

# Taking anisotropy into account in the analysis of small deformations in Beauchamp sands.

**Sonia Fanelli, Fabien Szymkiewicz, Emmanuel Bourgeois, Philippe Reiffsteck**  
 University Gustave Eiffel, Champs-sur-Marne, France, [sonia.fanelli@univ-eiffel.fr](mailto:sonia.fanelli@univ-eiffel.fr)

**ABSTRACT:** In urban environments, modern construction practices for buildings or large structures can lead to new problems of interaction between soils and structures, particularly when using materials that are less resistant to deformation (glass structures, partitions, etc.). Structures are mainly designed using calculation methods that integrate mechanical characteristics defined on the basis of a single type of test under isotropic conditions and, consequently, a specific and relatively unique stress path. However, depending on the stress path actually followed in the soil, the stiffness observed during elementary test may not be representative.

Indeed, depending on the nature of the soil, the type of structure and its location, the stress state may be different, inducing different mechanical behaviors such as compression, shear or extension. Improving the design of structures by better defining the response of soils to low-intensity loads therefore remains a major challenge. It is therefore necessary to compare methods for assessing the mechanical parameters of materials in order to identify the test that is most representative of the *in situ* stress. This paper presents the development of an approach to understanding small deformations based on two types of data:

- existing data from laboratory tests carried out under different stress path : compression, shear and other stress paths, and in *in situ* tests as part of various projects located in the Paris region,
- the results of new tests, carried out on Beauchamp sands sampled *in situ*, to study the contribution of anisotropy in the mechanical parameters corresponding to small deformations, in particular from resonant column tests.

By calibrating the parameters of conventional models for assessing modulus dependence on deformation, a sensitivity analysis will be carried out and discussed.

**KEYWORDS:** Laboratory tests, Beauchamp sands, shear modulus, anisotropy.

## 1 INTRODUCTION

Over the past ten years, a significant amount of data has been collected from laboratory and *in situ* tests for various projects in the Paris region. This paper presents a synthesis of some of this test data, focusing mainly on triaxial, oedometer, and Ménard pressuremeter tests carried out on Beauchamp sands for projects grouped into three main sites. After a brief presentation of the sites and their geological context, we will focus on gathered test data, which includes the main mechanical characteristics reported by companies according to current standards. Then, we will analyze additional laboratory test results on the same soil, allowing for a better characterization of mechanical parameters at small strains, particularly using resonant column tests.

Finally, a global analysis will highlight the sometimes heterogeneous and anisotropic nature of this geological formation depending on location, and the impact on mechanical parameters when focusing on small deformations along different stress paths.

## 2 SITES LOCATION AND GEOLOGICAL CONTEXT

All projects were grouped into three sites: A, B, and D (Figure 1).



Figure 1. Projects grouped into 3 sites (A, B and D) in Paris, Hauts-de-Seine, Seine-Saint-Denis and Val-de-Marne departments.

The analysis of geotechnical boreholes identified around twenty soil layers and led to a synthesis of stratigraphic profiles for each site (Figure 2). Site D, located in the Seine Valley, is represented by two different profiles with different soil types: the first in the west on the plateau (D1) and second in the east in the valley bottom (D2). The studied soils date from the Eocene to the Oligocene (Tertiary Era) and from the Pleistocene to the Holocene (Quaternary Era) for the most recent deposits like alluvium.

The Beauchamp sands formation shows irregular stratification, with medium to coarse sands in the upper part, sandy clays and marls in the middle, and fine clayey-sandstone sands at the top of the lower part, followed by coarse sandstone sands at the base (Filliat, 1981).

