Simplified three-dimensional numerical modelling of shield tunnel advancement

Modélisation numérique tridimensionelle simplifiée de l'avancement du tunnelier

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ABSTRACT: For shield tunnelling in urban areas with a soft subsoil, reliable prediction tools are indispensable. A three-dimensional finite element model is presented which can be used to simulate phased tunnel advancement using an ordinary computer only. In this planewise model, a significant reduction of the computional requirements is achieved by introducing some restrictions regarding the geometry and the material behaviour. With a comparatively simple input, this model enables a three-dimensional phased analysis of the tunnel boring process with slurry or EPB shields. It has been applied to the Second Heinenoord Tunnel near Rotterdam. Although the magnitude of the surface settlements is overestimated, the shapes of the time-dependent settlement troughs and the relative rate of increase of the settlements are reasonably well calculated in the simulation. For the bending moments and the normal forces in the tunnel lining a reasonable agreement is found between measured and calculated values.

RÉSUMÉ: La construction d'un tunnel foré dans un région urbain demande des techniques d'analyse sûres. Ici un modèle d'éléments finis 3D est présenté, qui permet de déterminer les déplacements et les contraintes dans le sol autour d'un tunnel foré si la géométrie du réseau des éléments soit indépendante du coordonné dans la direction de l'axe du tunnel. La solution des équations numériques se fait par une méthode itérative, d'une couche d'éléments à une autre, d'afin que l'analyse peut être effectué avec ordinateur PC. Le modèle a été utilisé pour l'analyse du second tunnel de Heinenoord. Bien que les déplacements de surface sont un peu surestimés, l'aspect général et le développement des déformations agréent bien avec les mesures réelles. Les forces et les moments dans le matériau du tunnel sont aussi prédits par le modèle avec assez de précision.

1 INTRODUCTION

The importance of shield tunnelling techniques for the construction of underground infrastructure in densely populated areas with a soft subsoil is still growing. Because of the sensitivity of these areas to any disturbance caused by tunnelling activities, there is a clear need for reliable methods to predict the deformations and stress changes in the soil and to determine the forces and bending moments in the tunnel lining.

In the present design practice, for bored tunnels often use is made of two-dimensional finite element analyses, analytical models and relationships based on experience in similar projects. In some cases three-dimensional finite element analyses are carried out. It will be clear that each of these methods has its drawbacks. In a two-dimensional analysis, for instance the influence of the excavation face and arching effects related to the limited length of the zone behind the shield in which fresh (i.e. unhardened) grout is present cannot be included. Analytical models do not account for heterogeneity of the soil, while empirical formulas can only be applied succesfully if enough knowledge has already been gained on projects which are indeed similar. Most three-dimensional finite element analyses of shield tunnelling are still associated with excessively high computational requirements, both in terms of memory and in terms of calculation time. Moreover, with many of the commercially available three-dimensional finite element packages, it appears that erroneous data is quite easily entered by geotechnical experts involved in the design of bored tunnels, as they are usually familiar only with two-dimensional finite element analyses, which involve less complicated modelling aspects.

At the Delft University of Technology, a simplified three-dimensional finite element model has been developed by which the advancement of a shield in soft soil can be simulated using an ordinary personal computer only (Koelewijn 2001). The input requirements of this new model correspond to the input required for a few number of two-dimensional finite element analyses. Procedures have been developed to enable an automated simulation of the phased construction of a bored tunnel. The model has been applied to a bored tunnelling project near Rotterdam, for which field measurements of surface settlements and bending moments and normal forces in the tunnel lining are compared with calculated values.

2 PLANEWISE 3D FINITE ELEMENT MODEL

From the notion that three-dimensional finite element analyses are practically always carried out using a brick-shaped finite element mesh with equal cross-sections in at least one direction, it has been decided to develop a new three-dimensional finite element model in which this repetition of cross-sections is exploited as much as possible in order to reduce the memory requirements. As a result, three-dimensional problems requiring a rather large number of finite elements, like for instance shield tunnel advancement, can be analysed using equipment commonly available in engineering practice. Meanwhile, the calculation time remains within acceptable limits.

