In situ empirical determination of earth pressures at-rest

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ABSTRACT: This paper presents in situ and laboratory test results obtained at various sites in France and in the USA where direct and indirect evaluation methods of the horizontal stress were carried out in soils varying from soft sensitive marine clays to very stiff calcareous clays. Tests sites in France include Sallèdes and the Paris Basin while in the USA it includes Newington-Dover (NH), Amherst (MA), Houston (TX) and Hamilton AFB (CA). At these sites, in situ tests performed included the flat plate dilatometer (DMT), the pre-bored pressuremeter (PMT) and the self-boring pressuremeter (SBPMT). Some of the laboratory test measurements were also used as comparison values. The results are presented in terms of effective or total horizontal stress and K_0. The results from these various measurements display the variability and the applicability of each method for each soil tested at these sites.

Keywords: Site Characterization, Case Studies, Uncertainties, Selection of design parameters, pressuremeter

1. Introduction

Knowledge of the coefficient of earth pressure at-rest K_0 is essential in modeling the behavior of soils and geo-structures under various loading conditions. Some areas where the value of K_0 is particularly useful is when evaluating the stability of geostructures such as slopes, embankments, walls, excavations, drilled shafts, earth dams and tunnels. This paper presents and discusses field measurements used to estimate K_0 obtained at different sites across France and the USA using various in situ test methods. These were collected over several decades by the authors. The results focus predominantly on tests carried out using the self-boring pressuremeter, the Ménard pressuremeter and the Marchetti dilatometer.

2. Horizontal stress and K_0

The determination of the in situ horizontal stress σ_{h0} remains challenging even when using tools specifically designed for that purpose such as the self-boring pressuremeter (SBPMT). As a result, empirical relationships have been developed using various penetration tools such as the flat plate dilatometer (DMT) or by accounting for borehole disturbance using pre-bored or full displacement pressuremeters. These relationships tend to be more reliable when calibrated against more direct measurements of lateral stress. To date, the self-boring pressuremeter remains the best suited tool for the measurement of the in situ lateral stress. Benoît and Howie [1] discuss some of the methods used to assess σ_{ho} using the SBPMT. The key to the success of any expansion test is minimal soil disturbance during insertion into the ground.

Fig. 1 shows the effect of installation procedures with the pressuremeter [2]. In situ penetration tests such as the cone penetrometer (CPT) and the flat plate dilatometer (DMT) fall into the same category as the full-displacement pressuremeter shown on Fig. 1. Mayne et al. [3] suggest that the PMT and the DMT provide modulus values that are intermediate along the shear modulus - shear strain curve while penetration tests such as the standard penetration test (SPT) and the CPT impose much larger shear strains.

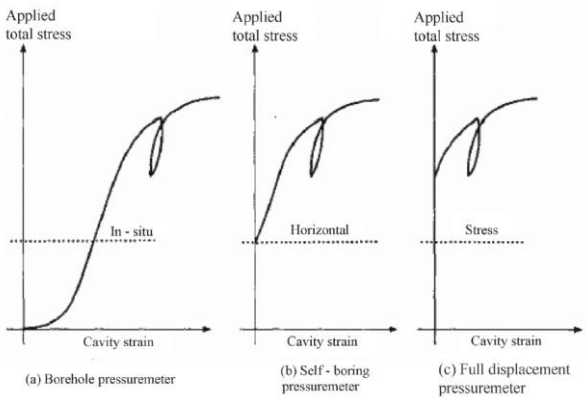

Figure 1. Effect of Pressuremeter Installation Procedures on the in situ horizontal stress [2]

Fig. 2 compares the results of various in situ and laboratory tests aimed at measuring or estimating the horizontal stress in the ground. The coefficient of earth pressure at-rest, K_0 is not an intrinsic parameter of the soil but closely relates to its composition and stress history. K_0 is a calculated value as shown in Eq. (1). Its determination is fully dependent on the horizontal stress.

$$K_0 = \frac{\sigma'_{h0}}{\sigma'_{v0}} = \frac{\sigma_{h0} - u_0}{\sigma_{v0} - u_0} \quad (1)$$

This ratio of effective stresses also requires knowing the pore pressure at the test level to have a reliable estimate of the coefficient K_0. In absence of direct measurement, the computation of the in situ vertical effective

stress is usually based on bulk densities of the overlying geological units and the piezometric levels.

For indirect methods of obtaining K_0, each in situ test uses different measurements that relates to the in situ lateral stress. For example, the dilatometer imposes a lateral pressure at the test level which can be related to the lateral stress in situ using an empirical relationship to account for the insertion disturbance around the test zone. Using the test measurements from the DMT, it is possible to estimate K_0 using the horizontal stress index K_D from the dilatometer.

$$K_D = \frac{(p_0 - u_0)}{\sigma'_{v0}} \quad (2)$$

From this index, Marchetti et al. [4] suggested the following relationship to estimate K_0 for cases where the material index I_D is less than 1.2.

$$K_0 = (K_D/\beta_k)^{0.47} - 0.6 \quad (3)$$

where $\beta_k = 1.5$.

Fig. 2 shows a profile of horizontal effective stress derived from various in situ and laboratory tests from the Connecticut River Valley varved clay deposit at the UMass-Amherst site. The tests include the SBPMT, the lateral and K_0 laboratory oedometer tests, the total stress spade cell, the full-displacement pressuremeter (FDPMT), the DMT dissipation test using the A-reading (DMTA) and the conventional DMT.

