Three dimensional simulation of slurry shield tunnelling

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ABSTRACT: The movements and settlements of the soil associated with slurry shield tunnelling depend on many parameters of the control of the tunnel boring machine: slurry pressure on the face, over cut of the machine itself, injection of the grout in the annular void behind the TBM. The two dimensional simulations by considering the concept of stress release or volume loss for every step of the construction enable to calculate approximately the measured movements considering the contribution of every parameter step by step with a corrective coefficient due to 2D simplification. But this corrective coefficient can be only determined by back analysis based on the experimental measurements. We propose a three dimensional numerical simulation for the excavation aiming to take into account the physics of the problem: face supporting, over cut and conical shape of the machine, the injection of grout in the annular void and its consolidation. After a precise description of the principles of simulation of the excavation process, an example of calculation applied to the CAIRO metro is presented and analysed.

1 INTRODUCTION

The movements and settlements of the soil associated with slurry shield tunnelling depend on many parameters of the control of the tunnel boring machine. In order to limit these movements, the pilot may control the bentonite slurry pressure on the face, the value of the over cut of the machine itself, and on the procedures of injection of the grout in the annular void around the final tunnel.

If observations on the site may help to analyse the contribution of the different parameters in the soil movements around the tunnel, meanwhile their forecast is still difficult and empirical. The two dimensional simulations by considering the concept of stress release or volume loss for every step of the construction enable to calculate approximately the measured movements considering the contribution of every parameter step by step. Nevertheless these approaches require the application of a coefficient similar to the "deconfinement coefficient" aiming to take into consideration the strongly three dimensional nature of the problem. Because of the complexity of the effect of every parameter and their interactions, this corrective coefficient can be only determined by back analysis based on the experimental measurements.

In order to be able to evaluate the influence of the choice of the control parameters of the tunnel boring machine on the magnitude of the settlements, we propose a three dimensional numerical simulation for the excavation aiming to take into account the physics of the problem: face supporting, over cut and conical shape of the machine, the injection of grout in the annular void and its consolidation. These simulations are realised with the aid of the computer program FLAC 3D using an explicit finite difference scheme and developed by ITASCA. After a precise description of the principles of simulation of the excavation process, an example of calculation applied to the CAIRO metro is presented and analysed.

2 PRESENTATION OF THE STUDY SECTION.

2.1 Experimental section.

Line 2 of Cairo subway network is 18.5 km long with 5.9 km of tunnel bored with the slurry shield technique. The 9.8 m in diameter tunnel runs through soils of relatively poor geotechnical characteristics corresponding to alluvial deposits from the Nile floods. A experimental section (with the tunnel 25 m deep) has been instrumented mainly with a 4 point extensometer (figure 1) taken as a reference in sequel.

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2.2 Geotechnical characteristics of the site

Extensive in situ or laboratory tests performed provide a description of the different geological formations encountered. Table 1 summarises the data necessary to the project.

For the sake of numerical modelling, an elasto perfectly plastic behaviour has been assumed with Mohr Coulomb criterium.

The simulations have been performed under drained conditions. Earth coefficient at rest is derived from Jaky’s equation $K_0 = 1 - \sin \varphi$.

3 NUMERICAL PROCEDURES

According to the experimental work of (Kastner 1996) and those reported here (figure 2), the observed subsurface movements due to the different phases of tunnel boring with slurry shield technique exhibit cycles of deconfinement and reconfinement.

Due to technical problems, the settlement of the extensometer head is not precisely known but can be estimated to 5-10 mm (result of comparison with other sections).

3.1 Tunnel boring phases.

The different loading cycles are mainly due to overcutting, shield conicity, grouting and the grout consolidation (figure 3).

These observations led to the definition of numerical procedures accounting for the different phases in two approaches: two dimensional and three dimensional.

Four excavation phases have been defined:
- Phase 1: The passage of the cutting shield.
- Phase 2: The passage of the tunnelling machine.
- Phase 3: Grouting at the extrados of the tunnel lining.
- Phase 4: Consolidation of the grout.

