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Results of a benchmark exercise of prediction of tunnel-pile interaction: the TULIP project

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ABSTRACT: The TULIP project, initiated by Société du Grand Paris with Université Gustave Eiffel, CETU (French Centre for Tunnel Studies) and ENTPE, consisted in a full scale experiment aiming at quantifying the impact of the passage of the TBM on three piles on a site located in Aulnay-sous-Bois (France). The piles were built especially for the project a few months before the TBM passage. They were equipped with topographic targets, vibrating wire gauges and optical fibers. The ground was instrumented with targets, inclinometers, extensometers, pore pressure cells. The evolutions of the displacements in the ground and of the piles heads, and the efforts in the piles were monitored during the TBM progression. A benchmark exercise was proposed to the French engineering companies; the aim was to provide “class A” predictions of: the settlement of the ground surface far from the piles, the settlement of the head of one of the piles, the variations of the axial load in the selected pile. This communication provides a short presentation of the numerical approaches adopted by the participants and draws some conclusions regarding the current practice of numerical modelling of TBM excavation process and of tunnel/ground/pile interactions.

Keywords: Surface settlements; inclinometers; extensometers; normal force in piles; TBM / soft ground / pile interaction

1 INTRODUCTION

The interaction between tunnels and existing foundations has been intensively studied numerically in recent years, but there is still no consensus on the choice of the methods to adopt. Case studies providing results of in-situ experiments that can be used for the validation of numerical models are rare and often incomplete, but one can mention the publications on various projects by Kaalberg *et al.* (2005), Pang *et al.* (2006), Standing and Selemetas (2013) or Liu *et al.* (2014).

This is why Société du Grand Paris, in charge of the construction of the future new express metro network around Paris, has launched an experimental program, called the TULIP project, aimed at better understanding the interactions between a tunnel boring machine (TBM) and piles in the context of the Paris basin.

A full-scale experiment was conducted to quantify the response of the ground and of three piles to the passage of a TBM on a site located in Aulnay-sous-Bois, France (figure 1). The piles were built especially for the project a few months before the TBM passage, which took place in July 2020. They were equipped with topographic targets, vibrating wire gauges and optical fibers. The ground was monitored with targets, 5 inclinometers, 5 extensometers and 2 pore pressure cells.

More details can be found in Mohamad *et al* (2022) and Michalski *et al* (2023).

Figure 1. View of the experimental site and of the three steel frames used to load the piles

In 2021, a benchmark exercise was proposed to the French engineering companies, who were asked to provide “class A” predictions (in the sense of the classification proposed by Lambe (1973)) of: the settlement of the ground surface far from the piles, the settlement of the head and the variations of the axial load in one of the piles. 17 engineering companies & design offices and 2 academic teams took part in the prediction exercise.

2 PRESENTATION OF THE EXERCISE

2.1 *Objectives*

The exercise is focussed on the settlement of the ground surface and the response of one of the three piles, called P3. It is a 500-mm concrete pile, reinforced by 8 steel bars HA14. It is 20.5 m long and placed with an offset of 10 m from the tunnel axis. During its construction, concrete was poured before the rebar cage was sunk in the concrete. A vertical load of 2060 kN was applied on the pile head before and during the TBM passage. The pile is considered elastic, with Young's modulus varying with depth from 38 GPa at the pile head to 48 GPa at the pile toe. The vertical displacement of the pile head induced by the applied load was equal to 1.9 mm: this information was provided in the exercise files.
Participants were asked to estimate:
- the normal force along the pile after applying the load,
- the normal force along the pile after the TBM has crossed the site,
- the final settlement trough far from the pile (i.e. corresponding to greenfield conditions), characterized by the maximum settlement and the distances where the settlement is equal to 30% and 60% of the maximum value,
- the final vertical displacement of the pile head.

The participants were free to use whatever methods and tools they deemed suitable.

2.2 *Input data*

The site comprises a 3.5 m layer of made ground (MG), 9.8 m of Saint Ouen Limestone (SOL), 10.2 m of Beauchamp Sands (BS); 11.3 m of Marly Limestones (ML), above a stiff layer of Coarse Limestone (CL) (figure 2). The participants had access to a wide set of data extracted from the geotechnical survey (mostly triaxial tests and pressuremeter tests, three of which had been carried out on the project site). The water table was assumed to remain stable 11.5 m below the surface.