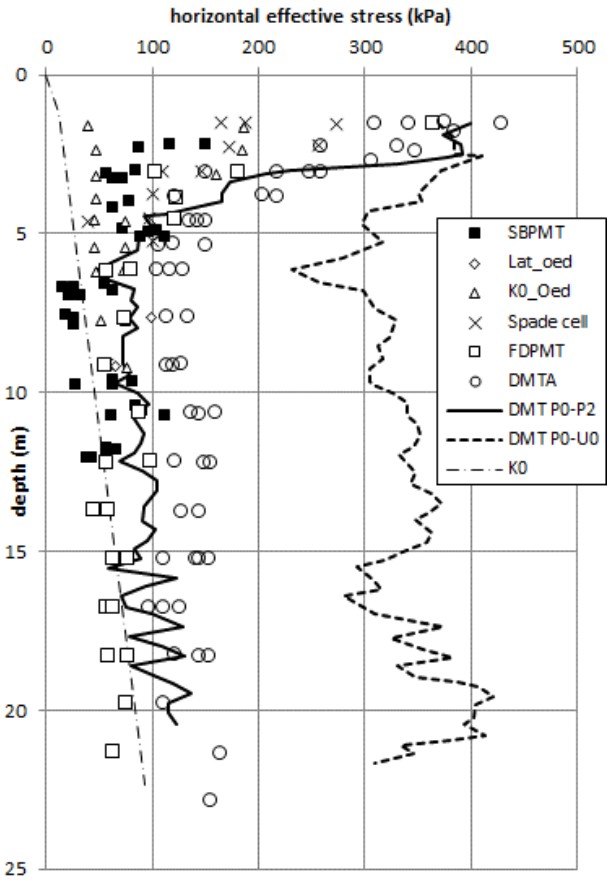

Figure 2. Comparison of effective horizontal stress measurements at UMass-Amherst site (after [4])

Benoît and Lutenegger [5] observed that intrusive type tests in the normally consolidated portion of the profile tended to yield similar values since all imposed significant reworking of the soil and thus started from a similar state. The results from the SBPMT tended to represent lower bound values as disturbance with this test is minimal. The DMT (p_0- p_2) values appeared to be useful in providing initial estimates of horizontal stress in this deposit. The p_2 measurement gives an indication of the total pore water pressure and is a close approximation of penetration pore pressures in cohesive soils and hydrostatic pressures in sands. The ($p_0 - p_2$) values provide an indication of effective stress conditions at the test depth.

Masood [6] and Masood et al. [7] estimated the lateral stress in the soft Young Bay Mud at Hamilton Air Force Base (HAFB) in Novato, California, USA by comparing the DMT, the Glötzl cell, the CPT and the SBPMT as shown in Fig. 3. Their CPT method uses the unit sleeve friction from the cone penetrometer to estimate the effective friction angle (φ′) and the K_o relationships proposed by Jaký [8] and by Mayne and Kulhawy [9]. The lateral stresses were estimated using the DMT dilatometer lateral stress index, K_D, calculated using (p_0-u_0) with the Schmertmann's [10] correlation for K_0.The figure was modified to include results from Benoît [11] and Benoît and Clough [12] using the SBPMT at HAFB whereas the data labelled Benoît [11] were performed using procedures that were developed to minimize disturbance in the Young Bay Mud.

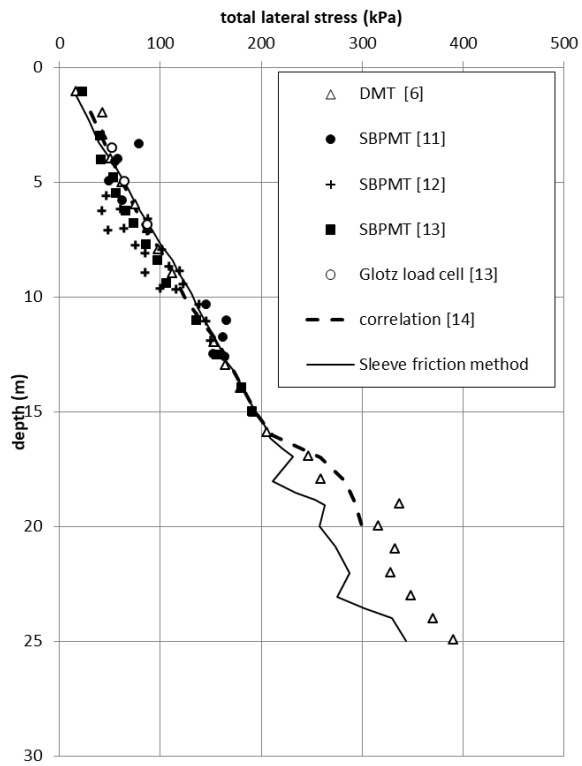

Figure 3. Comparison of total lateral stress measurements at Hamilton Air Force Base, CA

The data labelled Benoît and Clough [12] used different variations of cutting shoe (oversized), cutter positions, high cutting rate and retesting at same location after a long waiting period. The results suggested that the

cutter position had little influence on the results in this clay as long as clogging did not occur. However, the high cutting rate and the oversized cutting shoe yielded lower values of lateral stress. The retesting after 6 days also led to lower lateral stress. The figure also shows the SBPMT results of Denby [13] and the well-known correlation by Brooker and Ireland [14] which is in good agreement.

SBPMT tests using a Cambridge type probe were carried out on an unstable embankment in Sallèdes, France and compared to DMT profiles carried out parallel and perpendicular to the slope [15]. The results in terms of total horizontal stress were in good agreement in this stiff overconsolidated clay. Fig. 4 shows the DMT profiles, the SBPMT horizontal stresses and the earth pressure cell. The SBPMT values were obtained by two methods: visual inspection (VI) of the initial portion of the test curve and Iterative Forward Modeling (IFM) using a hyperbolic model as described by Jefferies [16].

