Phased calculation of stresses and displacements due to tunnelling the Botlek Railway Tunnel in the Netherlands

Calcul phasé des constraints et deplacements dus au creusement du Tunnel de Botlek aux Pays Bas

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ABSTRACT: In the Netherlands two pilot projects, The Second Heinenoord Tunnel and the Botlek Railway Tunnel, for tunnelling in soft soil are almost completed. Under authority of the Centre for Underground Construction (COB; Gouda) those projects were extensively monitored. In this abstract, a phased numerical analysis and modelling of stresses and displacements due to tunnelling at the Botlek Railway Tunnel will be discussed, including a finite element model to predict the settlements due to tail void grouting. In six cross sections the settlements on the surface together with deformations along a vertical line were measured in the underground. For cross section MQ4 an extensive set of predictions was made. The results are compared with the measurements which followed up the predictions.

RESUME: Il y a deux projets pilotes aux Pays-Bas pour forer dans des sols mou, le deuxième tunnel Heinenoord et le tunnel du chemin de fer Botlek, qui sont pratiquement terminés. Sous la direction du Centre de Construction Souterrain (COB; Gouda) ces projets furent très largement suivis. Dans ce résumé, une étape d'analyse et de modélisation de charges et de déplacements, dus au creusement du tunnel du chemin de fer Botlek, sera discutée, intégrant un modèle d'éléments finis afin de prévoir les tassements dus au *tail void grouting*. A six intersections, les tassements de la surface avec les déformations le long d'une ligne verticale, ont été mesurées dans le sous sol. Pour l'intersection MQ4, une plus large série d'hypothèses plus détaillé a été composé. Ces résultats seront comparés avec les mesures qui suivent le plan d'hypothèses.

1 INTRODUCTION

In the Netherlands, two interesting pilot projects have been set up concerning shield tunnelling in soft soil. The research programme and monitoring are executed under supervision of the Centre of Underground Construction (COB) with the co-operation of the participants of this centre.

The first project, The Second Heinenoord Tunnel with a hydro-shield, was successfully completed. The second pilot project, the Botlek Railway Tunnel is now under construction, using an earth pressure balance shield. Recently, the second of two tubes of this railway tunnel has been successfully completed.

The main objective of these pilot tunnelling projects is to obtain more experience with this construction technique in typical Dutch soil conditions. In a great part of the Netherlands the soil conditions are characterised by a high phreatic plane and a very low stiffness of the soil layers.

1.1 *Research programme for the Botlek Railway Tunnel*

In the second pilot project, the COB research programme at the Botlek Railway Tunnel K300 focuses on the following five main items:

1. Tunnelling technology;
2. Grouting process and control;
3. Interactive process control and effect (deformation) monitoring;
4. Cross passages;
5. Dynamic behaviour and vibrations.

In this paper the second item, grouting process and control, will be described. All knowledge from the first project, The Second Heinenoord Tunnel, is used at the second project.

1.2 *Aim of the phased calculation of stresses and displacements*

It is still difficult to predict stresses and displacements in the underground due to tunnelling. In this research programme the focus is on measurements of grouting pressures in the tail void, displacements, stresses and settlements and in particular to find a relationship between those parameters. One can imagine that the importance of these predictions is of high value for tunnelling, particular in urban areas and in the future the gained insight can be very useful when e.g. the North/South Metroline in Amsterdam will be constructed.

In committee L500 of the COB (Van Jaarsveld, 1999) this relation was investigated and resulted in a phased calculation of stresses and displacements due to tunnelling in soft soil. In each tunnelling phase the settlements at the surface and the stresses and displacements of the soil body can be analysed by considering the incremental and total displacements using an FEM model.

In this study PLAXIS release 7.11 (Brinkgreve 1998) was used. In the fourth phase of calculation in this process it is possible to model different grout pressure distributions around the tunnel lining. In this way, a complete overview of the effects of the tunnel boring process, including the process of compensation grouting in the tail of the Tunnel Boring Machine (TBM), can be accomplished.

For six cross sections along the alignment of the tunnel calculations have been made. These cross sections are abbreviated to MQ1 to MQ6. MQ4 is the deepest part of the alignment. After those predictions, measurements were executed during the shield tunnelling of the Botlek Railway Tunnel.

