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Probabilistic approach and observational method – application to the interaction between tunnel boring machine and piles

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ABSTRACT: Urban tunnel construction often uses pressurized front Tunnel Boring Machines (TBM). It is difficult to predict the displacements induced by the pressurized digging of tunnels in proximity to existing piles, particularly when the distance is smaller than the diameter of the tunnel. Limiting the impact of TBM on piles is crucial for the Grand Paris Express project to reduce the risk of damage to neighbouring structures. The TULIP research project (TUnnel boring machines and Limitation of Impacts on Piles), established by Société des Grands Projets, CETU, ENTPE, and UGE, conducted a full-scale experiment on line 16 lot 1. Eiffage Génie Civil, HEIA-FR and GeoMod have developed a probabilistic approach coupled with the observational method. This article presents the application of this probabilistic approach to better understand the mechanism of tunnel/soil/piles interaction, based on the published results of experimental tests. A 3D model is first produced to simulate the tunnel construction, then the sensitivity analyses are carried out to determine the probabilistic input variables that are the most important on the quantities of interest. Using the monitoring measurements in the pile zone, the Bayesian inference allows updating the calculation hypotheses to refine the evaluation of the probability of exceeding acceptable thresholds for both the surface settlement and the normal force in the pile (from a priori to a posteriori), thus optimizing the design if the value of the probability of exceeding these thresholds decreases a posteriori.

1 INTRODUCTION

The sustained expansion of urban areas is leading to an increase of underground projects such as the Grand Paris Express (GPE). Pressurized front Tunnel Boring Machines (TBM) are generally used to construct tunnels in urban areas. Today, forecasting the displacements induced by pressurized tunnels in the vicinity of existing piles, especially when the distance is smaller than the diameter of the tunnel, remains a complex subject, due to the following main problems:

- The interaction between tunnel, soil and piles is three-dimensional, and the excavation process generates stresses that vary over time;
- There are multiple sources of displacement around the TBM: frontal pressure and mechanical support of the cutting wheel, injection pressure of grouting mortar, shield geometry, progressive increase of mechanical properties of grouting mortar, consolidation in soils;
- The pile loading history and a suitable soil/piles interface law need be taken into account.

Limiting the impact of TBM on existing piles is an important issue for the Société des Grands Projets (SGP) to reduce the risk of damage to neighbouring structures (Zhang, 2024). SGP has set up the TULIP (TUnneliers et Limitation des Impacts sur les Pieux) research project with the participation of Centre d'Etudes des Tunnels (CETU), Ecole Nationale des Travaux Publics de l'Etat (ENTPE) and Université Gustave Eiffel (UGE).

This article presents a probabilistic approach (Minini et al., 2023; Zhang et al., 2024), coupled with the observational method, to gain a better understanding of the tunnel/soil/piles interaction mechanism. The application of this probabilistic approach to tunnel/soil/piles interaction is based

on the results of a full-scale experiment conducted as part of the TULIP project on line 16 lot 1 of the Grand Paris Express (Berthoz et al., 2022; Mohamad et al., 2022).

2 METHODOLOGY: PROBABILISTIC APPROACH COUPLED WITH OBSERVATIONAL METHOD

2.1 *Probabilistic approach*

The probabilistic approach presents an opportunity to see the problem as a whole and bring out new ideas, and is becoming more and more important with the help of computational capacity increase (Griffiths and Fenton, 2007; Marelli and Sudret, 2014; Phoon and Retief, 2016). Thanks to probabilistic analyses, risks can be better assessed and decision-making can also be facilitated, bringing the risk down to an acceptable level.

The probabilistic approach essentially involves assessing the reliability of the structure, which covers the safety, serviceability, durability and robustness of structures. The assessment of structure reliability is based either on the probability of failure P_f, or on the reliability index β (ECN, 2002; Phoon and Retief, 2016; Zhang and Toutlemonde, 2022). Determining the reliability index (or probability of failure) requires a mathematical function defining the failure state of the structure under study. Using a combination of probabilistic and finite element (FE) methods, a probabilistic approach has been developed to assess the reliability of underground structures (Minini et al., 2023; Zhang et al., 2024). The fundamental elements of this approach are: probabilistic analysis using a FE model of soil-structure interaction to study system performance, sensitivity analysis to identify the parameters with the largest impact on results, monitoring to obtain reliable field measurements, and Bayesian inference based on measurements to refine predictions of system behavior (Figure 1).