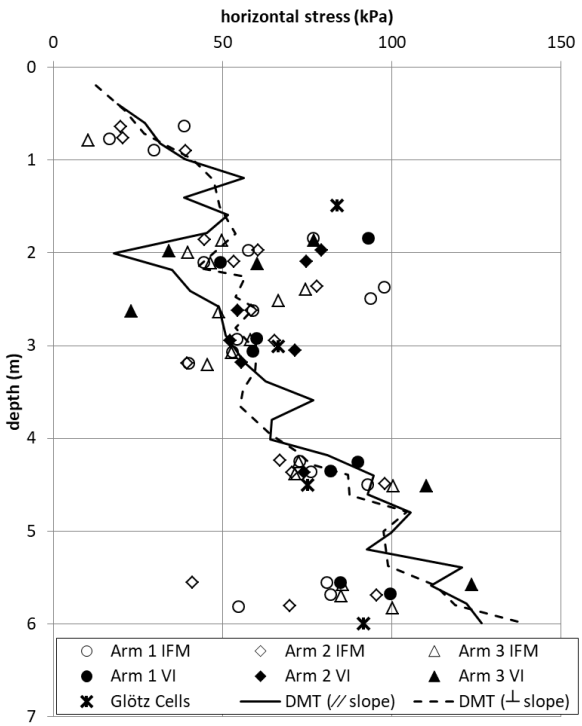

Figure 4. Comparison of horizontal stress measurements at Sallèdes, France (after [15])

An example of the IFM for one of the SBPMT test is shown in Fig. 5. This technique allowed the user to determine the horizontal stress by using the entire stress-strain curve.

Fig. 6 also shows values of K_0 by O'Neill at the National Geotechnical Experimentation Site (NGES) at the University of Houston, Texas, USA [17]. The site consists of a sequence of stiff to hard overconsolidated clays. Tests used at the site included the SBPM, the DMT, the Iowa stepped blade and some laboratory K_o consolidated triaxial tests. The SBPMT tests by Benoît [11] were carried out using a Cambridge type self-boring pressuremeter probe. Similarly to the analyses at Sallèdes, the horizontal stresses were evaluated using the IFM method. In general, all SBPMT tests resulted in higher values of K_0.

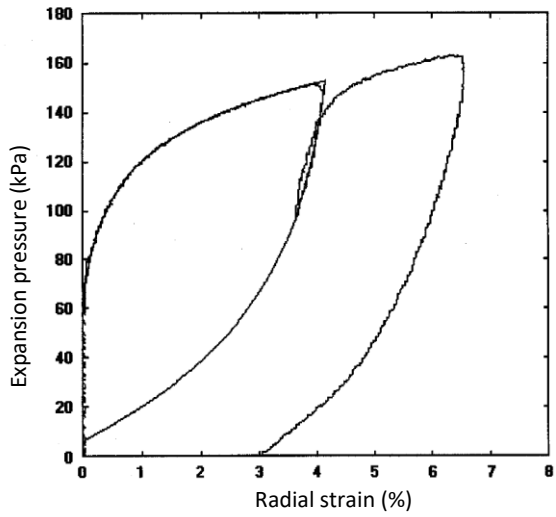

Figure 5. Iterative Forward Modeling example from an SBPMT at Sallèdes (after [15])

In reviewing these few case studies, it suggests that test methods such as the Marchetti flat dilatometer (DMT) and the Iowa stepped blade [18], even with relatively thin probe profiles, induce sufficient soil disturbance that provides estimates of in situ lateral stress σ_{ho} that often differ from the high quality SBPM test results. The full-displacement pressuremeter induces even greater displacement, simulating an expanding cavity at large strain. Consequently, the FDPMT is not recommended for determining the lateral stress with any significant accuracy.

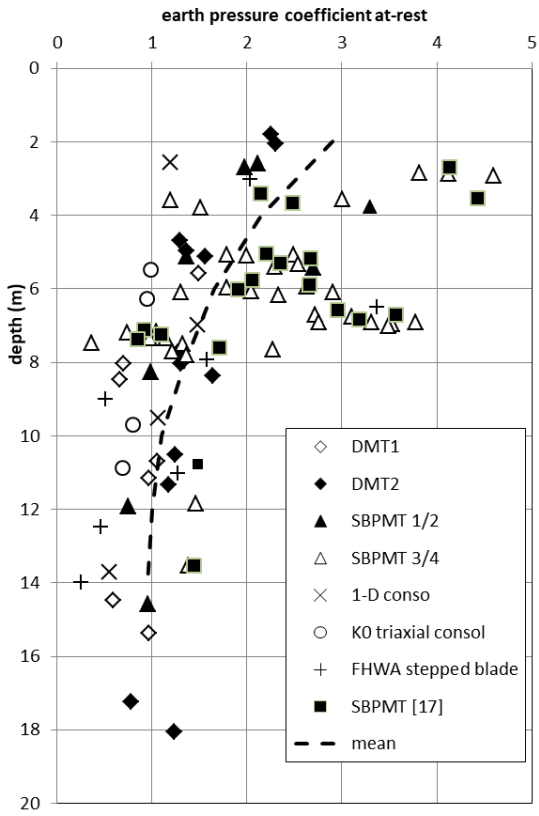

Figure 6. Coefficient of earth pressure at-rest at the University of Houston NGES test site (modified after [17] and [20])

A compilation of available correlations was presented by Lunne et al. [19] and Benoît and Lutenegger [5] in their general reports.

