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Combining Bored Tunnels: Optimal Construction Order of Multiple Independent Shield-Driven Tunnels

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Abstract

A three-tunnel configuration was proposed to strengthen the North-South connection in Brussels. The optimal construction order of the bored tunnels, mainly focusing on the settlements and deformations of the surrounding soil mass is investigated here. All two-tunnel and three-tunnel construction orders are investigated by mainly focusing on the surface settlements calculated with Plaxis 2D. An extended variant of the grout pressure method is developed to also incorporate the relative magnitude of the different settlement components due to shield tunneling. The accuracy of a simplified version is simultaneously tested by comparison of the obtained final settlement troughs. The influence of the constitutive model on the settlement values is also verified. More specifically, the difference in results between the Mohr-Coulomb model and the Hardened Strain model with small strain stiffness is investigated. Finally, a simple empirical superposition principle is established based on the method of Peck to approximate the Plaxis results. The research is based on the geometry of and other assumptions made for a new tunnel connection in Brussels but presents a general overall design concept. The results can thus be generalized to other multiple tunnel configurations.

Keywords: Multiple tunnels, Settlements, Construction order, Grout pressure method, Plaxis 2D.

1 Introduction

Brussels has the largest mobility issues in Belgium. To tackle these issues, kilometers of new metro lines including new substations are going to be build. Part of the plan is to strengthen the North-South connection starting from Schaarbeek. To minimize the amount of disruption to the daily city life, that part of the metro expansion is completely tunnelled.

For the tunneled part between the main North and Central stations, a new type of tunnel design was proposed. In general, a tunnel diameter is chosen in function of the required space that is requested. The tunnel diameter is limited, therefore when more space is desired the roads or rails are fitted into two tunnels. The idea was to construct three smaller tunnels with TBMs and to also utilize the area, enclosed by the three tunnels, as functional space. Combining multiple tunnel tubes into a larger whole of independently drilled tunnels is a delicate operation. The University of Ghent has been asked to further investigate the feasibility of the idea for the North-Central connection. Focusing on the settlements and deformations of the surrounding soil mass is investigated here.
2 General instructions

2.1 Empirical formulations

The most globally used empirical method is to approximate the surface settlement by a Gaussian curve according to Peck:

\[ S_T(y) = S_{v,max} \cdot \exp \left( -\frac{y^2}{2\sigma^2} \right) \]  

(1)

With \( S_{v,max} \) the maximal transversal settlement, \( y \) is the horizontal distance from the tunnel axis and \( \sigma \) is the horizontal distance from the tunnel axis to the point of inflection. O’Reilly and New proposed a straightforward linear relationship to the tunnel depth \( z_0 \) \( : y = K \cdot z_0 \). The settlement trough is represented by a Gaussian curve in Figure 1.

![Figure 1. Gaussian curve for transverse settlement through and ground loss](image)

The volume loss \( V_s \) is equal to the volume of the settlement trough and can be achieved by integrating (1). The ground loss \( V_t \) is defined as the volume of ground that is over excavated compared to the installed tunnel volume as visualized in the bottom part of Figure 1. The following can be assumed without introducing large errors: \( V_t = V_s \) [2]. The ground loss ratio (GLR) can thus be defined as follows with \( A_t \) the excavated tunnel volume:

\[ GLR = \frac{V_t}{A_t} \approx \frac{V_s}{A_t} \]  

(2)

The principle of superposition is often applied to determine the final settlement trough due to multiple tunnels. The transverse settlement troughs are then determined separately for each tunnel according to Peck and afterwards superimposed to estimate the final settlement trough. Many however confirmed its inaccuracy and recommended more complicated superposition relationships to among others obtain the correct trough skewness [4].

2.2 Finite element method – Plaxis 2D

The numerical calculations were performed in Plaxis 2D. An extended version of the grout pressure method was developed. Numerical methods in general overestimate the trough width. The grout pressure method however is known to best estimate the trough width [6].

Moreover, the influence of the constitutive model on the results was verified for the MC model and the HSsmall model. In particular the Oedometer modulus \( E_{oed,MC} \) of the MC model was related to the unloading reloading modulus of the HSsmall \( E_u \) to improve the accuracy of the MC model.