More specifically, Bayesian inference involves updating calculation hypotheses via monitoring measurements to improve response predictions. In the Bayesian framework, updated knowledge about the input data (a priori distribution) is represented by its a posteriori distribution, in which a likelihood function is introduced to reflect the model's fit with field observations. A number of probabilistic parameters and their interrelationships can also be considered in a systematic structure. A change in one parameter can influence the others through their interrelation.

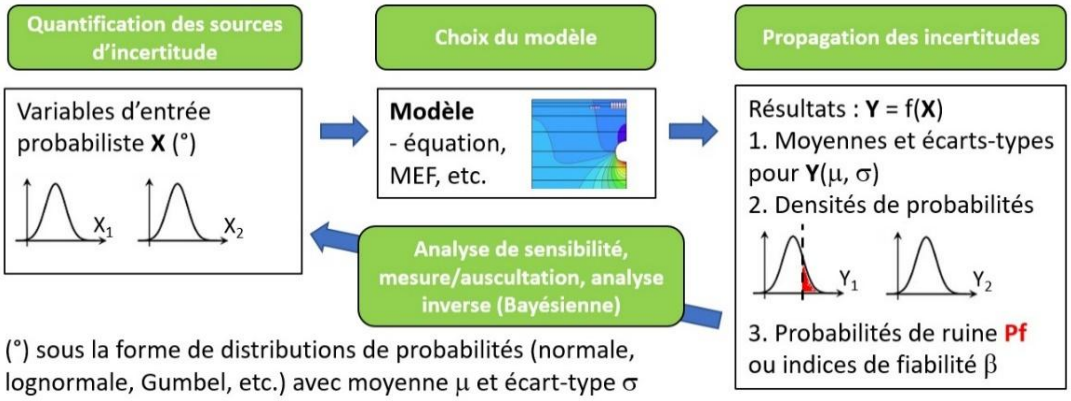

Figure 1. Probabilistic approach coupled with observational method (Zhang et al., 2024).

2.2 *Observational method*

Conventional geotechnical design methods may prove insufficient in certain contexts, because the cost of the project is directly linked to the safety margin attached to each geotechnical parameter. In these cases, the observational method is a relevant approach that, in these delicate contexts, can avoid unnecessarily oversized and costly structures, without compromising on the targeted objectives of safety, behaviour and durability (Terzaghi et al., 1996; Wu, 2011).

Terzaghi and Peck (Terzaghi et al., 1996) described the observational method as:

"Design based on the most unfavorable assumptions is inevitably uneconomical, but no other procedure provides the designer in advance of construction with the assurance that the soil-

supported structure will not develop unanticipated defects. However, if the project permits modifications of the design during construction, large savings can often be made by designing on the basis of the most probable rather than the most unfavorable possibilities. The gaps in in the available information are filled by observations during construction, and the design is modified in accordance with the findings."

The observational method defined in Eurocode 7 (ECN, 2004) is also quoted here:

"When prediction of geotechnical behavior is difficult, it can be appropriate to apply the approach known as the 'observational method', in which the design is reviewed during construction."

The observational method is an advantageous technique for large infrastructure projects. It can generate significant savings in time and cost, and more effective collaboration between designers and contractors. Moreover, in recent years, there have been significant improvements in the quality of instrumentation. These new monitoring and data management systems can provide real-time monitoring and important new information for the observational method.

3 APPLICATION: INTERACTION BETWEEN TBM AND PILES

3.1 *Description of experiment*

As part of the TULIP project, three piles (P1, P2 and P3) in reinforced concrete (C35/45) with a diameter of 500 mm were constructed and instrumented on a TBM passage route (Figure 2). This study focuses the Pile P3, with a depth of 20.5 m and a head load of 2060 kN. The excavated diameter of the tunnel is D = 9.87 m, and the depth of its axis is 21 m.

The soil stratigraphy at the test site consists of (Figure 2): fill (R), Saint-Ouen Limestones (CSO or SO), Beauchamp Sands (SB), Marls et Caillasses (MC) and Coarse Limestones (CG). The water level of construction phase at +48.8 NGF (General levelling of France) was used in calculations.