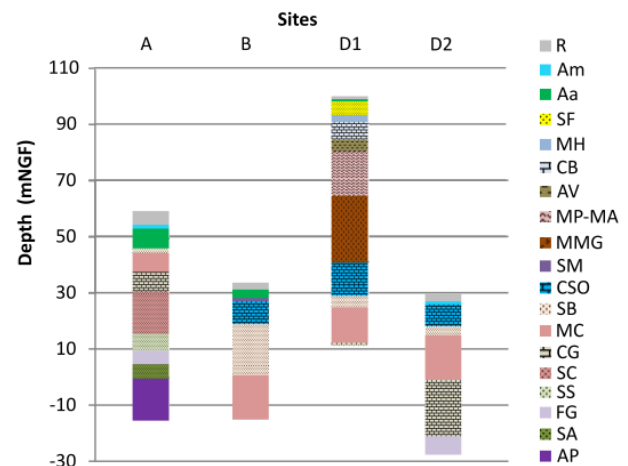


Figure 2. Simplified stratigraphic logs for the three areas studied. R : remblais ; Am : recent alluvium ; Aa : old alluvium ; SF : Fontainebleau sands ; MH : oyster marls ; CB : Brie limestone ; AV : green clays ; MP-MA : Pantin marls / Argenteuil marls ; MMG : gypsum beds and marls ; SM : Monceau sands ; CSO : Saint-Ouen limestone ; SB : Beauchamp sands ; MC : marls and limestone layer ;

CG : Lutetian limestone ; SC : Cuise sands ; SS : upper sands ; FG : false clays ; SA : Auteuil sands ; AP : plastic clays.

### 3 EXPERIMENTAL APPROACH

#### 3.1 Data collection

Several test results were analyzed based on the geological layer type, geographical location, and depth. The collected parameters include cohesion, internal friction angle, Poisson's ratio, preconsolidation stress, and Ménard pressuremeter modulus of the Beauchamp sands.

This approach partly builds on Georges Filliat's work (1981), who analyzed lab and field test results in the Paris region. His studies highlighted the heterogeneity and anisotropy of geological formations and the variability of mechanical parameters depending on location.

Other researchers have also studied these parameters and their spatial variability, including the heterogeneity of some soils in the Paris Basin (Gigan, 1974; Vuillaume, 2018; Egal, 2018; Zhang, 2022), as well as the London clays (Hight, 2007; Bagheri, 2020).

##### 3.1.1 Oedometer tests

Figure 3 presents the preconsolidation stress of upper Beauchamp sands versus initial vertical stress for soils from sites B and D2, derived from oedometer tests carried out by companies.

The overconsolidation ratios ( $OCR = \sigma'_p / \sigma'_{v0}$ ) vary significantly within the same formation at approximately equal depths. Values range from 1.1 to 3.4 for site B and are below 1 to 1.1 for site D2. Values below 1 for site D2 may be due to factors like sample quality, transport disturbance, test quality, or its interpretation. All these factors can lead to uncertainties in the definition of a parameter when carrying out a test (Bat *et al.*, 2000), especially test and sampling equipment and procedures which can influence the deformation parameters (Fanelli *et al.*, 2025).

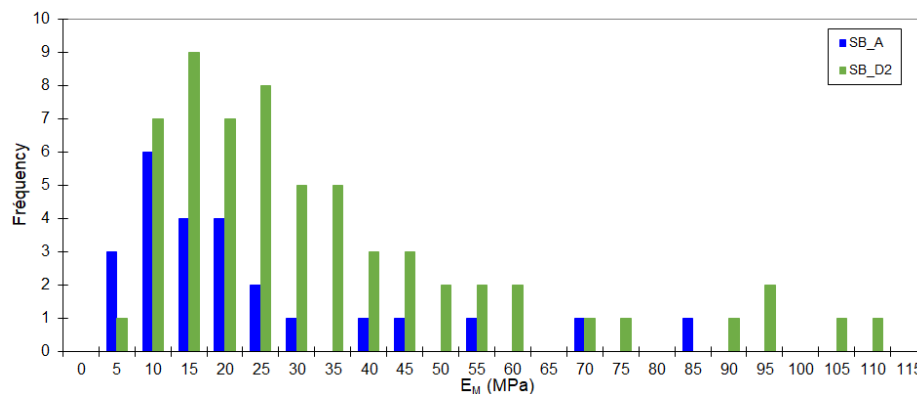
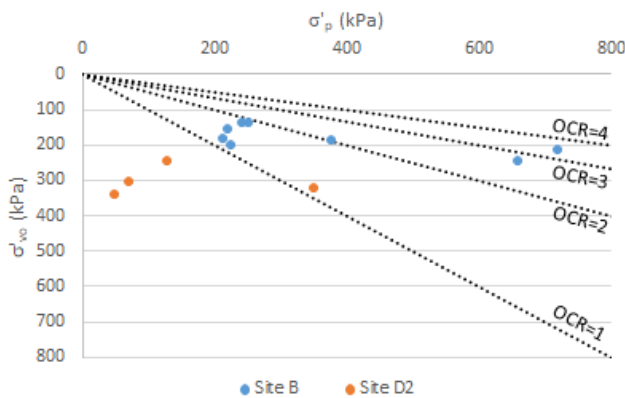


