4D grouting pressure model of a bored tunnel in 3D Tunnel

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INTRODUCTION

For some ten years TBM-techniques have been used to construct tunnels in the Netherlands. Ground conditions vary from loose to dense granular soils, sometimes clays. In all cases groundwater is close to ground level. Front stability is maintained by bentonite slurry or earth pressure balance shields. Several research projects have been initiated by the Dutch Centre for Underground Construction (COB) in order to increase TBM applicability in urban areas. The COB has brought authorities, engineering consultants and contractors together in research committees.

One COB research committee is investigating the interaction of soil and the tunnelling process using finite element method (FEM) analyses. The grouting pressure applied to fill up the tail void behind the TBM is believed to govern both deformations and internal lining forces.

Several two- and three-dimensional FEM models that include tail void grouting are available. However, they do not describe time-dependent longitudinal lining deformations or bending moments. As part of this COB project Fugro Ingenieursbureau B.V. has developed a 4D FEM model. The model describes the progressive tunnel boring process using PLAXIS 3D Tunnel software.

CASE STUDY

The 4D grouting pressure model was derived from the twin tube Sophia Railway Tunnel constructed in the western Netherlands as part of the Betuweroute railway link between Rotterdam and Germany. Each tunnel is 4.2 km long and has an inside diameter of 8.65 m. Construction used a TBM with a bentonite slurry shield.

Halfway along the tunnels a monitoring section was installed. This consisted of two lines measuring surface displacements laid out parallel and perpendicular to the tunnel axis. Also extensometers and inclinometers were installed. Grouting pressure transducers have been inserted in ring 2080 of the southern tunnel beneath the monitoring section. This instrumented ring was also monitored after installation. Along with TBM data this monitoring data has been used for achieving a history match with the FEM model.

ANALYSIS OF MEASUREMENT DATA

In order to compare calculation results with measurements at the monitoring section an analysis of the boring process has been performed over some 200 m tunnel length. Major goals are to determine whether the tunnel boring process parameters and response at ground level at the monitoring section can be correlated and whether they are representative for a larger area.

Data analysis for 140 rings (210 m)

Surface settlement at ring number can be compared with front pressure at ring number x —5 in figure 1. The monitoring section is located at ring number 2080. Over the entire length there seems to be some correlation between vertical displacement and front pressure.

In figure 2 the grouting pressure is given for a pressure transducer in the TBM tail. The grouting pressure in the boring phase varies by 100 kN/m² along this stretch. On this large scale there is no clear correlation between grouting pressure and final displacement other than that the average grouting pressure is constant at approximately 275 kPa and the average final settlement is 0 mm. In figure 3 the total number of strokes of the grouting pumps is given. The number of strokes varies considerably. Just like grouting pressure there is no clear correlation between the number of strokes and final displacement other than that the number of strokes is constant as well as the final settlement. On a smaller scale there is some correlation. For example between ring number 2070 and 2105 the final settlement is reduced by an increase in the number of strokes.

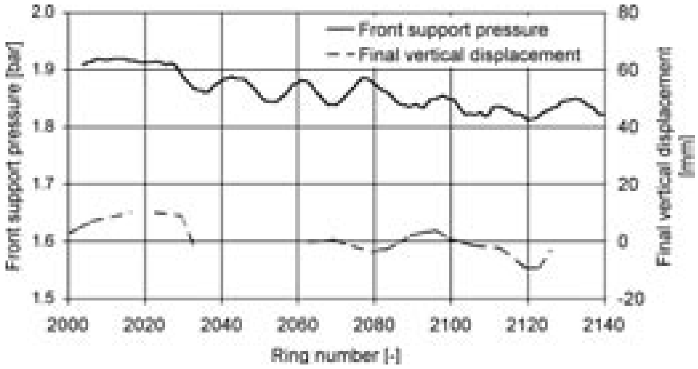

Figure 1: Face support pressure at the crown & surface settlement vs. ring number at the monitoring section.

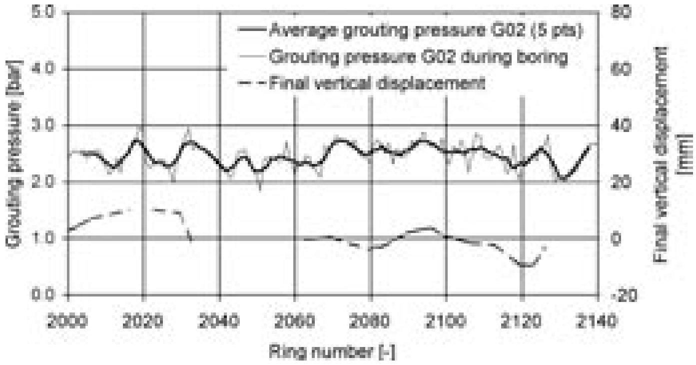

Figure 2: Grouting pressure & surface settlement vs. ring number (average uses 5 data points smoothing).