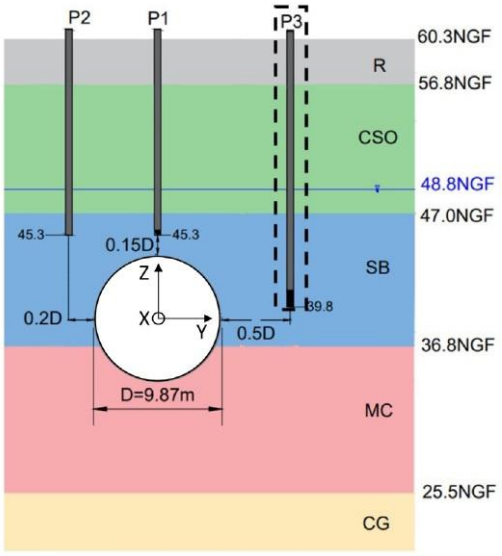

Figure 2. Position of the three piles and the tunnel (Berthoz et al., 2022).

3.2 *Construction mode*

The TBM used is called TBM6 for the works on line 16 lot 1, realized by Eiffage Génie Civil. It is an earth pressure balance TBM, comprising the following components:

- A cutting wheel with a diameter of 9.87 m;
- A front shield with an external diameter of 9.83 m and a length of 3.5 m, and a central shield with an external diameter of 9.815 m and a length of 3.5 m;
- A tail shield measuring 9.80 m in diameter and 4.0 m in length.

The characteristics of the tunnel rings (concrete C40/50) are: Intrados/extrados diameters: 8.7 m/9.5 m; Segment thickness: 0.40 m; Number of segments: 7; Ring width: 2.0 m.

4 NUMERICAL SIMULATION: MODELLING AND PHASING

4.1 *Finite element model*

A 3D FE model (Figure 3) was produced to simulate the interaction between the tunnel excavation and the P3 pile, using ZSOIL software (Zsoil, 2020). The model is 45 m high, 30 m wide and 30 m long, consisting of 100800 volumetric elements with 8 nodes and 1 super convergent integration point. The volumetric elements have an average size of 0.4 m^3. It was created with a plane of symmetry located at the tunnel axis to optimize computation time.

In this 3D model, the Muir-Wood method (Wood, 1975) has been used to take into account the presence of joints between segments and to define a reduced thickness for the rings. The applied confining pressure is 223 kPa in the key and 313 kPa in the invert, including two parts:

- the pressure in the excavation chamber: 130 kPa in the key and 220 kPa in the invert.
- the additional force exerted by the cutting wheel on the face (mechanical support): 7000 kN, or a uniform pressure of 93 kPa.

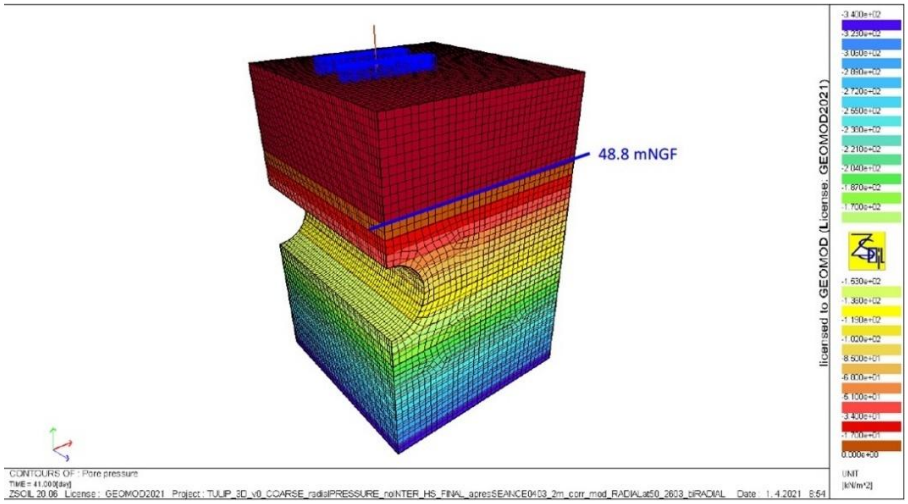

Figure 3. 3D finite element model.

