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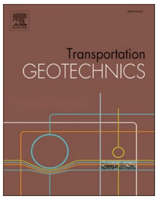

Case study

Probabilistic analysis of the swelling character of Paris plastic clay

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ABSTRACT

This paper presents a probabilistic analysis of the swelling character of Paris plastic clay using a tunnel of the Grand Paris Express project as a case study. Known for its highly plastic behavior, Paris plastic clay originates from the Sparnacian age (Lower Eocene) and constitutes the first Tertiary deposits of the Paris sedimentary basin, often overconsolidated with low permeability.

In addition, this plastic clay exhibits a strong swelling capacity and has already resulted in several accidents in the past. Hence, careful in situ investigations and laboratory tests were conducted to properly analyze Paris plastic clay. Due to the wide dispersion of swelling pressure, probabilistic analyses using finite element modelling of a tunnel laying on plastic clay were carried out. A sensitivity study was also performed to determine the key parameters of the swelling modelling. After that, the monitoring data of in-field swelling pressure was compared with the results of the numerical simulation. Based on these field measurements, Bayesian inverse analysis was employed to update the prior hypotheses so as to improve the posterior results, namely the prediction of the swelling pressure of the plastic clay and the heave of the tunnel raft.

Introduction

Plastic clay of Sparnacian age (Lower Eocene) is one of the clay deposits found in the sedimentary basin of the Paris region, it can be considered as originated from outcrops that were eroded by the warm, humid conditions of the late Cretaceous, and is the decomposition product of rocks by physicochemical weathering. In the west, south and east of the Paris basin, plastic clay forms the first Tertiary deposits and rests on Campanian chalk[1].

Paris plastic clay is similar to other swelling clays like the London clay[2–4]and the Flanders clay[5]. It exhibits complex hydromechanical behavior[6,7], and has already resulted in several accidents in the past due to rupture caused by large deformation under swelling[8,9]. It can also generate great difficulties for earthworks and the construction of underground structures[10]. As a result, it is considered as one of the major geotechnical issues for the Grand Paris Express project, which is one of the largest metro projects underway in the world[11–13].

In addition, Paris plastic clay exhibits a strong swelling capacity. Expansive soils are known to be hazardous for civil infrastructures because of the development of swelling pressure along with heave [14–16]. Soil swelling is a complex phenomenon with significant consequences for soil-structure interaction, it is a time-dependent hydro-mechanical-chemical process that leads to volume and pressure increases in the ground. Over the past decades, the swelling of compacted expansive soils has been extensively studied[17,18], and long-lasting experimental research has revealed the impact of multiple factors. Alonso et al. [19] proposed to model the behaviour of expansive clays at the microstructure level with active minerals' swelling and at the macrostructure level with major structural rearrangement. Mitchell and Soga [20] illustrated how the mechanisms of osmotic pressure and water adsorption could influence the swelling, as well as the mineralogical detail. Audiguier et al. [21] demonstrated the factors predisposing to shrinkage-swelling of the expansive soils in the Paris bassin, namely the mineralogical nature of soil and the initial condition of soil (water content, density, void ratio and suction). Ferber et al. [22] showed the coupling effect of water content and dry density on the swelling potential of four plastic clays in France. Masin and Khalili [23] analysed an extensive experimental database on compacted smectitic clays from the literature, the results were scattered but the effective stress was found to be applicable to predict the swelling behaviour. Zhang and Cui [24] showed the determination of swelling pressures by different common methods and the good coincidence of swelling pressure determination

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under the different methods with the similar micro and macro void ratios. All these studies reveal that there are numerous factors which could affect swelling, such as initial water content, pore water, suction water exchange, initial dry density or void ratio, mineralogical content, soil structure, confining pressure, and previous mechanical history of the soil. The results' dispersion is also revealed by these studies.

According to the published studies[7,10,25,26], the plastic clay found in the western section of Paris basin is primarily composed of smectites, with traces of interstratified kaolinites/smectites and kaolinites. The plastic clay in the eastern section of the Paris basin begins with a dominant kaolinite level and finishes with a slightly clayey sand that contains illites and interstratified lignite lenses. The X-ray diffraction tests showed an average composition of 47% kaolinites, 45% interlaminates illites/smectite and 8% illites at the Maison Blanche in Paris (MBP) site in the case study. The oedometer tests illustrated also its overconsolidated nature at the MBP site, the mean value of overconsolidation ratio (OCR) was evaluated to be 2.2. These results may explain the strong swelling capacity of Paris plastic clay.

In the engineering practice, the swelling pressure is an important parameter for the tunnel or underground structure design, which characterizes the swelling capacity of plastic clay. It results mainly from two distinct processes: hydration for unsaturated soils, depending on their physicochemical nature of clay minerals (especially smectites) following water inflow, and mechanical unloading for saturated or quasi-saturated soils following excavation. To gain a better understanding of the swelling character of Paris plastic clay, numerous geotechnical investigations were carried out. The swelling pressure measurements in different representative areas were presented by Zhang et al. [7] and Zhang and Cui [27], demonstrating a wide dispersion.

As far as the variability of available measurements is concerned, the choice of a single retained value for a deterministic or a semi-probabilistic calculation appears delicate. In this situation, the probabilistic approach might be a better solution[28–32]. A description of this variability using a probabilistic distribution with mean value and coefficient of variation seems more pertinent, associated with the target safety or performance levels with the corresponding failure probabilities or reliability indices[33–35], soil-structure interaction analyses can then be carried out using the probabilistic method in conjunction with a Bayesian inverse analysis and the observational method, based on the field measurements[34,36]. The probabilistic framework allows quantifying uncertainty by numerical modelling, a significant advantage of the probabilistic framework is to facilitate and improve tunnel or underground structure design decisions, as the target of design should achieve an acceptable level of reliability. The observational method allows flexible design and feedback loops using monitoring data can lead to design optimization. The Bayesian probabilistic framework coupled with the observational method can efficiently deal with field measurements and robustly quantifies the uncertainty in inferred parameters. More specially, the application of the Bayesian probabilistic framework to tunnel or underground structure design allows computing explicitly a probability of failure, or of trespassing a given settlement threshold for adjacent buildings, as shown in[37]. Once this probability of failure is known, it is then possible to compare it with acceptable target values, as described in[38].

Hence, in this article, we present probabilistic analyses of the swelling character of Paris plastic clay with a case study of a tunnel in the Grand Paris Express project. First, the geotechnical investigations and tests were analyzed to define the prior hypotheses. A sensitivity study was then performed to determine the key parameters of the swelling modelling. Subsequently, the probabilistic calculations based on finite element model were conducted to model the swelling of plastic clay beneath the tunnel raft. To verify the computation results, they were also compared with the measured swelling pressure. Finally, a Bayesian inverse analysis was carried out to update the prior hypotheses in order to improve the posterior results, based on the field measurements.

The application of probabilistic and Bayesian approaches to swelling clays is novel as few similar studies can be found in the literature. Furthermore, laboratory investigations on the swelling pressure show wide range, and in-situ measurements are rare. The probabilistic and Bayesian inverse analyses presented in this paper allow better estimating the swelling pressure value based on the field measurements and predicting the tunnel raft's heave.

Project site: Maison Blanche in Paris

The MBP project is located in the southern extension of Line 14 of the Grand Paris Express project. It includes the future Line 14 MBP metro station, a tunnel constructed using conventional tunneling methods and a link to the existing Paris metro Line 7.

It is characterized on the one hand by major geotechnical issues such as Paris plastic clay in the Bièvre river valley, and on the other hand by the immediate vicinity of very sensitive and very vulnerable neighboring structures (Fig. 1). In the MBP station, the tunnel remains on Paris plastic clay, an inverted counter-arch form was chosen for the tunnel and designed to withstand the swelling pressure of plastic clay.

Regarding the neighboring structures, the Super Italy Tower (SIT) is a 112 m tall building of 36 stories and 4 basement levels. Its raft foundation, just 1.7 m from the east diaphragm walls, is situated at + 42 NGF (General levelling of France in French) in the Lower coarse limestones. The existing metro line 7 is only 2.5 m from the west diaphragm walls. Its base is found in the Lower coarse limestones is located at + 40 NGF. Given these constraints, the project was executed with precise phasing [39,40].

Hereafter, the tunnel of the MBP station is used to study the swelling character of Paris plastic clay using a probabilistic approach.

Geotechnical study

Paris plastic clay is generally found at greater depths than other swelling clay formations in the Paris basin. On the MBP construction site, the plastic clay was found at depths of 20 m (approximately + 36 NGF) to 40 m.

Investigations and interpretation

The MBP project site's geology is characterized by a comparatively horizontal structure, due to a succession of sedimentary deposits (Fig. 2). It is situated in the Bièvre river valley, a tributary of the Seine River that is currently channelled in the study zone.