1.3 *The Botlek Railway Tunnel*

The Botlek Railway Tunnel is the first large diameter shield driven tunnel with an earth pressure balance shield in the Netherlands and is part of the so-called "Betuweroute" which will connect the Port of Rotterdam with the German "Ruhrgebiet".

The tunnel runs underneath the river Oude Maas, it consists of two tubes with an external diameter of 9.5m; the length of this double stack railway tunnel is 1850m. The depth of the tunnel at MQ4 is NAP–18.0m (NAP, Nieuw Amsterdams Peil, is a reference level in the Netherlands). The toe of the tunnel is at NAP–27.5m. The axis is located on NAP-22.6m.

Table 1. Geotechnical parameters of soil investigation.

name	description of layer		γ_{dry}	γ_{sat}	φ'	c'	ν	ψ	K_0	E_{oed}*	E_{50}	k_x	k_y
		[m NAP]	[kN/m³]	[kN/m³]	[°]	[kN/m²]	[-]	[°]	[-]	[kN/m²]	[kN/m²]	[m/day]	[m/day]
0A	sand/clay	4,00	17	19	30	0	0,33	0	0,50	8000	5300	0,8640	0,8640
17	sandy clay (layered)	0,00	17	19	27,5	0	0,35	0	0,54	8000	5000	0,0086	0,0086
18/18A	holocene sand/clayey sand	-9,48	17	19	34	0	0,31	4	0,44	19000	14000	0,4752	0,0238
16/17	clay/sandy clay	-13,96	16	17	25	7,5	0,37	0	0,58	7700	4400	0,0044	0,0044
9/31	peat/sandy clay	-17,45	14	15	254	10	0,37	0	0,58	3750	2200	$8{,}64\ 10^{-4}$	$8{,}64\ 10^{-4}$
32	pleistocene sand	-18,32	19	20	35	0	0,30	5	0,43	54000	40000	10,368	25,920

*$E_{50}=E_{oed}(1+\nu)(1-2\nu)/(1-\nu)$

1.4 *Geotechnical conditions*

On the West side of the river Oude Maas, the tunnel is constructed in relatively stiff holocene sands and clay layers. Under the river Oude Maas, the tunnel is driven through pleistocene sands. On the East side, the soil consists of very soft holocene clay and peat layers (see Table 1). The potential head of MQ4 is NAP+0.24m.

1.5 *TBM and lining related aspects*

This TBM is an EPB shield. The outer diameter (without overcutters) is 9.755m. The mass of the TBM is 844 x 10^3kg and its length is 9.91m. The conicity of this TBM is 1%. Lining segments are 0.40m thick.

2 PREDICTIONS OF SURFACE SETTLEMENTS AND DEFORMATIONS

To predict and calculate the settlements at the surface and the stresses and deformations of the soil body, a phased calculation method was set up.
Every step during construction of the tunnel boring process (see Figure 1) can be modelled by the following method:

1. Initial phase: neutral stresses applied by the K_0 ratio. In this phase the initial stresses and water pressures are calculated.
2. Shield drive phase: displacements due to disturbing the soil by TBM face stability during shield drive.
3. Contraction phase: displacements due to modelled contraction of the TBM caused by the conicity of the TBM.
4. Grouting phase: displacements due to grouting of the tail void of the TBM. In current practice the grouting pressure is controlled by injecting a grout volume simular to the theoretical tail void. Injecting pressures and grout pressure distributions in the tail void are often unknown.

   Therefore four different scenarios have been established, see Figure 2 (Van Jaarsveld, 1999):

   I. At the top of the tunnel the pressure of the grout will be equal to the 100% of the total vertical stress of the soil. This pressure distribution will increase to the toe of the tunnel with the gradient of liquid grout (approx. 20kN/m³). This scenario represents a rather fluid grout which is injected through all injection points.
   II. At the top of the tunnel the pressure of the grout will be equal to 50% of the vertical stress of the soil plus the waterpressure. This pressure distribution will increase to the toe of the tunnel with the gradient of liquid grout (approx. 20kN/m³). The pressure of the injected grout is lower in this scenario.
   III. At the top of the tunnel the grout pressure will be equal to 100% of the total vertical stress of the soil. The pressure distribution will increase to the water pressure in the toe of the tunnel of the surrounding soil. In this scenario less fluid grout will be injected with a lower pressure than scenario I and II. Then due to pressure loss the pressure gradient is lower than the volume weight of the grout.
   IV. At the top of the tunnel de grout pressure will be equal to 50% of the total vertical stress of the soil plus the waterpressure. The pressure distribution will increase to the water pressure in the toe of the tunnel of the surrounding soil.
5. Buoyancy phase: due to uplift after passing of the TBM displacements by pore pressures occur;
6. Consolidation phase: in which the long term displacements are taken into account.