The shield was not explicitly modeled, but using a radial pressure over the entire length of the shield, equivalent to the pressure in the key of excavation chamber (130 kPa). The presence of grouting mortar is neither explicitly introduced into the model, as its mechanical characteristics are better than those of the surrounding soils (SO and SB). We consider the influence of grouting mortar only with its injection pressure during the construction phase, which is 175 kPa in the key. The water table is modeled explicitly by acting directly on the hydrostatic conditions of each soil layer (Figure 3). The modeling is carried out under the assumption of permanent hydro-mechanical coupling. The voussoirs are assumed to be impermeable.

Table 1. Axial unit friction limit (q_s) and ground failure pressure (q_b).

Soil	γ_h (kN/m^3)	E_M (MPa)	p^*_{LM} (MPa)	Soil type	q_s (kPa)	q_b (kPa)
R	19	16	1.2	clay	64	
SO(2)	18	35	1.9	marly limestone	152	
SB(2)	21	98	4.9	gravelly sand	170	8085

The soil/pile interface has been modeled using a unitary axial friction limit q_s and a soil peak resistance q_b, explicitly considered by limiting the value of the normal force that the beam element representing the pile can support at its end. Their values are evaluated in accordance with the French standard NF P 94-262 - Deep foundations and presented in Table 1.

Finite element calculations are performed under effective stresses and drained conditions. Soil behavior is simulated on the basis of an elasto-plastic behavior law with strain-hardening, using a simplified HSM (Hardening Soil Model) (m=0.5) to differentiate the modulus of first loading from that of unloading/reloading. The soil characteristics considered are presented in Table 2.

Table 2. Soil characteristics.

Soil	α	E'=E_M/α (MPa)	E_{ur} (MPa)	c' (kPa)	φ' (°)	c_u (kPa)	K_0	K_h* (m/s)	K_v* (m/s)	Ψ (°)
R	1/2	32	80	0	28	40	0.53	$1*10^{-5}$	$4*10^{-6}$	0
SO(2)	1/3	105	263	10	33	60	0.46	$1.5*10^{-4}$	$6*10^{-5}$	3
SB(2)	1/2	196	490	10	33	60	0.46	$1.4*10^{-4}$	$1.9*10^{-5}$	3
MC(3)	1/3	501	1503	25	35	120	0.43	$2.5*10^{-4}$	$1*10^{-4}$	5
MC(5)	2/3	614	1534	50	35	-	0.43	$2.5*10^{-4}$	$1*10^{-4}$	5
CG(3)	1/2	954	2385	100	35	-	0.43	$2.1*10^{-4}$	$8.4*10^{-7}$	5

4.2 *Construction phases*

The main construction phases are as follows:

- Phase 1: Initialization of soil stresses (water table at construction phase level).
- Phase 2: Pile construction.
- Phase 3: Application of load of 2060 kN at the head of pile P3.
- Phase 4: Simulation of the passage of the TBM: Application of frontal containment pressure; 2 m passes, deactivating the corresponding volumetric elements, and applies radial pressures of 130 kPa to model the shield.
- Phase 5: Installation of tunnel segments, considered to be watertight and the hydrostatic pressure inside is zero.
- Phase 6: Grouting of mortar modelled using a radial pressure of 175 kPa 10 m behind the cutting wheel and over a width of 2 m.

5 NUMERICAL SIMULATION: RESULTS AND DISCUSSION

5.1 *Sensitivity study of geotechnical parameters*

In the probabilistic approach presented here, the important geotechnical parameters are considered as probabilistic variables, defined by a lognormal distribution and based on the results of geotechnical surveys or known knowledge. These are a priori distributions.

A sensitivity study was carried out on the layer modulus (E') using Sobol indices, the mean value (μ) and coefficient of variation (COV) of E' are presented in Table 3. In the probabilistic framework, the use of these indices enables us to break down the variance of one of the results (output) of the model into fractions that can be attributed to the input variables. This sensitivity study enables us to identify the two layers with the largest impact on surface settlement (Figure 4), namely the Beauchamp Sands E_{SB} (74%) and the Saint-Ouen Limestones E_{SO} (24%).

Table 3. A priori mean value (μ) and coefficient of variation (COV) of E'.

	E'=E_M/α (MPa)	
Soil	μ	COV
R	32	0.40
SO(2)	105	0.50
SB(2)	196	0.50
MC(3)	501	0.60
MC(5)	614	0.35
CG(3)	954	0.15

Table 4. A priori mean value (μ) and coefficient of variation (COV) of q_s.

