VALUES OF PRESSUREMETER MODULUS AND LIMIT PRESSURE INFERRED FROM STRESS OR STRAIN CONTROLLED PMT TESTING

L'EFFET DE LA MÉTHODE DE CHARGEMENT (PAR PALIERS DE PRESSION OU DE DÉFORMATION) SUR LE MODULE PRESSIOMÉTRIQUE ET LA PRESSION LIMITE

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ABSTRACT - This paper explores the effects of using either stress controlled or strain controlled loading procedure on interpreted values of the pressuremeter modulus (E_p) and the limit pressure (P_l). Pressuremeter tests were performed on different sites using these two loading procedures. A review of litterature is made, test results are presented, and a number of conclusions are given.

RÉSUMÉ - Cette communication présente une évaluation des effets de la méthode de chargement (par paliers de pression ou de déformation contrôlée) sur le module pressiométrique (E_p) et la pression limite (P_l). Des essais comparatifs ont été réalisés sur différents types de sols. Les résultats de ces essais de même qu'une revue de la littérature sont présentés, après quoi des conclusions sont tirées.

1. Introduction

A stress or pressure controlled pressuremeter test (PC PMT) applies constant pressure increments and the associated deformations are measured. A strain or volume controlled test (VC PMT) applies constant volume increments and the associated pressures are measured. During a PC test, strain increases slowly but constantly in the beginning, then it accelerates as the soil starts to yield. During a VC test, pressure increases quickly and constantly in the beginning, then it decelerates as the soil start to yield. The curves below illustrate these loading differences between a PC test ('*Ménard*') and a VC test ('*strain controlled test*'). It can also be noted that during a VC test, strain steps are imparted by the operator in a relatively quick manner: no deformation occurs during the stabilization phases. During a PC test, deformations are more gradual and occur during both loading and stabilization phases.

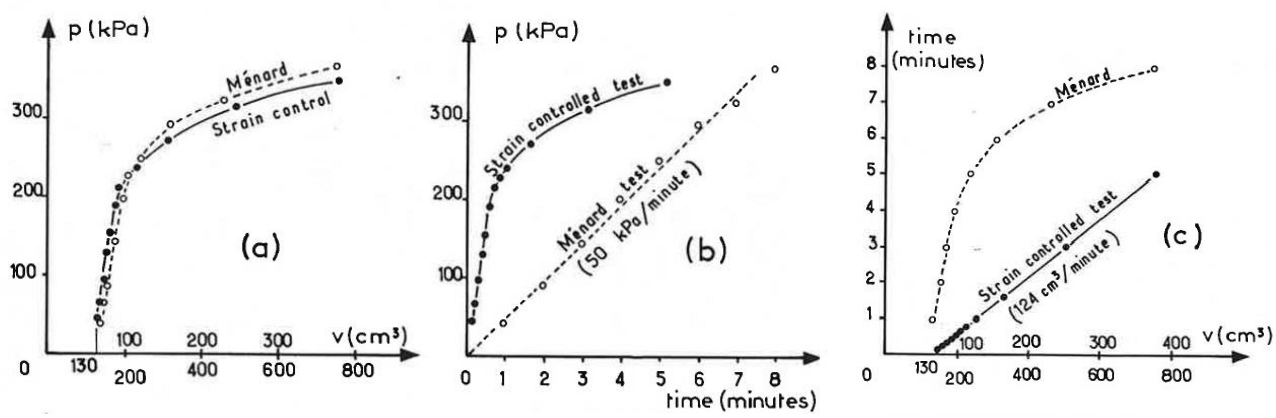

Figure 1. General Loading Pattern of PC vs. VC Tests (Baguelin et al, 1978)

Depending on the type of equipment used, the testing standard followed, and local practices, the pressuremeter test will be done following either stress or strain controlled methods. The ASTM standard related to the pressuremeter test (D4719) allows both methods to be used without distinction. The present paper explores the effects of these two methods on the pressuremeter modulus (E_p) and the limit pressure (P_l) from a North American perspective i.e. referring to equipment and tests methods specified in the D4719 ASTM standard. This study was carried out first, through a review of literature, and second, by presenting pressuremeter test results from different sites in various types of soils/material.