Current research postulates the following conclusions concerning the influence of the constitutive model. Firstly, the settlement trough becomes deeper when taking into account plastic deformations. Secondly, considering hardening mechanisms results in a wider settlement trough. Lastly, taking into account the small strain stiffness leads to a reduction in maximal settlements without affecting the through width [5]. The HSsmall model is known to be superior in predicting the settlements.

The interaction between sequentially constructed tunnels is known to be overestimated by FEMs. The simulation of a series of tunnel excavations appeared to lead to an accumulation of undesirable shear strains around the existing tunnels due to the latest excavated tunnels. The undesirable shear strains reduce the soil stiffness and lead to higher peak values and a wider settlement through [7]. Chen et al. discovered that modelling the construction of all tunnels simultaneously could lead to better approximations of the field results [8].

3 Model validation

3.1 Extended grout pressure method

The idea was to simulate all construction stages that belong to a slurry TBM excavation process. Table 1 provides an overview of the utilized
construction phases and its characteristics. The face pressures [9, 10] and tail void pressures [11-14] were carefully determined based on existing research. The simplified version of the proposed grout pressure method consists of the final two phases 5 and 6 listed in Table 1.

**Table 1. Overview of the grout pressure method**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Action</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 0</td>
<td>Initial phase</td>
<td>Generation of initial state</td>
</tr>
<tr>
<td>Phase 1</td>
<td>Face pressure</td>
<td>Deactivate soil cluster; Apply face pressure $P_{r,ref} = P_r + P_{water} + 20kPa$ $P_{inc} = 12kPa/m$</td>
</tr>
<tr>
<td>Phase 2</td>
<td>TBM</td>
<td>Remove face pressure; Activate TBM</td>
</tr>
<tr>
<td>Phase 3</td>
<td>Tail pressure 0</td>
<td>Remove TBM; Apply tail void pressure $P_{r,ref} = P_{ref,face} + 100kPa$ $P_{inc} = 16kPa/m$</td>
</tr>
<tr>
<td>Phase 4</td>
<td>Tail pressure 1</td>
<td>Apply tail void pressure 1 $P_{r,ref} = P_{ref,face} + 30kPa$ $P_{inc} = 11kPa/m$</td>
</tr>
<tr>
<td>Phase 5</td>
<td>Tail pressure 2</td>
<td>Apply tail void pressure 2 $P_{r,ref} = P_{water} + 30kPa$ $P_{inc} = 11kPa/m$</td>
</tr>
<tr>
<td>Phase 6</td>
<td>Final state</td>
<td>Remove tail void pressure 2; Activate tunnel lining</td>
</tr>
</tbody>
</table>

**3.2 Case study**

The proposed grout pressure method was validated by estimating the settlements of the second Heineoord tunnel. The results were compared with the field measurements and the calculations of Möller [15]. The full model slightly underestimated the amount of settlements, while the simplified model approximated the field measurements to the mm.

**4 New proposition**

**4.1 General information**

The final three tunnel configuration holds space for four rail tracks. The configuration is made up of the reinforced whole of three individually excavated tunnels and the enclosed area in between. The tunnel center of the bottom tunnels is situated at a depth of 20m. The water table is assumed to be located five meters below the ground level. The diameter of the two bottom tunnels and the top tunnel equal 10m and 8m respectively. After excavation of the three tunnels the soil surrounding the area enclosed by the three tunnels is grouted. The three tunnels are then reinforced and interconnected with concrete elements. Finally, the enclosed soil area can be excavated. The geometry of this configuration is visualized in Figure 2.

![Figure 2. Geometry of the proposed tunnel configuration](image)

The soil layer profile is simplified to one thick clayey sand layer. Several constitutive models exist to model the soil behavior. Each model is developed to provide more accurate results for certain situations and soil conditions in combination with a minimal computation time. The three most commonly used soil constitutive models for tunnelling projects are the Mohr-Coulomb (MC) model, the hardened strain (HS) model and the hardened strain model with small strain stiffness (HSmall). All calculations were performed using the HSmall constitutive model. The MC model came into play whenever the influence of the constitutive model on the results was investigated. The soil parameters corresponding to each model can be found in Table 2.