In compliance with French standard NF P 94–500[41], the plastic clay underwent a series of investigations and tests[7,42]during the geotechnical studies of G1, G2 and G3 missions.

The results of the principal soil index properties highlight:

- The average wet density (γ_h) is 20 kN/m^3 and the average dry density (γ_d) is 16 kN/m^3.
- The average degree of saturation (Sr) is close to 100%. Consequently, Paris plastic clay can be considered saturated in their natural state.
- The average water content (w) is 24%, the average values corresponding to the Atterberg limits are: $w_P = 31$, $w_L = 80$, $I_P = 49$. These values confirm the high plastic nature of Paris plastic clay.

Plastic clay swelling at Maison Blanche in Paris

To evaluate the swelling capacity of the plastic clay, oedometer tests with incremental loading in accordance with the NF EN ISO 17892–5 standard[43]and swelling tests type Huder-Amberg[44,45]were performed. At a given depth, the OCR is defined as the ratio of the preconsolidation stress (σ_p') to the vertical effective stress (σ_v'). It can significantly affect the soil's initial stiffness in both lateral and axial loading conditions. The value of the coefficient of earth pressure at rest

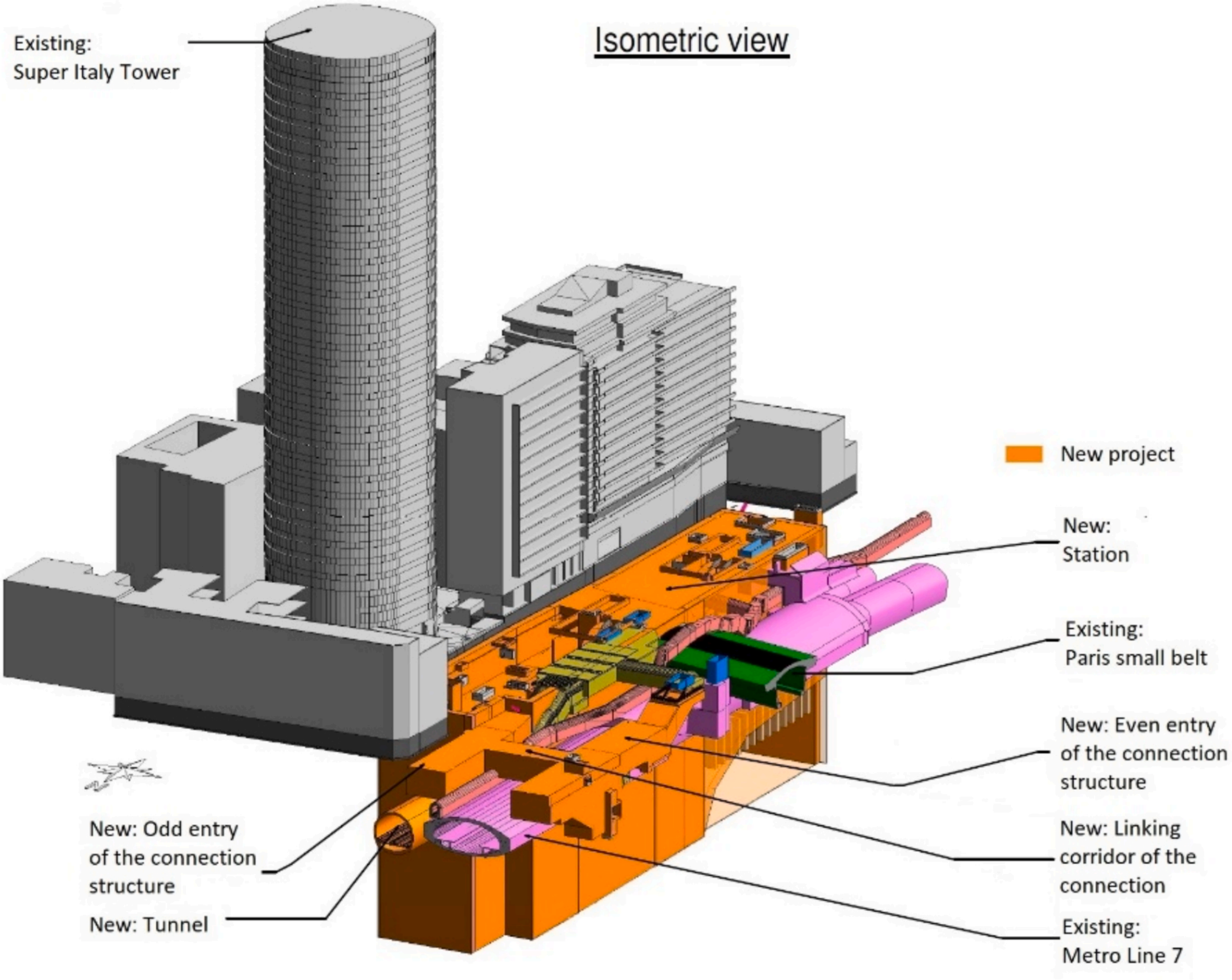

Fig. 1. 3D view of the Maison Blanche Paris site.

K_0 is calculated using the formula $K_0 = (1–\sin\varphi')*OCR^{1/2}$ [46].

The oedometer tests with incremental loading were performed once the samples had reached 100% saturation, the results are shown in Table 1. The indices Cc, Cs, OCR and K_0 have mean values of 0.23, 0.09, 2.2 and 1, respectively. It is noteworthy that the swelling index Cs = 0.09, which indicates the potential swelling of plastic clay due to mechanical unloading, is particularly high. According to Broquet's thesis [47], plastic clay that is normally consolidated in the same zone (apart from the Bièvre river valley) has average values of Cc = 0.15 and Cs = 0.05. The local heterogeneity of Paris plastic clay with a higher swelling index (Cs = 0.09) could be explained by its overconsolidated nature (OCR = 2.2) and high content of inter-laminates illites/smectite (45%). Furthermore, for non-swelling soils, the swelling index (Cs) is typically 10% of compression index (Cc). In this case, the average ratio of Cs/Cc is 39%, indicating and confirming the high swelling character of Paris plastic clay at the MBP site.

The results of the swelling tests are presented in Table 2. However, the measured swelling pressures show a large disparity from 122 to 1500 kPa. The spatial variation of Paris plastic clay is known to be important, a recent study shows the characterization of the vertical spatial variability of the plastic play[6]. In this case, the probabilistic analysis is well suited to deal with the wide range of the swelling pressure, coupled with a Bayesian inverse analysis to take into account the field measurements. It is worth noting that swelling pressure is not an intrinsic characteristic of the soil but a function of its state of humidity at the time of testing, the specific characteristics of the sample and the depth of the sampling.

Based on the results of the in situ investigations and laboratory tests, as well as the geotechnical analysis on these results[7,27], the retained geotechnical baseline for the plastic clay is shown in Table 3. For the plastic clay, the coefficient of ground at rest K_0 varies from 0.8 to 1.3, taken equal to 1 in this case study.

Probabilistic analysis

Finite element models

A full 3D finite element model was first created to simulate the tunnel excavation[39,40,48]. It takes into account the soil stratigraphy, the neighboring structures (surface loads and structural elements), the shaft's excavation with steel linings (beam elements), the bolts on the working face (nail elements), the temporary support (beam elements) and the shotcrete (shell elements), as well as the final tunnel lining (volumetric elements). This 3D model also enables the definition of an equivalent confinement loss rate λ of 40% for the 2D calculations, reproducing a comparable stress state.