The self-boring pressuremeter test remains the reference test for evaluating the in situ horizontal stress. However, it has not been widely used in practice due to a combination of cost, complexity relative to other tests such as the DMT and lack of availability. Prior to its inception, others have considered using the prebored pressuremeter to estimate the lateral stress. Tests carried out in predrilled borehole such as the Ménard pressuremeter (PMT) were however not previously considered reliable for the determination of the horizontal stress. In the classic pressuremeter text by Baguelin, Jézéquel and Shields [21], they discussed that using the initial portion of the pressuremeter curve probably suffered from too much yielding and subsequent recompression of the walls during expansion. They concluded that the SBPM "appears to be better suited to the measurement of K_o than is the conventional pressuremeter". A study by Jézéquel et al. [22] noted some drawbacks in using the Ménard pressuremeter to determine a consistent and reliable value of at-rest conditions in the ground, p_{oM} ($=p_{oh}$) where p_{oh} is the total horizontal stress. Notably, too few points are available at the beginning of the test curve and the magnitude of the membrane correction can be significant in comparison to the value p_{oM} in soft soils.

The comments suggest that in theory it should be possible to estimate the horizontal stress in situ using the PMT. Given the technological improvements in pressuremeter testing and data acquisition as well as improved borehole preparation techniques, the idea of using the conventional pressuremeter to obtain the horizontal stress in the ground deserves to be further investigated.

3. Horizontal stress determination with the Ménard pressuremeter

Briaud proposed in his book "The pressuremeter" a method to obtain the horizontal stress from the pressuremeter curve using the initial portion without modifying the standardized loading protocol [23]. His procedure is also based on the assumption that upon excavating the borehole the horizontal is reduced from the initial stress as the walls of the borehole move inward. The pressuremeter is then placed into the borehole and as the membrane expands against the sides of the borehole, the stresses re-establish the borehole cavity to its original position and then the expansion continues until the limit pressure is attained in the test. The point where the original position is restored is undoubtedly an indication of the initial in situ horizontal stress.

Fig. 7 describes the procedure proposed by Briaud using an approach similar to the Casagrande method of determining the maximum past pressure σ'_p from a consolidation test curve in the e-log σ'_v space where the point of maximum curvature (point A) is selected from the initial portion of the test curve as shown. The portion of the expansion before point A reflects the pressure required to restore the borehole to its initial condition. Beyond point A, the soil is recompressed and solicited with stresses greater than the in place condition (virgin loading). The determination of Point A is relatively easy if the borehole is drilled properly and carefully but is difficult if the walls of the borehole are significantly disturbed by the drilling process.

With a properly prepared borehole, the transition from re-compression to virgin compression is clearly delineated; with disturbance from drilling, this transition is however gradual and leads to a more rounded curve at the beginning of the loading making it difficult to obtain a reliable maximum point of curvature. One way to make the determination of Point A, the maximum curvature, is to plot the radius change ($\Delta R/R_o$) on a logarithmic scale against the applied corrected pressure. The resulting pressure corresponding to point A is the total horizontal stress.

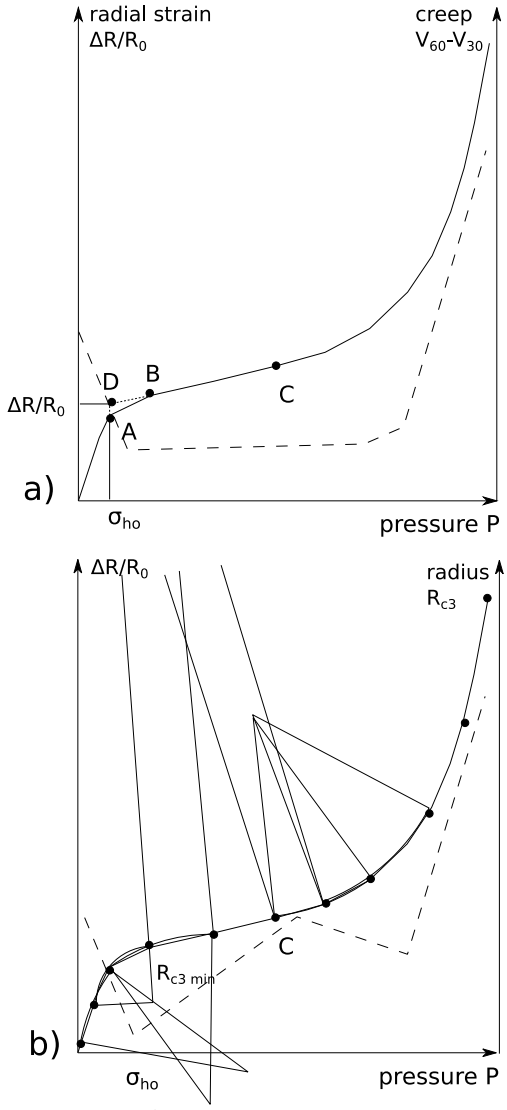

Figure 7. (a) Method for obtaining the at-rest pressure (adapted from Briaud [19]) (b) Curvature radius method

Gan and Briaud [24] suggest that the K_o values obtained using this procedure have been reasonable and consistent with other measures such as those from the SBPMT. It should be noted that Briaud carried out his tests without the use of drilling fluid. In cases where drilling mud is used, it should limit the reduction of horizontal stress from predrilling.

The horizontal stress is thus obtained from identifying the contact point between the expanding membrane system and the ground. The standard test procedure yields only a few points from which to deduct this pressure thus potentially limiting the accuracy of this evaluation.