2. Literature Review

Baguelin et al. (1978) presented results from comparative tests done in soft loess with both methods (ref. Fig. 1a). The PC test was done with a Ménard pressuremeter, and the VC test was done using a pressuremeter with a hydraulically-loaded single cell probe. The tests were done 2 meters deep in 2 adjacent boreholes made by hand augering. No significant difference was found in the results.

Mori (1982) presented the results of comparative tests performed in soft cohesive soils (silty clay and clayey silt with 5-20 % of mixed sand). Tests were done at three different elevations in two boreholes about 2 meters apart. Strain-controlled tests yielded higher deformation moduli by an average of 20% and higher undrained shear strengths - deducted from P_l - by an average of 14 %. The testing time was about 40 minutes for the stress-controlled test and 12.5 minutes for the strain-controlled tests. Results considered here are those obtained from a volumetric single cell self-boring pressuremeter. It must be noted that the equipment and test methods used in that case were not those specified in the D4719 standard (ASTM, 2012).

From the experience of Cambridge In Situ, a company which manufactures equipment and runs PMT tests following stress and strain-controlled loading methods, there would be no significant difference on the results (Dalton, 2005). It must again be noted that the equipment and test methods used in that case are not those specified in the D4719 standard.

Briaud (1992) analyzed the differences between the stress versus strain controlled methods. He pointed out the effect coming from the differences between them in terms of duration of the applied stress. This effect can be summarized as follows: the quicker the soil is loaded, the larger E_p will be, and the smaller P_ℓ will be. And since E_p is typically measured faster during a VC test, we should expect a VC test to yield higher E_p. For evaluating this effect, Briaud refers to the following viscous model (Riggins, 1981):

$$E_t = Et_0 \cdot (t/t_0)^{-n_t} \quad (1)$$

where, according to Briaud:

- E_t and Et_0 are the secant moduli at times t and t_0 respectively after the start of the application of the stress;
- n_t is a viscous exponent that can be measured during a special pressuremeter creep test.

This model assumes that the soil behaves like a viscoelastic material. The n_t exponent would range between 0.02 and 0.08 in cohesive soils with an average of 0.05 (Briaud and Garland, 1985).

With the reference time t_0 usually chosen as 1 minute:

$$E_t = Et_0 \cdot (t)^{-n_t} \quad (2)$$

So according to this relation, when the modulus is measured three times faster (t = 1/3 · t), with n_t = 0.05, the modulus would be higher by 5.6% :

$$E_{t/3} = Et_0 \, (1/3 \cdot t)^{-n_t} \quad (3)$$

$$E_{t/3} = (1/3)^{-n_t} \cdot E_t \quad (4)$$

$$E_{t/3} = 1.056 \cdot E_t \quad (5)$$

We see that this effect is relatively small and we can conclude that the time dependency of E can become a significant factor but only in cases where the difference of time during which E is calculated becomes very important. If we take an extreme case i.e. where nt = 0.08 and E is measured 10 times faster (t = 1/10 · t), then E would be higher by 20.2% :

$$E_{t/10} = (1/10)^{-0.08} \cdot E_t \quad (6)$$

$$E_{t/10} = 1.202 \cdot E_t \quad (7)$$

3. Test Results

All tests results presented below were obtained with a hydraulic, volumetric, single-cell probe, Texam pressuremeter. This pressurmeter applies pressure through a piston activated by a screw jack. This type of pressuremeter was used because it allows either stress or strain-controlled tests

3.1 Pressuremeter Tests in High-Density Polyurethane

In order to eliminate the variations coming from the heterogeneity of the soil and from the insertion effects of the probe in the soil, a series of tests were done by Roctest Ltd using a special tube that is normally used for demonstrating pressuremeter testing. This tube simulates in part the soil behavior with the two classical pseudo-elastic and plastic phases. It is made from high-density polyurethane and has the following dimensions ø 63x155x500 mm.

Figure 1. Pressuremeter Probe in the Polyurethane Tube

Three consecutive tests were done with each method. VC tests were done in 20 steps of 30 seconds each and E_p was measured over 2 minutes. PC tests were done in 11 one-minute steps and E_p was measured over 4 minutes. P_l was estimated by extrapolation using a 20-iteration calculation based on the Newton-Raphson method. Results are presented in Table I below.