Figure 4. Frequency distribution of the Ménard pressure modulus for Beauchamp sands in sites A and D2.

Figure 3. Data from oedometer tests on upper Beauchamp sands at sites B and D2.

##### 3.1.2 Triaxial tests

Other mechanical parameters such as cohesion, friction angle, and Poisson's ratio (when available) were identified from drained and undrained triaxial tests.

Tables 1 and 2 present the min, max, mean, and standard deviation values for each sand facies and number of data points used for sites B and D. For site B, the three facies of the Beauchamp sands were distinguished, unlike site D, where only global values are provided.

The breakdown of facies at site B reveals disparity in friction angles, despite limited data. Within each facies, minimum and maximum values vary regardless of the parameter, likely influenced by mineral composition depending on sand and clay content. Also, the number of data points used to compute averages differs between sites, possibly affecting parameter estimations. In particular, the middle facies has lower cohesion than the other two facies, while it is predominantly clayey.

		Min.	Max.	Mean	Std dev.	Nb val.
$c'$ (kPa)	SB sup	3.3	44.7	16	15.3	6
	SB med	-	-	12.2	-	1
	SB inf	-	-	36	-	1
$\phi'$ (kPa)	SB sup	35	46	40.9	4.7	6
	SB med	-	-	33	-	1
	SB inf	-	-	37	-	1

Table 1. Average parameter values from triaxial tests for site B.

	Min.	Max.	Mean	Std dev.	Nb val.
$c'$ (kPa)	0	318	27	50	53
$\phi'$ (kPa)	19	42	31	5	53
$\nu$ (-)	0.12	0.43	0.2	0.09	12

Table 2. Average parameter values from triaxial tests for site D.

##### 3.1.3 Pressuremeter tests

Several *in situ* Ménard pressuremeter tests provided geotechnical parameters such as pressuremeter modulus  $E_M$ , limit pressure  $P_l$ , and creep pressure  $P_f$ . This paper only focuses on  $E_M$  for Beauchamp sands.

Data from sites A, B, and D2 allowed for statistical analysis. Figures 4 and 5 show the distribution frequency of  $E_M$  for each site. For site B, the three sand facies were separated.