The first and last phase will be calculated in the finite element model as drained. This is a long term situation. All other phases will be calculated undrained, where only the sandlayers, due to the high permeability, are regarded as drained.

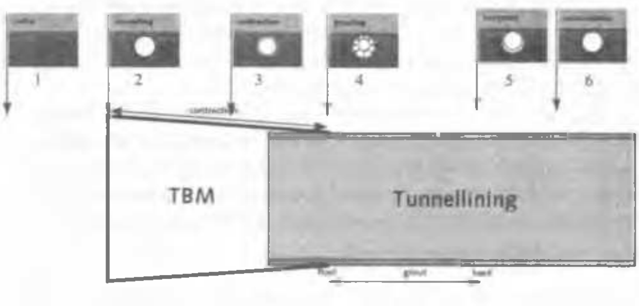

Figure 1. Scheme of the phased calculation of the tunnelling process.

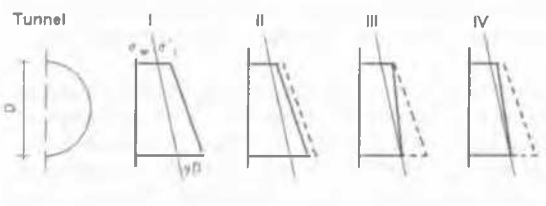

Figure 2. Grouting pressure distribution along lining.

3 APPLICATION OF THIS PHASED MODEL AT THE BOTLEK RAILWAY TUNNEL

First a set of predictions was made. Those calculations were made in the 2D finite element model PLAXIS release 7.11 (Brinkgreve 1998) with two material models: the Mohr Coulomb (MC) model and the Hardening Soil (HS) model for the cross section MQ4. This cross section is the deepest point of the alignment. This HS material model is specially developed for unloading situations like tunnelling. For this material model not all soil parameters were available from the geotechnical site investigation. Those parameters were derived by correlations.

3.1 *Finite element modelling*

To simulate the subsequent phases of tunnelling a 2D plane strain procedure with 6-node elements in the finite element code PLAXIS was carried out. The geometry of this mesh for the FEM model is height (2 x Diameter (D) + Soilcover (C)) and width is 3 (D + C) based on the relation of passive earth

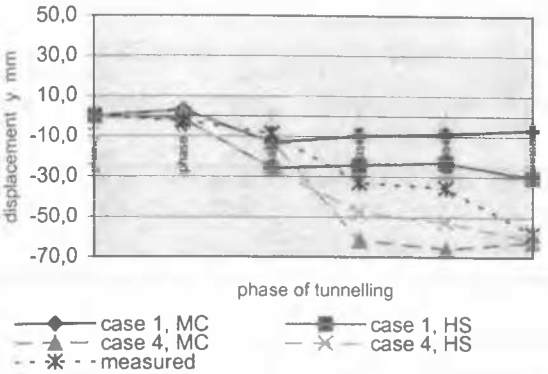

Figure 3. Vertical displacement versus phase of tunnelling Point A.

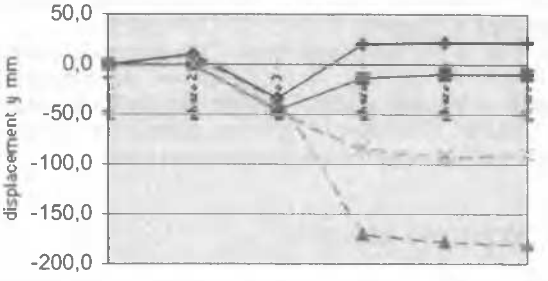

Figure 4. Vertical displacements versus phase of tunnelling Point B.

