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Cross analysis between different evaluation methods of small strain moduli in clays and marls of Parisian subsoil

Analyse croisée entre différentes méthodes d'évaluation des modules en petites déformations dans les argiles et marnes du bassin Parisien

N. Berthoz*
Centre for Tunnel Studies (CETU), Bron, France

N. Dufour
GéoCoD, Cerema, Aix-en-Provence, France

A. Rallu, Y. Aslan, D. Branque
University of Lyon, ENTPE, LTDS - UMR CNRS 5513, Vaulx-en-Velin, France

**Nicolas.berthoz@developpement-durable.gouv.fr*

ABSTRACT: The design of geotechnical structures requires an accurate assessment of the strain moduli of the grounds. Experience shows that these depend on the range of strain considered. In particular, for dynamic problems (e.g. vibrations induced by the excavation of a tunnel), the maximum shear modulus G_{max} has to be estimated. To contribute to this topic, the results of surface wave measurements under ambient noise (H/V method), cross-hole tests, resonant column tests and pressuremeters tests performed in various clay and marl formations in the Paris subsoil are presented. The analysis concerns the relationship between these different types of measurements and their comparison with data in the literature.

RÉSUMÉ: La conception des ouvrages géotechniques nécessite une évaluation précise des modules de déformation des terrains. L'expérience montre que ceux-ci dépendent de la gamme de déformation considérée. En particulier, pour les problèmes dynamiques (par exemple les vibrations induites par le creusement d'un tunnel), le module de cisaillement maximal G_{max} doit être estimé. Pour contribuer à cette problématique, les résultats de mesures d'ondes de surface sous bruit ambiant (méthode H/V), d'essais cross-hole, d'essais à la colonne résonnante et d'essais pressiométriques réalisés dans différentes formations argileuses et marneuses du sous-sol parisien sont présentés. L'analyse porte sur la relation entre ces différents types de mesures et leur comparaison avec les données de la littérature.

Keywords: Shear modulus; strain level; in-situ wave velocities; resonant column.

1 INTRODUCTION

In geotechnical engineering, predicting the movements of a soil subjected to external mechanical action requires knowledge of its stiffness. However, it is well known that the soil stiffness is not intrinsic to the material. Under a given stress condition (e.g. a fixed mean pressure), soils and weak rocks have a stiffness that decreases as the amplitude of their strain increases. In parallel, numerous experimental observations from laboratory tests have shown that the stiffness of these materials changes very little for strain levels below 10^{-5} (*e.g.* Clayton and Heymman, 2001; Vardanega and Bolton, 2013). For these very low strain levels, it is therefore possible to define a reference shear modulus (G_{max}). Knowledge of G_{max}, combined with data quantifying the degradation of the shear modulus G as a function of strain, is then required to predict ground displacements in geotechnical design.

In practice, there are several experimental methods for determining G_{max} (*e.g.* Atkinson, 2000; Clayton, 2011). On the one hand, in situ geophysical methods are based on the measurement of the propagation velocity of surface or volume seismic waves. For these methods, the value of G_{max} is generally derived from the measurement of the shear wave velocity (V_s) in the ground, using the relationship $G_{max} = \rho.V_s^2$ (with ρ the soil mass density). On the other hand, laboratory methods performed on cored or reconstituted soil samples placed in a triaxial cell are based either on the measurement of the shear wave propagation velocity (bender element testing) or on the measurement of the local or global strain of the sample under controlled mechanical stress (resonant column). It should be noted that cross-analyses of results obtained by these different methods tend to show that G_{max} values measured in situ are generally higher than those measured in the laboratory (*e.g.* Stokoe et *al.*, 1994).

Although laboratory methods have the disadvantage of using small soil samples that may have been disturbed during drilling and sampling, they have allowed us to demonstrate the influence of various parameters on G_{max}. On the basis of these laboratory tests, several authors have shown the dependence of G_{max} to various parameters as the mean effective pressure (p'), the void index (e), the degree of consolidation (OCR), the plastic index (PI) or the loading path. Several semi-empirical formulations relating G_{max} to these different parameters have been proposed (*e.g.* Hardin and Black, 1968; Hardin and Blandford, 1989; Viggiani and Atkinson, 1995).