Soil	q_s (kPa)	
	μ	COV
R	64	0.3
SO(2)	152	0.3
SB(2)	170	0.3

Another sensitivity study was also carried out on the unitary axial friction limit q_s, with the aim to find out the input variable having the largest impact on the difference between the normal force in the pile P3 before and after the TBM passage. Table 4 shows the a priori mean values and coefficient of variations.

Figure 5 shows the results of the sensitivity analysis. The unitary axial friction limit of the SB(2) layer has the biggest impact on the difference in the normal force in the pile.

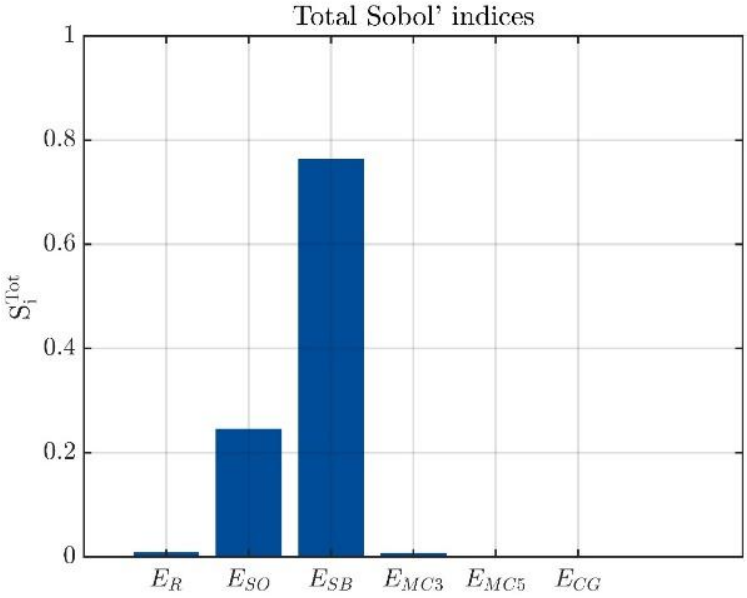

Figure 4. Sensitivity study of E' using the Sobol index.

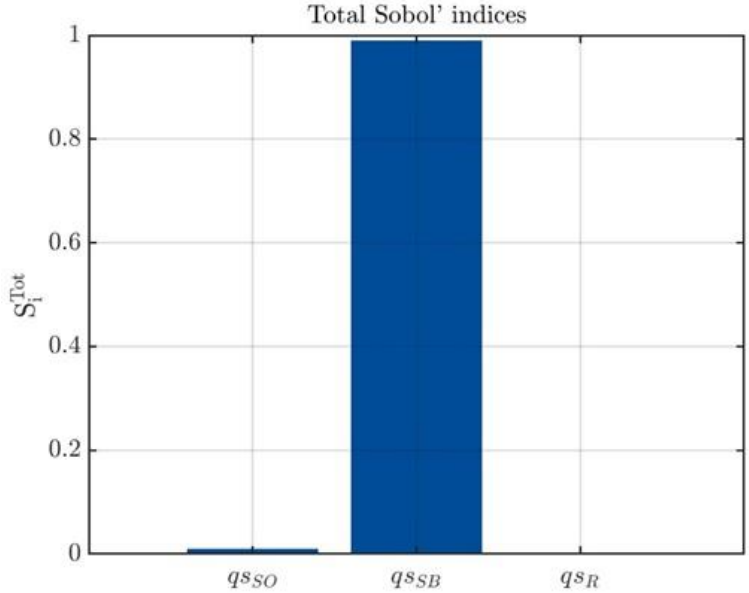

Figure 5. Sensitivity study of q_s using the Sobol index.

5.2 *Bayesian inference*

The monitoring measurements for the Bayesian inferences are the surface settlement trough measured at three points (Table 5) and the measured normal force in the pile P3 (Figure 7).

Bayesian inferences were then carried out by coupling ZSOIL and UQLab software (Marelli and Sudret, 2014). The aim was to update the PDFs (Probability Density Function) of the model's input variables according to the field measurements. As a result, Bayesian inference updates the mean value (μ) and coefficient of variation (COV) of the E_{SB}, E_{SO} modulus (Table 6). These a

posteriori mean values were then used in the 3D calculation model. The results of the calculation with the updated E_{SB} and E_{SO} values are presented in the following.