The tunnel construction steps in the 2D calculations consist of the following main stages:

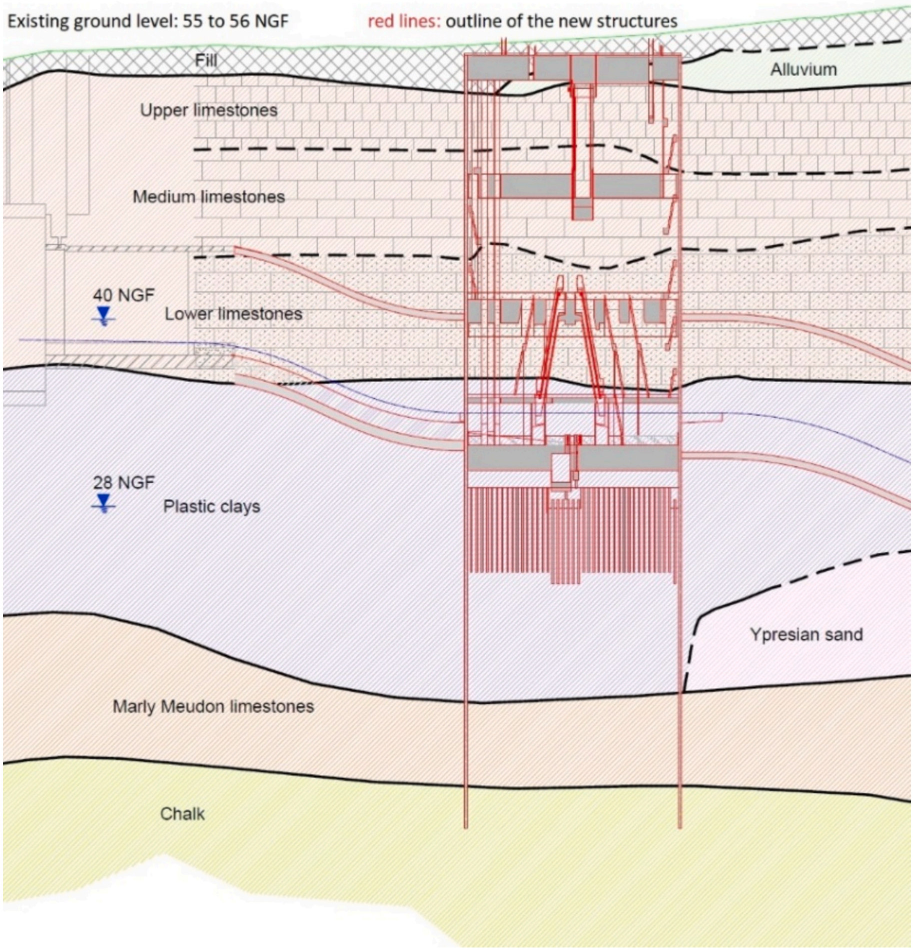

Fig. 2. Geological layers of the Maison Blanche Paris site.

Table 1
Compressibility oedometer tests results.

Z (NGF)	σ'_{v0} (kPa)	e_0	Cc	Cs	σ'_p (kPa)	OCR	K_0
36.1	400	0.52	0.17	0.06	850	2.1	1.1
34.8	420	0.65	0.27	0.09	2030	4.8	1.6
34.6	430	0.72	0.35	0.15	1200	2.8	1.2
33.7	450	0.70	0.18	0.10	550	1.2	0.8
33.7	450	0.43	0.20	0.09	980	2.2	1.1
32.8	460	0.74	0.27	0.13	1100	2.4	1.1
31.3	480	0.76	0.24	0.06	550	1.1	0.8
31.3	480	0.83	0.33	0.04	1050	2.2	1.1
30.7	500	0.70	0.20	0.12	950	1.9	1.0
28.6	540	0.58	0.16	0.08	800	1.5	0.9
28.6	550	0.47	0.12	0.04	880	1.6	0.9
27.3	570	0.65	0.25	0.11	1900	3.3	1.3
19.6	730	0.73	0.28	0.13	1000	1.4	0.8

Table 2
Swelling tests results.

Geotechnical study	Z (NGF)	σ'_{v0} (kPa)	σ_g' (kPa)	R_g
G1 and G2	–	–	1310	0.050
			760	0.110
			450	0.046
			360	0.077
			1500	0.013
G3	35.7	400	122	0.053
	34.6	430	360	0.027
	33.7	450	400	0.022
	33.4	450	1200	0.012
	31.0	500	1000	0.016
	28.6	540	350	0.017
	19.6	730	500	0.016

- initial state without deformation prior to work;
- tunnel excavation and temporary support installation with a confinement loss rate $\lambda = 40\%$;
- confinement loss rate $\lambda = 100\%$ on the temporary support;
- tunnel lining installation with $E = 10$ GPa and the construction stage water level;
- temporary support disappearance and passage to the high water level;
- application of the swelling law to plastic clay over a period of 2800 days.

In addition, the calculation results were compared with inclinometer measurements. The deformations of the plastic clay at the level of the tunnel excavation were accurately predicted by the 2D model with a confinement loss rate λ equal to 40% (Fig. 3).

The objective of this paper is to show how a Bayesian inverse analysis can help the tunnel designers predict the swelling pressure under the tunnel's raft. In this framework, it has appeared to the authors that a 2D analysis would be sufficient. In this 2D model, the temporary support is installed after 40% unloading, which has been calibrated on a full 3D model and verified by the inclinometer measurements. Zhang et al.[40] and Zhang and Commend[49] explained these detailed 3D finite element analyses involving the settlement analysis of the complex

Table 3
Geotechnical baseline for plastic clay.

Formation		Pressuremeter tests			Laboratory tests								
		E_M (MPa)	p_l* (MPa)	α (−)	γ_w (kN/m^3)	γ_d (kN/m^3)	c' (kPa)	ϕ' (°)	c_u (kPa)	Ψ (°)	OCR (−)	K_0 (−)	R_g (−)
Plastic clays	Upper	16.5	1.18	1	20.5	17	20	16	100	0	2	1	0.04
	Medium	21	1.5	1	20.5	17	20	16	130	0	2	1	0.04
	Lower	25.5	1.85	1	20.5	17	20	16	170	0	2	1	0.04

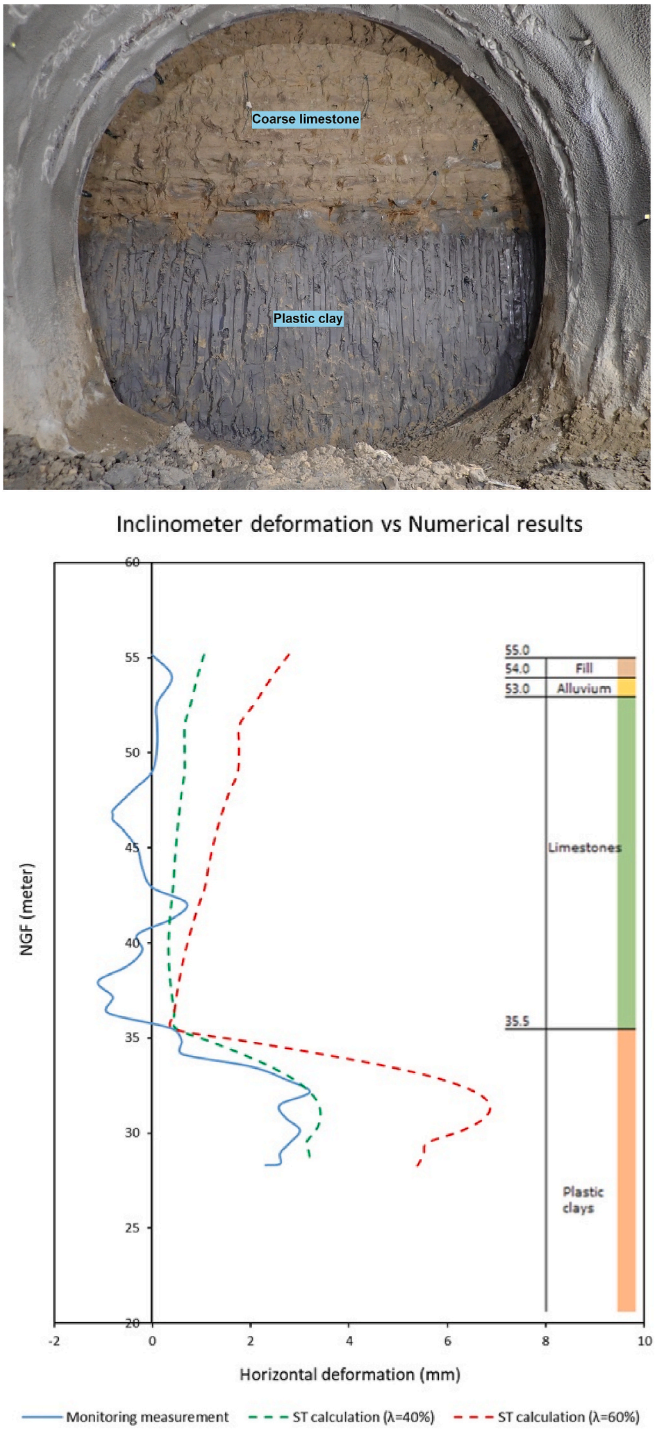

Fig. 3. Tunnel cross section photo (above) and inclinometer measurements vs. numerical results (below).

neighboring structures, including the Super Italy Tower. Therefore, for the probabilistic analysis, a simplified 2D finite element model was created, as illustrated in Fig. 4. This model was simplified compared to the original 2D model: an axis of symmetry has been admitted, the number of bilinear volumetric elements in the Enhanced Assumed Strains (EAS) formulation has been reduced from 6873 in the original model, which also includes the proximity of line 7 of the Paris metro, to 2273 elements. The temporary support and the foundation slab of the neighoring buildings were modeled using beam elements, while the tunnel lining was modeled using bilinear volume elements in Continuum For Structures formulation, a special case of EAS elements.