In the model, a three-dimensional finite element mesh is constructed on the basis of a limited number of cross-sections, each with the same division into elements. Corresponding elements in different input sections do not need to be of the same size and shape, as shown in Figure 1. The constructed mesh typically consists of a large number of blocks of finite elements with parallel planes between these blocks. The properties of the volume

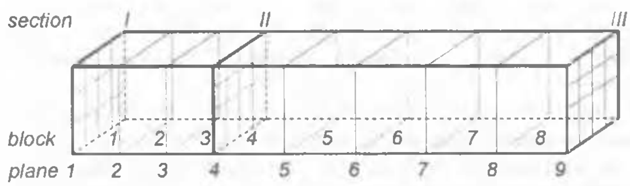

Figure 1. Example mesh with input sections, blocks with elements and calculation planes.

elements are attributed to the element nodes which are all located in these parallel planes.

Because of the above restrictions regarding the topology of the mesh, all calculation data can be arranged in a planewise manner. Thus the stiffness matrix which needs be solved will exhibit the same structure for each plane. In practice, the properties of a large number of parallel planes will be equal to each other. Now by creating and storing data of unique planes only, a significant reduction of the calculation requirements can be achieved in comparison with conventional finite element models where all mesh data is stored after first being created. Although it will help to reduce the storage requirements, the material properties of corresponding elements in different input sections do not need to be equal to each other, nor do the planar coordinates or the boundary conditions of corresponding nodes need to be equal.

For the calculation itself an iterative procedure is adopted, in which the parallel planes are solved one after the other using a sparse direct solver at the level of a plane. Details on the solution method and some basic characteristics of the model regarding memory requirements, calculation times and accuracy of the solution are given in Koelewijn (1999).

For most practical situations, a significant reduction of the calculation time is achieved at the cost of an error of less than one percent due to the iterative solution method. This error can be considered as negligible in comparison with the accuracy of geotechnical parameters usually available during design.

A further reduction of the calculation time can be achieved by adopting the iterative GMRES* scheme (Golub & Van der Vorst 1997) using the planewise iteration scheme as a preconditioner. This requires some more memory, but even then for practical calculations the total amount of memory can be less than with existing iterative solvers, like for instance the Conjugate Gradient method.

In the model, the well-known Mohr-Coulomb model has been implemented to account for soil plasticity. Both drained and undrained material behaviour can be simulated. Consolidation cannot be simulated in the model, because this requires a regular reformulation of the global stiffness matrix and because this would introduce different submatrices for initially equal parallel planes. Thus, the advantages of this new planewise model over a conventional three-dimensional finite element model would be lost. In combination with the rather simple input of mesh data, the model may easily be used by geotechnical engineers familiar with two-dimensional finite element analyses to quickly perform three-dimensional calculations, especially in situations in which parameters required for more advanced soil models are still lacking.

3 MODELLING OF SHIELD TUNNELLING

To facilitate the analysis of shield tunnelling, dedicated procedures have been developed to enable a more or less automated simulation of shield tunnel advancement. Attention has been focused on the modelling of tunnelling using slurry or earth pressure balanced (EPB) shield types, which are the most common types of machinery used for tunnelling in soft soils below the groundwater table. For a three-dimensional finite element analysis of shield tunnelling, four distinct phases may be discerned, as indicated in Figure 2.

The first phase extends to the excavation face. The soil ahead of the face is mainly influenced by the loading conditions applied at this face. The support pressure applied at the excavation face is modelled by a horizontal pressure which increases in depth.

