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In-situ validation of an innovative mono-cell pressuremeter probe: first results

Validation sur le terrain des capacités d'une sonde pressiométrique mono-cellulaire innovante : premiers résultats

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ABSTRACT: Membranes for pressuremeter probes have been considerably improved through recent technological innovation. The Mono-cell FC® probe takes advantage of these evolutions with a potential measuring range from small strains to complete soil failure. An experimental program was established to validate its measuring capabilities through both laboratory and *in-situ* tests. The present paper focuses on the first *in-situ* Mono-cell FC probe tests performed in sands and clays, and the evaluation of soil's deformability properties at low strain level. The obtained results were compared with those derived from laboratory tests in the same soil type and as described in literature. A discussion is held regarding the first results.

RÉSUMÉ : Des évolutions technologiques récentes ont apporté des améliorations considérables dans le domaine des membranes utilisées dans les sondes pressiométriques. La sonde Monochambre FC® bénéficie de ces avantages et permet potentiellement de couvrir un domaine de mesure allant de très faibles déformations jusqu'à la rupture du sol. Le programme de validation de ses capacités de mesure repose sur des essais de laboratoire et *in-situ*. Cette communication s'attache à décrire les premiers essais réalisés sur le terrain, dans des sables et des argiles, permettant l'évaluation des paramètres de déformabilité sous faibles taux de distorsion. Les résultats sont comparés à ceux obtenus à partir d'autres essais de laboratoire sur les mêmes types des sols. Une discussion porte sur les premiers résultats obtenus.

Keywords: *In-situ* tests, pressuremeter test, dilatometer test, shear modulus, mono-cell probe

1 INTRODUCTION

Pressuremeter tests are the most used *in-situ* test for underground investigation in French geotechnical engineering practice. Performed according to current standards, these tests make it possible to obtain the so called Ménard pressuremeter modulus and the pressuremeter creep and limit pressures. Deformation properties are determined under monotonic conditions or during a single unloading-reloading loop. Menard pressuremeter parameters are used in standard foundation design through well established and accepted empirical correlations. However, the design of a number of geotechnical structures (e.g. retaining walls, foundations under cyclic loading) is more demanding. Establishing foundation response under low strain rates is required for design, however the necessary parameters cannot be obtained through standard testing protocols, nor using the most common testing equipment due to measurement limitations.

The Mono-cell FC® probe offers new possibilities in soils and soft rocks. It enables measurement of both relatively small strains, traditionally reserved for "dilatometer" probes, and large "pressuremeter" deformations, with direct measurement of the limit pressure.

A validation program for the Mono-cell FC probes measuring capabilities has been undertaken using two approaches. The first regards tests conducted at reference sites with the soil layers well characterized by a large set of geotechnical and geophysical tests. The second approach, as described in a parallel communication (Lopes et al., 2019), consists of tests performed in a laboratory calibration chamber on soil specimens of reference Fontainebleau sand.

This paper presents the first *in-situ* test results using the Mono-cell FC® probe, confirming its potential to assess soil deformability properties at low strain rates. Results are compared with conventional laboratory tests and literature data.

2 PROBE DESCRIPTION

The Mono-cell FC probe was designed to overcome some of the recurring difficulties in measuring the limit pressure in stiff soils (high inflation volumes and high pressures).

It comprises a single water-cell surrounded by a restraining sheath, allowing the geometry to be controlled during inflation. This sheath minimizes the uncertainties associated with the expansion of the measuring cell and allows for a precise assessment of the relationship between injected water volume and the probe's outer diameter.

Controlling the geometry also enables avoidance of stress concentration near the membrane extremities and improves the membrane durability. These characteristics make the probe a favorable candidate for use in cyclic testing.

A detailed description of the probe, including its historical development, is presented by Cour and Lopes (2018).

3 INTERPRETATION METHODS

Several testing protocols and interpretation methods for tests with unload-reload loops are available in literature. Some of them allow the evaluation of soil stiffness at low strain rate. It will be noted that Ménard (1961) presented the first insights on the soil modulus degradation and its assessment from pressuremeter tests. He observed that modulus decreased with the increase of the cavity volume (cavity strain).

Recently, Bolton and Whittle (1999) proposed a procedure based on a non-linear elastic-plastic model which allows deriving shear stiffness decay in undrained soils. Whittle and Liu (2013) and Whittle et al. (2017) proposed simplified procedures for deriving either strain and stress dependency of stiffness on drained materials.