The prior hypotheses

The Hardening Soil Model (HSM) is used to simulate the mechanical behavior of the different soil layers, appropriate for modelling the displacements of underground works[50]because it allows for the consideration of various phenomena, such as dilatancy prior to rupture, modulus variation depending on the stress state, and modulus that varies between unloading and reloading[51]. In fact, the HSM model can be considered as an improvement of the Duncan-Chang hyperbolic model[52]. The yield surface is described by two mechanisms with isotropic hardening that rely on both the plastic shear and volumetric strains. Calibrated based on the oedometer and triaxial tests on samples, the HSM model enables the simulation of the mechanical behavior of soil layers under the effect of unloading following excavation. Parameter selections for the MBP’s soils described by the HSM model have been discussed in previous publications by the authors[53]or[49].

Moreover, the Huder & Amberg (HA) model[54]is used to simulate the hydric swelling of plastic clay, which is associated with the hydration of sensitive clay minerals (particularly smectites) following water inflow. This hydric swelling will be examined more thoroughly in the computation. The Huder-Amberg test is one of the most used tests for lab characterization of the swelling soils and rocks, see for instance[55]. Its implementation in ZSoil is shown to reproduce quite well the swelling behavior, as shown in the elementary benchmarks presented in the ZSoil theoretical manual[56], including the ability to stop the swelling process when reloading. The probabilistic calculations are performed with a Mohr-Coulomb model for the plastic clays (and HSM for other soil layers) as the key result is the hydric swelling, governed by HA model. The HA model’s parameters describing the swelling clays have been derived from the laboratory tests’ results, as explained in[49]or[48].

The laboratory tests have revealed a wide dispersion in measured swelling pressure, as previously mentioned. In light of this phenomenon, the prior swelling limit pressure was taken equal to 350 kPa. Based on interpretations of the geotechnical baseline, the retained mean values of geomechanical parameters as the prior hypotheses are presented in Table 4.

In order to undertake a Bayesian inverse analysis, the uncertainty of each probabilistic variable that could have an impact on the results should be introduced in the calculation. Here the Young modulus, the drained cohesion, and the friction angle of each soil layer are implemented as probabilistic variables. Their probabilistic distributions have been chosen according to Table 18 in[38]. Similar choices have already been made and validated on real-life cases by the authors in[37], as well as in the reference[57]. Accordingly, lognormal and Gaussian

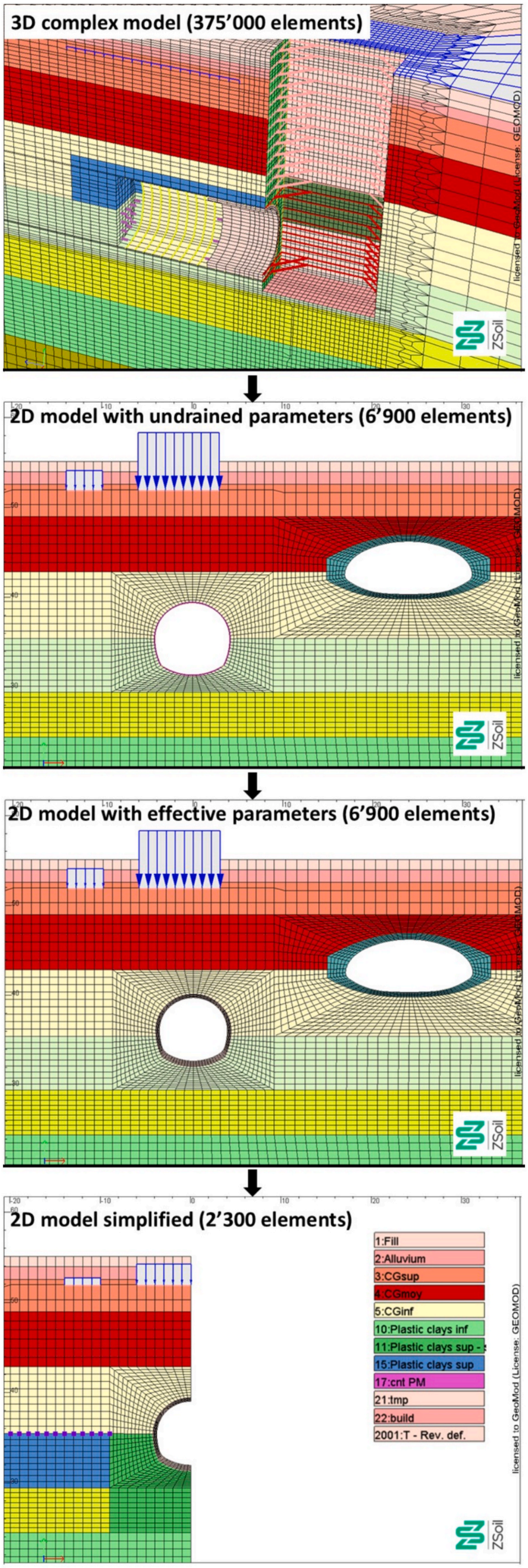

Fig. 4. Finite element models used in the analysis.

distributions have been chosen for the geotechnical parameters. The lognormal distribution has the feature of avoiding negative values for these parameters. More specially, the distribution is chosen as Lognormal for the Young Modulus (coefficient of variation of 30%) and the drained cohesion (coefficient of variation of 20%), and as Gaussian for the friction angle (coefficient of variation of 10%). Concerning the HA parameters, the authors choose Gaussian distribution for κ, the slope of the stress–strain curve in the Huder-Amberg swelling test (Fig. 5), and σ_0, the limiting swelling pressure, according to their experience. For the B parameter, which represents the characteristic period of swelling, a uniform distribution is chosen since it is a low informative prior, and the posterior distribution of B will be essentially based on the measurements. Based on the previous studies using 2D and 3D finite element models[39,40,48], the limiting swelling pressure applied to the liner invert varies between 250 kPa and 350 kPa, depending on the time of tunnel lining installation (variable thickness between 0.4 m in the crown and 0.6 m in the counter-vault) and the depth of tunnel raft. For this reason, the upper range of 350 kPa is taken as the mean value with a standard deviation of 75 kPa for the parameter σ_0.

Table 5 summarizes the probabilistic distributions of the twenty-one input probabilistic variables. The correlation between these variables is not taken into account. Although cohesion and friction angle are known to be negatively correlated, this interdependence has been neglected in this study. The authors believe that the bias introduced in the results is small resulting from this negligence, as the sensitivity analysis (Fig. 6) shows that these two variables do not influence the swelling pressure results. To verify this, another probabilistic analysis was carried out, introducing a Gaussian copula with a negative correlation of −0.3 between cohesion and friction angle for the plastic clays. It confirmed the little impact on the raft uplift (about 0.4%) associated with this bias.

With the mean values of the input variables, Fig. 5 shows the vertical displacement due to swelling, surrounding the tunnel raft after 2800 days.

Sensitivity analysis

The probabilistic analysis of the swelling was carried out taking into account the variation of the probabilistic input variables, using the coupling of the ZSoil[56]and UQLab tools[58].

The selection of the probabilistic inputs leads to twenty-one probabilistic input variables (Table 5), some of which may not affect the finite element model’s results. A sensitivity analysis is hence employed to quantify how input variables impact the calculation results, in this case the limiting swelling pressure applied to the liner invert.

Four of the twenty-one probabilistic input variables have been found to affect significantly the swelling pressure beneath the raft, based on the results of this sensitivity analysis using 300 samples of the probabilistic input variables. They are the Young modulus of plastic clays and the swelling parameters in the HA model (Fig. 6). The Young Modulus of plastic clays affects the stress distribution beneath the tunnel raft, which explains its contribution (total Sobol’ index greater than 0.15). The mechanical properties of other soil layers have little impact on the swelling pressure because they are situated above the tunnel raft. Note that the sample size was chosen based on the leave-one-out (LOO) error which has to be small in order to be certain that the metamodel approximates correctly the finite element response.

The Sobol indices were calculated in three time-steps following swelling: 100 days, 650 days, and 2800 days. The limiting swelling pressure σ_0 becomes more significant over time. After 2800 days, the total Sobol index of σ_0 is 0.9. It indicates that nearly all of the pressure under the tunnel raft is driven by the limiting swelling pressure after 2800 days of swelling.

Because the measurements are available over a period of 370 days, the inputs do not have the same impact as they would have during the time of interest, namely long-term swelling (2800 days). Consequently, the variable B needs to be taken into account in the Bayesian analysis.

Table 4
Geomechanical parameters for plastic clay.