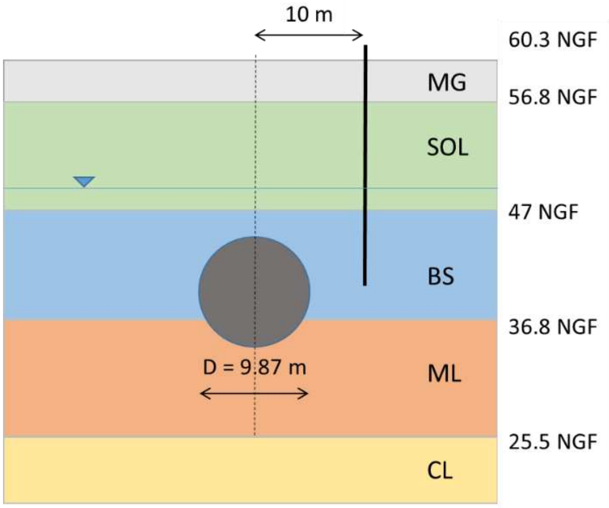

Figure 2. Cross section of the experimental site

The tunnel was built using an EPB-TBM, the outer diameter of the cutting wheel was 9.87 m, the axis depth was 21 m, and the outer diameter of the lining was 9.5 m: the lower part of the section lies in the ML layer, while the upper part is located in the BS layer (figure 2).

During the passage of the TBM under the site, the pressure in the excavation chamber was almost constant, varying linearly between 130 kPa at the crown and 220 kPa at the invert. The injection pressure of the mortar used to fill the gap behind the ground and the lining was close to 175 kPa at the depth of the crown (see Berthoz *et al.* (2022), Mohamad *et al.* (2022), Michalski *et al.* (2023), Berthoz *et al.* (2023) for more details.

3 OVERVIEW OF THE MODELLING ASSUMPTIONS

Participants had to make a number of choices and assumptions, which are briefly summarized hereafter.

3.1 *Types of analysis*

All the participants have presented results based on the finite element or the finite difference method, even if preliminary or sensitivity analysis have sometimes been carried out with empirical approaches.

In three answers, the response of the ground to the TBM passage was first discussed, then the displacements were introduced into an analysis of the pile response using the subgrade reaction coefficient method. The others used models combining the ground, the tunnel and the pile. 10 answers were based on 2D plane strain models, the other 9 resorted to 3D models.

Most participants used Plaxis, but 4 other finite element or finite difference codes were used (CESAR-LCPC, ZSoil, Lagamine and FLAC).

All analyses were performed in drained conditions: it was assumed that the pore pressure field was not significantly modified by the passage of the TBM.

3.2 *Constitutive models and parameters*

15 answers were based on the Hardening Soil Model (Schanz et al, 1999), one on the Hardening Soil-Small Strain (Benz, 2007), one on Mohr-Coulomb, one on an elastoplastic model that includes a non linear anisotropic elasticity (Gilleron *et al.* , 2021) and one on another model. The parameters adopted by the participants, notably the moduli, show a large dispersion. Using the same pressuremeter tests, the various authors have chosen values of the E_{50} modulus ranging between 50 and 350 MPa at mid-depth of the SOL layer and between 100 and 350 MPa at mid-depth of the BS layer. It is interesting to note that the results for the final settlement of the ground are much less scattered (see 4.3).

3.3 Choices for modelling the tunnelling process

Modelling the excavation is a difficult task, because of the complexity of the actual process. Many different modelling techniques were used (and unfortunately not always described very precisely) by the participants. They generally take as input parameters the pressure in the excavation chamber (which is more or less directly applied on the cutting face in the simulations), and the grouting pressure, but some methods seem to be partly based on a contraction of the lining (figure 3). In some models, the lining is explicitly discretized, but it is not always the case. Similarly, the variations of the grouting mechanical properties are not considered by all participants. As an illustration, Figure 3 proposes a simplified typology of approaches – for the 3D case only: (a) models in which the interaction between the ground and the TBM is described by means of pressures: p_c for the cutting face, p_s along the shield, and p_g for the grouting mortar; (b) models based on p_c and p_g but in which the pressure applied along the shield is zero as long as the cutting cap is not closed; (c) models explicitly based on the contraction of the lining.
A similar diversity of approaches can be observed for 2D models. In practice, the modelling of the boring process adopted by any two participants are generally not identical.

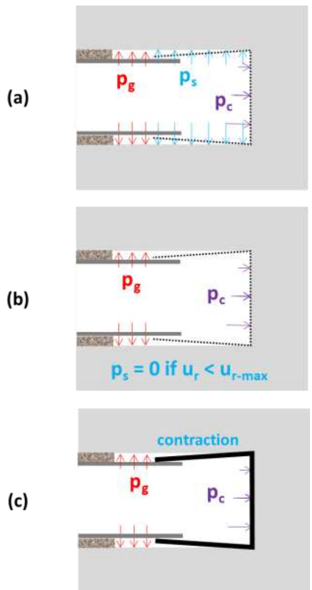

Figure 3. Simplified typology of 3D modelling approaches

3.4 Choices for modelling the pile

The models can be divided into three categories:
- pile modelled using 1D elements (beams),
- pile modelled using 3D elements,
- pile not included in the same model as the tunnel and analysed by the subgrade reaction coefficient method.