3.2 2D analysis

The TBM advance induces a change in boundary conditions in localised zones thus requiring a 3D approach in order to accurately model the excavation process (this method will be presented in the following section). Nevertheless a plane strain 2D analysis has been performed here because of very small displacements along the tunnel axis. Therefore this approximate approach requires a correction on...
the boundary conditions accounting for the 3D to 2D transition. This correction can be applied either on stresses around the lining trough a deconfinement coefficient (Bernat 1996) or on displacements by adjusting, for each phase, the tunnel diameter to meet the experimental value of the extensometer point next to the tunnel crown. This volume loss approach has been considered in the following.

Figure 4 shows the soil ring representing in a first stage the rigid shield and in a second stage the grout annulus. Interaction between soil and annulus has been modelled with interface elements of Mohr Coulomb's type behaviour.

The large strain 2D analysis have been performed with the finite differences code FLAC 3.40 developed by Itasca Consulting Group.

Now, the method used for the simulation of the different loading cycles occurring during the shield advance has to be detailed. All these simulations assume the invert is fixed (De borst 1996), (Benmebarek 1998).

The passage of the front has been firstly accounted for by a decrease of the soil/shield interface characteristics and no volume loss (two sets of values have been tested : C=8 kPa, \( \varphi =0^\circ \) and C=0 kPa, \( \varphi =0^\circ \)). This decrease induces a sliding around the tunnel lining. Since the computed displacements were not big enough to meet the extensometer results, it has been necessary to implement a volume loss. The important overcutting explains this phenomenon.

The passage of the tunnelling machine is modelled by a decrease of the annulus diameter using a dynamic soil-shield friction (C=8 kPa, \( \varphi =0^\circ \)).

The grouting at the extrados of the tunnel lining through injection pipes is accounted for by an increase of the annulus diameter (this procedure is physically more satisfying than applying a pressure on the soil (Benmebarek 1998)).

As for the grout consolidation, it has been modelled by a decrease of diameter until the experimental results are met.

3.3 3D analysis

The 3D numerical procedure aims at defining the different steps of boring without any correction due to localisation of boundary conditions. Figure 5 shows these steps.

The applied pressure at the face is 40 kPa at the tunnel axis level with a vertical gradient according to the slurry density (\( \gamma_{\text{slurry}} = 11 \text{ kN/m}^3 \)) as done by (Van eekelen 1997). Due to overcutting, it is likely that the slurry propagates along the shield. A maximum distance of propagation of 1,5 m has been assumed.

Nevertheless a partial filling of the void due to overcutting by this slurry is not taken into account in the calculations.

In the next phase, the soil converges towards the shield (supposed to be infinitely rigid).

A pressure of 300 kPa corresponding to the annular void grouting is applied on a distance of 1,5 m after the tail. Then consolidation of the grout occurs, the grout being assumed elastic (E=10 Mpa, \( \nu =0.3 \) according to oedometer tests) and the tunnel lining rigid.

The numerical model (figure 6) consists of 71000 zones and allows 60 excavation phases of 0,75 m long (ie 45 m), to reach a stationary state.

4 RESULTS OF 2D CALCULATIONS

Table 2 summarises the volumetric deconfinement and reconfinement cycles applied to the ring to
Figure 6: 3D Numerical model.

Table 2: Variations of the ring radius (mm).

<table>
<thead>
<tr>
<th>Phases</th>
<th>Real values</th>
<th>S-1</th>
<th>S-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passage of the front</td>
<td>-25,0</td>
<td>-4,12</td>
<td>-4,34</td>
</tr>
<tr>
<td>Conicity of the shield</td>
<td>-10,0</td>
<td>-6,74</td>
<td>-6,66</td>
</tr>
<tr>
<td>Grout injection</td>
<td>1,04</td>
<td>1,04</td>
<td></td>
</tr>
<tr>
<td>Consolidation</td>
<td>-4,56</td>
<td>-4,58</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7: Evolution of horizontal displacements

Thus the 2.5 cm of overcutting of the Cairo works qualitatively alter the horizontal movements.

At the tail exit, a small additional movement can be observed as well as a global heave of the soil (in disagreement with the extensometer measurement). Then experimental movements of the extensometer points are compared with the results obtained in the bidimensional calculations taking as a reference the closest point to the tunnel crown (figure 8).

Bidimensional approach does not qualitatively reproduce the damping of the settlements towards the surface, indeed it is noted that B, C and D have the same behaviour as A whereas experimental measurements shows a great damping from B and upwards.