Formation		Model	Drainage condition	Modulus			Strength			Stress				Swelling	
				E_{50} (MPa)	E_{oed} (MPa)	E_{ur} (MPa)	c' (kPa)	ϕ' (°)	Ψ (°)	σ_{h_ref}' (kPa)	σ_{v_ref}' (kPa)	ν_{ur} (−)	m (−)	σ_0 (kPa)	k (−)
Plastic clays	Upper	HSM/HA	Drained	20	20	60	20	16	0	400	400	0.2	0	350	0.04
			Undrained				Cu = 100 kPa					0.49			
	Medium	HSM/HA	Drained	42.5	42.5	128	20	16	0	400	400	0.2	0	350	0.04
			Undrained				Cu = 135 kPa					0.49			
	Lower	HSM/HA	Drained	65	65	195	20	16	0	400	400	0.2	0	350	0.04
			Undrained				Cu = 170 kPa					0.49			

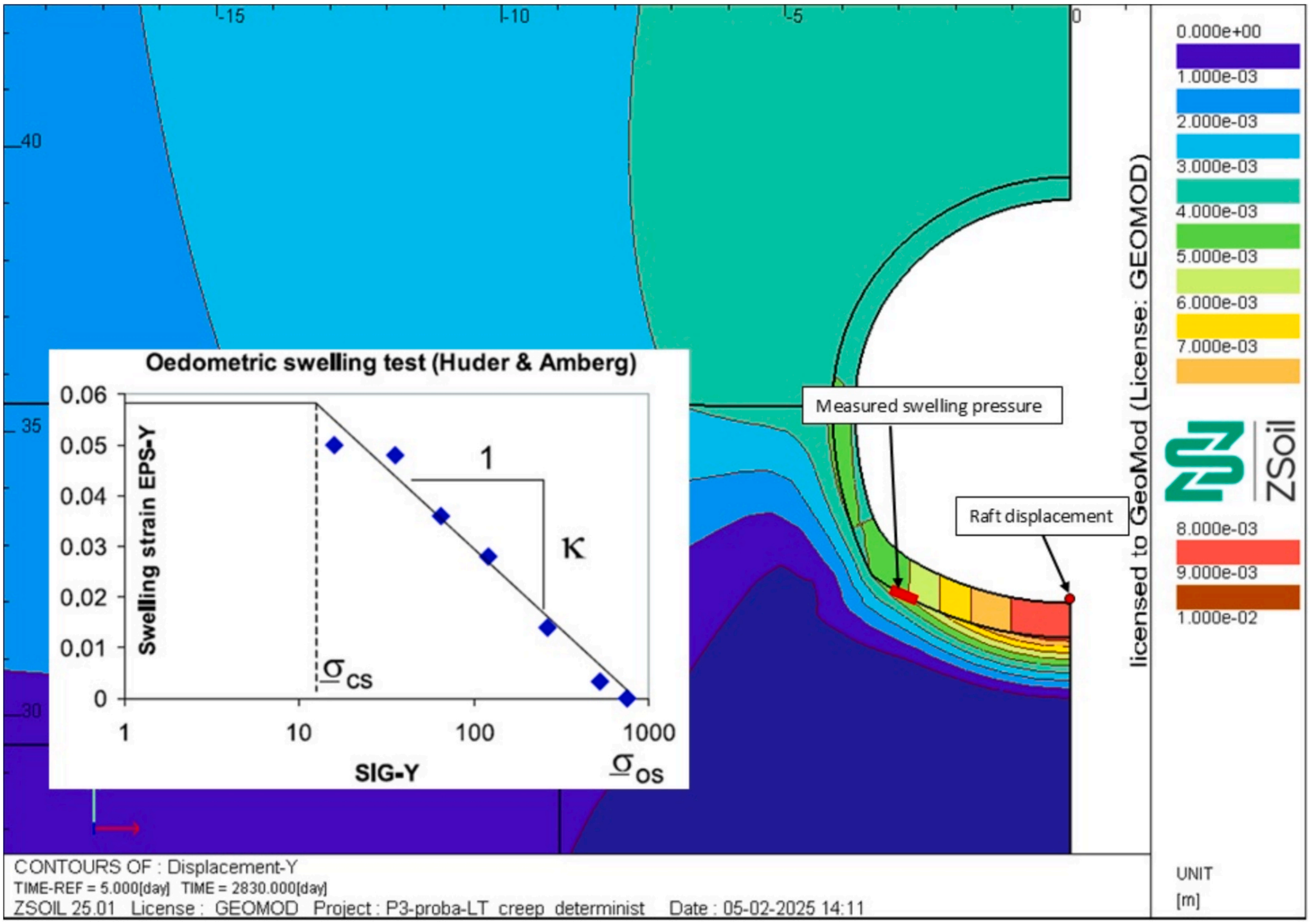

Fig. 5. Raft vertical displacement with the mean values of input variables after 2800 days.

The prediction uses short-term measurements to predict long-term behavior. The representativeness of short-term measurements for long-term forecasts is at the core of the Bayesian analysis. This process can be iterative, as shown in[37]. In this case study, we try to forecast the swelling pressure over 2800 days by using the monitoring results available for 370 days.

Reliability analysis

The sensitivity analysis identifies the input variables that affect significantly long-term swelling and heave of tunnel raft, and aids in understanding the model's behavior. The reliability analysis quantifies the probability of failure, or in this case study, the probability that the tunnel raft's heave will exceed a given threshold.

Fig. 7 represents the uplift of the tunnel lining raft as a function of the Young modulus of plastic clays and the limiting swelling pressure. As previously mentioned, the limiting swelling pressure is the most significant probabilistic input variable. Fig. 7 was created using 300 samples of the probabilistic input variables (the same set of samples used in the sensitivity analysis), the associated input files were then computed with ZSoil software.

Accounting for the twenty-one probabilistic input variables, the probability that the tunnel raft uplift will exceed 10 mm after 2800 days is $P_f = 25.1\%$ (Fig. 8). Similarly, the probability that the uplift will surpass 12 mm after 2800 days is $P_f = 4.5\%$. With a target tunnel raft heave of 15 mm, this probability is reduced to 0.03%. These probabilities were computed with the help of a Polynomial Chaos Expansion, a metamodel approximating the ZSoil response based on the previously calculated 300 samples.

Table 5
Statistical characteristics of the probabilistic variable.

Probabilistic variable		Type	Mean value		Coefficient of variation
Young Modulus	Fill	Lognormal	15,000	(kPa)	0.30
	Alluvium	Lognormal	12,000	(kPa)	0.30
	CG_{sup}	Lognormal	50,000	(kPa)	0.30
	CG_{moy}	Lognormal	300,000	(kPa)	0.30
	CG_{inf}	Lognormal	400,000	(kPa)	0.30
	Plastic clays	Lognormal	60,000	(kPa)	0.30
Friction angle	Fill	Gaussian	28	(°)	0.10
	Alluvium	Gaussian	23	(°)	0.10
	CG_{sup}	Gaussian	32	(°)	0.10
	CG_{moy}	Gaussian	38	(°)	0.10
	CG_{inf}	Gaussian	46	(°)	0.10
	Plastic clays	Gaussian	16	(°)	0.10
Cohesion	Fill	Lognormal	2	(kPa)	0.20
	Alluvium	Lognormal	10	(kPa)	0.20
	CG_{sup}	Lognormal	6	(kPa)	0.20
	CG_{moy}	Lognormal	60	(kPa)	0.20
	CG_{inf}	Lognormal	60	(kPa)	0.20
	Plastic clays	Lognormal	20	(kPa)	0.20
Swelling parameters of plastic clays (Huder Amberg)	σ_0	Gaussian	350	(kPa)	0.20
	κ	Gaussian	0.04	–	0.25
	B	Uniform	350	(day)	0.25

Field measurements

The auscultation system setup made it possible to monitor and quantify the swelling pressure of plastic clays by placing pressure cells (PC in Fig. 9) beneath specific supports[48,49].

Fig. 10 displays the calculated prior swelling pressure and the swelling pressure measured under the tunnel raft at the beginning of the swelling. Monitoring measurements contain the first 370 days of swelling pressure. These field measurements enable the application of the Bayesian inference to improve the results of probabilistic calculations, and consequently to refine the long-term prediction, by updating the prior distributions of the input variables.

Bayesian inference and the posterior results

The Bayesian inference was used to improve the predictions of the swelling pressure after 2800 days, taking into account the field measurements of swelling pressure available during the first 370 days. The following steps are taken to accomplish the Bayesian inverse analysis:

- Four important probabilistic input variables were determined by the sensitivity analysis, namely the Young Modulus of the plastic clays (E), and the swelling parameters (σ_0, B and κ). A second reliability analysis was then performed using these four important variables. Reducing the number of probabilistic input variables from twenty-one to four improves the accuracy of the Bayesian inverse analysis while minimizing its computational cost.
- 500 samples of these four important probabilistic input variables (E, σ_0, B and κ) were drawn, and the choice of the sample size is again based on the LOO error. Each input sample gave a different swelling pressure under the tunnel raft, the associated input file was calculated with ZSoil software (i.e. 500 finite element analyses).
- A Polynomial Chaos Expansion was generated to approximate the ZSoil results, using the 500 calculated samples. In terms of LOO error, this fitting of the ZSoil response has an accuracy of less than 3%. It indicates that for a new set of (E, σ_0, B, κ), the metamodel predicts the ZSoil swelling pressure (at any time) with 97% accuracy.
- A posterior distribution of input variables was obtained by performing a Bayesian inverse analysis using the field measurements.
- The posterior distribution of the swelling pressure was computed after 2800 days of swelling, with the obtained posterior distribution of input variables.