When the pile is introduced in the same finite element model as the ground and the tunnel, three main options are adopted for the ground/pile interaction: perfect adhesion, constant shear strength (Tresca criterion), shear strength described by a Mohr-Coulomb type model.

4 RESULTS

4.1 Normal force in the pile after loading

After the 2060 kN load was applied, measurements showed that the normal force in the pile was equal to 600 kN at a depth of 10 m, and in the order of 50 kN at the pile tip. As can be seen in figure 4, 17 of the 19 answers overestimate the force at mid-depth by at least 45%, and 8 answers give more than 300 kN at the pile tip, showing that friction is not correctly taken into account in the upper part of the pile shaft (made ground layer). A detailed analysis of the results shows that the model adopted to describe the soil-pile interaction has a strong influence: perfect adhesion does not make it possible to obtain realistic results, but a simple Tresca-type shear strength condition does. It can also be said that the difference between the results of plane strain models and 3D models is limited.

4.2 Normal force in the pile after TBM passage

Given that the initial distribution of normal force along the pile just after the loading was not always well reproduced, we have chosen to interpret the normal force in the pile after the TBM passage in terms of variations with respect to the initial loading.

Measurements showed an increase of the normal force in the pile, in the order of +400 kN at a depth of 7 m, and +850 kN at 16 m depth.
Six answers predicted the increase at 7 m with an error of less than 50%, 3 answers overestimated it by at least a factor 2 or 3, 7 on the contrary gave values at least 4 times smaller than the measured one. This result combines parameters relative to the pile-soil interaction and also to the tunnelling process, which explains why the discrepancy between approaches is spectacular.

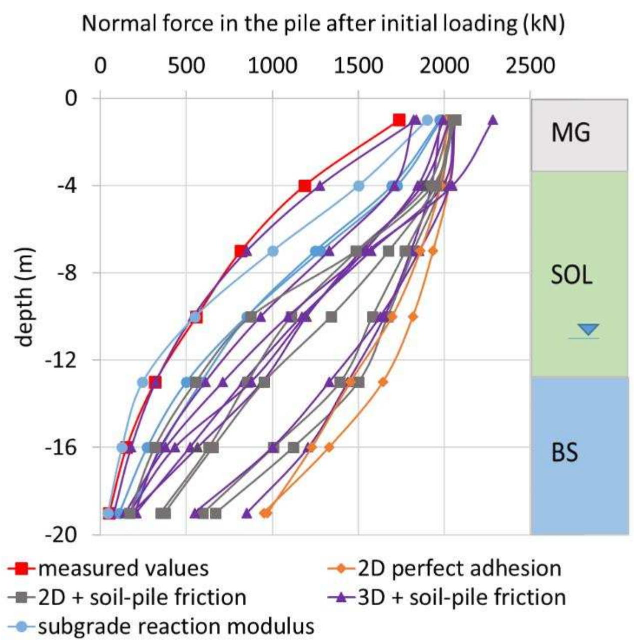

Figure 4. Normal force in the pile after loading

4.3 Settlement of the ground surface

According to the measurements, the maximum settlement above the tunnel axis was close to 10 mm. 10 answers estimated this result with an error of less than 50%. It is interesting to note that the maximum settlement is not controlled by the E_{50} modulus alone: similar settlements were obtained with very different values of the moduli, as can be seen in figure 5 in the case of the BS layer (numbers identify the participants and the pink stripe shows the interval corresponding to the measured value ±50%). A possible explanation is that the results depend on the procedure adopted to model the progress of the TBM - and also that the participants had in mind a range of acceptable values for the surface settlement.