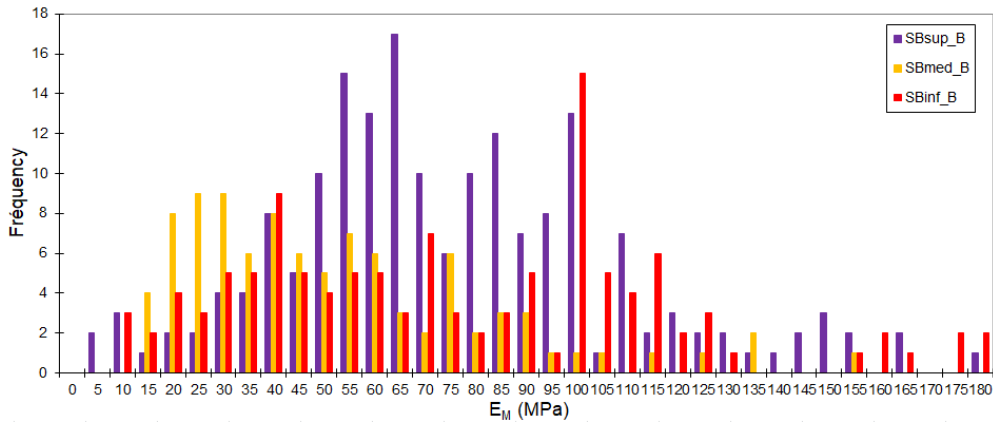


Figure 5. Frequency distribution of the Menard pressure modulus for the three Beauchamp sand facies in site B.

Sites A and D2 show a relatively narrow distribution: around 5–30 MPa for site A and 10–50 MPa for site D2. Site B shows a broader range of values of  $E_M$  (10–100 MPa), especially for the medium and lower facies, complicating the assignment of characteristic values to each layer. This variability could be explained by certain factors such as the depth of the layer tested and its composition (sandy, sandy-clayey, or sandstone).

Table 3 presents average  $E_M$  values per site. Despite the low value at site A, the values for site D2 and the average of the values for site B align with those proposed by Lachérade (2024) for line L15 West of the Grand Paris Express project.

		Sites			
		A	B	D2	L15 West (Lachérade, 2024)
$E_M$ (MPa)	SB sup		100.8		
	SB med	21.7	49.8	96.3	75.8
	SB inf		114.2		

Table 3. Average pressuremeter modulus values by location.

The data analysis method can be important in cases where a certain heterogeneity of values appears during testing. With this in mind, several authors, such as Baguelin and Kovarik (2000), Cassan (2000) and Lacherade et al. (2024), have studied methods for determining geotechnical parameters based on multi-criteria approaches such as uncertainties and observed variabilities.

### 3.2 Laboratory tests on Beauchamp sands

Beauchamp sand samples were reconstituted from borehole cores taken at depths between 7 and 12 m in Malakoff, southwest of Paris.

Figure 6 shows several grain size curves for site D2 at different depths compared to the 7.5 m sample used to reconstitute the specimens. The soil tested corresponds to the upper facies of the Beauchamp sand layer, with a predominantly sandy grading.

All the laboratory tests described below were carried out on identically reconstituted samples with a degree of overconsolidation of 1.1, based on mechanical characteristics obtained from tests performed by the companies.

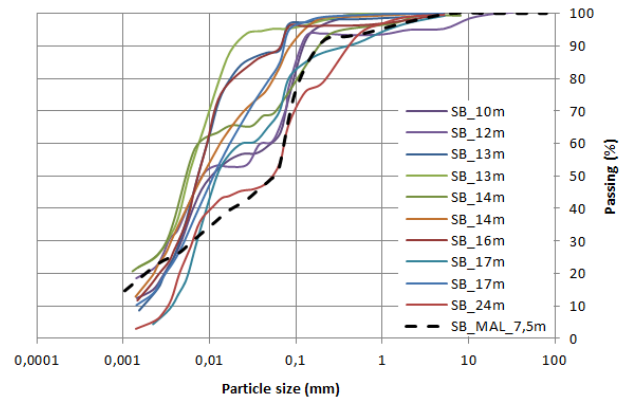


Figure 6. Grain size curves for Beauchamp sands.

#### 3.2.1 Triaxial tests

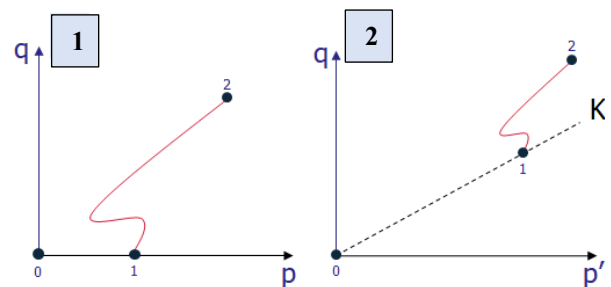
To better characterize mechanical parameters, stress-path triaxial tests were carried out to reflect the full life cycle of a soil sample—from extraction to lab testing. These tests differ from typical isotropic confinement test campaigns.