This method has the advantage of having a posterior probability of failure for long-term tunnel raft heave, which accounts for the uncertainty in the input variables and field data available during the first 370 days of the swelling.

Fig. 11 shows a comparison between the prior distribution (the initial distribution assumed at the beginning of the calculations) and the posterior distribution (the distribution given the field measurements) of the four important probabilistic input variables. Fig. 11 shows also a shift in the limiting swelling pressure σ_0. The histogram's shape has changed, and the mean value has decreased from 350 kPa to 323 kPa.

The posterior distribution of the input variables leads to the posterior distribution of the swelling pressure after 2800 days, and the long-term heave of the tunnel raft. Fig. 12 illustrates the swelling pressure

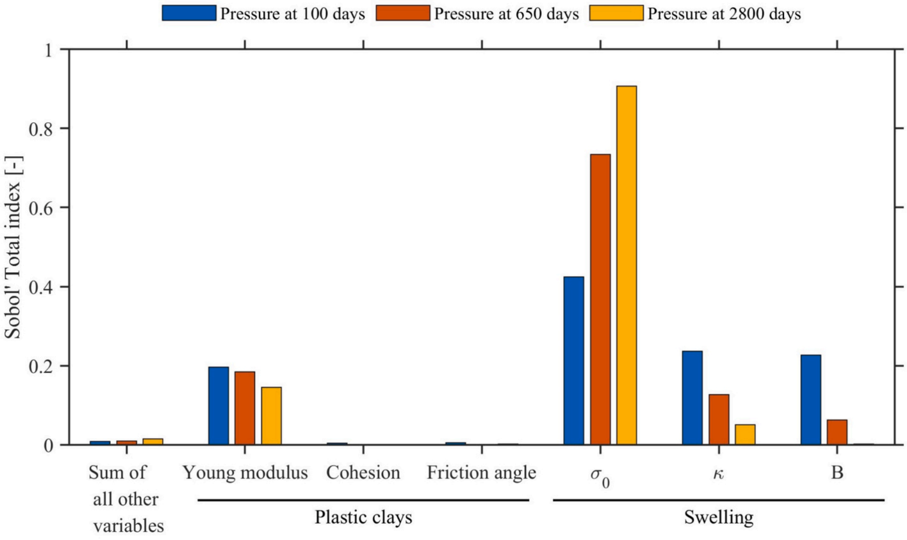

Fig. 6. Sensitivity analysis of input variables' impact to the swelling pressure under tunnel raft.

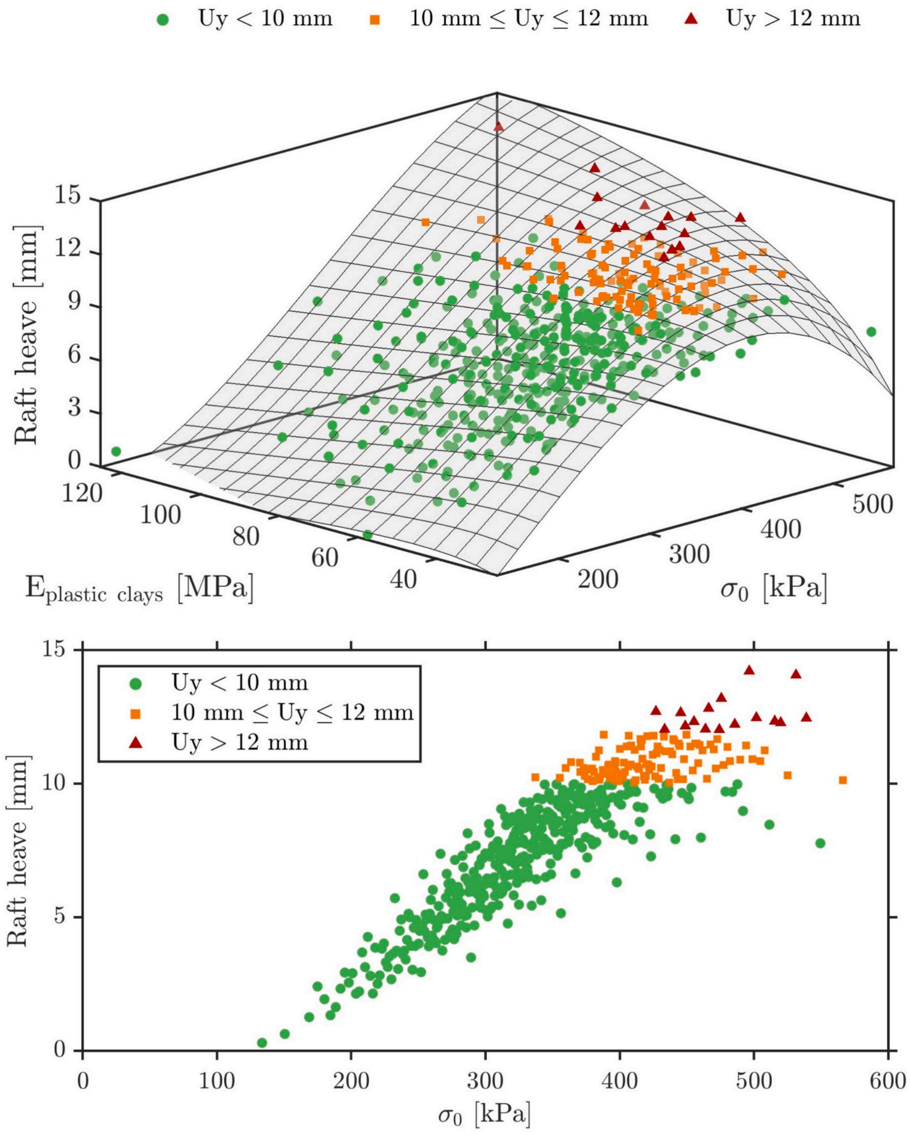

Fig. 7. Probabilistic calculation of the tunnel raft heave as a function of the Young modulus of plastic clays and the limiting swelling pressure.

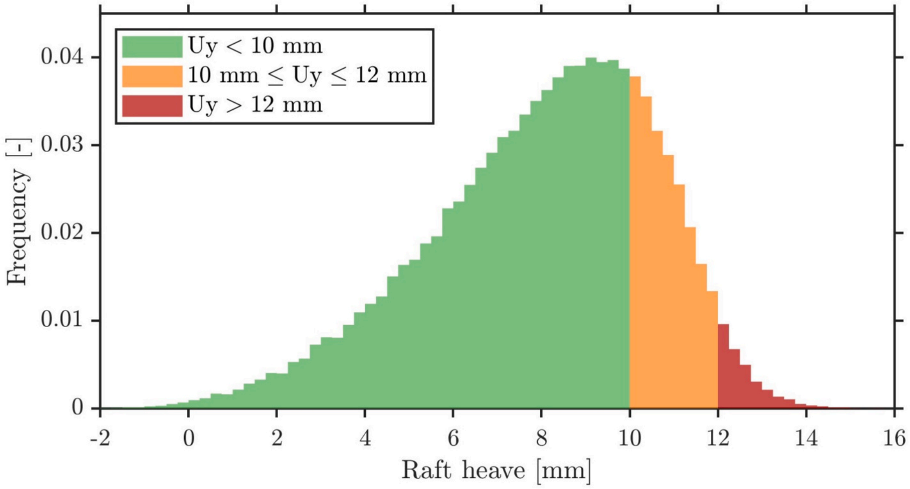

Fig. 8. Distribution of the tunnel raft heave as a function of the swelling pressure (the prior calculation).

calculated with the posterior mean values. The posterior prediction is closer to the field measurements and forecasts a lower long-term

