Influences of physical grout flow around bored tunnels

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ABSTRACT: The behaviour of the grout layer during the construction of bored tunnels is one of the determining factors for the stability and deformations of the tunnel structure and the surrounding soil. A new calculation model is presented which incorporates the relevant properties of and the interactions between soil, grout and lining. With this model the influence of different grout strategies on structural safety of the tunnel, surface settlements and plastic deformations in the soil can be analysed. The model was applied successfully to the Green Heart Tunnel in the Netherlands.

1 INTRODUCTION

After the construction of the first shield driven tunnels in the Netherlands it was concluded that the construction stage of bored tunnel linings is as normative as the serviceability stage (Blom et al., 1998). It was found that in the construction stage the concrete strains and the deformation of the tunnel lining could exceed the predicted values for the serviceability stage and that settlements deviated from expected values. Much effort has been put into research to understand the phenomena causing this normative construction stage.

The construction process of a bored tunnel is a continuous process. The tunnel boring machine (TBM) excavates the soil at the front and pushes itself forward using hydraulic jacks positioned against the already built tunnel lining at the back (see figure 1). The excavation is stopped periodically to allow for the erection of segmented rings inside the TBM. The difference between the external diameters of the TBM and the lining causes a gap between the soil and the lining at the tail end of the TBM. This gap is filled with grout while the TBM progresses. The behaviour of the grout layer is supposed to play a dominant role in the deformations of the tunnel lining and the surrounding soil during the construction stage.

The function of the grout is twofold:

1. The grout enables the embedding of the tunnel in the surrounding soil;

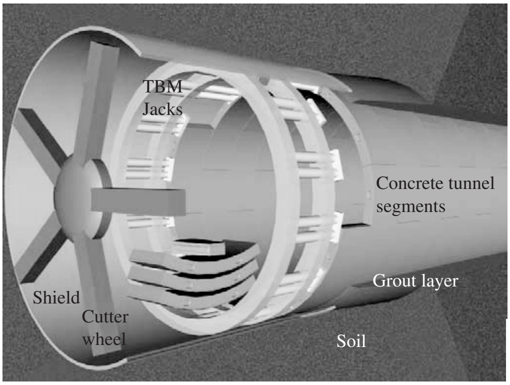

Figure 1. Tunnel boring machine, segmented tunnel lining and grout layer.

2. The grout prevents large deformations of the surrounding soil and settlements at the surface.

Usual basic components of grout are binders (cement), sand and water. The composition however will vary per project and/or per contractor and may be a well kept secret.

The grout is locally injected at the tail of the TBM. During injection the grout leaves the nozzles as a fluid and flows around the circumference of the lining. After injection begins the hardening phase ranging from very fast (e.g. almost immediately in case of a two component grout) to very slow (several weeks). Depending on the progress of the TBM the extent of the hardening stage of the grout near the TBM may vary considerably along the tunnel axis.

The influence of grout in the construction stage on the lining and on the soil is generally studied separately: i.e. from geotechnical point of view or from structural point of view. Both approaches struggle with the same problem: the grout load and the grout support on either soil or lining. In many calculation models the grout was assumed to be a hydrostatic material. However, it turned out that this simplification did not result in the required accuracy of models for the construction stage. Furthermore, from the results of various grout pressure measurements it can be concluded that the grout load is not a pre-defined hydrostatic load case. E.g., the grout load can vary in time between a hydrostatic grout load and a hydrostatic water load (Bezuijen & Talmon, 2003) as was measured at the Sophia Rail Tunnel. But it can also be a load case with a non-constant gradient (nearly parabolic) over the tunnel height (Koningen & Lokhorst, 2002) as was observed at the Botlek Rail Tunnel.

The section above clearly demonstrates that the behaviour of grout requires more attention in calculation models. In this article a calculation model is presented where lining, grout and soil are combined and the grout is modelled explicitly as a physical layer with material properties. The grout layer is assumed to be a paste with both flow and visco-plastic properties. These properties allow the grout to flow in the gap between lining and soil.

This model, which is called the SPARTA Grout model, is described in section 2. The model was applied to a practical case and the results of grout pressure calculations were compared to on site measurements (section 3). Observed trends in the behaviour of lining and soil related to the grouting strategy are discussed in sections 4 and 5.