Laboratory tests (resonant column, precision triaxial test) also have the great advantage of allowing the reduction in secant shear modulus G as a function of strain (γ) to be quantified over a relatively wide range of strains (*e.g.* from 10^{-5} to 10^{-2} for the resonant column). Thus, by considering a hyperbolic relationship between shear stress and strain (e.g. Duncan and Chang, 1970), several authors (e.g. Hardin and Drnevich, 1972; Vucetic and Dobry, 1991; Santos and Gomes Correia, 2001; Darendeli, 2001) have shown that it is possible to express the reduction in material stiffness as a function of strain in terms of a hyperbolic relationship between G/G_{max} and γ/γ_r of the following general form:

$$\frac{G}{G_{max}} = \frac{1}{1+(\gamma/\gamma_r)^{\alpha}} \quad (1)$$

where γ_r represents the reference shear strain and α is referred to the curvature parameter.

The aim of this paper is to contribute to this problem by taking advantage of a major measurement campaign carried out as part of the E-Pilot research project, dedicated to the study of vibrations induced by tunnel boring machines. Pressuremeter tests, cross-hole tests, surface wave measurements under ambient noise (H/V method) and resonant column tests were carried out in various clay and marl formations in the Paris subsoil. The analysis concerns the relationship between these different types of measurements and their comparison with data in the literature.

2 EXPERIMENTAL SITE DESCRIPTION

2.1 Geological context

The study site is located in the city of Wissous, in the southern suburbs of Paris. It is located on a plateau (Orly plateau) with a succession of subhorizontal clay-limestone and marl formations.

A T6-116 survey (116 mm diameter double tube core barrel), 39.5 m deep, referenced SC08198, was drilled on site in December 2022. This hole revealed the stratigraphic succession described in Figure 1 with, from bottom to top, the Masses and marls of gypsum (Lower Ludian, -38 My), the Suproagypseous marls of Argenteuil and Pantin, the Green clays, the Brie and Sannois limestones, and the quaternary plateau silts.

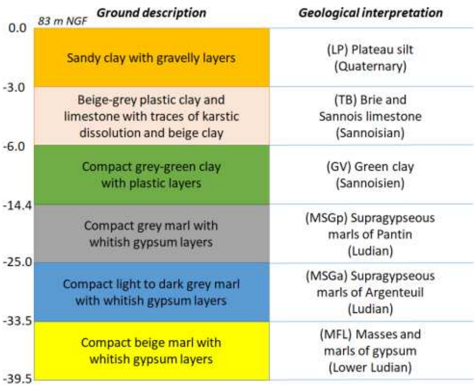

Figure 1. Geological profile (scale not observed). 83 NGF correspond to the surface of the work site.

2.2 Geotechnical characteristics

Table 1 summarises the main state parameters of these different formations: wet mass density ρ, dry mass density ρ_d, water content w, voids index e, degree of saturation Sr, blue-value VBS, plasticity index PI, fine content FC and over-consolidation ratio OCR.

Table 1. Geotechnical characteristics of the grounds.

	LP	TB	GV	MSGp	MSGa	MFL
State parameters						
ρ (kg/m³)	1980	1990	1950	1930	1980	1810
ρ_d (kg/m³)	1660	1640	1560	1530	1600	1380
w (%)	20	21	25	26	23	31
e (-)	0.58	0.61	0.70	0.73	0.65	0.92
Sr (%)	--	93	97	97	97	92
VBS (-)	3	2	6	2	5	3
PI (-)	12	19	33	28	37	45
OCR (-)	1	1	2	1	1.5	1
FC (%)	80	56	97	86	97	87
Mechanical parameters						
E_M (MPa)	8	23	13	43	45	180
p_l^* (MPa)	0.8	2.1	1.1	3.2	3.1	5.8
c' (kPa)	5	15	20	30	30	60
φ' (°)	28	32	15	25	20	35

These were measured in the laboratory on samples taken from the aforementioned core hole, and consolidated by other measurements taken from other surveys carried out in the same geological context.

Pressiometric caracteristics (geometrical means of Ménard moduli E_M and limit pressure p_l^*) and plastic parameters (effective cohesion c’ and friction angle φ') are also given in Table 1. These values are deducted of all the tests made for the construction of line 18 metro on the Orly plateau. Note in particular that these values are consistent with the results of the two pressiometric boreholes made in the study site.