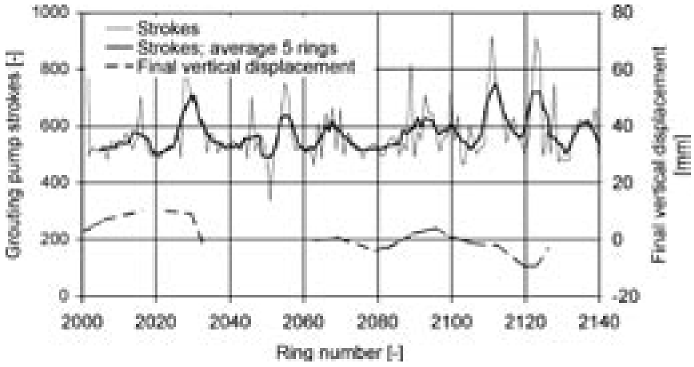

Figure 3: Grout pump strokes & surface settlement vs. ring number.

Data analysis near monitoring section

Other monitoring results near ring 2080 have been analysed in detail. Surface settlement versus time can be plotted as settlement versus TBM position. For a uniform tunnel boring sequence these plots should show the influence of front pressure, TBM volume loss and tail void grouting. Such plots have been given for ground level at the location of three rings in figure 4. Surface settlement has not been constant in relation to TBM position.

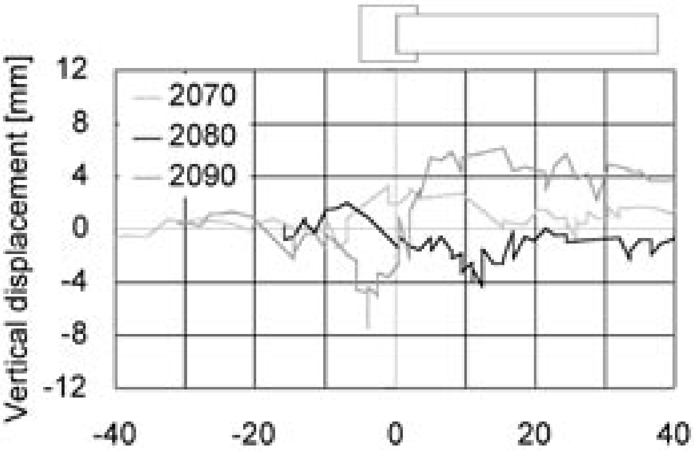

Figure 4: Surface settlement ring numbers 2070, 2080 & 2090 vs. position.

In order to find the source of these differences, settlement at ground level and displacement of extensometer points are given as a function of time in figures 5 and 6. Extensometer E7113 is located at the tunnel centreline near ring 2080. In these figures the TBM progress has also been plotted; boring for ring number n given on the right hand scale starts at the moment given on the time scale. During boring the centre of this ring is inside the TBM with a decreasing distance of approximately 5.2 to 3.7 m from the tail end.

At all locations settlement occurs at the same time and in most cases due to TBM stops. The largest settlements are found at ring 2090 during TBM stops after boring for ring number 2087, 2088 and 2089. Heave is mainly found during boring for ring numbers 2090 through 2094. In addition the extensometer point at ground level —12.5 m shows heave during boring for ring 2080. At that moment ring 2080 was located within the TBM at a distance decreasing from approximately 5.2 to 3.7 m from the tail end. Thus the measured heave did not originate directly from entering the grouting zone. This heave is limited to the zone directly above the tunnel and does not extend to ground level. Interesting is the response of the extensometer at 12.5 depth to every boring phase at least up to ring number 2094 which is located at 21m distance.

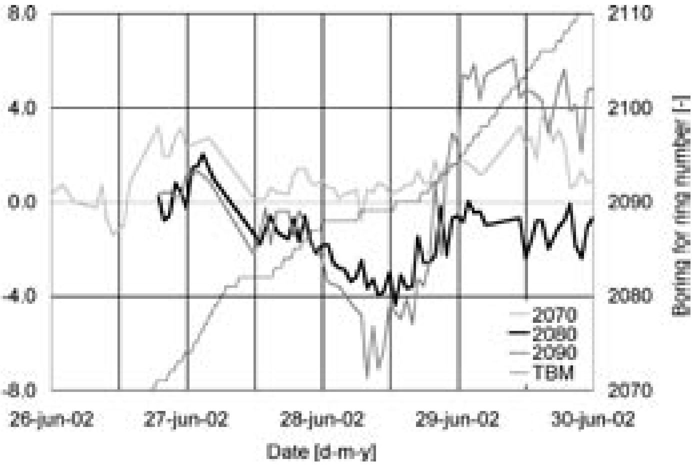

Figure 5: Vertical displacement at ground surface above rings 2070, 2080 and 2090 as a function of time. Also plotted is the TBM position.