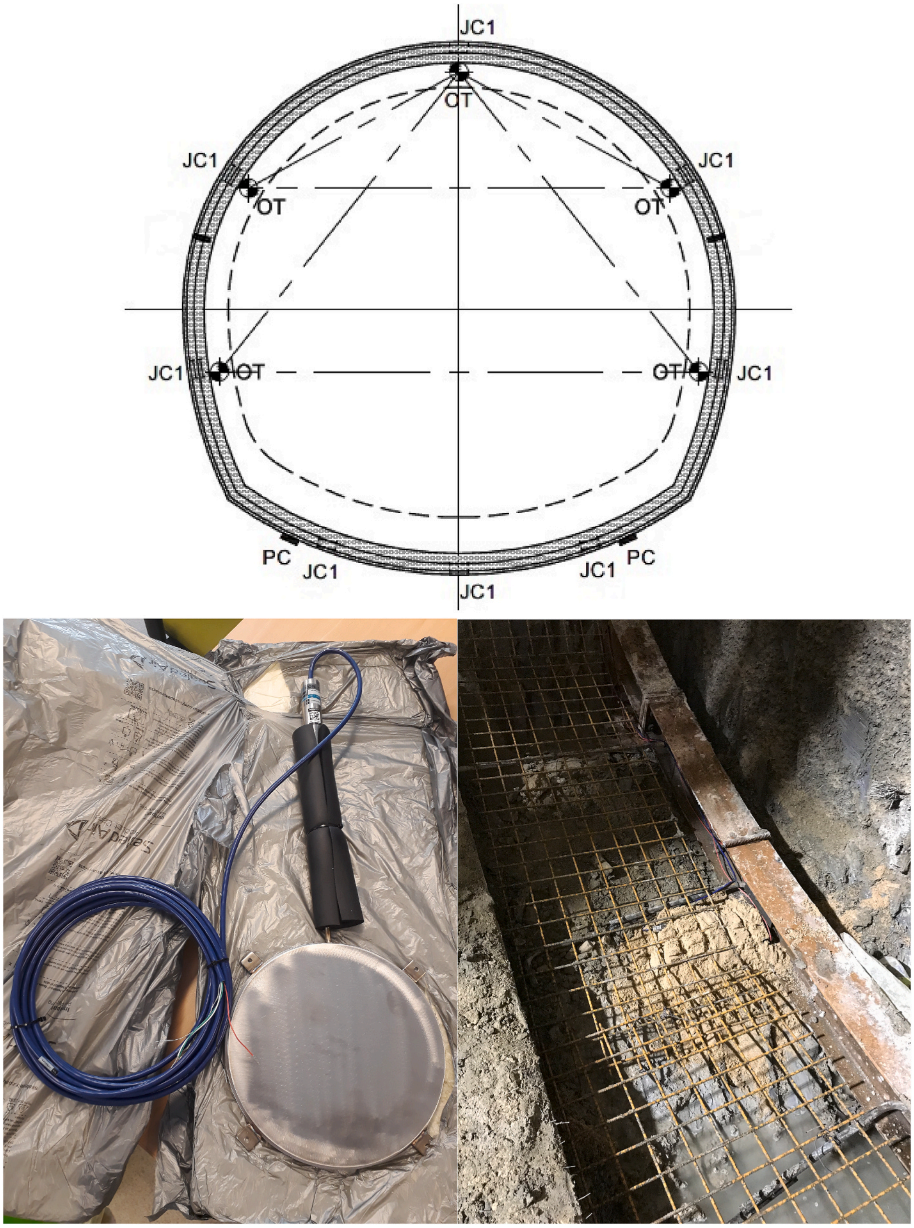

Fig. 9. Monitoring system beneath specific supports (above), photos of pressure cell (PC) and its set up (below).

swelling pressure under the tunnel raft.

The posterior results demonstrate that the swelling pressure under the tunnel raft decreases in terms of the mean value and 95% quantile value after 2800 days (Fig. 13). In fact, the prior's 95% quantile is 173 kPa, while the posterior's is 132 kPa. It means there is 5% probability to have more than 173 kPa of pressure under the tunnel raft with the initial hypothesis. By considering the field measurements of the first 370 days, the 95% quantile value is reduced to 132 kPa. This quantifies the safety gain on the swelling pressure under the tunnel raft.

Fig. 14 displays the updated distribution of the tunnel raft heave. The posterior histogram has smaller mean value and standard deviation than the prior one, it means the prediction is more optimistic and accurate, when the first 370 days field measurements are taken into account.

Fig. 15 displays a 5% posterior probability of exceeding 10 mm, whereas Fig. 8 displays a prior probability of $P_f = 25.1\%$. The Bayesian inference performed on the limiting swelling pressure allows largely reducing the uncertainty on the tunnel raft heave, as well as the probability of exceeding specific threshold values.

Discussion and conclusions

In the Grand Paris Express project, many underground structures (shafts, stations, diaphragm walls, tunnels, etc.) come into touch with Paris plastic clay, which frequently generates problems for these underground structures because of its swelling character. In fact, decompression process during the excavation and water absorption from the tunnel can disturb the plastic clay's structure, thereby increasing its volumetric swelling potential.

In this MBP case study, numerous in situ and laboratory tests have been realized on Paris plastic clay. The swelling tests results confirm its strong swelling character with $Cs = 0.09$ and a swelling pressure varying between 122 and 1500 kPa.

Due to the wide dispersion of the swelling pressure measured in the laboratory, a probabilistic analysis was performed. By means of the reliability analysis, the probability of failure of the tunnel raft heave was evaluated with respect to the predefined thresholds. Twenty-one probabilistic variables were first considered. The reliability analysis results showed that the probability of the tunnel raft uplift exceeding 10 mm

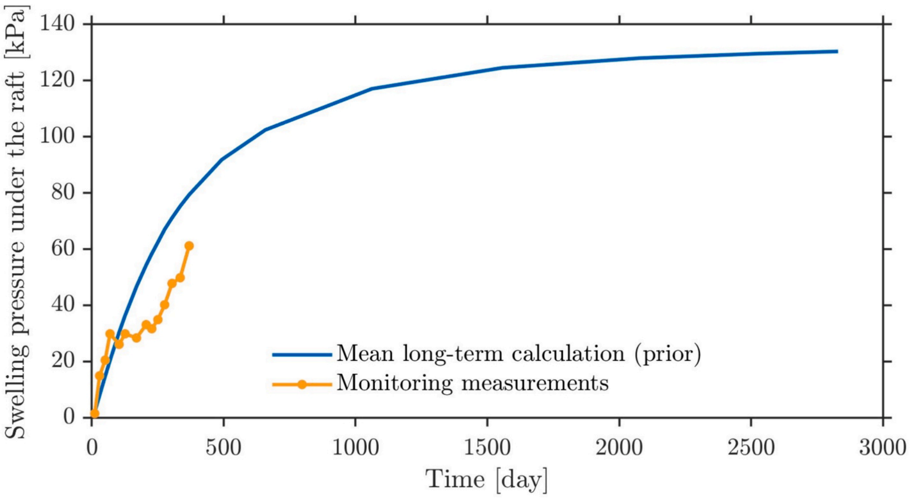

Fig. 10. Comparison of the calculated (prior) and measured swelling pressures under the tunnel raft.

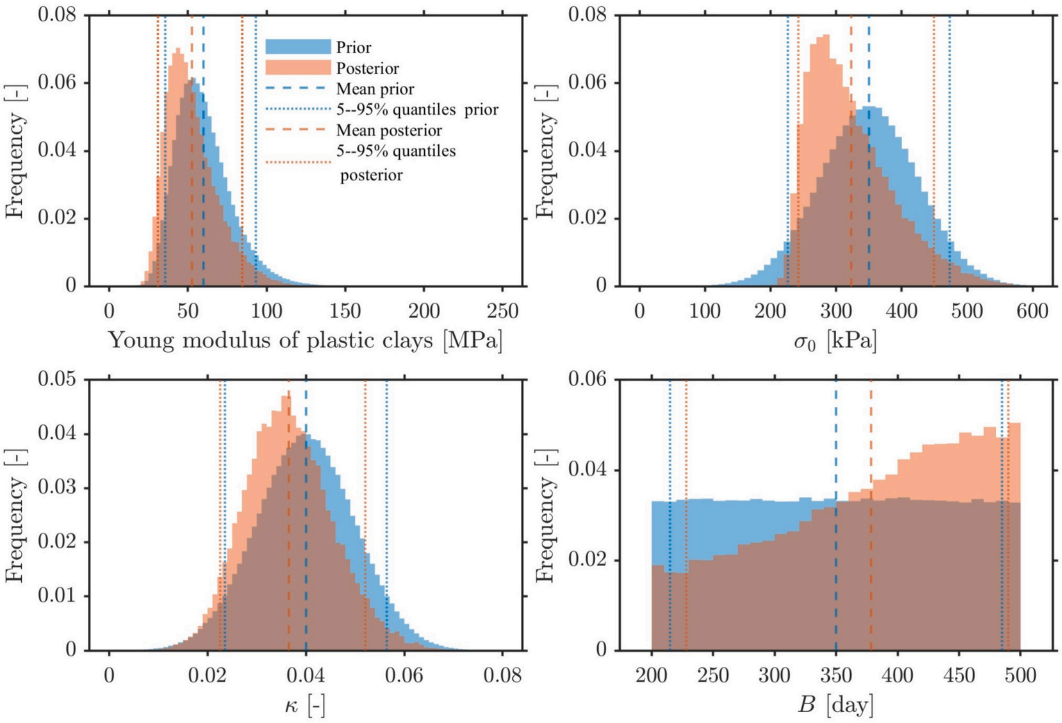

Fig. 11. Comparison of the prior and posterior distributions of the input variables.

after 2800 days is $P_f = 25.1\%$.