3 MEASUREMENTS OF V_S PERFORMED

Three types of measurements of the shear wave velocities V_s have been performed on the study site to assess the maximum shear modulus G_{max}: in-situ cross-hole test, in-situ ambient noise measurements (H/V method), laboratory tests on resonant column apparatus.

3.1 Cross-hole measurements

Measurements of shear wave velocity V_s were carried out between two boreholes 12 m apart, 80 mm in diameter, lined with PVC pipe and sealed to the ground. The signals obtained were of good quality and interpreted in accordance with ASTM D4428.

Significant contrasts appear between the different layers of soil, with little dispersion by layer. The geometric means of V_s by layers are: 353 m/s in LP, 448 m/s in TB, 200 m/s in GV, 423 m/s in MSGp and 471 m/s in MSGa.

It should be noted that the measurements taken beyond a depth of 26 m correspond to oblique paths between the transmitter (maintained at a depth of 26 m) and the receiver of variable depth. The wave speeds measured in the MFL formation are therefore underestimated. The corrected value considering the oblique path is equal to 750 m/s.

3.2 Ambient noise measurements (H/V)

The H/V method is a geophysical method used to analyse the structure of the subsurface. Its primary purpose is to investigate parameters such as the depth to bedrock then, through inversion processes, the shear wave velocity of soil layers. This method entails the comparison of the amplitude of horizontal ground motion (H) with the amplitude of vertical ground motion (V) across various frequencies. During in-situ monitoring, five 3D geophones (TROMINO from the Moho brand) are positioned at 10-meter intervals on the ground surface. These geophones feature three highly sensitive orthogonal acquisition channels with high resolution and a precision of 10^{-7} mm/s. Placed on the natural surface of the ground, 3 m above the worksite platform, measurements were conducted for 30 minutes under ambient noise, without specific mechanical excitation. Considering the superficial layer's depth 6 m (cross hole test), calculations were performed for a frequency range of 0.5-20 Hz.

H/V curves are calculated simultaneously from all sensors using Geopsy software (Figure 2a) and from each sensor using Grilla software (example of one sensor is given in Figure 2b). These profiles are almost identical, showing a similar response of all the sensors.

Classifying H/V peaks as of geological or non-geological origin involves examining the corresponding spectra. A geological peak is characterized by a maximum in the X and Y directions (blue and green) and a minimum in the Z direction (pink), forming an eye shape (Figure 2c). Consequently, based on this criterion, three peaks of stratigraphic origin are identified: $f_3(2.1Hz)$, $f_2(8\,Hz)$ and $f_1(14\,Hz)$.

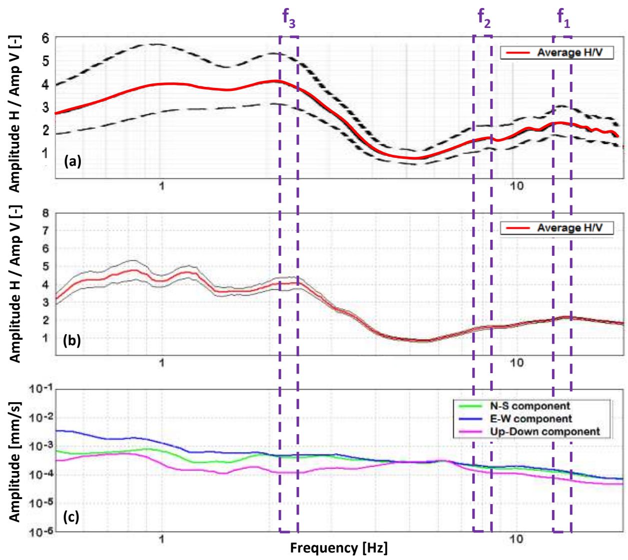

Figure 2. Visualization of (a) Global spectrum amplitude ratio H/V across all sensors, (b) Individual spectrum amplitude ratio H/V from a single sensor, and (c) Spectrum amplitude by direction from the single sensor.