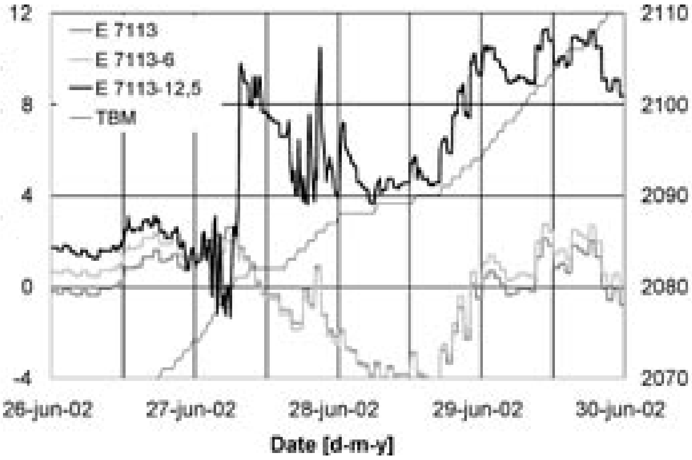

Figure 6: Vertical displacement extensometer E 7113 at ground level (GL) , GL —6 m and GL —12.5 m as a function of time. Also plotted is the TBM's position.

The question can be raised whether these deformations can be directly related to TBM drilling data. They are plotted versus time in figures 7, 8 and 9.

From figure 8 it appears that there is a positive correlation between grouting pressure and vertical displacement: a decreasing grouting pressure in the morning of June 27 results in settlement just as the relatively low grouting pressure in the morning of June 28 (see figure 6); the latter a result of TBM stops. An increase of grouting pressure around mid-night June 29 results in heave at all locations. The correlation of displacement with the number of strokes in figure 9 is less obvious as has been concluded from figure 3.

From the above mentioned it is evident that tunnel boring from rings 2070 to 2090 has not been constant: TBM stops and variation in grouting pressure have resulted in different longitudinal settlement troughs versus TBM position.

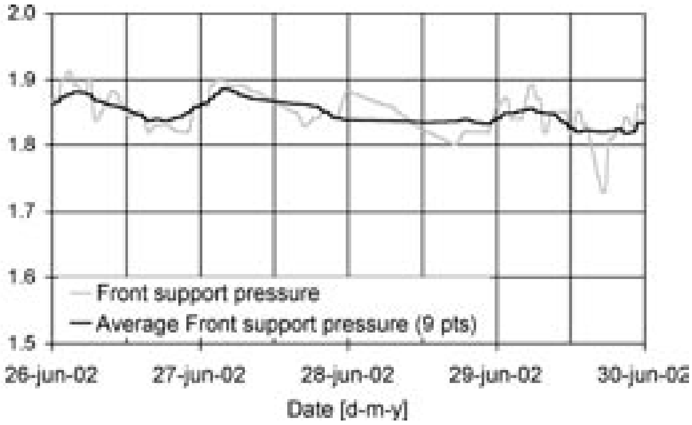

Figure 7. Face pressure measured at the crown of the TBM as a function of time.

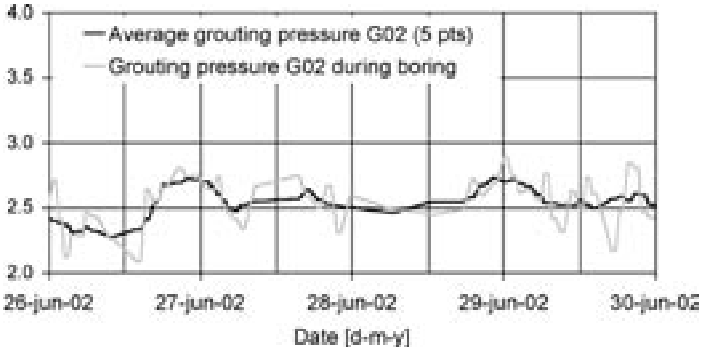

Figure 8: Grouting pressure measured in the grout injection zone transducer G02 as a function of time.

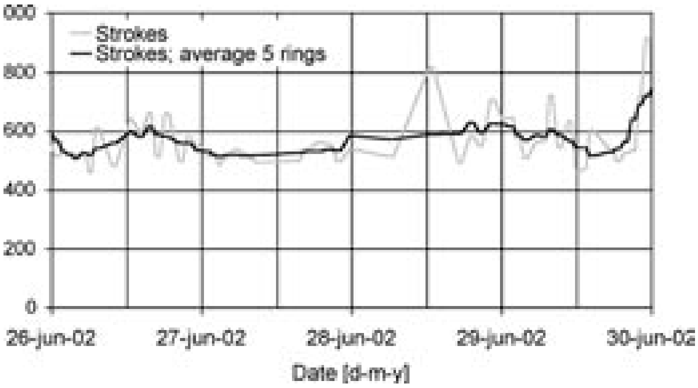

Figure 9: Grouting pump strokes as a function of time.

FEM-MODELLING

Geometry and soil parameters

The model has been built using PLAXIS 3D Tunnel (Brinkgreve & Broere 2004). The model was extended modularly, i.e. first starting with only a tunnel and face support, then adding a new component in order to investigate the model's response. Subsequently adding the TBM weight, a grouting pressure zone, jack forces and finally TBM contraction and backup train weight.

Half a tunnel is modelled with standard boundary conditions for soil and lining. The length of one tunnel ring is 1.5 m. In longitudinal direction 70 slices of 1.5 m have been used to model the phased construction. This number of stages is required in order to create a constant bending moment at some distance from both TBM and model boundaries. The total length and width of the model is 165 m and 75 m respectively. The model base has been chosen at the base of the Kedichem formation (stiff sandy clay). The underlying sand formation is even more stiff regarding unloading (E_{UR}^{ref} = 150 MN/m²). The major part of the tunnel was bored through Pleistocene sand; only a small part protrudes in the Kedichem clay. Part of the model is sketched in figure 10.