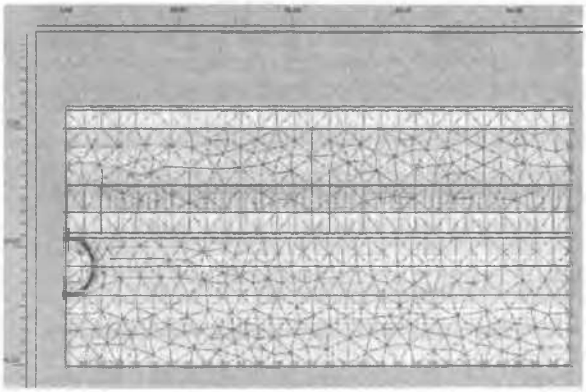

Figure 5. Mesh and soil layers of MQ4

pressure friction angle. Because of symmetry only half of the cross section is modelled. In this area all instrumentation was installed for monitoring the tunnel and no disturbing effects were expected along the edges of this finite element model.

The material models used for this analysis were the elasto plastic MC model and the HS model as implemented in this code of Plaxis. The lining elements are modelled as elastic beam elements with a very high stiffness. For the modelling of grout as a Newton fluid, a groundwater flow calculation was performed. Interface elements are assumed as elasto-plastic MC elements. The input for all different phases of the process was integrated into one model and the calculation took place for each phase resulting in a stepwise calculation of the entire process.

Evidently the analysis and modelling has some limitations. In this model no leakage or consolidation of grout and no effects of creep, shrinkage and thickness of the grout layer are taken into account.

The displacements at four reference points where A is at the surface, B at the top of the tunnel and D at the toe of the tunnel on the vertical axis and C on the horizontal axis.

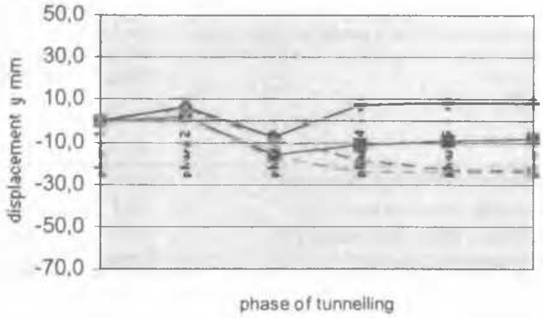

Figure 6. Vertical displacement versus phase of tunnelling Point D.

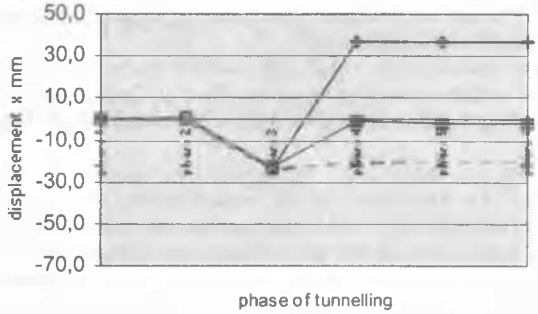

Figure 7. Horizontal displacement versus phase of tunnelling Point C

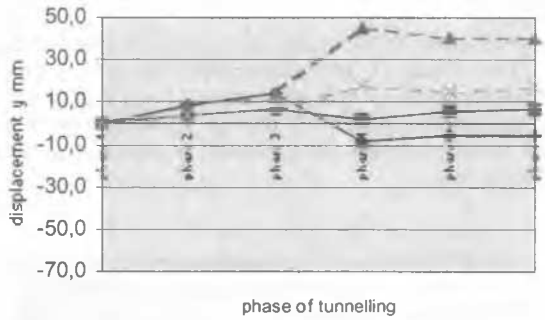

Figure 8. Vertical displacement versus phase of tunnelling Point C

3.2 *Predictions and measurements of MQ4*

Only cross section MQ4 is presented here. For surveyability only the extreme scenarios of grouting pressure (i.e. scenario I and IV) are presented.

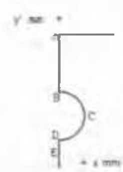

Figure 9. Outline of points at cross section MQ4.

4 DISCUSSION OF THE RESULTS

The calculations for each scenario results in similar curves for both material models. Until phase 3 a difference between the material models can be recognised clearly, generally by smaller displacements for the HS model.

The strongest influences at the surface (point A) in both models occur in the contraction and grouting phase.