Several alternative methods can be envisaged to automate this determination using simple spreadsheet manipulations as described herein:

- use the minimum value of V_{60s} - V_{30s} which must correspond to the instance when the probe makes contact with the borehole walls. The V_{60s} corresponds to the volume 60 seconds after each load application while V_{30s} is the volume at 30 seconds. The curve of V_{60s} - V_{30s} reaches a plateau corresponding to the so-called "pseudo-elastic" phase of the expansion test;

- determine the maximum tangent modulus (calculated for each segment) because when the probe inflates in the drilling fluid or in air, the stiffness is low and close to that observed during membrane calibration. When the probe contacts the borehole wall the modulus increases rapidly and is easily detected;

- locate the minimum radius of curvature R that corresponds to what Briaud describes as the maximum curvature point. This is easily done with a spreadsheet by calculating a sliding method using three points as shown in Eq. 2 as R_{c3}.

$$R_{c3} = \frac{\sqrt{\left((x_2-x_1)^2+(y_2-y_1)^2\right)\left((x_2-x_3)^2+(y_2-y_3)^2\right)\left((x_3-x_1)^2+(y_3-y_1)^2\right)}}{2\left|x_1y_2+x_2y_3+x_3y_1-x_1y_3-x_2y_1-x_3y_2\right|} \quad (2)$$

As shown in Fig. 7, an interesting alternative that can be used to overcome the variability of the curve is to calculate these radii and graph them on the double hyperbola of the corrected curve to assess the quality of the fit.

The contact pressure obtained from any of these techniques should correspond to a relatively close value of σ_{ho}. As the test is considered undrained or partially drained possibly generating some excess pore pressures, the value of σ_{ho} should be reduced by the total pore pressure ($u_o + \Delta u$) and normalized by the existing vertical effective stress in place to obtain K_o. Other methods based on an iterative process for determining the horizontal stress on a pressure –ln ($\Delta V/V_o$) graph are also effective [25, 26].

4. Applications to the green Paris basin clay and Flanders clay

The pressuremeter tests presented for this Paris clay come from 3 boreholes conducted by two separate testing companies. Fig. 8 shows an example of the application of these three alternative methods. It can be observed that for some of these tests at least one of the methods is not applicable (see blue curves with axes on the right side of the figures). For example:

- for the volumetric deformation rate (Fig. 8a), some tests have a continually decreasing rate, making it impossible to determine the minimum value.

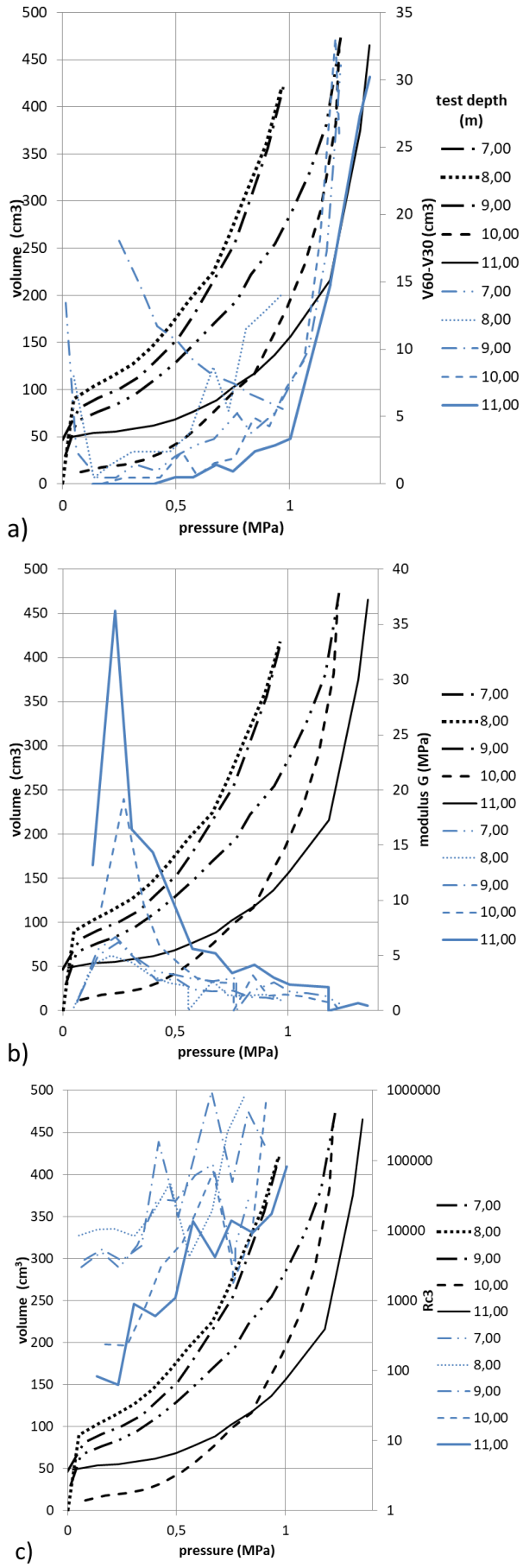

Figure 8. Example of application on pressuremeter tests carried out by a service provider on green clay; methods (a) deformation rate (b) modulus (c) radius of curvature

This is likely the result of significant disturbance of the borehole wall;

- for the modulus approach (Fig. 8b), some tests provide a distinct peak, which is not always observed in soft or remodeled soils;

- for the radius of curvature (Fig. 8c), it is possible to observe minimum values at the creep pressure. The value retained is the first one observed.