Behind the excavation face, the soil elements inside the shield are deactivated. The shield itself is modelled as a ring of very stiff elements (with properties of steel) with another ring of elements representing the concrete lining inside. The conical shape of the shield is accounted for by application of a certain amount

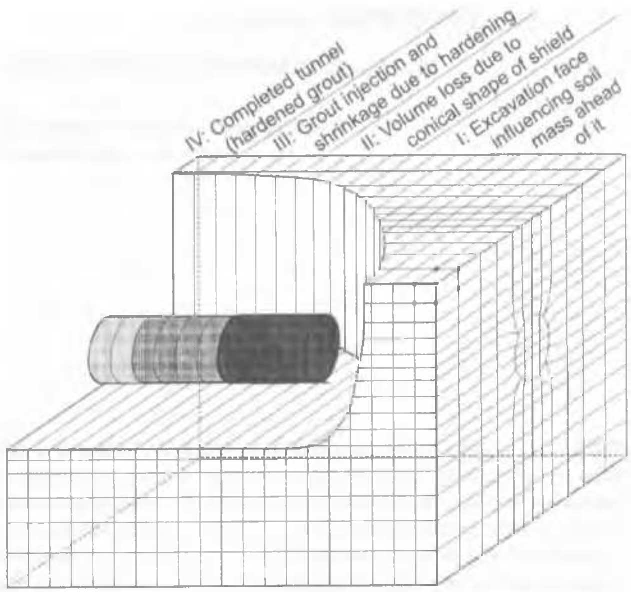

Figure 2. Phases in shield tunnelling.

of contraction to the nodes along the circumference of the shield. This results in a loss of volume around the shield without fixing the tunnel in space.

At the tail of the shield, where in reality grout is injected during shield advancement, the properties of fresh cement grout are assigned to the ring of finite elements which represented the shield in the second phase. The volume of grout material to be injected is simulated using the same procedure as applied to simulate the conical shape of the shield, although at this location usually an expansion will be prescribed. It has been decided to simulate the grouting process by means of a strain-controlled procedure rather than a stress-controlled procedure, because usually the amount of volume to be placed in the shield tail gap is better known than the actual pressure at the grout-soil interface during injection, especially when the tunnel is yet to be built. Shortly after injection of the grout, the hardening process will start. During hardening a certain amount of shrinkage will take place. This is again modelled by means of the procedure simulating contraction.

After hardening, the tunnel may be considered to be completed. The properties of the 'grout' elements are replaced by those of hardened grout.

The advancement of the shield is simply modelled in a discontinuous manner, by simulating the location of the shield a number of blocks farther in the mesh at each subsequent calculation step. Alternatively, shield advancement may be modelled as a continuous process, as for instance shown by Komiya et al. (1999). However, this requires far more computational power than available on ordinary personal computers. It therefore falls well beyond the scope of application of the planewise three-dimensional finite element model described here.

4 APPLICATION TO THE SECOND HEINENOORD TUNNEL

The second tunnel under the Oude Maas river near Rotterdam has been commissioned by the Dutch government as a bored tunnel in order to obtain experience with shield tunnelling in Dutch soft soil conditions. The tunnel actually consists of two tubes with an external diameter of 8.3 metres and a length of about 950 metres. Boring activities started in January 1997 and were completed in July 1998. The tunnel is situated in strongly heterogeneous soil conditions, as shown in Figure 3. Because of the experimental character of this project, an extensive research program has been set up to predict and monitor various aspects related to the construction of this tunnel, as described by Bakker et al. (1999).

