The pressuremeter: recent developments in testing and design methods

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ABSTRACT: This lecture concerns both the on-site implementation of tests and the qualification of new tools, as well as new calculation developments from measurements made with different types of standard or innovative pressuremeters. It takes up some developments of works carried out within the framework of the collaborative research project ARSCOP.

Keywords: pressuremeter tests, Ménard pressuremeter test, innovation, geotechnical design

1. Introduction

This lecture starts with pressuremeter testing in geotechnical practice compared with the standard, then the development of new equipment in order to expand the measurement range or collect new information, and finally with new calculation approaches.

2. About drilling, probes and implementation

The expansion test with a pressuremeter is the only in situ test that allows the deformability and rupture of the material to be assessed in a state very close to its initial state, whatever its nature.

Pressuremeter probes are either put in the soil by preboring a hole into which the probe is lowered, by pushing, driving or vibro-driving the probe, or by self-boring (SBP) where the instrument makes its own hole. Modes of placement of the pressuremeter probe have a preponderant influence on the expansion tests (Fig.1). A wide variety of factors determines the quality and reliability of the parameters evaluated by the pressuremeter and are presented in this lecture.

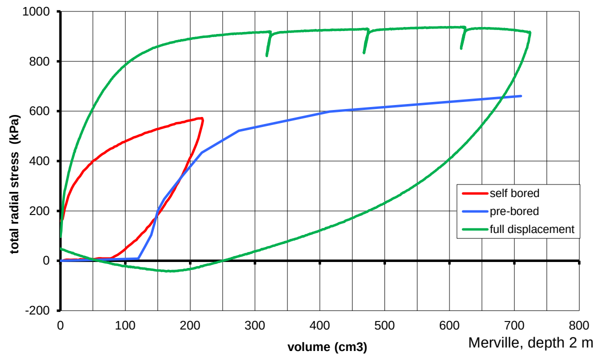

Figure 1. Test curves for 3 types of probe in Flander's clay(® Reiffsteck)

2.1. Tests comparison in soft and medium soils

Some test campaigns with several insertion methods were carried out with different types of probes and protective sheaths, in different types of soils (clay, lime, sands, hard soil and weak rocks) in order to confront the state of practice with requirements of the standard ISO 22 476-4[1].

Tests in soft organic clays of Cran (Brittany) [2] presented on Fig.2, and in medium dense sands of Messanges (Landes) are compared as well as two types of slotted tube with inside disintegrating tool (SDTD) tested in sands will also be discussed in this paper (TUBA® from FONDASOL and RotoSTAF® from APAGEO)[3].

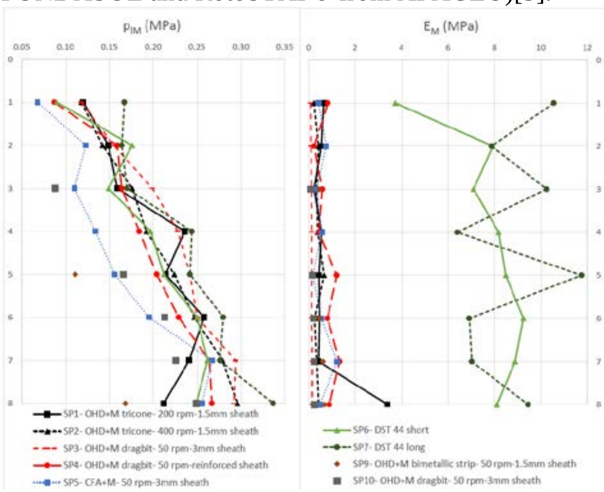

Figure 2. Pressuremeter results at the Cran site (©Ginger)

2.2. Influence of the insertion method

The Ménard probe has been described as well as the influence of the insertion method of the pressuremeter probe for borehole expansion tests was compared [4] at several sites.

2.3. Tests comparison in rocks

Tests were carried out in a limestone quarry (Figure 3) in Gouvieux [5] with 3 types of probes: a dilatometer probe (ISO 22 476-5) used in a 101 mm diameter core borehole; the monocell FC® probe in a 66mm core borehole; and Hyperpac© Apageo monocell probe in a 46 mm diameter core borehole. The results will be discussed.