A combination of these methods is therefore preferred.

Fig. 9 compares the three methods for all boreholes. The results suggest that a trend is visible in the upper part of the deposit with a K_0 decreasing from about 2 to 0.7 to an approximate constant of about 0.8 at depth of 10 m. For one of the providers, the volume rate criterion of V_{60s} - V_{30s} is not reliable (open symbols) while it is applicable for the others (solid symbols).

It should be noted that the swelling nature of the Paris green clay may have been exasperated by the action of the drilling fluid and thus introduced an additional unknown variable.

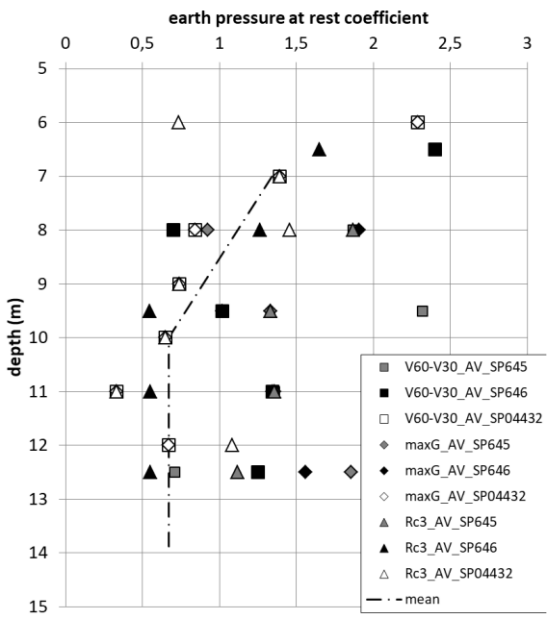

Figure 9. Comparison of profiles obtained using the 3 methods for PMT in Paris green clay

Since this analysis technique was applied to tests carried out to strictly obtain the pseudo-elastic and plastic phases (pressuremeter modulus, E_M and limit pressure, p_ℓ), such application resulted in a considerable dispersion but similar to what is observed for the limit pressure and the modulus values. However, a trend is still evident. This variation in results should decrease once a sufficient number of points are used during the initial phase of expansion if a suitable and standard procedure can be established.

Fig. 10 also includes test results using the self-boring pressuremeter, the slotted tube method with material removal (STDTM) as well as results from laboratory triaxial K_0 tests. The protocols for the pressuremeter tests followed the NF EN ISO 22475-6 [27] standard for the self-boring pressuremeter. The dispersion of K_0 deduced from these techniques is of course lower than that obtained for the K_0 calculated from commercial production-type pressuremeter tests. The correlation by Mayne and Kulhawy [9] is also shown and is in good agreement with these field and laboratory results.

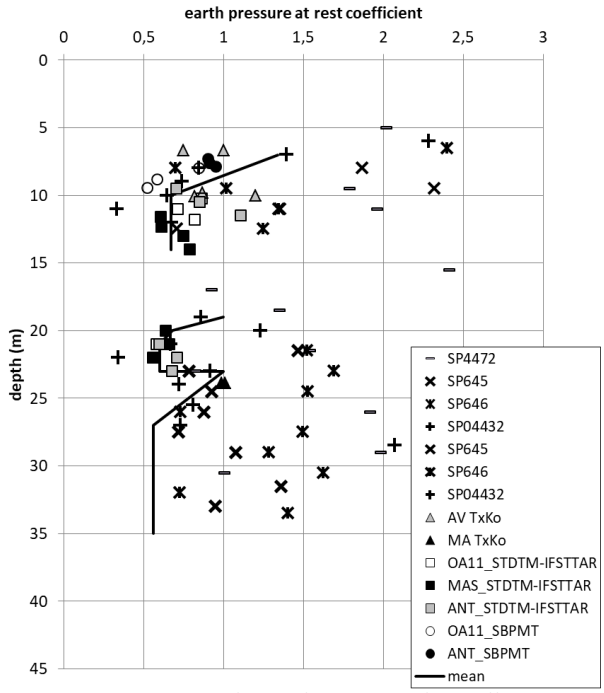

Figure 10. Comparison of K_0 profiles obtained from different techniques in Paris green clay

Fig. 11 compares the predictions from an experimental site of the LPC (Laboratoires des Ponts et Chaussées). The profiles from the 3 borings carried out in Merville, France by the LPCs show the variability specific to these tests with respect to the limit pressure and the Ménard pressuremeter modulus. In the figure are superimposed the results of the self-boring pressuremeter tests used as a reference in the article by Josseaume [28] on the Flanders clay. The results are in good agreement. The K_0 values derived from CPT profiles overestimate. The transition zone from silt to the Flanders clay is observed at a depth of about 2.7 m.

5. Testing in Dover, New Hampshire, USA

As part of the New Hampshire Department of Transportation (NHDOT) highway expansion project in the New Hampshire seacoast, the University of New Hampshire (UNH) has completed several test campaigns to assist in the design of embankments over the soft sensitive marine clay of the Presumpscot formation.

Fig. 12 shows DMT, CPT, PMT and SBPMT results at the Dover site. The DMT results from Getchell et al. [29] were modified using equation 3 with a factor $\beta_k = 2$ to account for sensitive clays based on Kulhawy and Mayne [31]. The results suggest that in the lower normally consolidated clay, the DMT profiles show consistent and repeatable K_0 results throughout the deposit with reasonable estimated values of about 0.7 to 0.8 in the nearly normally consolidated marine clay using these modified DMT KD values. The (p_0-p_2) not shown here gave a similar trend but with significantly and unrealistic lower magnitudes. The figure also shows the estimated values from the CPTu (piezocone

type 1). The trends are similar with the CPTu estimated values lower than those from the DMT especially in the upper portion of the normally consolidated clay deposit. As stated by Robertson and Cabal [30] there are no reliable methods to determine K_0 from the CPT. They suggest using the method of Kulhawy and Mayne [31] or Andresen et al. [32] with knowledge of OCR, undrained strength and plasticity index.