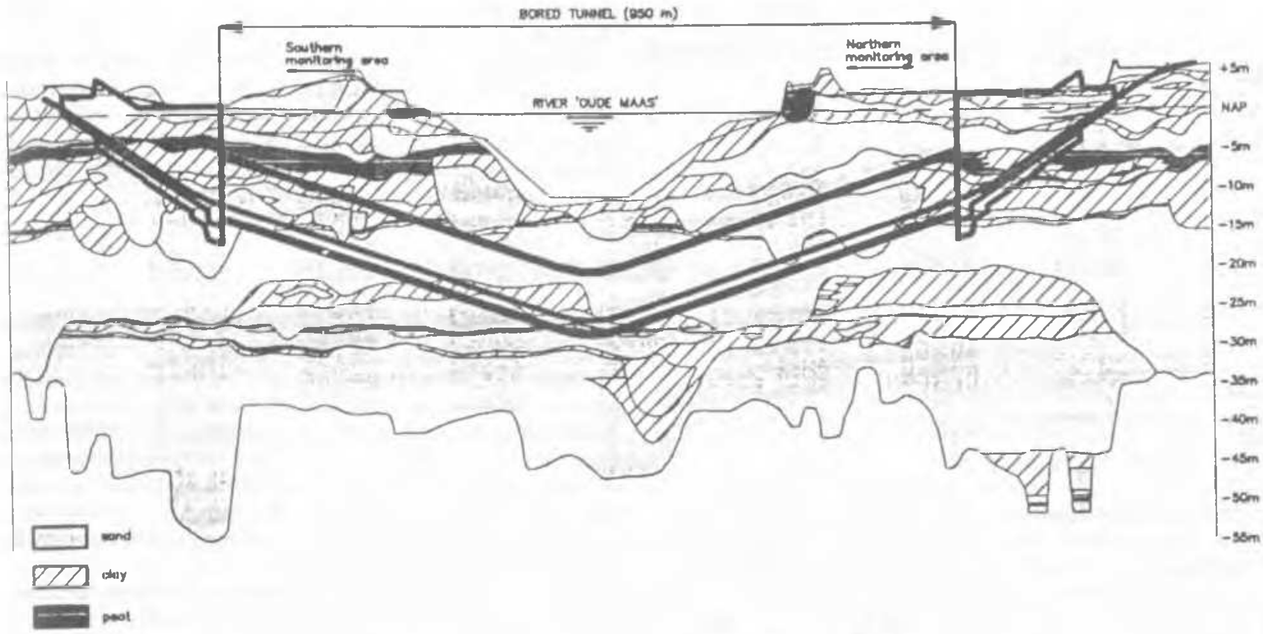

Figure 3. Geotechnical profile of the Second Heinenoord Tunnel in longitudinal direction (from Van Jaarsveld et al. (1999)).

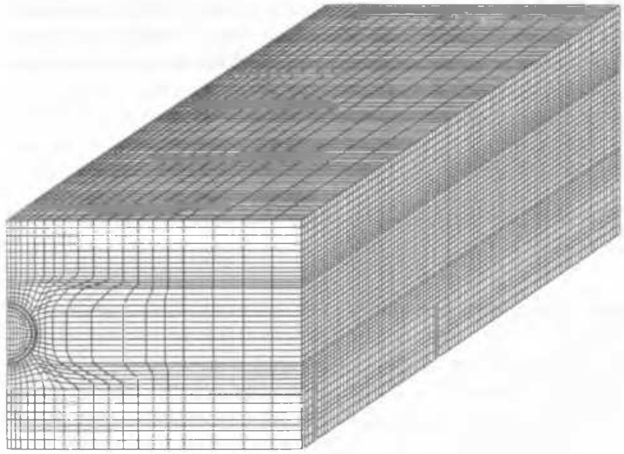

Figure 4. Finite element mesh used to calculate the first passage of th Northern monitoring area.

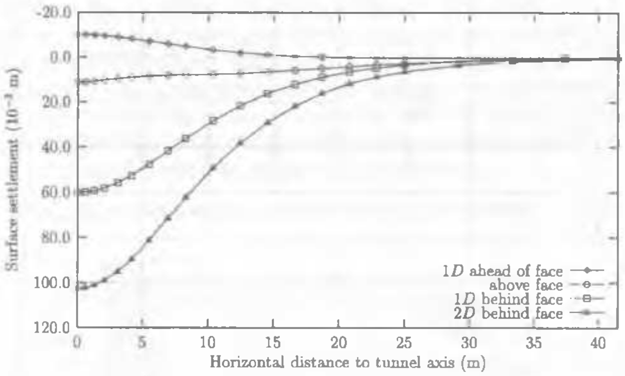

Figure 5. Calculated transverse settlement troughs for several positions of the excavation face.