Layer	level NAP*/**	γsat kN/m³	φ	c kN/m²	E_{50}^{ref} MN/m²	E_{oed}^{ref} MN/m²	E_{UR}^{ref} MN/m²
Sand	-1.5	19	35	1	25	25	85
Peat	-1.9	11	25	10	2	1	15
Clay	-8.0	13	28	4	4	2	20
Sand***	-13.2	20	38	1	40	40	150
Kedichem Clay	-24.6	20	32	1	9	6	60
Bottom	-36.0						

* *NAP = Dutch reference level*

** *Top of the layer*

*** *Pleistocene*

Table 1: Hardening Soil parameters

The soil has been modelled using the Hardening Soil model (Brinkgreve & Broere 2004). This model implements soil behaviour under the unloading-reloading conditions governing tunnel construction. Soil parameters were derived from in situ and laboratory tests. Table 1 lists important soil parameters.

Tunnel Boring Machine (TBM)

The TBM is modelled by plate elements. The diameter, stiffness and unit weight vary along the length of the TBM. Contraction of the TBM results in volume loss as tunnelling progresses. TBM face pressure is modelled by a pressure at the crown and a pressure gradient of 14 kN/m²/m (measured values). The jack forces measured during tunnelling have been applied on the tunnel lining using point forces. Like the face support they are modelled as external forces not linked to the TBM. The horizontal balance forces of the face support and jack forces have not been modelled. This is because the resulting horizontal force is relatively small, as is confirmed by additional calculations. The backup train is modelled by point loads behind the TBM. Figure 11 displays the different process parameters implemented in the 4D grouting pressure FEM model.