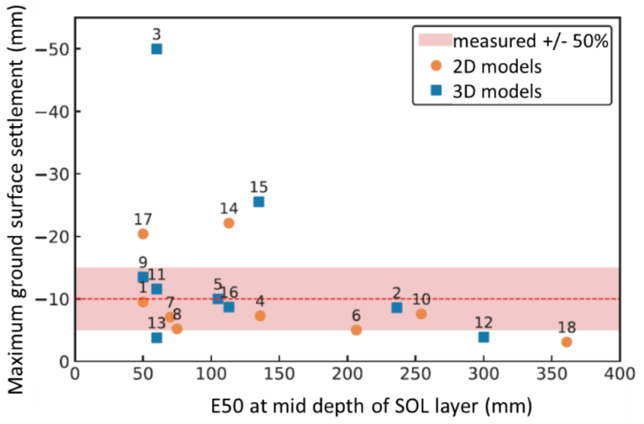

Figure 5. Max. ground settlement vs E_{50} of the SOL layer

The participants were also asked to evaluate the distance from the tunnel axis for which the settlement is equal to 60% of the maximum value of the surface settlement. The famous model proposed by Peck (1969) considers that the final settlement of the surface at a distance x from the tunnel axis can be described by:

$$S(x) = S_{max} \exp\left(-\frac{x^2}{2i^2}\right) \qquad (1)$$

where S_{max} is the maximum settlement and i corresponds to the position of the inflection point. For x=i, the settlement is equal to 60% of the maximum settlement. Measurements led to i = 8 m (or 0.4 H, where H is the axis depth). All the answers overestimated the width of the settlement trough (most values of i being in the interval [10, 12 m]), with the exception of the anisotropic model proposed by Gilleron *et al.* (2021), which gave a value close to the measures.

In a second phase of the exercise, the maximum settlement and the distance at which the settlement of the surface was equal to 60% of the maximum were communicated to the participants, to let them tune their model in order to improve the results regarding the pile head settlement or the normal force distribution along the pile. The calibration made it possible to reduce the discrepancy between answers for the maximum settlement, but not for the width of the settlement trough.

It is generally recognized that finite element simulations tend to overestimate the settlement trough width; if only greenfield settlements are to be estimated, this error can be anticipated and corrected on an empirical basis. But it is difficult to propose the same type of correction for the influence of the TBM passage of the piles.

4.4 Settlement of the pile head

After the passage of the TBM, the total settlement (including the initial settlement due to loading) of the pile head was equal to 5.2 mm. Again, the answers showed a wide scatter. Figure 6 shows the values of the pile head settlement and of the maximum ground settlements in greenfield conditions; the pink rectangle corresponds to the values for which the error with respect to the measured values is less than 50%. Seven answers gave the values of the maximum settlement of the ground surface and of the settlement of the pile head with an error of less than 50%, but some answers are correct for one of these results and incorrect for the other; this confirms that a correct representation of the ground response in terms of surface displacements is not sufficient to fully understand the pile response. Also, the figure shows no clear difference in performance between the approaches.

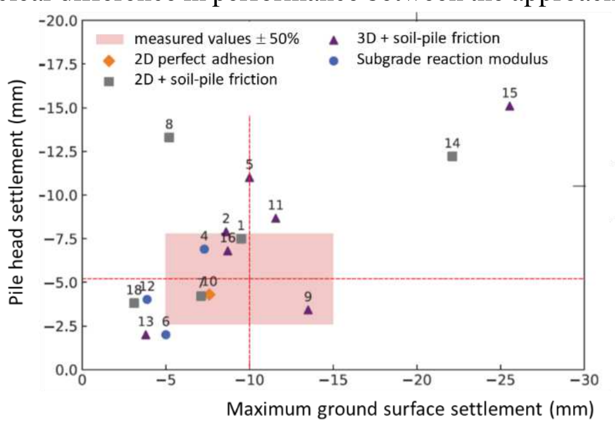

Figure 6. Max. ground settlement vs pile head settlement

5 DISCUSSION

5.1 General observations

The experiment provided orders of magnitude of the performance that can be attained with a TBM in the Paris basin for conditions representative of the Grand Paris Express project (tunnel diameter of 10 m, depth axis of 20 m): in the TULIP zone, the maximum settlement is in the order of 10 mm, the i parameter of Peck's formula close to 8 m, the volume loss is close to 0.25%, which proves that ground movements were well controlled.

In the second place, the detailed analysis of the experimental results shows that they are consistent enough to be taken as a basis for improving numerical models: the acquisition frequency and the redundancy of the measurements make it possible to trust the experimental data.

On the other hand, the number of participants involved in the prediction exercise makes it possible to use it to draw several conclusions about the way the impact of TBM tunnelling is currently dealt with by engineering companies and design offices.

5.2 Numerical simulation of soil-pile interaction

The distribution of normal force in the pile after the loading (and before the TBM passage) was relatively poorly reproduced by most models of the prediction exercise. For the experiment, the available geotechnical data were abundant and of high quality. By contrast, little information was provided in the exercise regarding the conditions in which the pile was built (except that the rebar cage could not be sunk to its theoretical position). If the initial state of existing foundations is crucial to anticipate their response to tunnelling, it is likely that an appropriate characterization of the existing state (for instance a carefully monitored static load test) is necessary to obtain realistic results.