Only little variations were observed between the two methods i.e. less than 2% for E_p and 0.4% for P_l when comparing average values. These variations are comparable to variations coming from the repeatability error when using the same loading method. This repeatability error is essentially related to the performance of the equipment and of the polyurethane tube.

Table I. Results Obtained in the Polyurethane Tube

	PC Test Results			VC Test Results		
Test no.	E_p (kPa)	P_l (kPa)	E_p / P_l	E_p (kPa)	P_l (kPa)	E_p / P_l
1	13 556	2822	4.80	13 499	2910	4.64
2	13 805	3047	4.53	13 448	2992	4.49
3	13 819	3082	4.48	13 415	3013	4.45

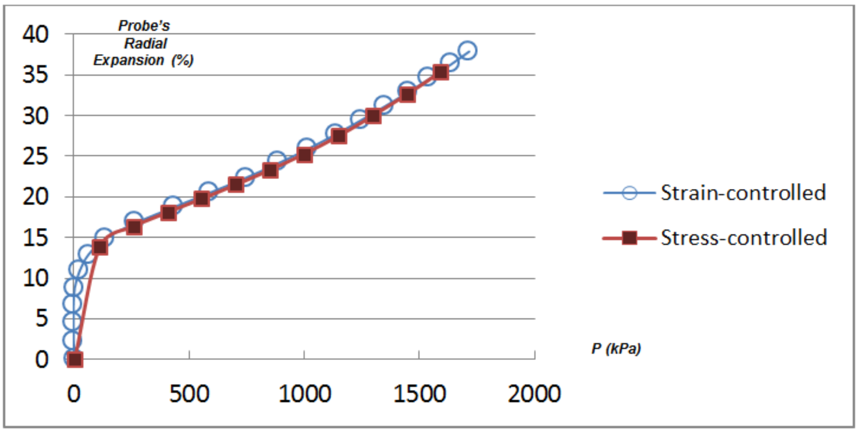

Figure 2. Tests no. 1 in the Polyurethane Tube

3.2 Pressuremeter Tests in Clay

Tests were done by R.M. Kenyon for Dr. Shields of the University of Manitoba with the assistance of Roctest. First tests were done at Roctest facilities in St-Lambert, Québec, in two boreholes prepared with a bucket auger. A second series of tests was done at the University of Manitoba in four boreholes prepared with a hand auger. Boreholes were spaced 2 m or more apart. Test results are presented in the table below. VC tests were done with 30 equal volume increments each held for 30 sec, and E_p was measured in about 1.5 minute. The PC tests were done with 8-10 equal stress increments each held 1 minute, and E_p was measured in about 3 minutes. P_l was extrapollated by ploting log injected volume versus corrected pressure.

Table II. Test Results.

Location	Depth (m)	Soil	Type of test	E_p (MPa)	P_l (kPa)	E_p / P_l
St-Lambert, Qc	1.7	Soft medium plastic silty clay	PC	5.5 (+25%)	720 (+20%)	7.6
			VC	4.4	600	7.3
U of Manitoba	8.2	Medium stiff lightly consolidated clay	PC	13	880 (+18.9%)	14.8
			VC	13	740	17.6
			PC	15	920 (+15%)	16.3
			VC	15	800	18.8

Note: % in brackets show difference with value obtained with the other testing method.

Overall, the average E_p obtained from the PC method is 8.3% higher than the one obtained from the VC method. The average P_l obtained from the PC method is 18% higher than the one obtained from the VC method.

Regarding the tests performed in St-Lambert, we note that the E_p obtained from the PC method is higher than the one obtained from the VC method, which is in contradiction with the viscous model presented at (1). We conclude that other effects, among which the heterogeneity of soils, played a predominant role in that case.

Regarding the tests performed in Manitoba, it is interesting to note that the tests were done in pairs and that the results obtained from each method show good repeatability. This would indicate that the soil was homogeneous. And more interesting, the variations of results between the two methods is comparable to the repeatability error when using the same method.

3.3 Pressuremeter Tests in Silty and Clayey Soils

Comparative testing was also done by In-Depth Geotechnical Inc. at a site in the city of Hamilton, Ontario. Two boreholes located approximately 2.5 meters apart were prepared using mud rotary drilling. Soil conditions in the testing zones are as follows:

Surface to 1.1 m: Silty Sand Fill, moist, compact to dense, reddish brown.
1.1 to 2.8 m: Sandy Silt, dense, moist, greyish brown.
2.8 to 5.0 m: Silt, trace of sand and clay, wet, compact becoming loose, grey.
5.0 to 7.4 m: Silty Clay, firm to soft, grey, moist, dark grey.
7.4 to 8.4 m: Silt Till, trace of clay, pebbles, damp, very dense, reddish brown.