Undrained triaxial tests were performed to observe soil behavior under different loading paths. Three consolidation protocols were applied before shearing (Figure 7 and Table 4):

1. Isotropic consolidation
2.  $K_0$  consolidation
3.  $K_0$  consolidation, then unloading to isotropic confinement.

For each protocol, three specimens were tested at three different confinement (100 kPa, 200kPa and 300 kPa) with a back pressure of 400 kPa.

The  $K_0$  loading tests were conducted to reproduce initial stress states by applying vertical stress while preventing radial strain through volume control.



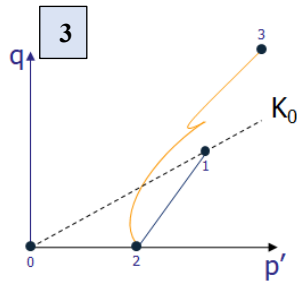


Figure 7. Consolidation protocols for triaxial tests.

Protocols	Stages		
	1	2	3
1	Isotropic consolidation	Shear	-
2	$K_0$ consolidation	Shear	-
3	$K_0$ consolidation	Unloading to isotropic confinement	Shear

Table 4. Stages of consolidation protocols for triaxial tests.

The Figure 8 shows the deviator stress for isotropic undrained triaxial tests based on the first protocol.

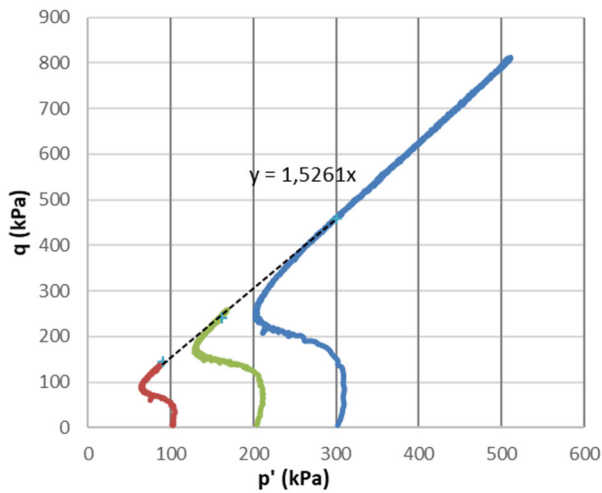


Figure 8. Undrained triaxial tests (protocol 1).

The couple cohesion and internal friction angle calculated here is 0 kPa and  $37.5^\circ$ . This corresponds to a  $K_0$  coefficient of 0.41 according to equation (1) of Jaky (1984) modified by Mayne and Kulhawy (1982) for overconsolidated soils (2). These results are consistent with those obtained by companies that have conducted triaxial tests on intact samples.

Figures 9 and 10 show the test curves from protocols 2 and 3, and Table 5 gives the resulting parameters. It can be seen that the  $K_0$  coefficient obtained after anisotropic consolidation for these two protocols is close to that calculated from the angle of friction.

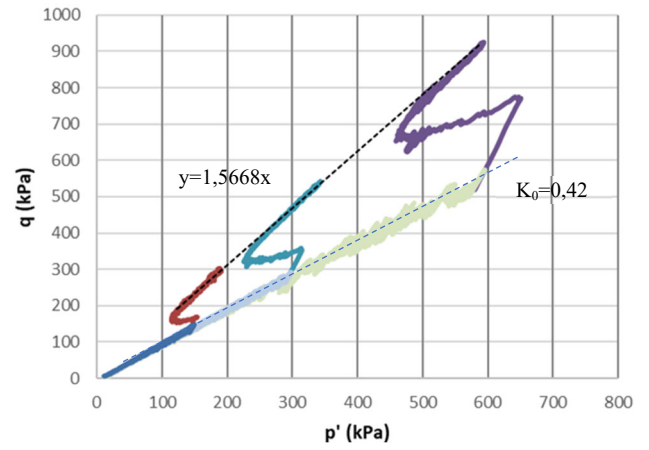


Figure 9. Undrained triaxial tests (protocol 2).