Table 2. Calculated volume loss with Plaxis (HS material model) Negative means a lowering of the surface and positive means a heave of the surface. In the contraction phase a predefined contraction of the tunnel of 1% is assumed.

volume loss	boring	contraction	grouting		buoyancy		consolidation	
			scenario I	scenario IV	scenario I	scenario IV	scenario I	scenario IV
	%	%	%	%	%	%	%	%
incremental volume loss calculated	-0,15	-1,45	+0,14	-0,99	+0,06	-0,14	-0,84	-1,28
total volume loss calculated	-0,15	-1,60	-1,45	-2,58	-1,40	-2,72	-2,24	-4,00
incremental volume loss measured	-0,08	-0,62	-0,11		-0,59		-0,01	
total volume loss measured	-0,08	-0,70	-0,80		-1,39		-1,41	

The grouting phase shows a great variation in axial deformations along the lining (points B, C and D).

In point A, especially the grouting phase results in different predicted ranges of final settlements for both material models. With the MC model the range is roughly two times wider than with the HS model.

After grouting only small deformations occur and vertical displacements are similar for points B to D. Only at the surface different effects of the consolidation phase are not negligible.

When the results from the predictions for point A (see Figure 3) are compared with the measurements the similarity is generally well: the level of the settlement is within the predicted range. Only the settlement due to contraction (phase 3) is less than calculated and more settlement due to consolidation (phase 6) occurred. This results in a final settlement close to the prediction for scenario IV. An explanation for the different deformations calculated with both models is the higher unloading (and reloading) stiffness, which is characteristic for the HS model.

Figure 10 shows the settlement curves directly after boring (phase 5) and Figure 11 after consolidation (phase 6). Grouting pressure scenario I results in an about 2 times smaller settlement through than scenario IV. A more remarkable result is that the measured curves are considerably steeper than the predicted curves.

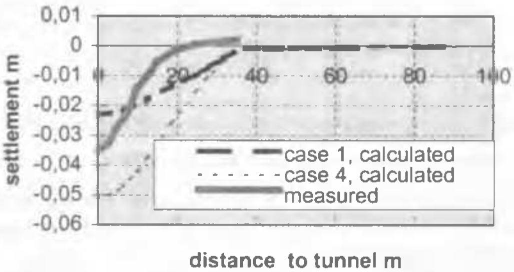

Figure 10. Predictions (HS model) and measured data after boring.

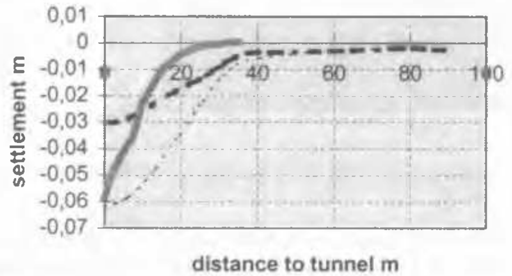

Figure 11. Predictions (HS model) and measured data after consolidation.

4.1 *Volume losses predicted and measured*

The measured and calculated volume losses are shown in Table 2. The volume loss is calculated by dividing the surface area of the settlement trough by the front surface (without overcutters) of the shield.

Because of the higher steepness of the settlement trough (see Figures 10 and 11) it is very clear that the meausured volume loss is almost a factor 2 smaller after the boring phase than predicted. This result is very characteristic for 2D finite element models compared with the measured data.

5 CONCLUDING REMARKS

By using the discussed analysis method the settlements at the surface, stresses and displacements in the underground can be predicted and analysed for different aspects of the modelled phases in shield tunnelling. All effects due to tunnelling, no matter which phase, can be estimated, controlled and managed. The influence of the injection pressure of the grout on the soil is modelled. Full consistency has not yet been reached in with real soil and tunnelling conditions but an useful estimation for the settlements and volume losses is available.

The effect of this phased modelling depends on the material models which are used, the accuracy of the in situ and laboratory soil investigation and the derived soil parameters. The HS model shows better results for the displacements than the MC model. In the grouting phase the HS material model scenario IV results in a 2 time less settlement of point A in comparison with the scenario IV in the MC material model.

Little experience is available with this model at this moment. Because of the 2 dimensional character of this analysis, the 3D results would result in lower displacements. The beam reaction of the lining segments in the constructed tunnel is not taken into account in this model.

The prediction of the settlements on the surface in relation with the injection pressure of the grout is a remaining topic of high interest. The modelling of the grout itself as fluid or plastic behaviour can influence the surrounding soil and the pressure gradient of the injected grout. More insight in this field, combined with 3D analysis, will allow more accurate prediction of deformations.

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