The model has been applied to simulate the first passage of the Northern monitoring area, for which the soil profile and the geotechnical parameters to be used with the Mohr-Coulomb model are given in Table 1. Because of the permeability of each of these soil layers, a fully drained analysis was carried out. All input data has been taken from technical reports prepared for the Dutch Centre for Underground Construction (COB) before the construction of the tunnel started, in order to provide a clear parameter set to be used for all predictions. Further details are given in Koelewijn (2001).

Table 1. Soil profile and geotechnical parameters for the Northern monitoring area.

Layer type	top of layer (m)	γ_{sat} (kN/m^3)	K_0	G (kPa)	ν	ϕ (°)	c (kPa)
clay and sand	+2.70	17.2	0.58	1440	0.34	27	3
sand, locally clay	-1.50	19.5	0.47	7400	0.30	35	0.5
sand with clay	-5.90	19.0	0.47	7100	0.31	33	0.5
sand, locally clay	-9.90	20.5	0.45	11,400	0.30	36.5	0.5
sand, gravel	-17.15	20.5	0.50	17,100	0.30	36.5	0.5
clay, locally sand	-20.75	20.0	0.55	4500	0.32	31	7
sand	-25,10	21.0	0.55	22,800	0.30	37.5	0.5
clay, locally sand	-26.60*	20.0	0.55	4500	0.32	31	7

*The bottom of this layer is at -29.20 m below the reference level.

The finite element mesh used in the simulation is shown in Figure 4. It consists of 100 blocks of 920 elements each, i.e. 92,000 elements in total, and covers the full length (75 m) of the Northern monitoring area. As the length of each ring of precast concrete lining segments equals 1.50 m, each block of finite elements covers half the length of a lining ring.

For the simulation itself first an initial stress field has been generated by application of gravity loading to the mesh in which the tunnel was not yet present. After gravity loading, all horizontal stresses have been recalculated using the values for the lateral earth pressure coefficient given in Table 1, to account for the slight overconsolidation of the soil layers. Next, shield advancement has been simulated in 22 calculation steps in which the shield has been advanced over 58 blocks (43.5 m). With a simulated shield length of 8.25 m and a grout hardening zone (phase III in Figure 2) of 10.5 m, the completed tunnel length at the end of the simulation comprised 33 blocks (24.75 m).

The calculation has been performed on a personal computer with a Pentium-II processor and 236 Megabytes of internal memory available. The calculation time was within acceptable limits.

The calculated transverse settlement troughs for several positions of the excavation face are shown in Figure 5. In front of the shield some heave is calculated, but above and behind the excavation face the surface settles. At a distance of two times the outer diameter of the tunnel behind the excavation face, the surface settlements are nearly at their maximum value. The meas-

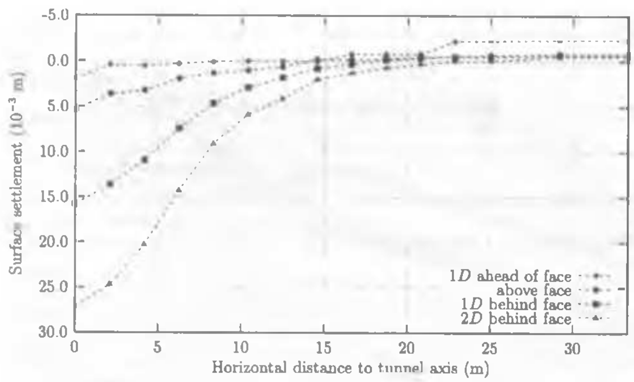

Figure 6. Measured transverse settlement troughs during the first passage of the Northern monitoring area for several positions of the excavation face.