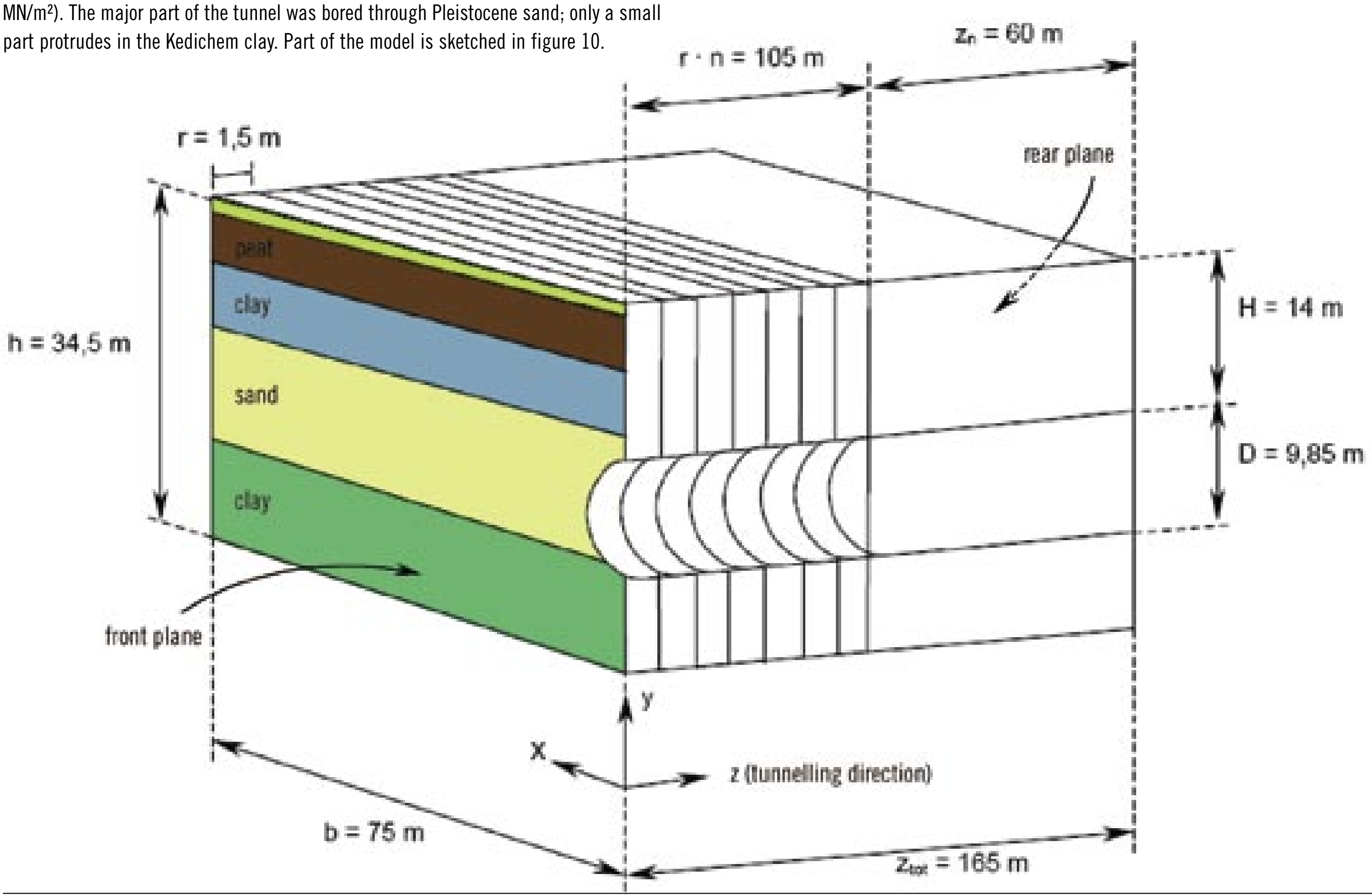

Figure 10: Schematic FEM model geometry

Tunnel lining

The tunnel lining is modelled by plate elements. The bending stiffness in both ring and longitudinal directions have been assessed by FEM analyses accounting for reduced stiffness caused by joints between ring segments. It is possible to select a plate thickness and Young's modulus such that both ring and longitudinal bending stiffness can be modelled correctly. Three slices of lining have been applied in the tail end of the TBM corresponding to the actual situation. These additional tunnel rings inside the TBM result in a downward force on the lining next to the grouting zone.

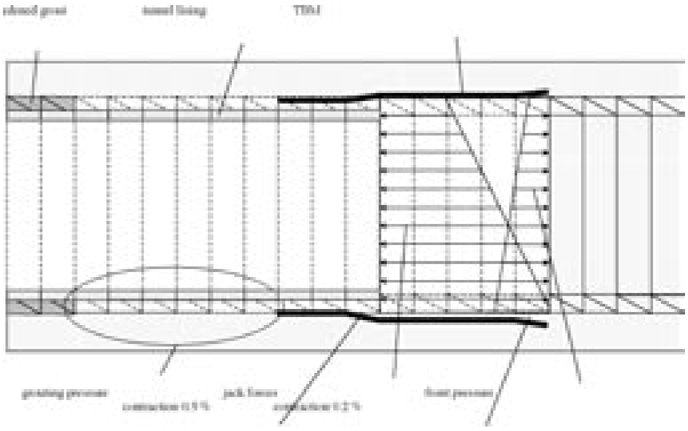

Figure 11: Tunnel boring process parameters featured in the 4D grouting pressure FEM model

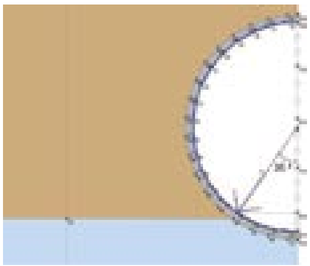

Figure 12: Close up of the tunnel, showing the location of the point loads representing the backup train

GROUT

During boring of the second tunnel the grouting pressure has been measured at 14 locations along the circumference of one instrumented ring. Both the measured pressure and pressure gradient vary with distance. They also differ during periods of excavation (high pressure (gradient)) and standstill (lower pressure (gradient)). The grouting pressure has been modelled for a length of six rings behind the TBM. The modelled pressure and pressure gradient are given in figure 13. Behind the grouting pressure zone, the grout is assumed to behave like a soil and is therefore modelled by volume elements as an elastic material with a Young's modulus assumed equal to the surrounding soil.

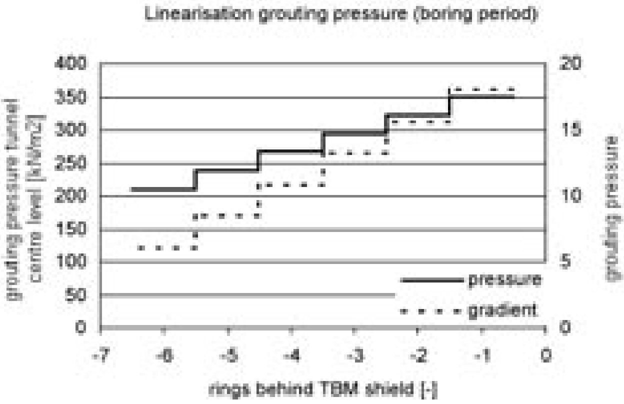

Figure 13: Modelling the grouting pressure

Calculation process

The tunnel boring process has been modelled by a staged construction calculation with PLAXIS 3D Tunnel V2, where in approximately 60 stages one ring per stage is 'bored'. This version includes a copy option whereby the features (e.g. loads, structures, state of soil elements, water pressures etc.) of one stage can be easily copied to the next. This results in an efficient modelling procedure and a minimisation of input errors.