This simplified procedure was applied to interpret the tests presented on the following text.

3.1 Description of the method

Test interpretation was based on the method proposed by Whittle et al. (2017), with some modifications concerning the testing procedure. The method is detailed below.

For all unload-reload loops, unloading and reloading parts are isolated. The analysis can be done either on the unloading or reloading portion: on the worked examples it was done on the reloading portion.

A change of origin is made so that the point of reversal of the direction of loading corresponds to $\sigma_r = 0$ and $\epsilon_r = 0$ (with $\epsilon_r = \Delta R/R_0 = \gamma/2$); For each loop, a power law curve of the following type is fitted:

$$\sigma_r = \eta\gamma^{\beta} \qquad (1)$$

and the parameters η and β can be obtained. The shear stress can be estimated as:

$$\tau = \gamma(d\sigma_r/d\gamma) = \eta\beta\gamma^{\beta} \qquad (2)$$

Once those parameters were obtained for each loop, the secant shear modulus can be calculated as:

$$G_s = \eta\beta\gamma^{\beta-1} \tag{3}$$

With this expression, the value of shear modulus at a strain rate of 0.1% can be obtained:

$$\mathrm{G}_{\mathrm{s},0.001} = \eta \cdot \beta \cdot 0.001^{\beta-1} \tag{4}$$

For each loop, the effective mean stress on the cavity plane, σ'_{av} can be estimated as (Whittle and Liu, 2013):

$$\sigma'_{av} = \frac{1}{2}(\sigma'_r + \sigma'_\theta) \cong \frac{p'_c}{1+sin\varphi} \tag{5}$$

where p_c' is the radial stress imposed by the probe at the beginning of the loop. The exponent n of the power law relating shear modulus and the confining stress can be obtained by plotting $G_{0.001}$ against σ'_{av}:

$$G_{ref} = G_{measured}\left(\frac{\sigma'_{ref}}{\sigma'_{av}}\right)^n \tag{6}$$

A reference stress shall be selected. On this work the effective vertical in-situ stress was used.

Consider α the product $\eta\beta$. For each loop, the stress adjustment parameter α_{ref} is then calculated:

$$\alpha_{ref} = \alpha\left(\frac{\sigma'_{ref}}{\sigma'_{av}}\right)^n \tag{7}$$

Finally, for each loop the values of the reference shear modulus as a function of the distortion are adjusted using the coefficient α_{ref}:

$$G_{s,ref} = \alpha_{ref}\gamma^{\beta-1} \tag{8}$$

4 TESTS ON SANDS

A test was conducted at 63 meters depth in Auteuil sands in the Parisian region. The layer is described as dark-gray fine silty-sand.

Three unload-reload loops performed were interpreted according to the procedure proposed in the previous paragraph.

Soil samples collected on the same layer were tested by CU+u triaxial shear tests resulting in a friction angle of 34 degrees and zero cohesion. The saturated density is 20.6 kN/m^3, the water content is 22.5% and the degree of saturation is 82%. Granulometry tests showed that 58% of the particles passes through the 80-μm sieve and 28% passes through the 2-μm sieve, which indicates a well sorted granulometry with high content of fines. The void ratio is between 0.52 and 0.61.

A resonant column (RC) test conducted with a confining stress of 696 kPa resulted in a $G_{max,CR}$ value of 160.5 MPa for a distortion rate equals $1.2 \cdot 10^{-6}$. In the absence of geophysical tests on the studied site, this value will be considered as reference for the estimation of the maximum modulus.

It should be noted, however, that sand sampling may result in sample disturbance, resulting in underestimation of maximum shear modulus by the RC test (Stokoe and Santamarina, 2000).

The loading protocol applied in the pressuremeter test was a compromise between that of a standard pressuremeter test in virgin loading (according to standard NF EN ISO 22476-4, AFNOR, 2015) and that of a quick test during the loops (15-second load steps in unloading and reloading). This mixed protocol was concepted to maximize the amount of measurement points on the loops while staying close to the standard test procedure.

Test results are presented in Figure 1. The conventional pressuremeter limit pressure was effectively measured at 12.7 MPa (which corresponds to doubling the cavity volume, at a radial strain rate of 41%).

The loops were started at different stress levels (2.5 MPa, 5.4 MPa and 10.4 MPa) and the unload portions were conducted to a minimum pressure of 1.5 MPa. Figure 2 presents a detail on the loops, the change in origin and power law fitting.