5.3 Estimation of the ground settlements

The maximum settlement of the ground far from the pile (i.e. in greenfield conditions) was relatively well anticipated by most models. This may be due to the fact that experience - or empirical methods - are sufficient to get a rough estimate of the final settlement: this can be kept in mind to take a critical look at the simulations results. Similarly, in the context of the Paris basin, on the basis of previous studies, one can expect that the width of the settlement trough is exaggerated by numerical simulations based on the most common constitutive models.

5.4 Discrepancy due to the geotechnical model

In the initial phase of the exercise, the participants were free to choose their models and parameters. To reduce the scatter between answers, they were proposed to re-run their analyses with a unique set of geotechnical parameters for the HSM model: this set was determined by the organizers. This part of the exercise showed that, with the same parameters, large differences remained between the results of the various participants, highlighting the role of the other modelling assumptions, notably those relative to the tunnelling process.

5.5 Numerical simulation of TBM tunnelling

Results show a considerable scatter between the estimations of the pile response to tunnelling, and it can be related to the spectacular variety of numerical methods used to model the excavation process.

However, the participants have mostly used methods based on forces representing the excavation and the applied pressure rather than methods based on the contraction of the lining (or of a given zone of the mesh). It can be pointed out that the observed volume loss (in the order of 0.25%) is negligible with respect to the gap between the lining and the outer diameter of the shield (in the order of 7%); besides, the volume of mortar injected between the ground and the lining is similar to that of the gap. This is probably why most models were not based on the volume of the gap.

One can also wonder what is required to get a correct result, and what details of the modelling can be seen as secondary.

For instance, the objectives of the exercise did not make it strictly necessary to model the lining itself. From the results of the exercise, there is little evidence that the lining behavior or the type of model used to describe the interaction between the lining and the ground is a key factor in the modelling. The same can be said of the progressive hardening of the mortar.

To conclude, there is no consensus about the modelling of the TBM advance. The participants proposed very different models with a large number of parameters, which makes it difficult to directly compare the approaches. Besides, no method proved definitely more accurate for all aspects of the ground and pile responses simultaneously.

5.6 Further works

5.6.1 The other two piles of the TULIP project

In order to limit the amount of work required from the participants, the exercise was limited to one of the piles. Yet, similar data are available for the other two piles of the TULIP project, that were shorter and closer to the tunnel. Further work remains to build numerical models for those piles.

5.6.2 Parametric studies and sensitivity analyses

The results show that many different models have been proposed, notably as regards the modelling of the excavation. It would be useful, at least for some of them, to conduct parametric studies in order to identify the parameters or the elements of the simulation that do not play a significant role, making it possible to focus the discussion on the most important ones.

5.6.3 Influence of TBM on the pore pressure field

During the preparation of the experiment, it was assumed that the TBM advance would not affect significantly the pore pressure distribution around the tunnel face, given that the sand layer has a relatively large permeability coefficient. This is the reason why only two pressure cells were placed in the ground in the TULIP site. One of the feedbacks of the experiment is that this initial assumption was not necessarily relevant.

It would be very interesting to gather data on the Grand Paris Express project (even if not precisely on the same site) to rediscuss this assumption, and to build a model making it possible to quantify its consequences.

5.6.4 *Modelling the TBM advance*

As stated before, different methods have been proposed but no unique solution has emerged as the most representative of the project. A perspective of this work is to refine this analysis. For instance, it seems legitimate to try and identify the minimum level of complexity, or the minimum features that are required to obtain realistic results. Good quality experimental results are a way of demonstrating the advantages of a method in terms of representativeness.

5.6.5 *Exploring the data*

In the last place, many data have not been thoroughly presented here, but can be found in the references by the same authors.

For instance, the measures show that the settlement of a point located just above the tunnel face was small (less than 1 mm or 10% of the final value). The participants to the exercise were not asked to provide this information, but it is in itself a criterion to discuss the validity of a numerical approach.

5.6.6 *Extending the scope*

The TULIP project concerns three piles relatively far from one another. The more realistic situation of a building founded on a large number of piles remains to be discussed.

A French national research project, called E-Pilot, has been set up to study such configurations.

6 CONCLUSIONS

The TULIP project has been an opportunity to benchmark the numerical techniques for modelling the impact of a TBM on existing deep foundations. The authors of this communication will do their best to publish as fully as possible the data of the project in a spirit of open science: a data paper is currently in preparation (Berthoz *et al*, 2023). All scientists and engineers involved in such problems are welcome to use the data of the project to improve, challenge, validate their modelling approaches.

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