RESULTS 4D FEM ANALYSIS

Introduction

After performing the modular construction of the model and assessing the governing process parameters the final model was constructed using best estimate values for every possible input parameter. This calculation is called the standard run. The standard run is equipped with:

- measured (applied) face pressures
- real bending stiffness for TBM
- values of contraction of the TBM fully supplied
- measured (applied) jack forces
- real bending stiffness lining in both ring and longitudinal direction
- measured grouting pressures

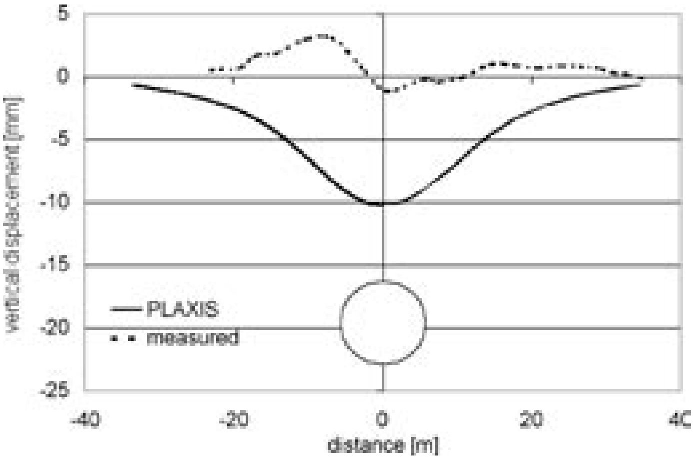

Figure 14: Standard run: calculated and measured transverse settlement troughs.

Where possible, the results of the standard run have been compared with measured soil deformations. In addition a series of calculations have been conducted in order to determine the model's sensitivity to certain parameter variations.

Results of the standard run: surface settlement

The results show that the maximum of the calculated final surface settlement is about 10 mm (figure 14 and 15 depict the transverse and longitudinal troughs). The final

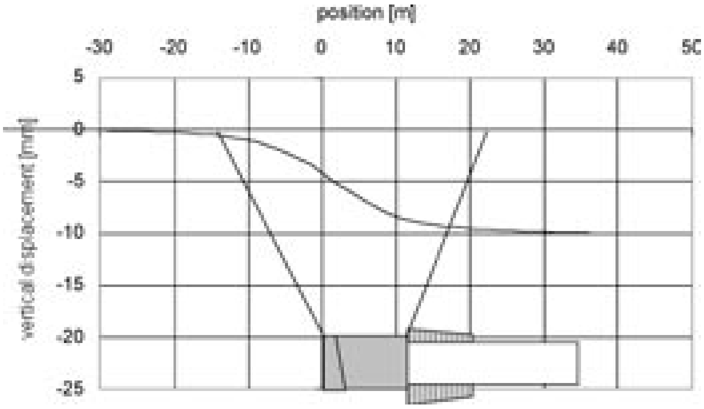

Figure 15: Standard run: calculated longitudinal settlement trough

deformations at surface level measured at the monitoring section varied between approximately 15 mm heave and 10 mm settlement. Hence the 4D model with best estimate parameters calculates the maximum of the measured settlements.

The calculated transverse trough is symmetric, while the measured one is not. This asymmetry is probably caused by variations in grouting pressure at the monitoring section and / or the presence of a safety shaft constructed before the tunnels. The calculated longitudinal trough is one of three possible troughs found during the passage of the TBM underneath the monitoring section (see also figure 4).

Results of the standard run: tunnel displacement

When performing a staged construction calculation with PLAXIS 3D Tunnel, every new ring is added in a stressless situation. In obeying this condition the new ring is placed with an offset onto the tunnel. This repeated process causes a displacement of the tunnel as displayed in figure 16, where uplift is plotted against distance from the front of the model. After having modelled 60 rings this displacement is about 60 mm. This phenomenon is believed to stem from the stressless procedure in PLAXIS, excluding real life construction effects. This means that in reality newly added rings are probably built in warped (intentionally or unintentionally) and / or a downward force is exerted on the tunnel by the TBM (see figure 18).

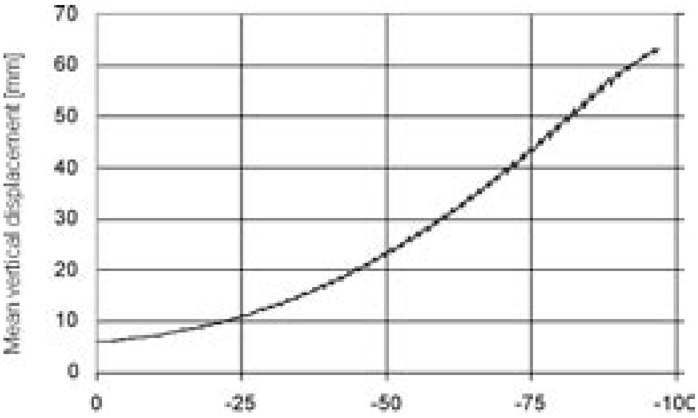

Figure 16: Calculated displacement of the tunnel over 60 rings

The calculated net uplift of a tunnel segment caused by grouting pressures after installation is displayed in figure 17. Also shown are the measured displacements of ring 2080, the only ring monitored after installation. The measured uplift is about 20 mm and occurs over a distance of approximately 12 m after installation. The calculated uplift is only 4 mm and occurs over a length of 9 —12 m. The difference is significant. Figure 17 indicates that further uplift is suppressed by backup train loads