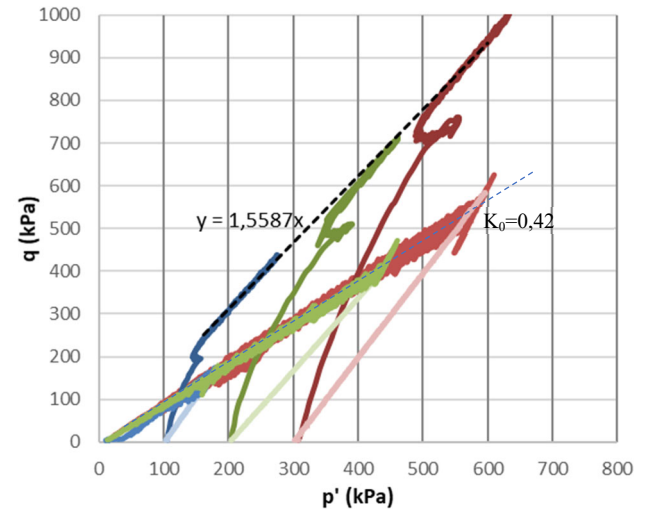


Figure 10. Undrained triaxial tests (protocol 3).

Protocols	$c'$ (kPa)	$\phi'$ ( $^\circ$ )
1	0	37.5
2	0	38.5
3	0	38.2

Table 5. Parameters from undrained triaxial tests.

All three stress paths yielded similar cohesion and friction angles. Hence, consolidation conditions (isotropic vs anisotropic) had little influence on resistance parameters in these tests.

Figure 11 shows shear stage curves for the three protocols.

$$K_{0,nc} = 1 - \sin \phi' \quad (1)$$

$$K_{0,ov} = K_{0,nc} * OCR^{\sin \phi'} \quad (2)$$

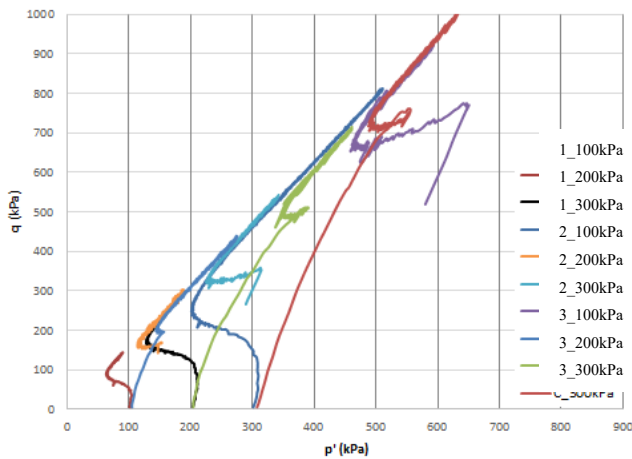


Figure 11. Results of triaxial tests for three protocols at different confinement.

### 3.2.2 Resonant column tests

Resonant column tests were conducted to study soil behavior at small strains.

Four  $K_0$  stress-path protocols were used. The first three mirrored those used for triaxial tests, with an additional one (Figure 12 and Table 6):

4.  $K_0$  path, unloading to zero radial/axial stresses, then isotropic consolidation.

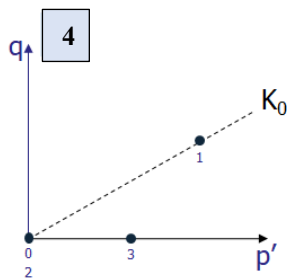


Figure 12. Additional consolidation protocol for resonant column tests.