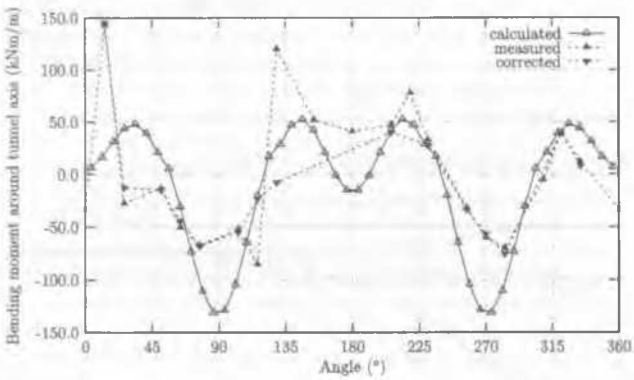

Figure 7. Calculated and measured bending moments in the tunnel lining

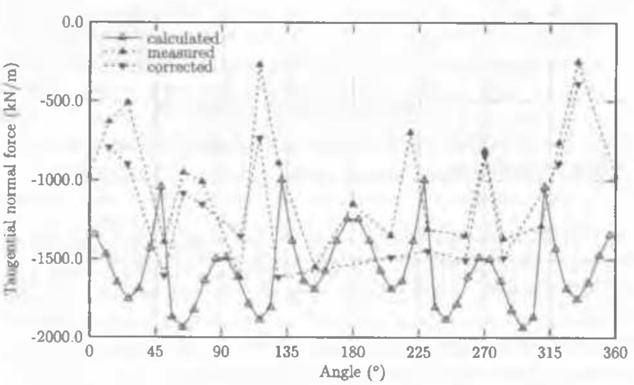

Figure 8. Calculated and measured tangential normal forces in the tunnel lining.

ured transverse settlement troughs for comparable positions of the shield with respect to the line of measurement are shown in Figure 6 (Van Jaarsveld, 1997). The measured maximum surface settlement increased to 32 millimeters after some time. No heave has been measured, but otherwise comparable graphs are found. However, the values of the calculated settlements are roughly four times larger than the measured values. This is likely to be related mainly to the values of the shear modulus used in the calculations, which is related to primary loading, whereas the use of much higher values would have been more appropriate to account for unloading/reloading behaviour at comparatively small strains.

The values of the bending moments and the tangential normal forces in the tunnel lining are much more in agreement with the measured values, as shown in Figure 7 and 8. In these figures, both the initially reported values as given by Blom and Van Oosterhout (1997) and the values corrected for temperature effects and supposedly erroneous signals as submitted by Bakker (2000) are given.

It is expected that the use of a higher shear modulus for the soil to improve the values calculated for the surface settlements will not have much influence on the values calculated for the bending moments and the normal forces in the lining, as the latter are mainly determined by the weight of the overlaying soil and the properties of the lining itself.

5 CONCLUSIONS

To analyse the influence of shield tunnelling on the soil a three-dimensional analysis of the tunnel boring process is desirable. By introducing some restrictions regarding the geometry and the material behaviour, a significant reduction of the computational requirements may be achieved. This enables a three-dimensional finite element analysis of shield tunnel advancement using an ordinary personal computer. In the planewise three-dimensional finite element model described in this paper, the tunnel boring process using slurry or EPB shields can be modelled by a limited number of consecutive phases.

The resulting model has been applied to the Second Heinenoord Tunnel near Rotterdam. Although the magnitude of the surface settlements is overestimated, the shapes of the time-dependent settlement troughs and the relative rate of increase of the settlements are reasonably well calculated in the simulation. For the bending moments and the normal forces in the tunnel lining a reasonable agreement is found between measured and calculated values.

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