Table 5. Settlement measured at 3 points (CETU data).

Final state (far behind the front)		
Maximum surface settlement	Uzmax-terrain	-10.0 mm
Transverse distance settlement is 60% of Uzmax-terrain	Y60%-uzmax	8.0 m
Transverse distance settlement is 30% of Uzmax-terrain	Y30%-uzmax	12.5 m

Table 6. Prior and posterior PDF with μ and COV.

	Deterministic value (kPa)	Prior PDF	Posterior PDF
E_{SO}	105000	LN(μ = 105000, COV = 50%)	LN(μ = 94490, COV = 43%)
E_{SB}	196000	LN(μ = 196000, COV = 50%)	LN(μ = 183100, COV = 13%)

The surface settlement trough of the a priori (E_{SO}: μ = 105000 kPa; E_{SB}: μ = 196000 kPa) and a posteriori (E_{SO}: μ = 94490 kPa; E_{SB}: μ = 183100 kPa) simulations are shown in Figure 6.

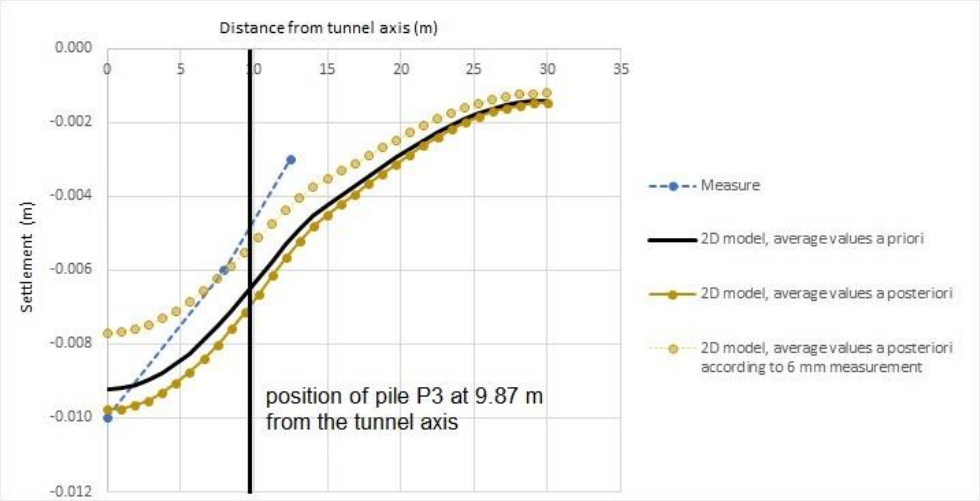

Figure 6. Bayesian inference on the surface settlement trough at the pile P3 section.

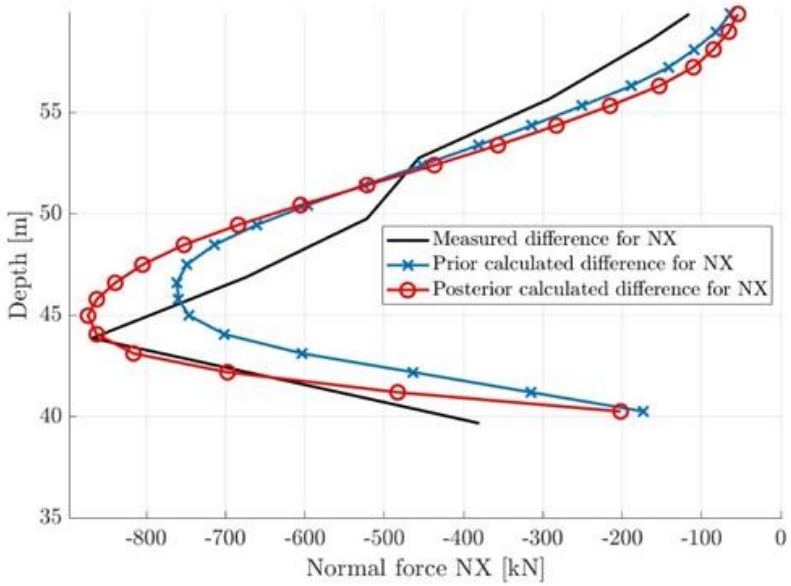

Figure 7. Bayesian inference on the difference between the normal force in the pile P3 before and after the passage of the TBM.