Protocol	Stages		
	1	2	3
4	$K_0$ consolidation	Unloading to zero stresses	Isotropic consolidation

Table 6. Stages of additional consolidation protocol for resonant column tests.

Figure 13 presents shear modulus degradation curves vs distortion. Table 7 shows  $G_{max}$  values and applied stress states at the end of each protocol.

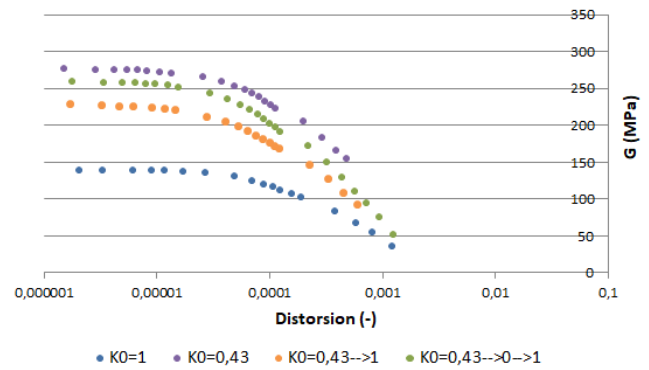


Figure 13. Shear modulus degradation curves as a function of the applied stress path.

Protocols	$K_0$ (-)	$G_{max}$ (MPa)	$\sigma'_1$ (kPa)	$\sigma'_3$ (kPa)
1	1	138.6	355	350
2	0.43	270.8	815	350
3	0.43 / 1	225.3	350	350
4	0.43 / 0 / 1	258.8	355	350

Table 7. Table of resonant column test values.

Results show clear differences between protocols, especially between isotropic and anisotropic confinement. Anisotropic specimens have the highest moduli, up to twice those of isotropic specimens.

Here we see the impact of anisotropy on moduli in small deformations, also demonstrated by the work of Nguyen *et al.* (2011) on the anisotropy of reconstituted soils, whether due to historical overloads or to the initial structure of the sample.

Although anisotropy has not been shown to affect the characterization of mechanical parameters in large deformations, failure to take it into account could lead to an underestimation of displacements of the designed structures.

## 4 CONCLUSIONS

The database gathered from various projects in the Paris region allowed for an in-depth analysis of the reference geotechnical parameters—particularly for the Beauchamp sands layer studied in this paper.

Several factors should be considered when analyzing test results: geographic location, facies characterization, sample heterogeneity and disturbance, and test interpretation. Given the variability of the Beauchamp sand formation within the layer itself, determining typical mechanical parameters seems questionable.

The first part of this article highlighted that soil such as the Beauchamp sands, considered unique from a geological point of view, does not appear to be geotechnically uniform given its observed vertical and lateral variability. This underscores the complexity of this exercise between the proposed case study and the scientific analysis performed. The latter would also require further analysis, particularly with regard to the statistical approach.

Depending on location, a soil layer may show anisotropy in stress states not replicated in classic lab tests (typically under isotropic confinement). Although anisotropy did not significantly affect mechanical parameters like cohesion and friction angle, resonant column tests revealed its clear impact

on small-strain behavior. Stress paths that simulate sample remolding stages clearly influenced the results.

Taking anisotropy into account is therefore useful for better characterizing small-strain soil behavior and incorporating it into large-scale project modeling.