Ground water elevation at the site was 2.70 m below ground surface. PC and VC testing procedures were completed as per ASTM D4719 Method A and Method B respectively. Values of the E_p moduli were measured for both cases in approximately 1 minute. P_l was estimated by a $1/V$ to P plot according to the ASTM D4719 standard.

Table Ill. Test Results.

Depth (m)	Soil	Type of test	Drilling tool	E_p (MPa)	P_l (kPa)	E_p / P_l
4.72	Silt with trace of sand & clay	VC	Tricone	23.0 (+55%)	800	28.8
4.72		PC	Tricone	14.8	805 (+0.6%)	18.4
6.73	Silty clay	VC	Drag bit	9.4	675	13.9
6.31		PC	Tricone	9.4	780 (+15.6%)	12.1
7.82	Silt Till	VC	Drag bit	17.8 (+7.9%)	1390	12.8
7.72		PC	Tricone	16.5	1760 (+26.6%)	9.4

Note: % in brackets show difference with value obtained with the other testing method.

Tests results at the water table elevation and at the Silt Till layer were omitted as they exhibited large variations of soil properties in very small distances.

Moduli from volume controlled method were higher by an average of 21%, and limit pressures from pressure controlled method were higher by an average of 14.3%.

The higher value of E_p obtained from VC tests cannot be explained by the time dependency of E_p considering that E_p was measured over the same period of time for both testing methods. Other factors must be responsible for these differences. It is also noted that for tests occuring in harder soils under partially drained conditions (silts and sand), the VC method appears to predict higher values of E_p than for the one occuring in softer soil under undrained conditions (clay soil).

4. Summary of Tests Results and Discussions

The table below summarizes the effects of the loading method that were observed during our tests:

Table IV. Summary

Test Reference	Type of soil / material	No. of Tests	E_p	P_l
Roctest Ltd	Polyurethane tube	6	No significant difference	
U of Manitoba & Roctest Ltd	Soft silty clay and stiff clay	6	PC produced equivalent or higher E_p (+8.3%)	PC systematically produced higher P_l (+18%)
In-Depth Geotechnical Inc.	Silt, clay, and silt till	6	VC produced equivalent or higher E_p (+21%)	PC systematically produced higher P_l (+14.3%)

Note: % in brackets show difference with value obtained with the other testing method in average.

The following observations can be made from these results:

- Tests following VC and PC methods performed in a polyurethane tube were repeatable within 2%.
- Strain-controlled tests produced in average slightly higher E_p and systematically lower P_l.
- These differences cannot be explained by time dependency of E_p and P_l only. Other factors might have played a role in that. Our opinion is that differences in loading pattern specific to each method must also be considered. Among others, the fact that during a strain controlled test, deformations are imposed during shorter periods of time could result in a quicker degradation of the soil, yielding a lower P_l.
- These differences are within a range comparable to the one observed in the consulted literature.
- These differences must be put in perspective. From our experience, it is reasonable to expect a 5 to 10% variation when using a single testing method in a single borehole. These variations come from the making of the borehole, the operator, the equipment repeatability, and the data reduction calculations. Taking into account the heterogeneity of soils in the presented cases, the observed variations ranging from 8.3% to 21% can be considered as not very significant.
- Our opinion however is that for soils much harder than those considered in the present paper, these variations could become more significant.

5. Conclusions

Tests performed in specific soils (mainly clay and silt) have shown that strain controlled tests generally yield slightly higher E_p and systematically lower P_l than the stress controlled method. These differences could not be explained only by the time dependency of E_p and P_l ; other elements, probably related to loading pattern specific to each method, must be considered. But whatever the reason, it is important to note that for the soils considered these differences remained small and not very significant.

It would be interesting to carry out a series of tests in harder soils and evaluate how these differences would evolve. As far as the ASTM-D4719 methods are concerned, it is probable that at some point these differences will become significant if no adjustments of the magnitude and the number of volume steps are made.

6. References

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