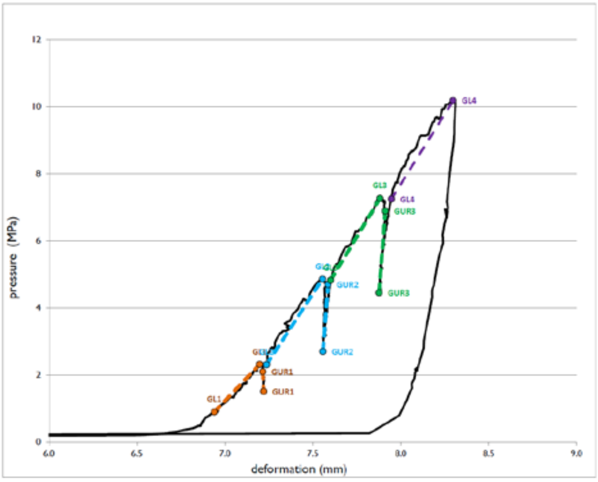

Figure 3. Dilatometer test in Gouvieux (©Fondasol)

2.4. Pore water pressure measurements

Karagiannopoulos [6, 7] performed static and cyclic expansion tests at different sites with a prototype probe developed by Jean Lutz SA which measures pore pressure (Fig.4). Also presented are the contribution of the cyclic tests and measurement of pore pressure on the soil characterization and some tests performed on a site at Newington, New Hampshire with Cambridge SBP and the Lutz (Fig. 5).

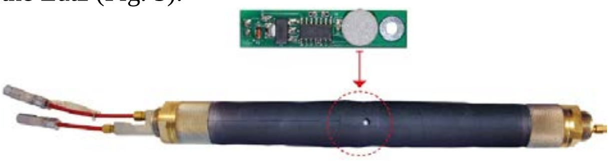

Figure 4. Electronic card with integrated sensor for pore pressure measurement and its place on the sheath (SA jean Lutz®)

Several multi-cycle tests were conducted in order to characterize the liquefaction potential, and compared with results of cyclic triaxial test, and with empirical correlations from CPTu. Figure 6 represents the CSR evaluation [8] based on the chart proposed by Reiffsteck[9].

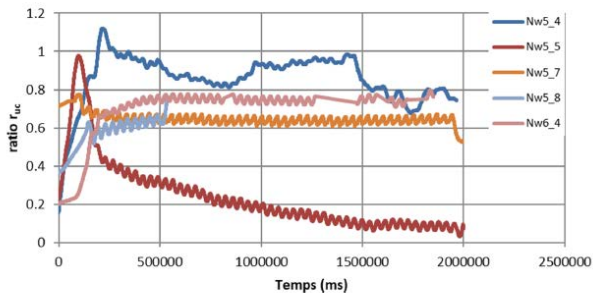

Figure 5. Pore pressure measurement during Newington cyclic tests

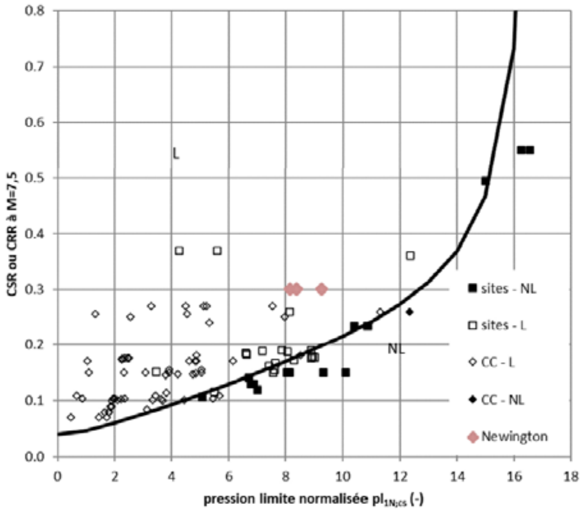

Figure 6. Newington cyclic and monotone tests on the CSR versus normalized pl_M diagram

2.5. At rest earth pressure measurement

It is also interesting to note that at-rest earth pressure may be detected at the beginning of the first loading and corresponds to the change of curvature of the pore pressure curve (Fig.7). This is comparable to the phenomenom observed with SBP Cambridge (Fig.8).