Zhang Y., Commend S., Gros Lambert M. 2022. Analyses et modélisations sur les argiles plastiques du Sparnacien du Bassin parisien. *Revue française de géotechnique*, 171, 3. <https://doi.org/10.1051/geotech/2022003>

## 5 REFERENCES

- AFNOR, norme NF EN ISO 17892-9. 2018. Reconnaissance et essais géotechniques - Essais de laboratoire sur les sols - Partie 9: essais en compression à l'appareil triaxial consolidés sur sols saturés.
- AFNOR, norme NF EN ISO 22476-4. 2021. Reconnaissance et essais géotechniques – Essais en place – Partie 4: Essai au pressiomètre Ménard.
- Bagheri, M., Rezaia, M. 2021. Geological and Geotechnical Characteristics of London Clay from the Isle of Sheppey. *Geotech Geol Eng* 39, 1701–1713. <https://doi.org/10.1007/s10706-020-01572-3>.
- Baguelin F., Kovarik J.-B. 2017. Une méthode de détermination des valeurs caractéristiques des paramètres géotechniques. *Rev. Fr. Géotech.* N° 93, pp. 35–41 (2000). <https://doi.org/10.1051/geotech/2000093035>.
- Bat A., Blivet J.-C., Levacher D. 2000. Incidence de la procédure de prélèvement des sols fins sur les caractéristiques géotechniques mesurées en laboratoire. *Revue française de géotechnique* n°91, 2<sup>e</sup> trimestre.
- Cassan M. 2000. Utilisation de la statistique descriptive en géotechnique. *Rev. Fr. Géotech.* N° 93, pp. 21–34 (2000).
- Delage P. 2020. Mécanismes de gonflement dans les sols fins ; application aux sols gonflants de la région parisienne. *Rev. Fr. Géotech.*, 165, 3. <https://doi.org/10.1051/geotech/2020026>
- Egal E., Piraud J. 2018. Révision de quelques idées reçues sur le Lutétien parisien (calcaire grossier, marnes et caillasses). *Journées Nationales de Géotechnique et de Géologie de l'Ingénieur – Champs-sur-Marne*.
- Fanelli S., Szymkiewicz F., Reiffsteck P. 2025. The Cran experimental site in Brittany: 50 years of geotechnical investigations and on site testing. *AIMS Geosciences*, Volume 11, Issue 3: 540-557. doi: 10.3934/geosci.2025023
- Filliat G., Duvauchelle C. 1981. La pratique des sols et fondations – Chapitre 29 : Géologie et géotechnique de la région parisienne. ISBN: 2-86282-162-4. Éditions du Moniteur, Paris.
- Gigan J.P. 1974. Relations entre composition, texture et quelques propriétés géotechniques des Marnes et Caillasses. *Bulletin de liaison Labos Ponts & Ch.*, n° 72, juillet-août 1974.
- Hight W., Gasparre A., Nishimura S., Minh N.A., Jardine R.J., Coop M.R. 2007. Characteristics of the London Clay from the Terminal 5 site at Heathrow Airport D. *Géotechnique*, Volume 57 Issue 1, February 2007, pp. 3-18. <https://doi.org/10.1680/geot.2007.57.1.3>
- Lachérade L. 2024. Apports de la modélisation de la variabilité spatiale géotechnique appuyée par la géologie dans un projet de creusement du tunnel : application au grand Paris Express. Thèse de doctorat.
- Lacherade L., Halfon I. 2024. Evaluation of the reliability of pressuremeter tests using a multi-criteria analysis. XVIII European Conference on Soil Mechanics and Geotechnical Engineering. ISBN 978-1-032-54816-6. <https://doi.org/10.1201/9781003431749-318>.
- Nguyen, T. L., Szymkiewicz, F., Reiffsteck, P., Bourgeois, E., and Mestat, P. 2011. Caractérisation et effet de l'anisotropie sur le comportement de sols reconstitués. *Revue canadienne de géotechnique*, 48 :1520-1536. xii, 21.
- Reiffsteck P., Averlan J.-L., Zerhouni M. 2018. Essais de laboratoire pour la mécanique des sols et la géotechnique. Les outils pour la reconnaissance des sols et des roches. *Presse des Ponts*. ISBN: 9782859785208 2859785205
- Vuillaume B., Jacquard C. 2018. Caractérisation des paramètres de déformabilité des argiles vertes de la région parisienne. *Journées Nationales de Géotechnique et de Géologie de l'Ingénieur – Champs-sur-Marne*.