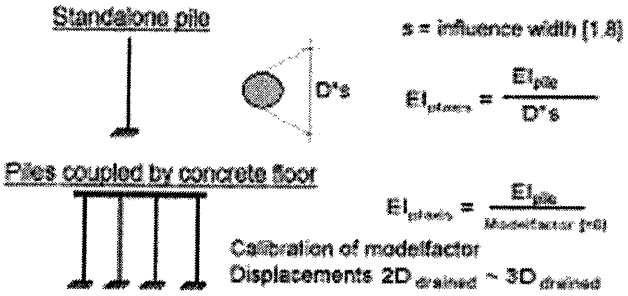

Fig. 4 Influence width and model factor

Step 4: Undrained analysis of the structure in the PLAXIS 2D programme. In this run, the stiffness of the piles was determined by using the model factor of step 3. The results of this run in terms of horizontal displacement of the track have to be checked with the requirements defined by the HSL organisation.

Step 5: Sensitivity analysis. In this analysis, the steps 1 to 4 were repeated with 30% higher and lower values of the analytical consolidation parameters to test the sensitivity of the model to more favourable or unfavourable properties of the subsoil. The results of these analyses showed a range of +/- 20% in horizontal displacements of the structure.

After calculation of the horizontal displacements for each 35 m section, the results were used as an input for a "beam on elastic foundation" calculation. From this "chain line" calculation the relative displacements of the 35 meter sections and the coupling forces between these sections were determined.

6. Results

For one cross-section, the procedure mentioned above is worked out in detail. This cross section is approximately 3 m below groundlevel.

Step 1 is the calibration of the PLAXIS Soft Soil Creep parameters to the analytically derived settlements.

Step 2, 3 and 4 are the 2D and 3D finite element calculations. The results of these steps are summarised in table 1. For this cross section, a model factor of 5 was necessary to give the 2D drained analysis the same results as the 3D drained analysis. This value of the model factor was used in the 2D undrained analysis.

Three phases were considered:

- Completion of the structure and hand-over to the infraprovider
- 25 years after completion (lifetime of the track system)
- 100 years life time period of the structure

Table 1: horizontal displacements [mm]

	3D drained		**2D drained**		**2D undrained**	
	total	**Additional**	**total**	**additional**	**Total**	**Additional**
completion	7,6		14,8		29,2	
25 years	22,2	14,6	25,8	11,0	38,2	9,0
100 years	23,2	15,6	31,0	16,2	44,1	14,9

The last step was the sensitivity analysis based on a 30% range of the Koppejan primary and secondary settlement parameters. For this cross-section the range found in the horizontal displacements of the structure and the track was 14,0 to 18,3 mm in 100 years period.

7. Chain line

Based on aspects as the stratigrafy of the subsoil, geometry (depth of the cutting, geometry of the embankment and construction sequence) more than twenty cross-sections were analysed with PLAXIS 2D (undrained calculation) including the model factor. As a result of the differences along the cutting and the use of coupling between the sections, the structure will behave like a chain line of various 35 m sections (being the distance between the expansion joints). Using the horizontal displacements of each section and horizontal equivalent springs, a "beam of elastic foundation" type of analysis was performed to determine the actual displacements of the sections and the shear forces of the joints. Nominal displacements of 30 mm maximum have been calculated. The result of this analysis is presented in figure 5.

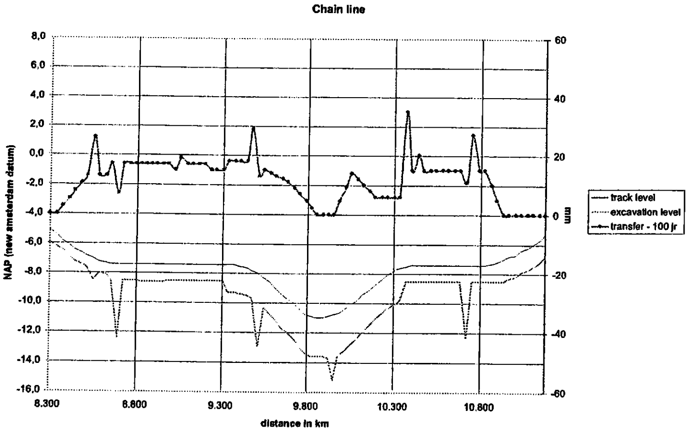

Fig. 5 Chain line

The coupling between the sections should allow for the expansion of the sections in longitudinal direction and for the small rotation of the sections due to the “chain line”, but should limit the horizontal differential displacements at the coupling to 0.6 mm. From the evaluated concepts, a concrete dowel structure as shown in figure 6 was selected. Sliding plates of UHMWPE material have been attached to the sides of the pin and recess of the dowel structure. This material has a high stiffness (approximately 1 GPa in compression) and a very low friction ratio (0.1 to 0.2). A plate of 230*180 mm is capable of transferring a horizontal force between the sections of approximately 600 kN. The expected differential displacement between the sections is expected to be less than 0.2 mm.

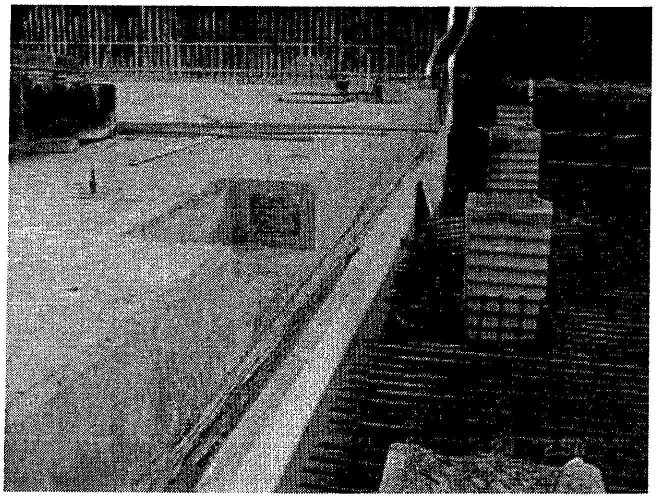

Fig. 6 Dowel structure

8. Conclusions

For the HSL cutting in Bergschenhoek, various F.E.M. calculations were carried out with 2D and 3D PLAXIS. The 3D analyses are time consuming and complex; therefore for most sections a 2D calibrated PLAXIS model had been applied. The calibrated 2D model was suitable to calculate the horizontal displacements in time. However, to predict reliable bending moments in the piles the 3D model was necessary to take into account the complex pile-soil-pile interactions.

On the basis of the results of the time-dependent soil-structure interaction analysis, it was concluded that the differential displacements of the 35 m sections of the cutting remain within the requirements.

The bending moments in the piles are in the order of 150 kNm, which can be taken by the prestressed concrete piles, which are fixed, into the concrete floor.

The conventional methods for computation of settlements and horizontal displacements should always be used to verify or to calibrate the complex 2D and 3D analyses. Also the sensitivity of the model should be verified.

Although the horizontal displacements calculated for the lifetime of 100 years remain within the requirements defined for the concrete structure of the cutting, the Infraprovider (the party responsible for the track system) could not accept the predicted displacements in view of the required track maintenance and passengers comfort. Therefore the HSL organisation decided to move the embankment over a distance of 22 m further away from the cutting, thus reducing the overall horizontal displacement to less than 5 mm.