Using the sensitivity analysis, four input variables were identified as most influent to the swelling pressure beneath the tunnel raft. The field measurements allowed quantifying the swelling pressure over a period of 370 days. A Bayesian inverse analysis was then carried out with these four important probabilistic input variables and the 370 days' field measurements to update the prior calculation hypothesis. Thanks to the Bayesian inverse analysis and with the posterior calculation hypothesis, the probability that the tunnel raft heave exceeds 10 mm after 2800 days has been reduced from 25.1% to 5%.

More generally, within the probabilistic framework, the geotechnical analyses of the tests results allow the establishment of the prior hypotheses regarding the probability density function of the swelling pressure. The constitutive laws and their well-calibrated parameters enable to accurately simulate the mechanical and hydric swelling behavior. In addition, the main premise of the observational method is feedback loops using monitoring data can lead to design optimization. Bayesian updating can enrich the observational method with probabilistic information on the evolution of hypotheses and uncertainties. The posterior probabilities can then be used in design check, design decision-making and design optimization. Monitoring field measurements can also be used to update the reliability of the structure.

In the future, continuous monitoring will still be necessary to obtain more monitoring data in order to better understand and evaluate the long-term behavior of tunnel constructed in Paris plastic clay. Using the observational method, in situ measurements make it possible to verify the results of numerical simulations and to update the prior calculation hypotheses. To be exhaustive, model-form uncertainty and measurement errors should also be taken into account in the future studies. Combined with the Bayesian inverse analysis, the observational method

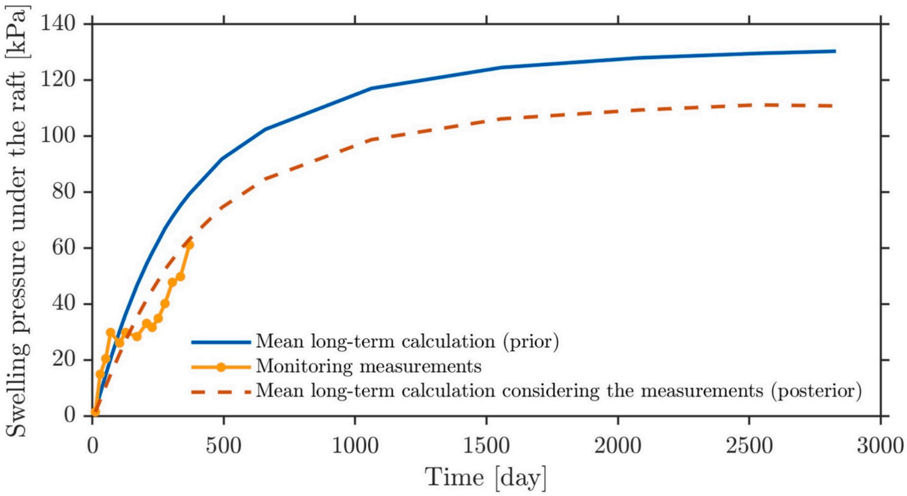

Fig. 12. Comparison of the calculated (prior and posterior) and measured swelling pressures under the tunnel raft.

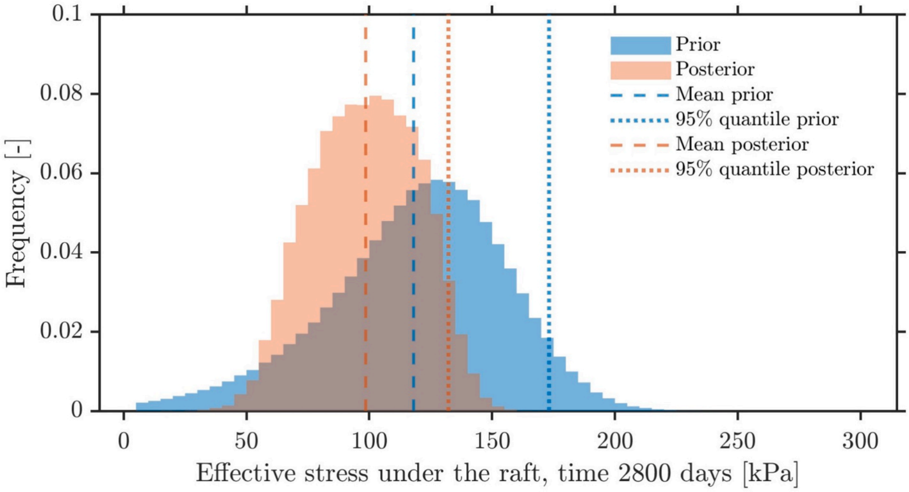

Fig. 13. Bayesian updating of the long-term swelling pressure under the tunnel raft.

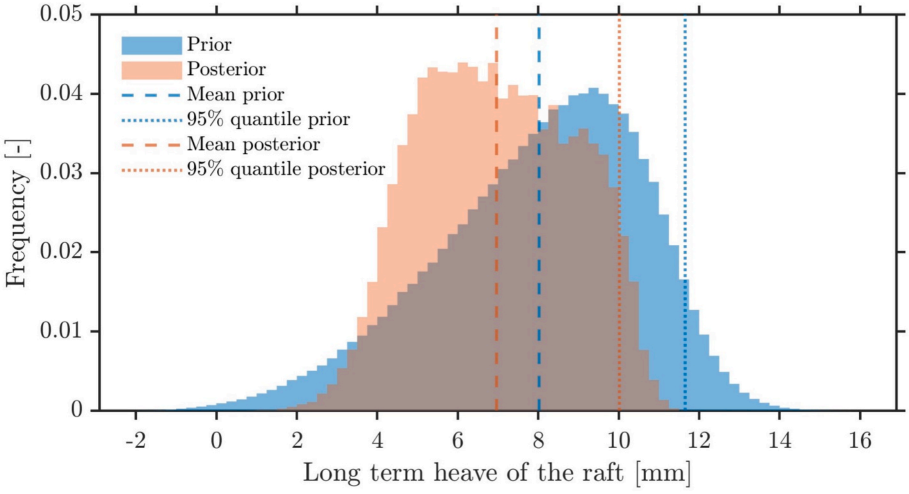

Fig. 14. Bayesian updating of the long-term heave of the tunnel raft.

can improve the accuracy in the prediction of the Paris plastic clay's swelling character, therefore guiding technical choices and optimizations for the rest of the project, as for a general use of Bayesian analyses with respect to geotechnical reliability-based design.

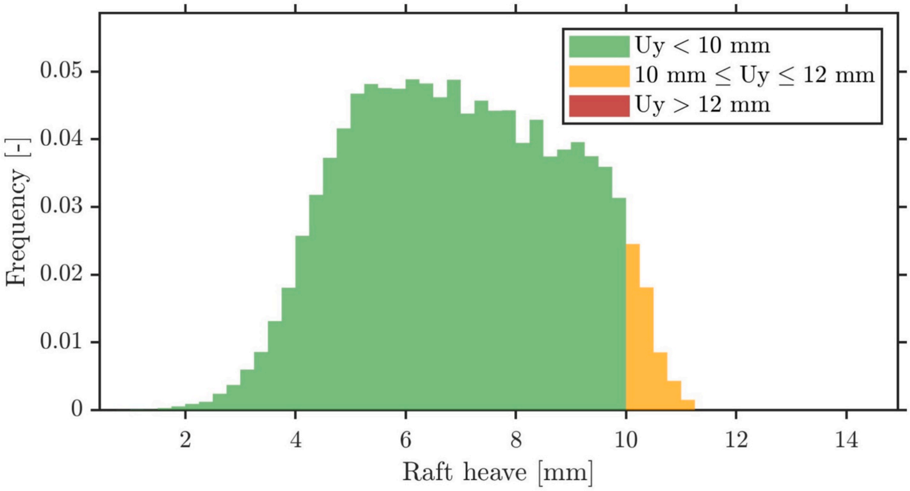

Fig. 15. Distribution of the tunnel raft heave as a function of the swelling pressure (the posterior calculation).

CRediT authorship contribution statement

Yi Zhang: Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Stéphane Commend:** Writing – review & editing, Validation, Supervision, Software, Methodology, Formal analysis. **Marc Groslambert:** Writing – original draft, Software, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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