Based on these three peaks, the first three geological layers can be identified. Constraints are required in the inversion process of H/V peaks, either on depth or shear wave velocity. For the upper layer, a depth constraint is specified as $H_1 = 6$ m. Although the resonance equation layer $\frac{V_S}{4H} = f$ cannot be applied in multilayer scenarios, it can serve as a preliminary approximation. Consequently, the shear wave velocity V_S of the resonating layer is estimated as $V_{S1} \approx 4\,H_1\,f_1 \approx 4 \times\ 6\,\text{m} \times 14\,\text{Hz}\ \approx\ 340\,\text{m/s}$.

The second layer, characterized by the frequency $f_2(8\,Hz)$, underwent analysis using a trial-and-error method in Grilla software to achieve the best fit of the H/V Spectral Ratio at this specific frequency. This analysis shows the existence of a layer with a shear wave velocity V_{s2}= 450 m/s situated at depths between 6 and 9 m below the worksite platform (77 to 80 m NGF). Similarly, the third layer, identified with a shear wave velocity V_{s3} of 130 m/s (Figure 4), is located at depths between 6 and 12 m (71 to 77 m NGF).

3.3 Fixed-base resonant column measurements

Five resonant column tests were carried out in the laboratory, one in each of the present layers, with the exception of the LP. These tests, conducted in accordance with ASTM-D4015-15, were carried out on specimens 50 mm in diameter and 100 mm high, loaded in torsion.

The samples, which were nearly saturated in their natural state, were resaturated by applying an internal back-pressure. The Biot coefficients obtained were greater than 0.93. The tests were carried out at confining pressures equal to the geostatic mean effective stress at the depth of each sample.

The shear wave velocities measured for each test, in function of the distortion are presented in Figure 3.

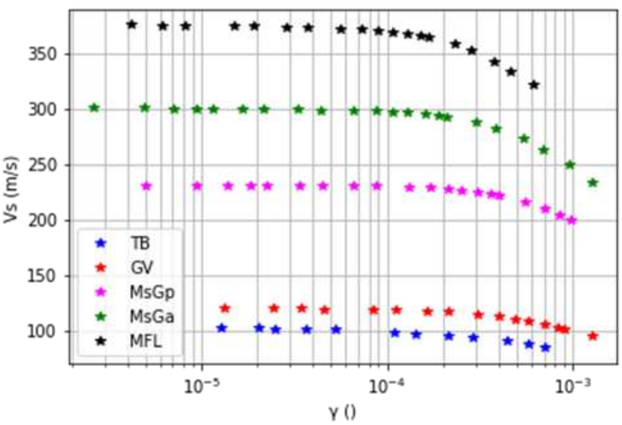

Figure 3. Results of the resonant column tests.

4 CROSS ANALYSIS OF THE MEASUREMENTS OF G_{MAX}

Figure 4 summarises the shear wave velocities measured on cross-hole tests, resonant column tests (values for a distortion of 10^{-5}) and estimated by H/V approach.

Firstly, Figure 4 illustrates that employing measurements under ambient noise using the H/V approach enables estimation of shear wave properties up to a depth of approximately 15 m. It is crucial to note that achieving these results relies on the engineer possessing prior knowledge of local stratigraphy. This understanding is essential to initiate the trial-and-error approach with certain constraints, such as the layer thickness in our case.

Figure 4 shows a good agreement between the Vs measured in situ using the cross-hole tests and those derived from the H/V method, particularly for the top two layers. It illustrates also that the V_s measured at the laboratory scale (resonant column tests) are 1.5 to 4 times lower than in-situ (cross-hole tests).

The maximum shear moduli ($G_{max} = \rho.V_s^2$) calculated in each layer by the two methods are summarised in Table 2. In this table, the geometric means of the V_s measured per layer presented in Figure 3 are used, together with the wet densities given in Table 1. The large difference between the V_s values obtained from the different types of measurements is further increased by squaring them.

Table 2. G_{max} deduced from shear wave velocities.