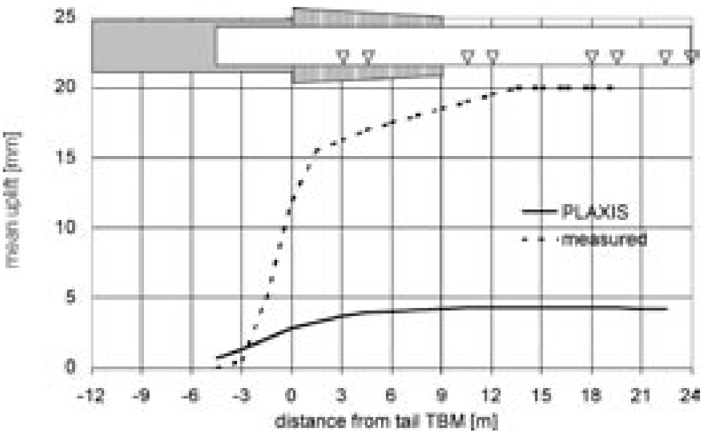

Figure 17: Displacements of 1 tunnel ring after installation. Small triangles represent backup train wheel loads.

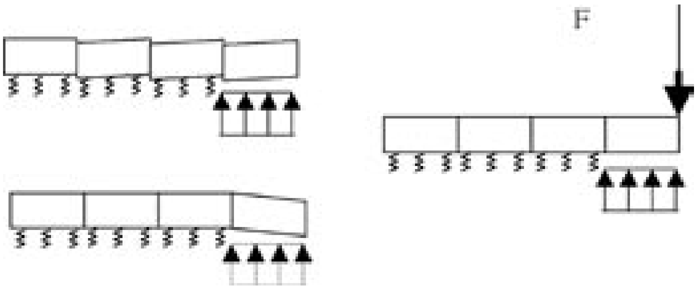

Figure 18: Warped position of newly placed tunnel rings (left) or downward force exerted by TBM on tunnel (right)

Results of the parameter variation study

In order to assess the sensitivity of the 4D FEM model to parameter variations, additional calculations were performed. The most important variations were carried out for:

- tunnel bending stiffness reduced by a factor 0.5
- soil stiffness E_{UR}^{ref} reduced by a factor 0.7
- modelling TBM without contraction

The results of the variations study are presented in tables 2a and 2b, where the focus is on the maximum final surface settlement and the calculated net uplift of the tunnel construction respectively. The results can be compared with the results of the standard run, given in the top row.

standard run	10 mm settlement
tunnel bending stiffness x 0.5	no effect
soil stiffness x 0.7	8 mm settlement
front pressure +10 kN/m² *	no effect
grouting pressure +20 kN/m² **	8 mm settlement
grouting pressure +50 kN/m² ***	2 mm settlement
grouting pressure +100 kN/m² ****	30 mm heave
no contraction TBM	2 mm settlement

** +10 kN/m² equals +5% ** +20 kN/m² equals +6 to +10% *** +50 kN/m² equals +14 to +25% **** +100 kN/m² equals +28 to +50% ***** N/I = not investigated*

Table 2a: Maximum value calculated surface settlement

standard run	4 mm
tunnel bending stiffness x 0.5	7 mm
soil stiffness x 0.7	4 mm
front pressure +10 kN/m²	4 mm
grouting pressure +20 kN/m²	5 mm
grouting pressure +50 kN/m²	6 mm
grouting pressure +100 kN/m²	N/I *****
no contraction TBM	N/I *****

Table 2b: Maximum value calculated net uplift tunnel

Finally the measured and calculated horizontal displacements are plotted in figure 19. The shapes match well. When omitting TBM contraction the calculated curve shifts toward the measured one. On raising the grouting pressure uniformly by 50 kN/m² the calculated curve closely matches those measured.

Correlating the calculated surface settlements and the results from figure 19 indicate that either the applied contraction is too high or the grouting pressures are too low in the standard run. Possibly a combination of these two should be implemented to match the measured ground deformations.`

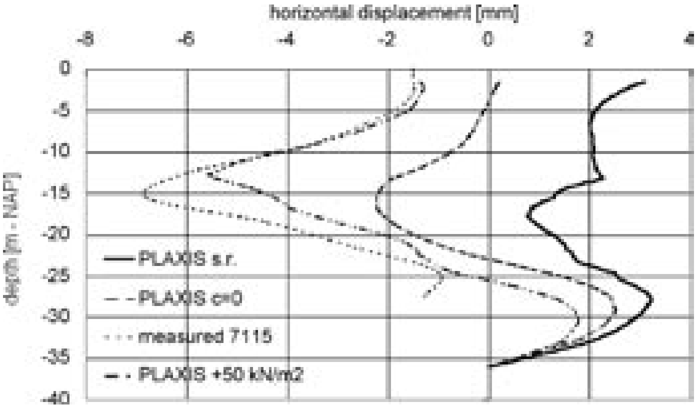

Figure 19: Inclinometer results showing measured values and calculated values for three calculations (s.r. means standard run; c = 0 means zero contraction; +50 kN/m² indicates the raised grouting pressure).