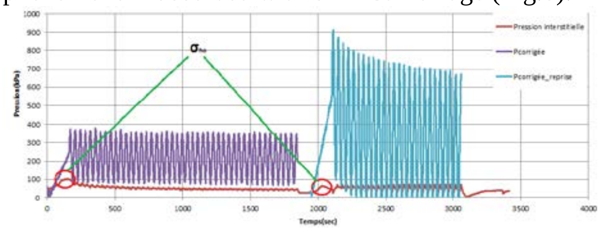

Figure 7. Measurement of K0 with SA Jean Lutz probe

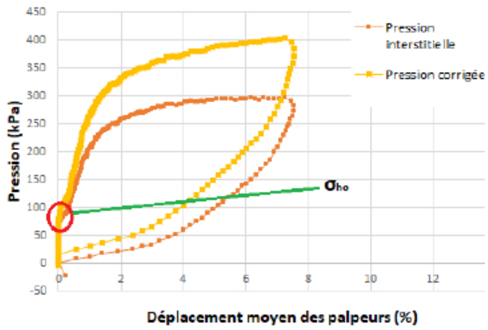

Figure 8. Measurement of K0 on pore pressure behavior with SBP Cambridge

2.6. Seismic measurement

The lecture will also present a prototype device called 'geotechnical gun' developped by Geomatech: it is an innovative tool able to measure in the same hole waves velocity to obtain shear modulus at small strain, as well as performing classical pressuremeter tests [10]. It includes wave source at the bottom of the probe, and a receiver with accelerometers at the top; this device is fixed at the bottom af the pressuremeter probe (Fig.9). The device could as well be used as a down hole test.

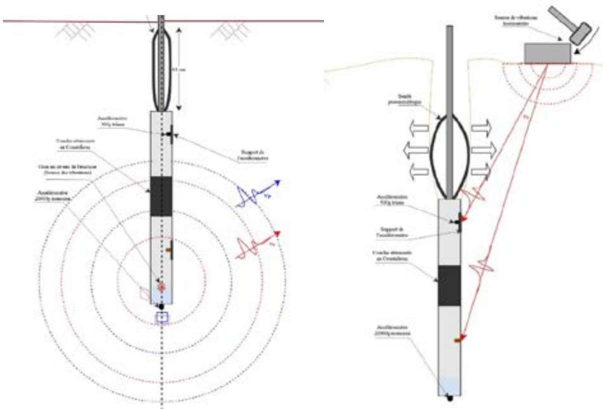

Figure 9. Geotechnical gun: principles of measurement. Left transmitter and receiver on the same probe; Right: transmitter at the top of soil, like down-hole

2.7. Cyclic tests and shear modulus

The lecture will also present recent research carried out aiming at assessing the shear modulus of soil at small strain levels for the application to the design of piles under cyclic loading. A. Lopes [11, 12] proposed the use of a new pressuremeter probe and revised testing and interpretation procedures for this purpose. The monocell FC® probe [13,14] was used, and the test protocols described on Fig 10 were carried out on two well geotechnically known sites in Dunkirk (dense sands) and Merville (overconsolidated clays). Emphasis was placed on determining the shear modulus in the small strain range, between 10^{-4} and 10^{-2}.

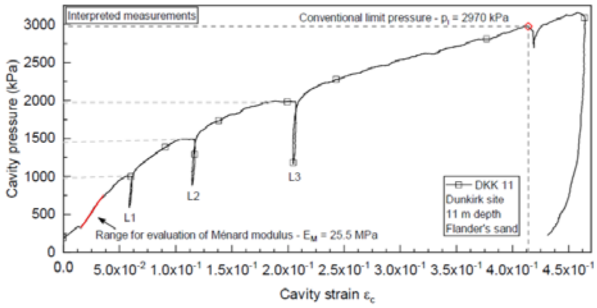

Figure 10. Example of test protocol performed at Dunkirk site (© LOPES)

Figure 11 shows the shear modulus decay curves evaluated from the three unloading loops performed in this test. It can be observed that the shear modulus increases for loops performed at higher cavity pressures. Within each loop, the shear modulus decays as the shear strain increases. These results were confronted to the behaviour of Dunkirk sand evaluated from empirical relationships found on literature, presented in blue in this same figure. A stress adjustment procedure was applied in attempt to evaluate the initial shear modulus at-rest on the site. The method was applied to three pressuremeter tests performed at 6, 8 and 11m depth. The results are presented in Fig. 12 and were compared to those measured on site using seimic cone penetrometer and obtained by correlation from CPT [15,16]; the values obtained with the proposed method for the pressuremeter are very similar to CPT correlation and conservative compared to the ones directly measured by SCPT.