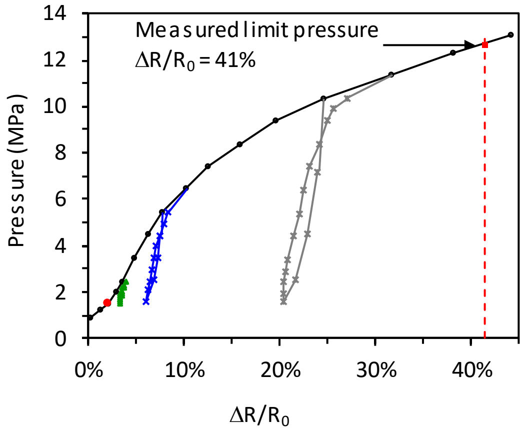

Figure 1 – Pressuremeter test on sands

After setting the power law for each loop and obtaining the parameters η and β, the shear modulus was calculated, for each loop, for a strain level of 0.1%. These values were plotted against the estimated average stress in the loop (**Error! Reference source not found.**). For the estimation of the average stress, the angle of friction of 34 degrees was considered in conjunction with the proposal described in the previous paragraph (eq. 5). This resulted in a coefficient *n* equals to 0.71. The reference stress chosen for the test was the *in-situ* vertical effective stress (978 kPa).

The secant shear modulus degradation curve obtained by eq. (3) for each cycle is shown in Figure 4 (a). Punctual values calculated using eq. 3 and the measured values of strain are also presented.

The three calculated curves are presented in Figure 4 (b) adjusted for the same reference stress using the coefficient *n* of 0.71 calculated as previously described. On this same graph are plotted the results of the resonant column test adjusted to the chosen reference stress of 978 kPa.

One should notice that due to stress adjustment, $G_{max,RC}$ increases from 160 MPa to about 205 MPa. The calculated curves were plotted only within the proposed limits of use of the method (γ between 10^{-4} and 10^{-2}).

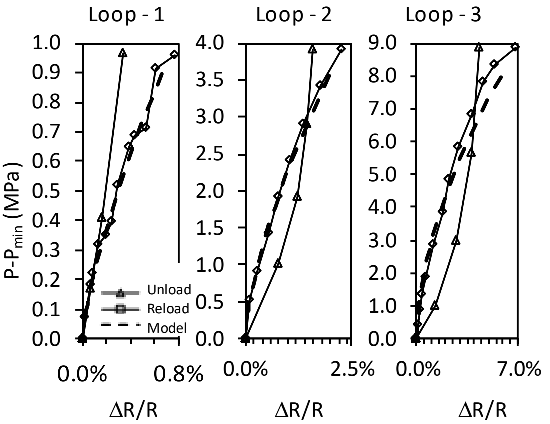

Figure 2 – Detail on power law fitting for loop 2

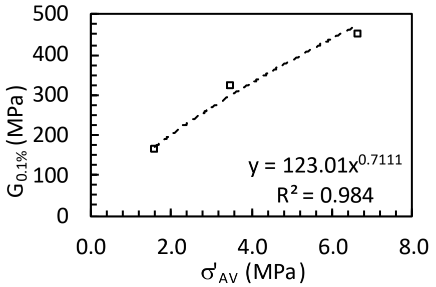

Figure 3 – Obtaining power law coefficient for three loops

The three adjusted curves presented should be equivalent in theory, the obtained differences lye on experimental issues. There is good agreement between the shear modulus degradation curve obtained with the proposed procedure and that obtained with the resonant column test for distortion levels between $5 \cdot 10^{-4}$ and 10^{-3}.