Bending moments and normal forces in the tunnel lining

Apart from displacements, also the forces and moments in the tunnel lining can be derived from the calculation. In figure 20 the bending moments in various cross sections are given for various distances to the TBM. In cross section 1 the moments are given in the lining, just before the lining exits the TBM tail. In section 2 the lining is loaded by the grout pressure and the point load from the wheels of a backup train. The influence of this wheel load can be clearly seen. The other sections are taken further back and show a diminishing influence of the wheel loads. Figure 21 shows the distribution of these moments over the entire lining.

CONCLUSIONS & RECOMMENDATIONS

The results presented in this paper show that state of the art FEM software and computer technology combined with the practical experience currently available it is feasible to model tunnel boring with a 4D approach. Process parameters can be modelled without difficulty and their individual influence on model response can be evaluated with certain parameters can be varied easily (soil / tunnel properties) and the PLAXIS copy option now available limits repetitive data entry and minimises input errors. However, changing contraction or grouting pressure distribution demands means defining and running a new calculation. This is more time consuming.

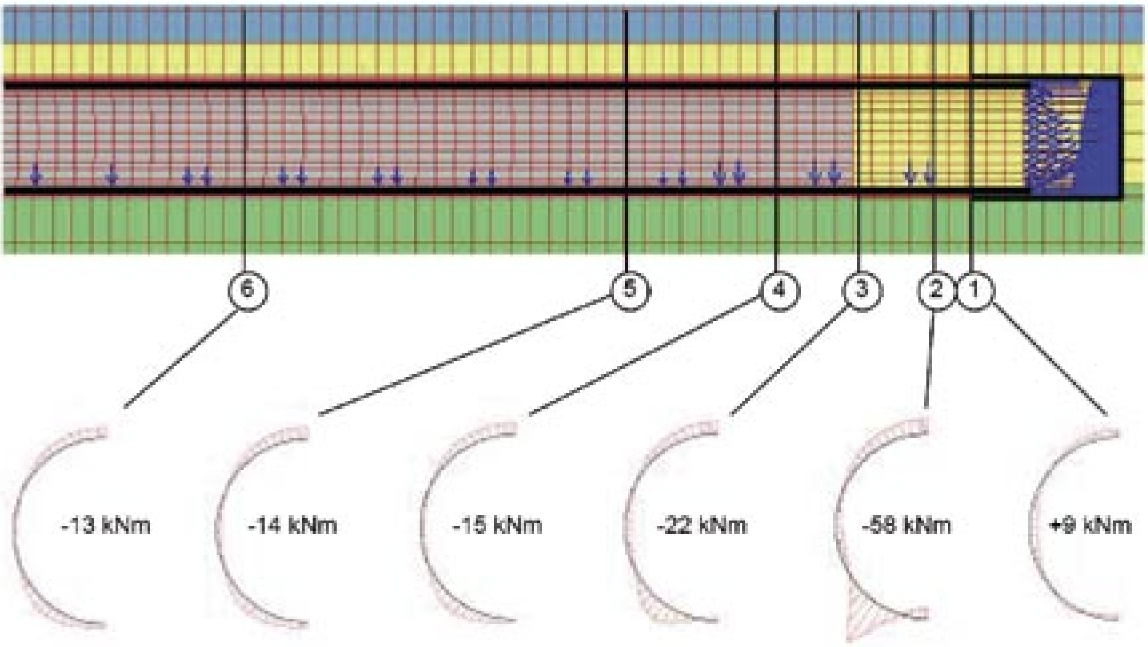

Figure 20: Bending moments at various cross sections in the 3D Tunnel model

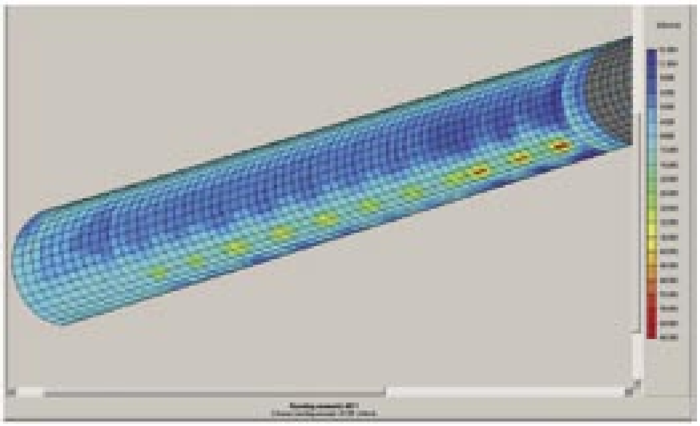

Figure 21: bending moments M11 in the tunnel linng

Both monitoring and TBM data show that the boring process has not been constant at the section used for the history match with the FEM model. However, the case study and parameter variations show that recalculation of a tunnel boring process in terms of soil displacements is feasible.

Grouting pressures and TBM contraction govern soil displacements. Hence, these parameters should be carefully assessed. Measured grouting pressures provided the input for this 4D FEM model. In future predictions grouting pressure distribution can be determined using the recently developed grout consolidation model as presented by Bezuijen & Talmon (2003). It is questionable whether TBM contraction should be fully applied. In practice contraction might be limited by either face or grouting pressures.

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