G_{max} (MPa)	LP	TB	GV	MSGp	MSGa	MFL
Measurements						
Resonant Column	-	22	29	105	182	260
Cross Hole	248	425	78	352	404	1018
Estimation by empirical formula						
Carlton & Pestana (2016) $G_{max-lab}$	--	110	170	184	289	163
Reiffsteck et al. (2022) $G_{max-insitu}$	96	340	93	452	474	867

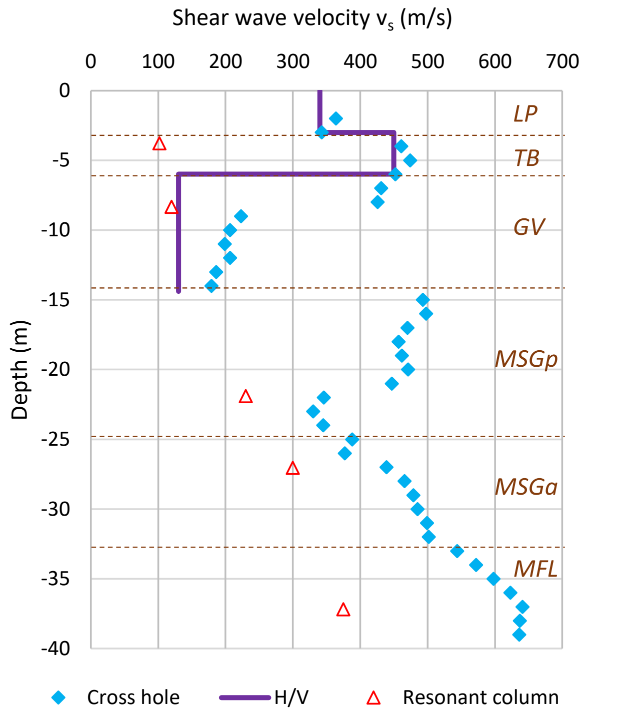

Figure 4. Shear wave velocities measurements.

To go deeper on comparison between in-situ and laboratory shear moduli, the summary provided by Carlton & Pestana (2016), which includes the large-scale test campaign carried out in the USA in the 1990s as part of the ROSRINE project, is used. All the experimental results considered by the authors are shown in blue in Figure 5. These points mixed tests on 331 different soils (sands or clays of different countries), reconstituted or "undisturbed". Our measurements are added in red on this figure.

According to this summary, the moduli measured in the laboratory are lower than those measured in situ (cross-hole). However, the difference observed here appears to be very large, particularly for TB and MFL. The low moduli measured in the laboratory are probably related to sample disturbance during coring or sample preparation (Stokoe *et al.* (1994), cited by Cami (2017)).

By calibration on 1680 laboratory measurements, Carlton & Pestana (2016) propose an estimate of the laboratory measured shear moduli $G_{max,lab}$ as a function of the void index e, the average effective stress p', the over-consolidation ratio OCR, the plasticity index PI and the fine content FC of the soil. In the case of fine soils (FC > 30%), this equation applies:

$$G_{max,lab}(\text{MPa}) = 0.1 * 790.2 * e^{-1.309} * p'^{0.465} * OCR^{2.022*(IP/100)^{1.933}} * (FC/100+1)^{-0.124} \quad (2)$$

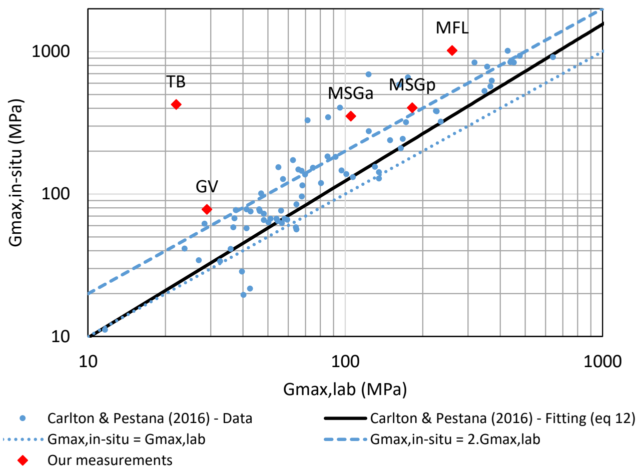

Figure 5. Ratio between the shear moduli measured in-situ and in laboratory.

The moduli measured (Table 2) appear to be 3 to 5 times lower than estimated in the TB and GV. As a result, it seems that the resonance column tests carried out on the most superficial are not very representative of the real shear strain moduli. However, the samples taken appeared to be little disturbed. Multiply systematically the type of tests and consolidate their consistency with empirical expressions would therefore appear to be a good principle to adopt in projects.