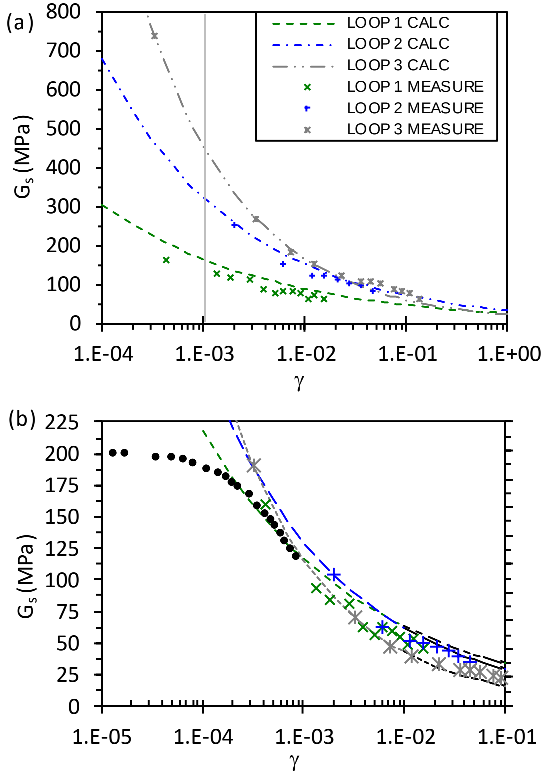

Figure 4 – Shear modulus decay: (a) measured and calculated; (b) adjusted and compared to RC test

5 TESTS ON CLAYS

A test was performed at 72 meters depth in plastic overconsolidated clays, on the same testing site. The same procedure as that described in the preceding paragraph was followed. The layer is described as a very firm gray clay. Two intact samples were collected 1.5 m above and 2.2 m below the pressuremeter test level. Laboratory tests resulted in an effective friction angle of 12° and 6° and cohesion of 20 kPa and 49 kPa, respectively.

The overconsolidation ratio obtained by oedometric tests was 2.3. The plasticity index was 59% and 55% and the liquidity limit was 88% and 81%. Two resonant column tests, performed at a confinement stress of 697 kPa resulted in $G_{max,CR}$ values of 112.2 and 94.8 MPa, for strain rates of $1.6.10^{-5}$ and $2.6.10^{-5}$ respectively. In the absence of geophysical tests, these values will be considered as a reference for the estimation of the maximum shear modulus of the clays.

The results of the test are shown in Figure 5. The conventional pressuremeter limit pressure has been effectively measured and is 3.7 MPa.

The unload-reload loops were started at different stress levels (2.2 MPa, 3.2 MPa and 3.7 MPa) and the unload portions were conducted to a minimum pressure of 1.6 MPa. A detail on the loops and the power law fitting are shown in Figure 6.

The adjustment for the stress state as presented in Figure 3 has also been realized. On this case, however, the best result is obtained for $n = 0$. This result is consistent with the fact that the test in the clays is predominantly undrained and that there is therefore no influence of the state of stress on the measured stiffness (no changes in effective stress).

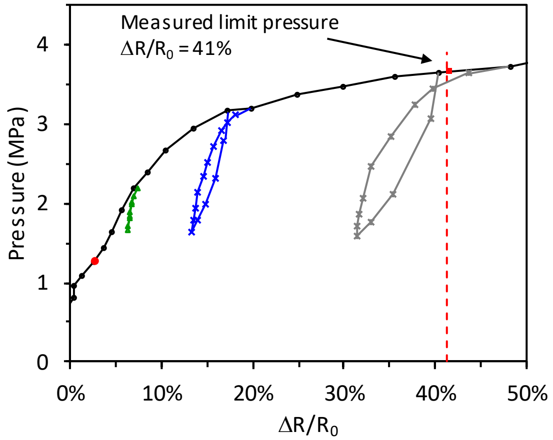

Figure 5 – Pressuremeter test on clays

Shear modulus degradation curves obtained for the three loops are presented in Figure 7(a). One should observe that the three curves are very close to each other, which reflects the non-dependence of the stress. The curves are compared to the results of the two resonant column tests in Figure 7 (b). Shear modulus obtained by pressuremeter tests seem to be in good agreement in comparison to those obtained by laboratory tests. It is also important to notice that both laboratory tests show a variability of almost 20% in $G_{max,RC}$, which can be attributed to the natural soil variability within the layer.