The material characteristics of the tunnel linings are listed in Table 3. The thicknesses of the tunnel
lining are 0.5m and 0.4m for the 10m diameter tunnel and the 8m diameter tunnel respectively. The stiffness and other parameters are calculated based on these thicknesses. The weight of the lining is calculated per meter tunnel lining in plane of the tunnel's cross section and per meter in the longitudinal direction of the tunnel axis. A density of 260 kg/m³ [12] is assumed for the density of the gantry in order to be able to calculate the weight of the TBM. The TBM is assumed to be undeformable and is ascribed the following stiffnesses:

\[
EI = 10^9 \frac{kN.m^2}{m}; EA = 10^9 \frac{kN}{m}
\]  

Table 2. Overview of the soil parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>HSsmall</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_{\text{unsat}} )</td>
<td>kN/m³</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>( \gamma_{\text{sat}} )</td>
<td>kN/m³</td>
<td>19,8</td>
<td>20</td>
</tr>
<tr>
<td>( E_{\text{oed,ref}} )</td>
<td>MPa</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>( c' )</td>
<td>kPa</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( \phi' )</td>
<td>/</td>
<td>34,3</td>
<td>32</td>
</tr>
<tr>
<td>( \psi )</td>
<td>/</td>
<td>4,3</td>
<td>5</td>
</tr>
<tr>
<td>( v )</td>
<td>/</td>
<td>0,3</td>
<td>0,3</td>
</tr>
<tr>
<td>( K_0 )</td>
<td>/</td>
<td>0,47</td>
<td>0,47</td>
</tr>
<tr>
<td>( G_{\text{o0,ref}} )</td>
<td>MPa</td>
<td>94</td>
<td>8,57</td>
</tr>
<tr>
<td>RD</td>
<td>%</td>
<td>50</td>
<td>/</td>
</tr>
<tr>
<td>( E_{\text{ur,ref}} )</td>
<td>MPa</td>
<td>90</td>
<td>/</td>
</tr>
<tr>
<td>M</td>
<td>/</td>
<td>0,544</td>
<td>/</td>
</tr>
<tr>
<td>( \gamma_{0,7} )</td>
<td>/</td>
<td>1,5E-7</td>
<td>/</td>
</tr>
<tr>
<td>( R_t )</td>
<td>/</td>
<td>0,938</td>
<td>/</td>
</tr>
</tbody>
</table>

The chosen model characteristics consist of a full model width of 100m, a model height of 40m, a fine mesh size with enhanced mesh refinements and 15 node triangular mesh elements.

4.2 Singel tunnel configuration

The main parameters of the final settlement trough of one of the bottom tunnels are listed in

Table 4. The obtained maximal settlement value and the GLR value are realistic. Peck classifies the soil as a sand below groundwater level based on the inflection width and the depth of the tunnel center [1], which is the case. The final settlement trough and its empirical approximation according to Peck, for a mean sand and a GLR of 1%, are displayed in Figure 3. The final settlement value is very accurately estimated and the trough width is slightly underestimated by Peck. It can be concluded that both literature and the empirical results confirm the correctness of the Plaxis model. The Peck-modified trough is based on the Plaxis results and was created to be used as the base settlement trough to establish the superimposed settlement troughs for the two and three tunnel configurations.

Table 3. Overview of the tunnel lining parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Bottom tunnel</th>
<th>Top tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>m</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>( E_c )</td>
<td>kPa</td>
<td>37000</td>
<td>37000</td>
</tr>
<tr>
<td>( \rho_c )</td>
<td>kg/m³</td>
<td>2450</td>
<td>2450</td>
</tr>
<tr>
<td>t</td>
<td>m</td>
<td>0,5</td>
<td>0,4</td>
</tr>
<tr>
<td>A</td>
<td>m²</td>
<td>14,92</td>
<td>9,55</td>
</tr>
<tr>
<td>I</td>
<td>m⁴</td>
<td>168,8</td>
<td>69,1</td>
</tr>
<tr>
<td>EA</td>
<td>kN</td>
<td>1,85E7</td>
<td>1,48E7</td>
</tr>
<tr>
<td>EI</td>
<td>kN.m²</td>
<td>3,85E5</td>
<td>1,97E5</td>
</tr>
<tr>
<td>( W_{\text{lining}} )</td>
<td>kN/m</td>
<td>12,02</td>
<td>9,61</td>
</tr>
<tr>
<td>( W_{\text{TBM}} )</td>
<td>kN/m</td>
<td>18,1</td>
<td>14,5</td>
</tr>
</tbody>
</table>

Table 4. Main parameters final settlement trough (simplified, HSsmall)

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>( S_{\text{max}} ) (mm)</th>
<th>i (mm)</th>
<th>GLR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom</td>
<td>44,9</td>
<td>9,38</td>
<td>1,13</td>
</tr>
<tr>
<td>Top</td>
<td>22,7</td>
<td>6,5</td>
<td>1,28</td>
</tr>
</tbody>
</table>
A phase wise settlement trough is visualized in Figure 4. It is clear that mainly the face pressure face and the tail void 2 pressure phase contribute to the final settlement trough. The proposed grout pressure method can thus not be used to calculate the relative magnitude of all settlement components.