2 SPARTA GROUT MODEL

2.1 *Model description*

The SPARTA Grout model has been developed by Holland Railconsult and CST (Blom, 2004). With this model the stresses and deformations in the tunnel lining, the grout layer and in the surrounding soil can be calculated using different grout fill ratios and different grout material parameters. The model is a two-dimensional model of the tunnel cross-section surrounded by a grout and a soil medium (see figure 2). The requirement of the vertical equilibrium of the tunnel cross-section is the basis of the calculation procedure. The model initially assumes an equally distributed grout layer around the lining. In this initial situation, generally, there is no vertical equilibrium. Equilibrium will be found due to grout flow, vertical displacement of the tunnel (uplift) and deformation of the soil, of the lining and of the grout layer.

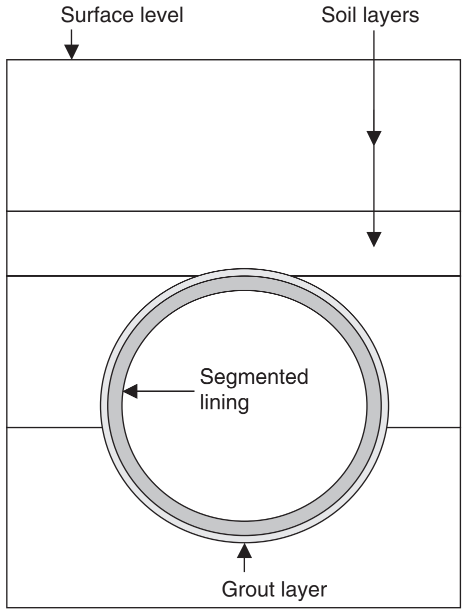

Figure 2. Schematic representation of the SPARTA Grout model.

2.2 *FEM characteristics*

The model is based on the FEM package ANSYS. The model has three regions, i.e. soil, grout and lining, and two interaction surfaces, i.e. grout-soil and grout-lining. The lining consists of concrete segments, with interaction surfaces between the separate segments. The grout layer surrounding the concrete lining is modelled as an isochoric visco-plastic material necessary for a curing paste. The isochoric behaviour is used to model the fluid character of the paste, while the visco-plastic behaviour is used to model the solid character of the paste. For each soil layer elastic and plastic material properties are defined. For the elastic material properties the E_{50}-values of the separate layers are used as modulus of elasticity. The Poisson ratio is calculated from the K0 values of the separate layers. For the density of the soil only the effective density is used. For the plastic material properties the cohesion, the internal friction angle and the dilatancy angle of the separate layers are adapted for use in a Drucker-Prager plasticity model, to have the same yield load as the more general Mohr-Coulomb plasticity model under plane strain conditions. The interaction surfaces between the grout and the soil, and the grout and the lining are defined as having cohesion contact and sliding capabilities.

2.3 *Validation*

The applied soil model is based on the Drucker-Prager yield criterion. This criterion uses the "outer-cone-law" of the Mohr-Coulomb criterion. However, the model also allows the use of the "inner-cone" approximation, as well as the "plain-strain" or the "equal-volume" approximation. For testing the correctness of the four approximations a validation with the FEM-package PLAXIS was carried out. All four approximations were applied in the SPARTA Grout model. Then the resulting radial grout pressures on the soil were adopted in a PLAXIS model in which the soil is represented by elements with the Mohr-Coulomb yield criterion. The grout shear yield stresses, acting in tangential direction, were neglected, as these stresses are small in comparison with the grout pressures in radial direction. The contour plots of the SPARTA Grout and the PLAXIS calculations were compared and it was found that the general behaviour of both models confirmed each other. Similarities were observed for soil stresses as well as deformations. Thus the application of the Drucker Prager yield criterion proved a reliable approximation for this model.

2.4 *Calculation strategy*

In the SPARTA Grout model the followed order of calculation steps is:

1. Determine the initial soil stress distribution;
2. Excavate the soil due to the boring process of the tunnel;
3. Activate the lining and the grout layer;
4. The soil is allowed to relax (deform) until the initial grout thickness given by the user;
5. Calculate the force equilibrium of the soil layers, the grout layer, the concrete lining and the water pressure;
6. Increase the grout volume from the initial value in several steps to the final value and re-calculate the force equilibrium in each step.