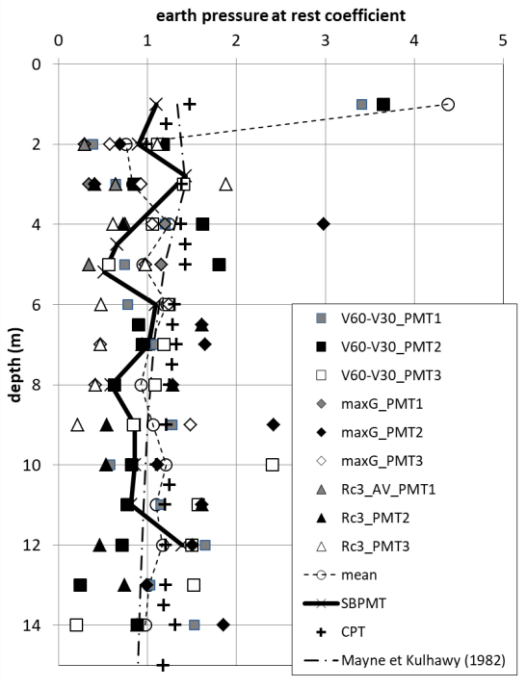

Figure 11. Comparison of the profiles obtained for the Merville test site

IFSTTAR in collaboration with UNH and Jean Lutz SA carried out several pressuremeter tests in 2017 that are also presented on Fig. 12.

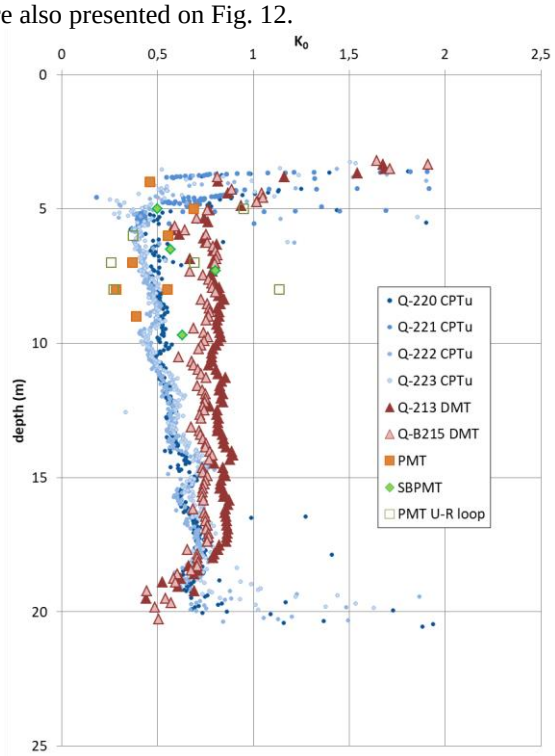

Figure 12. In situ testing K_o comparison at the Dover site in NH (modified from Getchell et al. [24])

The loading procedures followed the EN ISO 22476-6 standard for SBPMT and EN ISO 22476-4 standard for Ménard pressuremeter. All techniques used at this site showed similar trends with depth for this soft compressible clay although the DMT results need to be adjusted to match other test methods in the normally consolidated portion of the profile. The pressuremeter tests at shallow depth were executed in a borehole carefully executed manually using a hand auger and drilling mud which resulted in much less dispersion in the results.

Fig.13 clearly shows the effect of predrilling on the initial portion of the expansion curves. An average volume of 80 cubic centimeters corresponded to the annular volume before the measuring cell of the probe reached the borehole wall.