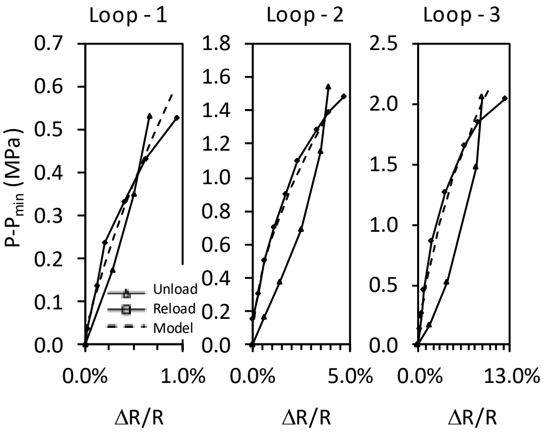

Figure 6 – Detail on power law fitting for loop 2

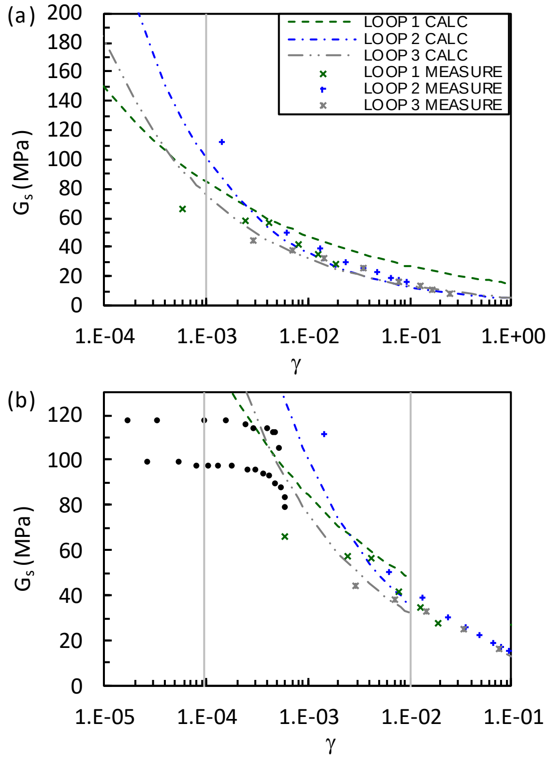

Figure 7 – Shear modulus decay: (a) measured and calculated; (b) adjusted and compared to RC test

6 COMPARISON WITH LITERATURE

Oztoprak and Bolton (2013) presented a range of values for the G/G_{max} ratio based on a large database of resonant column tests in sands. A hyperbolic law was fitted on these tests.

The results of the pressuremeter and laboratory tests conducted in Auteuil sands, adjusted according to the procedure described above, are compared to the range of values proposed by these authors (Figure 8 (a)).

They are located near upper limit, which can be explained by the high value of the confinement stress used (696 kPa), the well sorted granulometry of Auteuil sands and the high content of fine particles. This could also be attributed to an underestimation of the $G_{max,RC}$ modulus as explained previously, due to the possibility of sample disturbance.

Conducting in-situ geophysical tests (e.g., cross-hole testing, seismic cone) may help answer this question and this remains one of the objectives for the future of this research.

Similarly, Massarch (2004) and Vardanega and Bolton (2013) proposed an average relationship for the degradation of the secant shear modulus of fine soils based on their plasticity index. Figure 8 (b) presents a comparison between the curves proposed in literature, laboratory measurements and pressuremeter test results.

Literature curves were plotted considering plasticity index IP = 59% for the tested clays, and the highest value of $G_{max,RC}$ obtained by RC tests as reference value for maximum shear modulus.

In the two cases presented, a good agreement is observed between the measured data and the values calculated according to literature, especially for shear strain rates of the order of 10^{-3}. On the other hand, it seems clear that the proposed degradation curve for the pressuremeter is not suitable for very small strains (10^{-4} and lower), because it has no asymptote when the deformation tends to zero.

Concerning high shear strain levels (greater than 10^{-2}) the model also tends to overestimate moduli. It is probably because the power law does not allow modeling the strong decay of the module at the end of the loop. The use of a hyperbolic law could be considered, as already proposed by Briaud et al (1983).