4.3 Twin tunnel configuration

The twin tunnel configurations were investigated in an intermediate step. More literature is available concerning twin tunnels making it easier to validate the results and the main conclusions of the proposed configuration. Figure 5 gives an overview of the final settlement troughs of the investigated twin tunnel configurations. It can be noted that constructing the top tunnel first, leads to the least amount of settlements. Do keep in mind that the tunnel diameters equal 8m and 10m for the top tunnel and the bottom tunnels respectively.

4.4 Triangular tunnel configuration

The three possible construction orders by which the proposed configuration can be achieved were investigated. The final settlement troughs are displayed in Figure 6. The results indicate that constructing the top tunnel before the bottom tunnels leads to the least amount of settlements. It can even be stated that the sooner the top tunnel is constructed, the less settlements are generated. The maximum settlement value due to each tunnel is provided in Table 5, in order to give a better insight into the relative contributions. As such it can be noted that the later constructed tunnels lead to less settlements compared to its single tunnel variants constructed in greenfield conditions.

<table>
<thead>
<tr>
<th>Conf.</th>
<th>(S_{\text{max, tot}}) (mm)</th>
<th>(S_{\text{max, 1}}) (mm)</th>
<th>(S_{\text{max, 2}}) (mm)</th>
<th>(S_{\text{max, 3}}) (mm)</th>
<th>GLR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-Left-Right</td>
<td>-58,9</td>
<td>-22,7</td>
<td>-31,5</td>
<td>-32,9</td>
<td>1,45</td>
</tr>
<tr>
<td>Left-Top-Right</td>
<td>-68,2</td>
<td>-44,7</td>
<td>-17,6</td>
<td>-31,3</td>
<td>1,62</td>
</tr>
<tr>
<td>Bottom-Top</td>
<td>-69,1</td>
<td>-42,6</td>
<td>-26,5</td>
<td>/</td>
<td>2,47</td>
</tr>
<tr>
<td>Top-Bottom</td>
<td>-67,0</td>
<td>-44,9</td>
<td>-18,2</td>
<td>/</td>
<td>2,15</td>
</tr>
<tr>
<td>Hor.</td>
<td>-59,4</td>
<td>-59,0</td>
<td>-56,4</td>
<td>/</td>
<td>2,51</td>
</tr>
</tbody>
</table>
conditions in the field is to linearly increase the Oedometer value with increasing depth [16].

Figure 7 displays the final settlement trough after each phase for the optimal Top – Left – Right construction order. The contribution due to each tunnel is clearly visualized, as is the contribution due to each phase.

The difference in absolute settlement values between using the HSsmall model or the MC model was approximately a factor 2. After extensive modelling research the value of the Oedometer modulus $E_{oed}$ appeared to be the most important cause. The Oedometer moduli of both the MC and HSsmall model were chosen equal to 30MPa. The HSsmall model utilizes an additional unloading reloading modulus $E_{ur}$, which was taken equal to 90MPa as listed in Table 2. The influence of the Oedometer modulus was investigated for the three-tunnel configuration for which the top tunnel was excavated first. It can be concluded that the appropriate value of the MC’s Oedometer modulus is situated in the range of $E_{oed}$ to $E_{ur}$ of the HSsmall model. An Oedometer modulus of 60MPa (=66% of $E_{ur}$) approximates the HSsmall model within 10% in this sandy soil situation. Another possibility to better model the soil conditions in the field is to linearly increase the Oedometer value with increasing depth [16].