Test	Depth (m)	r_0 (mm)	E_M (MPa)	G_M (MPa)	p_l (kPa)
DKK6	6.0	30.9	60.0	22.6	3890*
DKK 8	8.0	31.0	38.2	14.4	3100*
DKK 11	11.0	32.0	25.6	9.6	2970

(*) extrapolated value

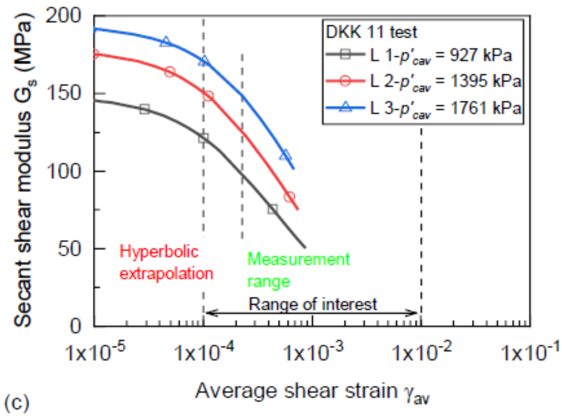

Figure 11. Degradation curves and secant shear moduli at Dunkirk site (© Lopes)

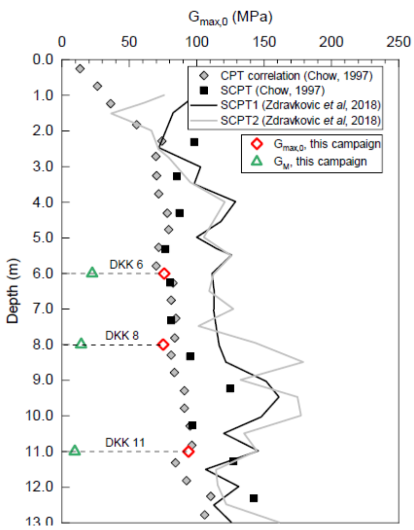

Figure 12. Comparison between the initial shear modulus obtained with pressuremeter and other values at Dunkirk site (© Lopes)

3. New design approaches

The interest of improving pressuremeter measurement is obviously to provide more relevant parameters for geotechnical design. The evaluation of the ultimate strength of geotechnical structures from the pressuremeter is essentially implemented for shallow and deep foundations, in particular within the framework of the application of French design codes. For thirty years now, these different calculation models have been progressively updated, and are now formalized in the French application documents of Eurocode 7 [17,18].

3.1. Settlement of rafts

The estimation of Young modulus E from Ménard pressuremeter modulus E_M in French practice was first described by a very simple eq (1) where α is an empirical rheological coefficient described by Ménard, and now in French standard [17].

$$E = E_M/\alpha \tag{1}$$

This formulae overestimates settlements, and was progressively replaced by eq. (2), where k is a corrective factor. But the choice of k depends on the type of soil and the amplitude of deformation. With regards to the settlement of footings, [17] proposes values for k, depending on the soil and its state.

$$E = \mathrm{k}\, E_M \tag{2}$$

An alternative methodology for the choice of deformation moduli based on the result of Ménard's pressuremeter test was recently developed for large shallow fondations such as rafts [19, 20, 21]. It is proposed to take into account the modulus decay with strain level, and to vary the E/E_M ratio with of strain level (approach A) or stress (approach B). Eq.3 expresses the evolution of the E/E_M ratio with level of vertical strain ε.

$$\frac{E}{EM} = \frac{1}{a+b\varepsilon} \tag{3}$$

E/E_M laws are then used concomitantly with stress diffusion derived from classical theory of Boussinesq elasticity and further developements of Steinbrenner in a one dimensional (1D) or three-dimensional (3D) framework. (see Fig.13).

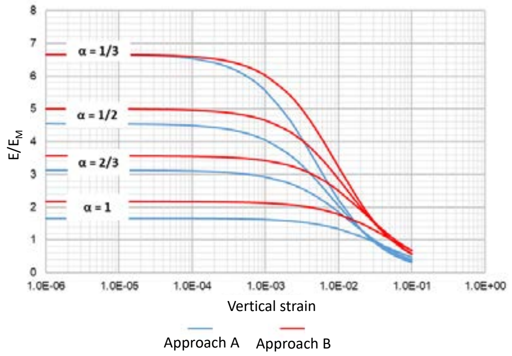

Figure 13. Decrease laws for approaches A and B (© Hoang)

Values of a and b (eq.3) depend on the type of soil and they were calibrated with measurements of rafts instrumented since their construction.