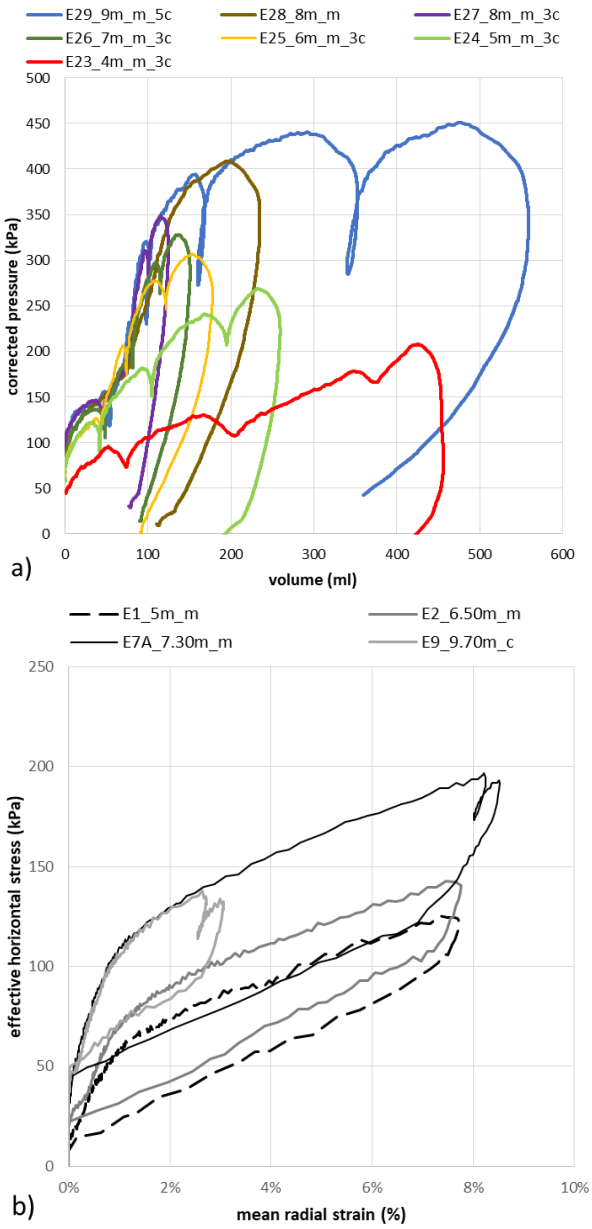

Figure 13. Pre-bored and self-bored pressuremeter test curves obtained at the Dover site in New Hampshire, USA.

Fig. 14 shows the Ménard pressuremeter tests performed following the test procedure proposed by Hoopes and Hughes [33]. During the unloading phase a reload-unload loop is performed in a specific value of

effective horizontal pressure. During the unloading, at specific times they hold the membrane pressure constant and observe whether the membrane contracts or expands. The goal is to determine a pressure at which the membrane does not move which they refer to as the balance pressure. Using this method allows the determination of the lateral earth pressure. Fig. 15 shows the unload-reload loop during the unloading part of the pressuremeter test.

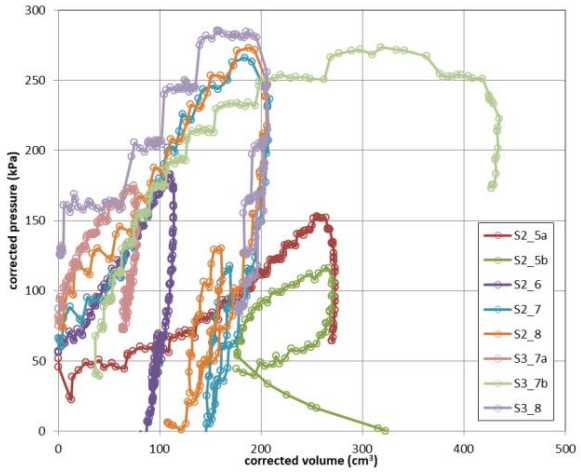

Figure 14. Pre-bored pressuremeter test curves with Ménard procedure obtained in 2019 at the Dover site in New Hampshire, USA.

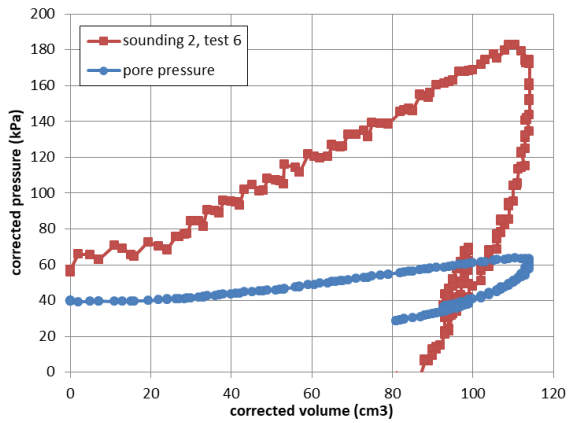

Figure 15. Example of pressuremeter test curve.

Using measured creep strains as a function of holding time for different pressure hold, a graph of applied pressure versus creep strain can be developed as shown in Fig. 16 for the test shown in Fig. 15. Hoopes and Hughes results show that a creep time under 60 seconds is sufficient for proper evaluation of the horizontal pressure.

The pressure balance method results shown on Fig. 12 (labelled PMT U-R loop) depict greater scatter compared to the other methods. These results may suggest that the method is more applicable for higher depths.

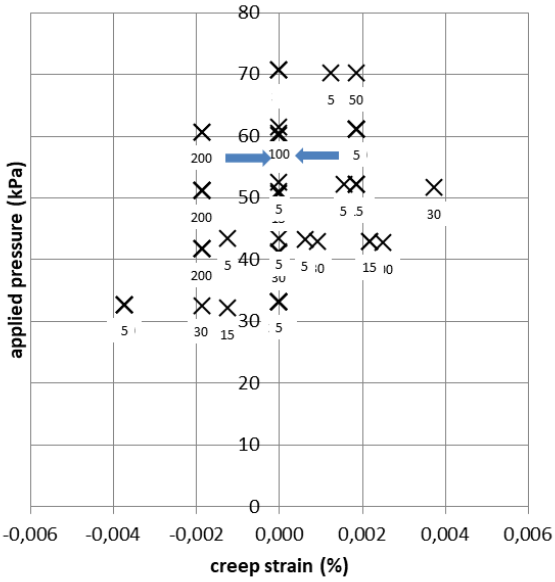

Figure 16. Interpolation of horizontal pressure on unload-reload loops during unloading phase

6. Conclusions

This paper suggests that it is possible to estimate the horizontal stress in place and consequently the coefficient of earth pressure at-rest K_0 using the pre-bored Ménard pressuremeter. To improve the accuracy of the technique it is necessary of record more data points during the early stages of the test and, of most importantly, to prepare a pre-drilled hole of good quality with minimal disturbance of the borehole walls.

The scatter observed using this method is not any higher than that obtained during test campaigns carried out for research (Fig. 1) or that accepted by consultants and builders on the pressuremeter profiles used during the design of the structures.

7. Acknowledgment

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