The a posteriori results after Bayesian inference are closer to the measurements in terms of the maximum settlement value, thanks to the updated hypotheses (E_{SB} and E_{SO} modulus). In the present case, the a priori prediction was relatively close to the settlement measurements, which implies a relatively modest update of the mean values of the E' modulus. The shape of the trough remains less steep than that of the experimental profile, due to the continuous approach of the finite element model. Note that an alternative update to the displacement value at 6 m from the axis (instead of at the axis) significantly modifies the a posteriori profile (Figure 6).

Figure 7 shows the measured difference between the normal force NX in the pile P3 before and after the passage of the TBM, the a priori calculated difference and the a posteriori calculated difference. We can see that the maximum value of the normal force is well matched.

6 CONCLUSIONS

This article presents the application of a probabilistic approach to tunnel/soil/piles interaction on an experimental site of line 16 lot 1 of the Grand Paris Express project using a finite element model, coupled with the observational method. In this probabilistic approach, the modulus of the soil (E') and the unitary axial friction limit (q_s) are considered as probabilistic variables, and the calculation hypotheses (a priori distributions) are based on the performed geotechnical investigations and known knowledge. Sensitivity studies using the Sobol index were used to identify the parameters the most influential on surface settlement and normal force difference.

Based on monitoring measurements, Bayesian inferences were then carried out to refine the surface settlement trough and the normal force prediction at the pile P3 section (a posteriori distributions). In addition, the developed probabilistic methodology using numerical tools can considerably reduce the computational time required for back analyses, which will help to promote the application of the observational method. The modern real-time instrumentation systems, complemented by a sufficient number of high-quality geotechnical surveys, will also provide the observational method and Bayesian inferences with reliable field measurements. These results will provide a sound basis for optimizing designs with associated cost savings.

7 REFERENCES

Berthoz N. et al. 2022. Impact du creusement au tunnelier sur un pieu : synthèse de l'exercice de prévision TULIP, *Revue française de géotechnique,* 173(2): 1-16.

European Committee for Normalization 2002. EN 1990-Eurocode 0: Basis of structural design.

European Committee for Normalization 2004. EN 1997-Eurocode 7-1: Geotechnical design.

Griffiths D.V. & Fenton G.A. 2007. Probabilistic methods in geotechnical engineering, Springer.

Marelli S. & Sudret B. 2014. UQLab: A Framework for Uncertainty Quantification in MATLAB, *In the 2nd International Conference on Vulnerability and Risk Analysis and Management (ICVRAM 2014),* p.2554–2563, University of Liverpool, United Kingdom.

Minini J. et al. 2023. Finite element-based probabilistic framework including Bayesian inference for predicting displacements due to tunnel excavation, *Computers and Geotechnics,* 162, 105604.

Mohamad W. et al. 2022. Full scale study of pile response to EPBS tunnelling on a Grand Paris Express site, *Tunnelling and Underground Space Technology,* 124, 104492.

Phoon K.K. & Retief J.V. 2016. Reliability of geotechnical structures in ISO2394, CRC Press.

Wood M. 1975. The circular tunnel in elastic ground, *Géotechnique,* 25(1): 115-127.

Wu T.H. 2011. 2008. Peck Lecture: The Observational Method: Case History and Models, *Journal of Geotechnical and Geoenvironmental Engineering,* 137(10): 862-873.

Terzaghi K. et al. 1996. Soil mechanics in engineering practice (3rd edition), John Wiley & Sons.

Zhang Y. & Toutlemonde F. 2022. Calibrating partial safety factors in line with required reliability levels for concrete structures, *European Journal of Environmental and Civil Engineering,* 26(9): 3863-3879.

Zhang Y. 2024. Application of risk management plan to technical risks in metro construction: case study of the Grand Paris Express project, *Tunnelling and Underground Space Technology,* 147, 105716.

Zhang Y. et al. 2024. Analyse probabiliste, inférence bayésienne et méthode observationnelle : application au tassement dû au passage d'un tunnelier, *Revue française de géotechnique,* 179(4): 1-15.

Zsoil (User manual ZSoil.PC) 2020. Soil, Rock and Structural Mechanics in dry or partially saturated media. ZACE Services Ltd, Software Engineering, Lausanne, Switzerland.