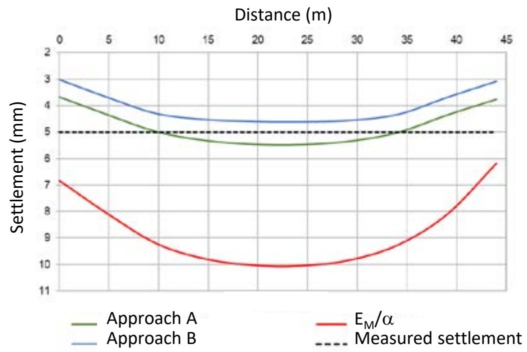

Figure 14. Settlement measured and calculated on the slab Tour Aurore for 80% of consolidation of plastic clays which represent 50% of the total settlement (Hoang, 2020)

An example is provided on Figure 14, where settlements measured and estimated by both approaches for the Aurore high rise tower in La Defense, a 27-floor building with 5 basement levels on a 25.4m x 43.4m footsprint, and a 2m thick slab. The geotechnical model and explanations are developed by Hoang [19]. The calculation with eq.1 largely overestimates settlements, where booth approaches give values similar to the measurements.

Another example is presented with the complex project of Trinity Tower in La Défense district (Fig. 15). Settlements calculated under the bottom of deep foundations are evaluated using the decay curves from thesemethods and with FEM modeling (Fig.16).

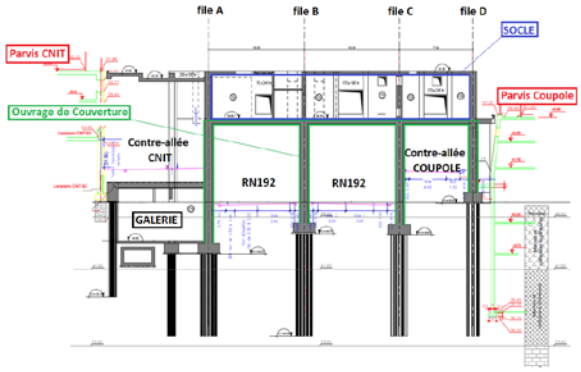

Figure 15. Cross section of Tour Trinity Project

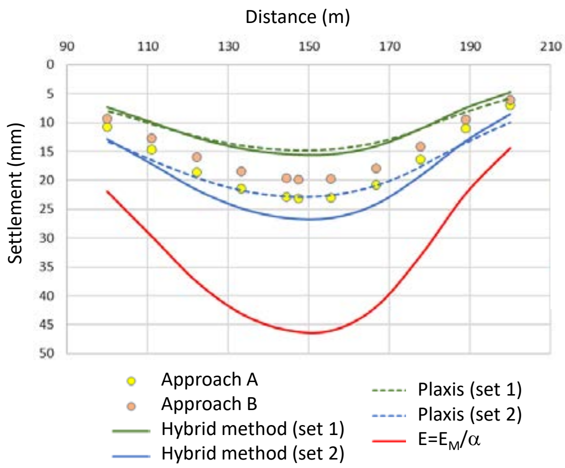

Figure 16. Settlement calculated on file C of Trinity Tour (©Hoang)

These examples demonstrate the relevancy of the use of the elastic modulus decrease with the levels of strain and stress to evaluate the settlements of flexible shallow foundations such as rafts from Ménard pressuremeter modulus E_M.

3.2. Piles under cyclic loading

The lecture will also present part of the works of A. Lopes [11] who observed that the soil response under cyclic repeated pressuremeter loading is analogous to the behaviour of piles under cyclic axial loading. The author presented the tests results in a stability chart (Fig. 17), similar to the cyclic stability diagrams presented by several autors [23,24,25] for bored or driven piles under cyclic loading. While it was not yet possible to establish a formal design method to evaluate pile the bearing capacity degradation using the pressuremeter, the author suggests this as a future research perspective.

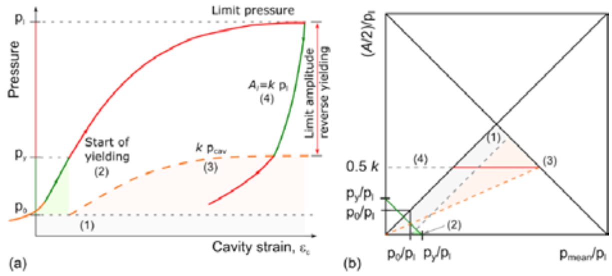

Figure 17. Representation of a schematic pressuremeter curve into an analogous stability chart (©Lopes)

4. Conclusions

The lecture aimed to present some results from the ARSCOP program, currently in progress, which provides an opportunity to compare the state of practice with standards and to propose improvements of probes and testing protocols. This program also enables the implementation of innovative calculation methods which are already used in some French geotechnical design.

This work will contribute and feed into the drafting of the next ARSCOP recommendations on the use of pressuremeter in geotechnical design.

Acknowledgement

I specially thank the French National ARSCOP and the scientific commission who guided me in the preparation of this lecture.

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