Figure 7. Final settlement trough after each phase for the Top – Left – Right configuration

Figure 8. Influence of the Oedometer modulus $E_{oed}$ on the settlement trough

Figure 9 indicates that simply superimposing the modified-Peck curves at the correct locations does not lead to a good empirical approximation of the Plaxis results. A modified superposition principle was established in order to better approximate the Plaxis results. The idea was to first approximate the shape of the settlement trough and to afterwards scale the settlement trough to the correct size. The correct shape was approximated by summing up the trough $T_1$ due to the first tunnel and the scaled troughs $T_{i,\text{scaled}}$ due to the later constructed tunnels. The summed trough is then sized by trial and error to best match the Plaxis trough by playing with value of the size factor $S$. Equations (4) and (5) illustrate the utilized expressions.

$$T_{\text{Tot,Modified}} = S \left(T_1 + T_{2,\text{scaled}} + T_{3,\text{scaled}}\right)$$

with

$$T_{i,\text{scaled}} = T_i \frac{S_{\text{max,Plaxis},i}}{S_{\text{max,Pec},i}}$$
The simple modified superposition principle accurately estimates the trough shapes obtained by Plaxis for all investigated configurations, both for the two-tunnel as for the three-tunnel variants. Table 6 gives an overview of the sizing factor for the investigated construction orders. It can be concluded that simply scaling the settlement troughs of the later constructed tunnels already provides a good approximation of the Plaxis results. The Plaxis results are almost perfectly approximated when the sizing factor is taken into account. The trough width of the Plaxis results however always remain larger than obtained by the empirical calculations.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-Left-Right</td>
<td>0.9</td>
</tr>
<tr>
<td>Left-Top-Right</td>
<td>0.87</td>
</tr>
<tr>
<td>Left-Right-Top</td>
<td>1.00</td>
</tr>
</tbody>
</table>

5 Alternative configurations

5.1 Vertically spaced twin tunnels

The influence of the construction order for vertically spaced twin tunnels is visualized in Table 6. It can be concluded that constructing the top tunnel first leads to smaller overall settlements. It was moreover noted that the horizontally spaced twin tunnel configuration led to less settlements that the vertically spaced twin tunnel configuration.

5.2 Horizontally spaced twin tunnels

The idea behind the alternative horizontally spaced twin tunnel configuration is to form an alternative to the three-tunnel configuration proposed earlier. The tunnel diameters were chosen equal to 11m, so that the space for the same four rails is provided within the two tunnels. At the same time, the influence of the intermediary distance between the tunnels is investigated. The reference situation is chosen to have the same intermediary distance as the proposition of 5.5m, being half of the diameter of the tunnels. Figure 10 displays the settlement troughs of the investigated intermediary distances. It can be concluded that the maximal settlement value decreases when the intermediary distance between the tunnel is increased. Moreover, the interaction between both tunnels becomes negligible when the intermediary distance is larger than 2D.

The results of the alternative tunnel configuration is compared with the proposed proposition in Table 5. The GLR and the total amount of settlement are higher for the alternative configuration. Both values are even underestimated in the respective calculations due to the considerable settlements at the vertical mesh boundaries. The discussed situation thus seems to be a good proposition settlement wise.

6 Conclusions

The main goal of the paper was to investigate the optimal construction sequence for the multi-tunnel situation. The results are clear and indicate that the construction of the top tunnel before the
bottom tunnels leads to the least amount of settlements.

The following conclusions could be made concerning construction orders and relative tunnel positions. A horizontal twin tunnel configuration leads to less settlements than a vertical twin tunnel configuration. When the intermediary distance between horizontally spaced tunnels is increased, the maximal settlement value decreases and the overall settlement volume increases. Overall it could be concluded that the intermediary distance between the tunnels and the depth relative to the surface have a large influence on the settlement values. Moreover, it was the case that the sooner the top tunnel was constructed, the smaller the final settlements were. A final observation was that later constructed tunnels led to smaller individual settlements compared to its single tunnel variants in green field conditions.

The proposed grout pressure method turned out to provide accurate results. The simplified model approximated the full model very well. The determination of accurate tail void grout pressures is therefore crucial in obtaining accurate settlement troughs. Definitely with the encountered sensitivity of the settlement values to variations in the bentonite and grout pressures.

The choice of the constitutive model and its parameters has a large influence on the results obtained with Plaxis. The HSsmall model results in the best approximation of the settlement trough. The stiffness modulus of the soil should be carefully determined when utilizing the MC model.

The proposed superposition principle proved to be a simple empirical way to estimate the Plaxis results. A negative characteristic of the principle however is that the scaling and sizing factors need to be calibrated with Plaxis.

7 References