Taking the extensometer point closest to the tunnel crown as a reference does not yield the complete displacements field around the tunnel.

In this case, the limits of the two dimensional approach are reached, since it does not consider the localisation of boundary conditions. Finally the comparison of real shield radius variations with those imposed in the calculations taking A as a reference (table 2) clearly shows the three dimensional effects: while the overcutting is about 25 mm, it is simulated by a decrease of the shield radius of only 4 mm. Furthermore the 10 mm of shield conicity is simulated by a radius decrease of about 7 mm. A constant ratio between the imposed radius variations and the real radius variations can not be found for this two bidimensional simulation of a three dimensional problem.

5 RESULTS OF 3D CALCULATIONS

The computed behaviour (figure 9) is qualitatively the same as the observations measured in situ, more particularly the surface settlement is smaller than the settlement at a given depth before the passage of the TBM. This phenomenon observed in the
 experimental results is highlighted here and more in the Vaise works (France) (Kastner 1996). Two dimensional calculations can not in any case yield this kind of movements before the passage of the TBM.

The main difference with in situ observations comes from the fact that we do not take into account the progression of the slurry in the void between soil and shield. Therefore it greatly overestimates final displacements. Nevertheless the ratio between the settlement at the passage of the TBM and the final settlements remains constant (about 30%).

In the present case, 3D calculation allows to correctly simulate soil behaviour by simply applying the real injection pressure: we note that the deepest point of the extensometer presents a 1 mm upwards displacement as it is shown by the measurements. In addition, the points located above are not affected by injection in accordance with the in situ observations. On the other hand, grout consolidation after injection is very clearly underestimated by calculation. It is simulated by a simple elastic compression of the grout. In fact, the consolidation of the grout has been found to be an initial water release followed by a progressive setting after approximately 24 hours. Mean bulk modulus which simulates this set of stages is obviously overestimated in our simulations.

Figure 12 illustrates movements around the tunnel. It is worth noting movements localisation due to shield conicity and the effects of injection pressure. The maximum settlement is reached 20 meters behind the face in agreement with the experimental observations.

Of particular interest is also the computed 3D settlement trough (figure 10) even though it is difficult to clearly compare these results with in situ measurements. This is mainly due to the fact that the filling of the annular void between soil and shield by slurry has not been accounted for.

In order to compare the 2D and the 3D computed settlement troughs, the Gaussian distribution curve proposed by (Peck 1969) has been used:

$$S_z = S_{\text{max}} e^{-\frac{x^2}{2i^2}}$$  \hspace{1cm} (1.1)

which describes the 2D vertical surface displacements profiles transverse to an infinitely long bored tunnel. $S_{\text{max}}$ represents the maximum surface displacement at the tunnel centre-line, $x$ is the offset from the tunnel centre-line, and $i$ is the trough width parameter equal to the offset from the tunnel centre-line to the point of inflection in the profile.

It is noted that the transverse trough obtained in a 3D analysis has a smaller width than the one derived from 2D analysis (table 3 and figure 11). This result is qualitatively interesting because experience shows that 2D analysis assuming linear elasticity generally overestimate the actual settlement trough width.

6 CONCLUSIONS

The comparisons between two dimensional numerical simulations, three dimensional simulations and experimental results gives a good evaluation of the improvements of a 3D analysis.

With the 3D approach, we can obtain a displacement fields close to the ones observed in situ, in using the pressures and the volumetric deconfinements measured in real sites. We do not have to use corrective coefficients such as the stress (or the volumetric) deconfining factor used in a 2D computation, which can only be obtained by back analysis.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>2D</th>
<th>3D - Transverse</th>
<th>3D - Longitudinal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\text{max}}$ (mm)</td>
<td>8.48</td>
<td>15.82</td>
<td>16.93</td>
</tr>
<tr>
<td>$i$ (m)</td>
<td>15.01</td>
<td>11.50</td>
<td>19.10</td>
</tr>
</tbody>
</table>
The full displacement history of an underground work done with a pressurised shield TBM can be correctly simulated with a 3D approach. In the studied case presented in this paper, it seems necessary to refine the simulations by taking in account the partial filling of the void between the tunnelling machine and the soil with bentonitic slurry (near the face) and a more realistic behaviour with time of the grout (near the tail).

REFERENCES