In the calculations presented here the grout volume is gradually increased from 90% to 110% where 100% means that the theoretical void between the lining and the excavated soil is filled completely.

3 GROUT PRESSURE DISTRIBUTIONS

The SPARTA Grout model was applied in a practical case at the Green Heart Tunnel in the Netherlands. In this tunnel project grout pressure distributions around the tunnel were measured in an extensive measurement program.

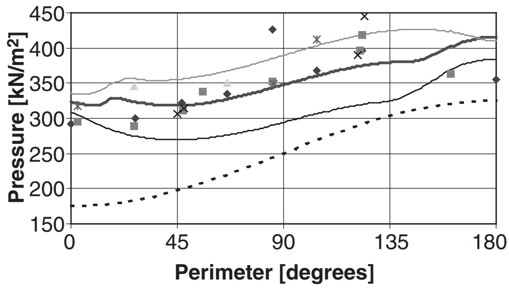

Figure 3. Calculated and measured radial grout pressures along the perimeter of the tunnel lining. The three continuous lines in the graph represent the calculated grout pressures distributions at 90, 100 and 110% grout fill ratios. The dots are the measured grout pressures on the five instrumented rings. The dashed line is the radial water pressure.

The Green Heart Tunnel is part of the High Speed Line South in the Netherlands. The bored part of the tunnel is 7.1 km in length. The tunnel outer diameter is 14.5 m being the worlds largest to date. This diameter provides the space for two tracks and a division wall in between. The TBM drive was completed in 2004.

In five consecutive rings, grout pressures were measured using pressure cells cast in the concrete segments. The pressure cells were distributed over the perimeter of the lining. Figure 3 shows the results of both the measured and the calculated radial grout pressures. The vertical axis of the graph represents the grout pressure. The horizontal axis represents the perimeter of the tunnel (rotation angle). Note that the grout pressures from the left and right side of the tunnel are projected on one side only. The results of the calculations are given for three grout fill ratios (90%, 100% and 110% of the theoretical grout layer thickness of 250 mm). A shear yield stress of the grout of 1.5 N/mm^2 is used.

In the calculations the geometry and properties of the lining, the geotechnical profile of the soil and the properties of the individual soil layers at the location of the measurements (25.4 km) were accounted for. At this location the centre of the tunnel is approximately 27 m below surface level.

In figure 3, the ground water pressures are shown as well. The pressure at the centre of the tunnel is estimated at 250 kN/m^2. The gradient over the tunnel height is assumed to be hydrostatic (N.B. the cosine shape is the result of the tunnel perimeter on the horizontal axis).

From figure 3 it can be seen that the measured grout pressures increase from about 300 kN/m^2 at 0° (the crown of tunnel) to 400–450 kN/m^2 at 135° and then decrease again to 350 kN/m^2 at 180°. The range of three lines representing the calculated grout pressures generally coincides with the measurements. The measured (and calculated) grout pressures differ considerably from the water pressures. The magnitude of the water pressures is much lower whereas the gradient of the water pressures is higher.

The comparison between the measured and calculated grout pressures indicates that the magnitude of the pressures can be predicted quite well. Also the gradient of the grout pressures agrees rather well with the gradient in the measurement. The use of a hydrostatic load based on the water table would be a crude approximation.

These conclusions provide sufficient confidence that the other results of the SPARTA Grout calculations i.e. soil stresses, lining stresses, lining deformations etc. can be used to evaluate the structural safety of the lining, the embedding of the tunnel in the soil, and the surface settlements. In the next sections trends observed in the calculation results will be presented and discussed.

4 TUNNEL LINING BEHAVIOUR

In the model an interaction between grout and tunnel lining exist. For a grout fill ratio of 100% the calculation results show an upward displacement of the lining of approximately 5 cm. The shape of the ring remains almost round; the ovalisation of the ring is very small (0.2 cm of the radius). The tangential stress distribution in the lining confirms this: the stress gradients over the lining thickness are very small indicating hardly any bending. For both 90% and 110% fill ratios, however, large stress gradients are observed indicating ovalisation of the tunnel. It was found that for a fill ratio of 90% the tunnel has a lying oval shape and for a fill ratio of 110% a standing oval shape.