Pressuremeter tests were also carried out on the site studied. The pressuremeter moduli measured E_M are summarised in Table 1. These moduli correspond to large distortion ranges (10^{-2} to 10^{-1}), greater than those discussed previously. However, Reiffsteck et *al* (2022) proposed a correlation between G_{max} and E_M on the basis of 750 couples of [E_M; V_s] deduced from 26 different sites (Equation 3):

$$G_{max} = \rho . V_s^2 = \rho . (a . E_M{}^b)^2 \quad (3)$$

where the coefficients (a; b) depend on the type of soil. For clays (LP and GV formations can be considered belong to this category here), this pair is (a = 98; b = 0.29). For marls (TB, MSGa, MSGp, MFL), the values are (189; 0.25).

The calculated moduli are summarised in Table 2. They appear to be in fairly good agreement with the results of the cross-hole test, which supports the expression proposed by Reiffsteck et *al* (2022).

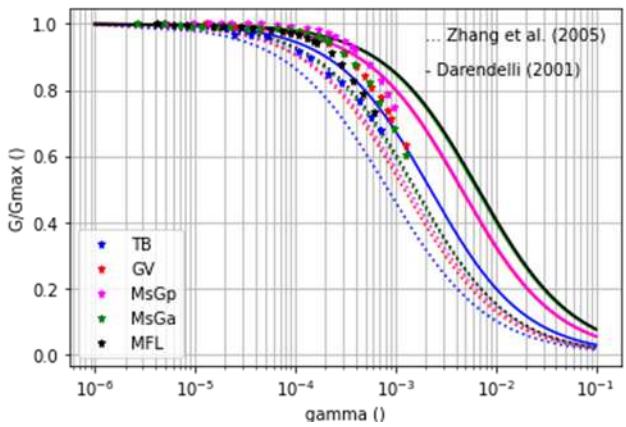

Figure 6. Decrease of the normalised shear modulus with the shear strain magnitude.

5 EVOLUTION OF THE SHEAR MODULUS WITH SHEAR STRAIN

The resonant column tests carried out enable the evolution of the shear modulus with the amplitude of the distortion to be quantified. The curves obtained of normalised shear modulus G/G_{max} are shown in Figure 6 (colored stars). Normalized shear modulus is the current shear modulus G divided by G_{max} obtained in laboratory with a resonant column apparatus.

Experimental results are compared to empirical relationships (solid and dotted lines) that have been proposed in the literature for clay, under the Eq. 1.

Darendeli (2001) and Zhang et *al.* (2005) proposes the expression of γ_r and α given in Eq. 5 and 6 respectively, where p' is the confining pressure and Pa the atmospheric pressure:

$$\alpha = 0{,}919 \tag{5}$$
$$\gamma_r = \left(0.0352 + 0.00101\, I_p . OCR^{0.325}\right) . p'^{0.348}$$

$$\alpha = 0.0021\, PI + 0.834 \quad ; \quad \gamma_r = \left(0.0749 + 0.0011\, I_p\right) .\ (p'/Pa)^{0.316 \exp(-0.0142\, I_p)} \tag{6}$$

These curves are presented in Figure 6: markers and lines in blue correspond to TB, in red to GV, in pink to MsGp, in green to MsGa and in black to MFL. These two types of empirical relationship frame the measured curves.

6 CONCLUSIONS

Analysis of the different methods of measuring G_{max} in the laboratory and *in situ*, and comparison with the literature, mainly show that:

- the cross-hole tests provide reference values for G_{max} to evaluate the vibratory phenomena associated with TBM excavation because they affect a volume of soil representative of the problem studied;
- the H/V method under ambient noise allows to recover V_s values close to those measured by the cross-hole tests, on condition to have a prior knowledge of the stratigraphy in order to constrain the inversion process;
- laboratory measurements using a resonance column give G_{max} values 2 to 4 times lower than those measured in situ (cross hole), in line with observations in the literature;
- the decrease of the normalised modulus G/G_{max} with the distortion observed in the laboratory appears to be little affected by any disturbance of the sample due to the sampling.

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