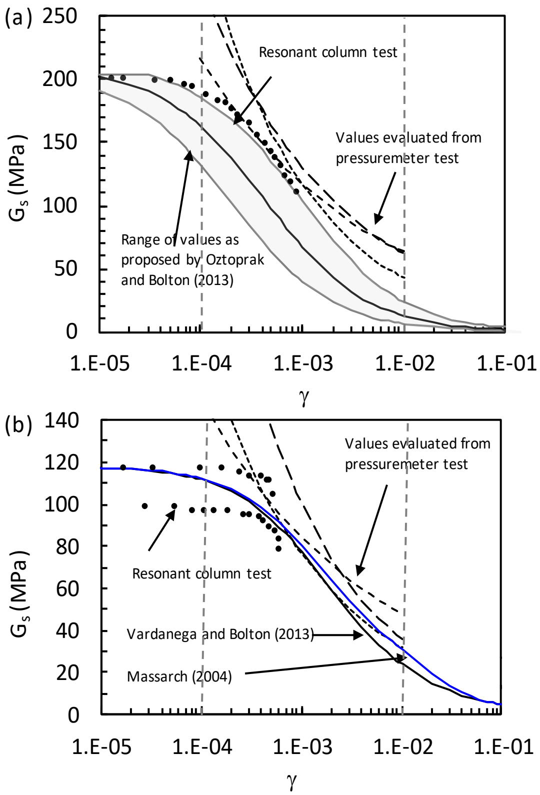

Figure 8 – Comparison of the results in (a) Auteuil sands with the range of values proposed by Oztoprak and Bolton (2013) and (b) in plastic clays with the average values proposed by Massarch (2004) and Vardanega and Bolton (2013).

7 CONCLUSIONS

The Mono-cell FC pressuremeter probe was used for performing tests with unload-reload loops in sands and clays in the Parisian region. This probe has been initially designed to allow the effective measurement of the conventional pressuremeter limit pressure in soils and soft rocks (high pressures and high volumes).

However, the advantages of using it to perform cyclic tests were evident: the benefits brought by the technological innovation on its membrane allows a more precise control of the test.

By maximizing the number of measuring points on each loop in comparison to standard procedures, it has been possible to perform measurements with good accuracy in the field of relatively small strains, which is the domain of application of dilatometers with local measurement of deformations.

An interpretation procedure was applied to evaluate shear moduli in the shear strain range of 10^{-4} to 10^{-2}. This procedure allows to determine the shear modulus degradation curve and to determine the dependence between the stiffness and stress. Moduli can thus be adjusted to a reference stress level.

The results obtained were compared to resonant column tests performed on samples collected from the same testing site and to degradation curves proposed in literature, calibrated according to the laboratory tests. It is considered that, for the proposed shear strain range, the used method provides consistent and representative shear moduli values of the soils tested.

A complete validation program of this probe's capabilities is underway with the completion of a series of tests in laboratory (as presented in Lopes et al, 2019) and other *in-situ* tests on reference sites, where soil layers were characterized by a wider range of laboratory tests (CR, triaxial with bender elements) and geophysical measurements in place (cross-hole, down-hole, seismic cone).

8 REFERENCES

AFNOR. 2015. NF EN ISO 22476-4, Reconnaissance et essais géotechniques – Essais en place – Partie 4: Essai au pressiomètre Ménard, AFNOR, mai 2015, 55 pages.

Briaud, J. L., Lytton, R. L., Hung, J. T. 1983. Obtaining moduli from cyclic pressuremeter tests. *Journal of Geotechnical Engineering*, 109(5), 657-665.

Cour, F., Lopes, A. 2018. Une sonde monocellulaire innovante pour la réalisation des essais d'expansion de cavité cylindrique. *Journées Nationales de Géotechnique et de Géologie de l'Ingénieur*. Juin 2018. Champs sur Marne, France.

Massarsch, K. R. 2004. Deformation properties of fine-grained soils from seismic tests. *Key-note lecture of International Conference on Site Characterization*, ISC (Vol. 2, pp. 19-22).

Ménard, L. 1961. Influence de l'amplitude et de l'histoire d'un champ de contraintes sur le tassement d'un sol de fondation. V *International Conference on Soil Mechanics and Foundation Engineering*, Paris, 249-253.

Oztoprak, S., Bolton, M. D. 2013. Stiffness of sands through a laboratory test database. *Géotechnique*, 63(1), 54.

Stokoe, K. H., Santamarina, J. C. 2000. Seismic-wave-based testing in geotechnical engineering. *International Symposium. International Society for Rock Mechanics*.

Vardanega, P. J., Bolton, M. D. 2013. Stiffness of clays and silts: Normalizing shear modulus and shear strain. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(9), 1575-1589.

Whittle, R., Liu, L. 2013. Method for describing the stress and strain dependency of stiffness in sand. *18th International Conference on Soil Mechanics and Geotechnical Engineering*. Paris.

Whittle, R. Palix, E. Donaghy, D. 2017. The Influence of Insertion Process on Determining the Stiffness Characteristics of Chalk, using Pre-Bored, Self-Bored and Pushed Pressuremeters. *Offshore Site Investigation and Geotechnics, 2017.*