The calculated stresses in the concrete lining can be transformed into normal forces and bending moments at each position in the ring. The combinations of normal force and bending moment can be used to determine a safety factor for the lining under the applied load case. Safety factors can be determined for both failure of the lining and for initial cracking. To estimate the safety factor of the lining here the combinations of calculated normal force bending moment in the ring will be compared to the concrete bearing capacity in the ultimate limit state.

The SPARTA Grout model predicts a high structural safety for the lining of the Green Heart Tunnel. For a 100% fill rate the minimal safety factor is 7.85. This value is used as a reference. It was found that for lower or higher fill rates the safety factor decreases. These results are presented in a relative way in figure 4, in which the safety factor at a 100% fill rate is defined as 100%.

The tail void grout injection process clearly influences the deformations (ovalisation) of the lining. At the investigated cross-section the (relatively) most

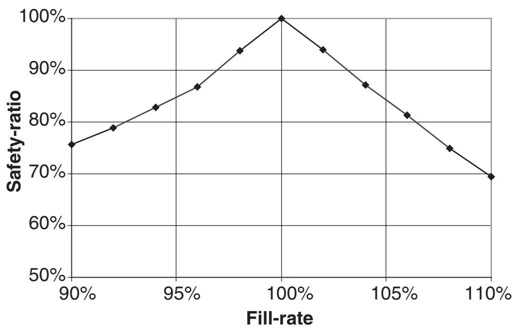

Figure 4. Structural safety of the lining as a function of the grout fill ratio (presented is a relative way).

favourable condition for the lining (small bending moments and high safety factor) occur at a 100% fill rate. At lower or higher fill rates the safety factor decreases and the ovalisation increases.

The 2-Dimensional character of the model implies that the beam action of the tunnel is not explicitly accounted for. The beam action originates from the transfer of vertical loads on one tunnel ring to the neighboring rings and/or the TBM to establish equilibrium. In the SPARTA Grout model the uplift forces on a ring can only be counteracted by the resistance of the grout and the soil, the weight of the ring and the dead weight of TBM or inlay. The use of a fictitious weight of the tunnel, however, provides a good 2-D solution to study the influence of beam action on the soil-grout-lining interaction.

5 SOIL DEFORMATIONS

Due to the tunnel boring process i.e. the excavation and the grout injection, the soil around the tunnel deforms. As a consequence the stresses in the soil will change. The changes of the vertical stress distribution in the soil are clearly visible in figure 5. In the graph, colours indicate the stress levels. At the left and right of the graph the original vertical stress distribution is still visible figure. Around the tunnel however the stress pattern of horizontal layers is disturbed. The disturbance is such that -except at the crown of the tunnel- the soil stress around the tunnel has decreased. For the horizontal stress distribution a similar decrease of stresses is found (figure 6). As a result of the changes in the horizontal and vertical stress around the tunnel the stability of the soil may decrease and plastic deformations may occur. The plasticity can influence the stiffness of the support of the tunnel. For the case in view the effects on the stability were small en very local.

The influence of the grout injection will also be visible in the surface settlements. The settlements can be deduced from the results of the vertical displacements

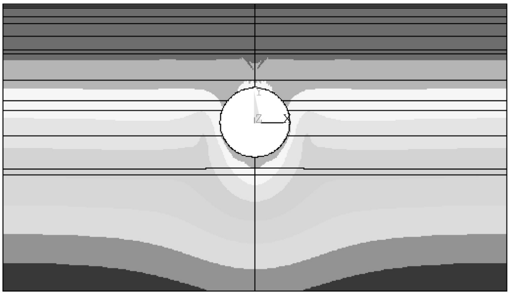

Figure 5. Vertical effective stress distribution in the soil for a grout fill ratio of 100%.

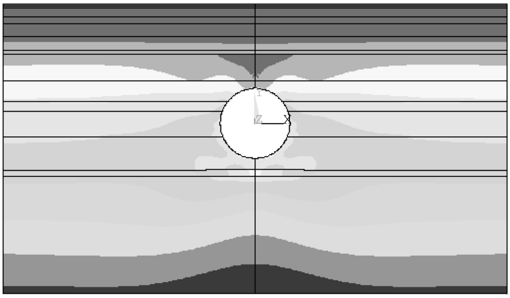

Figure 6. Horizontal effective stress distribution in the soil for a grout fill ratio of 100%.

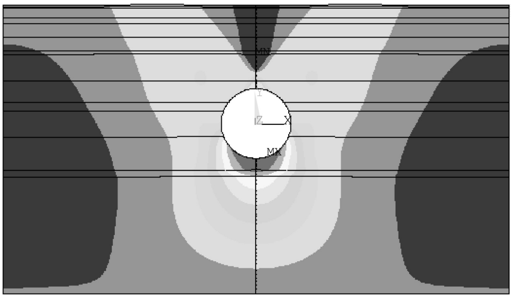

Figure 7. Vertical soil displacements for a grout fill ratio of 100%.

of the soil around the tunnel. An example of the vertical displacements is given in the contour plot in figure 7.

A summary of the displacements of the surface level and the border of the excavated circle in the soil is given in figure 8. The soil at the bottom of the tunnel rises 7 cm. The soil right above the tunnel rises 4 cm. The surface level right above the tunnel subsides by 1 cm, while the surface level next to the tunnel rises by 1 cm. Such a displacement pattern may explain the occurrence of settlements troughs steeper than expected.

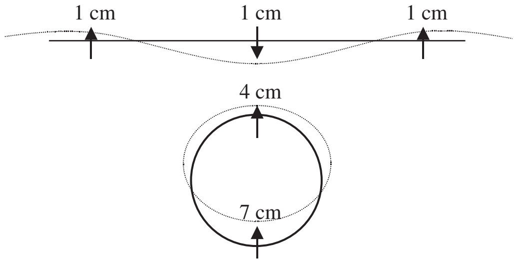

Figure 8. Schematic representation of the vertical displacements of the surface level and the perimeter of the excavated circle in the soil for a 100% grout fill ratio.

At the crown of the tunnel the soil moves upward whereas at the surface the soil moves downward. This will be the effect of a softening in the soil due to changes in the vertical and horizontal stress pattern. The resistance of the soil acting on the tunnel is generated at the shoulders of the tunnel in zones in the soil at an angle of 45° directing towards the surface.

The results presented here agree very well with the results of the research by Nakken et al. (2004). Nakken used the soil dedicated package PLAXIS to study the effect of grouting strategies on soil and lining. This model focuses on the solid character of the grout using visco-plasticity to model the limited shear strength of the grout.

Although the ovalisation of the ring is very small (0.2 cm as mentioned in section 4), figure 8 implies an ovalisation of $(7-4)/2 = 1.5$ cm of the border of the excavated circle in the soil. This means that the shape of the gap between lining and soil has changed and a considerable amount of grout has moved (flowed) to the bottom of the tunnel.

6 CONCLUSIONS AND PERSPECTIVE

The SPARTA Grout model combines three components of bored tunnels (soil-grout-lining) and their interfaces in one model. The model focuses on the solid and fluid properties of the grout layer and their influence on both the tunnel lining and the surrounding soil.

The model was applied to a practical case of the Green Heart Tunnel. From the comparison between the measured and calculated grout pressures it was concluded that the magnitude and the gradient of the grout pressures could be predicted quite well.

This conclusion provides sufficient confidence that other results of the calculations (i.e. soil stresses, lining stresses, lining deformations etc.) can be used to evaluate the structural safety of the lining, plasticity in the soil and surface level settlements.

For the practical case several trends in the behaviour of lining and soil were presented. It was concluded that a 100% fill rate was the (relatively) most favourable condition for the lining. However, in a parallel study for a different cross-section of the tunnel a grout fill rate of 90% was most favourable. The main difference between the two cross-sections was the depth of the tunnel: a cover of more than the tunnel diameter and a cover of less than the diameter respectively. The results suggest that a similar grouting strategy for rings with different ground cover, leads to different structural safety of the lining. Of course such a grouting strategy may affect other aspects in a negative way (e.g. settlements, plasticity, support of the tunnel).

The SPARTA Grout model is able to explain the trends in the behaviour of the tunnel lining and the surface settlements during construction as observed in practice. The model also enables the evaluation of different grouting strategies in order to minimise lining deformations and/or surface settlements focused on the projects interests.

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