Comparisons between pressuremeter tests carried out in a controlled environment with monocell vs. Menard-type tricell pressuremeters

Louis Marcil
Roctest Ltd, Saint-Lambert, Qc, Canada, louis.marcil@roctest.com

ABSTRACT: This paper compares tests results from two types of pressuremeters: one equipped with a monocell probe and the other equipped with a tricell probe (Menard type). These tests were carried out in polymer tubes specifically designed and manufactured for this purpose. These tubes of different stiffness were chosen because they allowed the simulation of a large range of soil stiffness, they ensured a good repeatability of the results, and because they exhibited a three-step deformation pattern similar to the one obtained in soil with pre-bored pressuremeters. These tests show a difference between the moduli measured with these two types pressuremeters. Possible reasons for this difference were therefore analyzed. Finally, a method for reducing this difference was proposed.

Keywords: Pressuremeter; monocell or tricell probe; modulus; limit pressure

1. Introduction

Pressuremeters (**PMT**) can be divided into two categories : those using electrical probes and those using hydraulic probes. Electrical probes integrate sensors that directly measure the radial expansion of the probe's membrane for determining ground deformation. Hydraulic probes contain no electronics. With these, ground deformation is determined by measuring the volume of fluid injected into the probe from the surface. Hydraulic probes, in turn, may consist of a Monocell (**MC**) or a Tricell (**TC**) probe – including one measuring cell and two guard cells. TC pressuremeters (using TC probes), also known as Menard pressuremeters, are the most common ones and consist of a reference from which many foundation design methods have been developed over the last 60 years. MC pressuremeters (using MC probes) are often used interchangeably with TC pressuremeters and are hence assumed to yield comparable results. This assumption comes from the works of people like Hartman [1] and Briaud [2] and is based on theoretical analyses and comparative tests performed in soils. The present study aims to quantify the potential differences between the two types of PMT, but as determined from practical experiments in a controlled environment i.e. in polymer tubes of different stiffness and sizes.

2. Test Methodology

2.1. Description of the test simulation tubes and equipment used

A special mold was manufactured and used for casting three Test Simulation Tubes (**TST**) of stiffness ranging from Duro Shore 85A to 95A. The Duro Shore A scale is a classification system of hardness used for polymers and rubbers. High numbers indicate harder material. These TSTs consist of high-density polyurethane and are 76 x 141 x 618 mm, which is suitable for testing N-size (74 mm) probes. This size of probe is common in North America.

The main advantage of these tubes is that they exhibit a deformation pattern similar to the one of the soil i.e. with a linear portion followed by a segment that looks like a creep zone, and this, with no permanent deformation of the material. This feature allows multiple and repeatable use of a single tube.

Additional tests were performed in a B-size (63 mm) polyurethane TST.

The stiffness of these polyurethane TSTs is equivalent to soils ranging from stiff to very hard.

We also performed tests in a much harder TST, made of ABS polymer. This 76 x 89 x 920 – mm TST, suitable for testing an N size probe, was used to simulate extremely hard soil. Since reaching a yielding zone in this TST without damaging it was difficult, this zone was never reached, and no useful information about the strength was obtained in this TST.

The control unit used with the TC probe was a model GAM-ll manufactured by Apageo (France). The one used with the MC probe was a model TEXAM manufactured by Roctest (Canada). These are the most common pressuremeters in North America. See figure 1.

The probes were fitted with a low-resistance (60 – 150 kPa) rubber membrane protected with steel strips, and with vulcolan (polymer) rings (**VR**). See figure 2. Considering that the measurements of the MC probe were potentially affected by the type of rings, the tests with this probe were repeated using metallic rings (**MR**). See figure 3. Measurements obtained with the TC probe are considered not to be affected by the type of rings. So the TC probe was only used with VR rings.

2.2. Testing procedure

The calibrations and tests were performed following the ASTM D4719-20 Standard [3]. The tests with the TC PMT were done in the polyurethane tubes in 60-second pressure steps following a sequence refered to as Procedure A (Equal Pressure Increments). And the tests performed with the MC PMT were done in 15-second volume steps of 40 cm^3, according to Procedure B (Equal Volume Increments). These loading sequences were chosen because they are the ones usually followed with these types of PMT, respectively. One exception: considering the very high stiffness of the ABS TST, it was decided to always follow Procedure A in that material for obtaining a better definition of the curve. No unload-reload cycles were performed. Tests were done at 21 degrees Celsius. Only the PMT moduli of the first loading (**E**) and limit pressures (**Pl**), as defined in D4719-20, were used for comparison purposes. E and Pl are indicators of stiffness and strength, respectively.

Figure 1. Equipment used: TC and MC PMT, N-size probe, steel calibration tube, and polymer TSTs

Figure 2. MC probe with VR rings

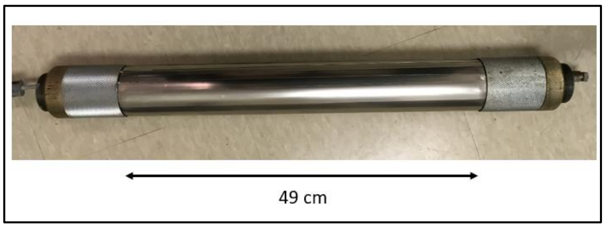

Figure 3. MC probe with MR rings

The data were reduced using the Texam Companion [4] and Pressio Companion [5] spreadsheets according to the methods described in the D4719-20. Pl was estimated using the reciprocal method i.e. the Pressure vs. 1/Volume method as defined in D4719-20. The volume correction factor 'a', representing the slope of the volume loss calibration curve, was selected in a very conservative way i.e. between 3000 and 6000 kPa.

The tests were repeated at least three times for each combination of control unit / probe / TST. This allowed assessing the repeatability of the TST and testing equipment, which proved to be within +/-2%. Typical test results are shown at figure 4. It can be noted that the polyurethane tubes properly reproduce a soil's response, except that apparent yielding is more gradual.

3. Test results

3.1. Tests with N-size (74 mm) probes

The test results obtained with the N-size probes are summarized on table 1. No tests were done with the MC-MR probe in the Shore 90A TST because this one was not available at the time of testing.

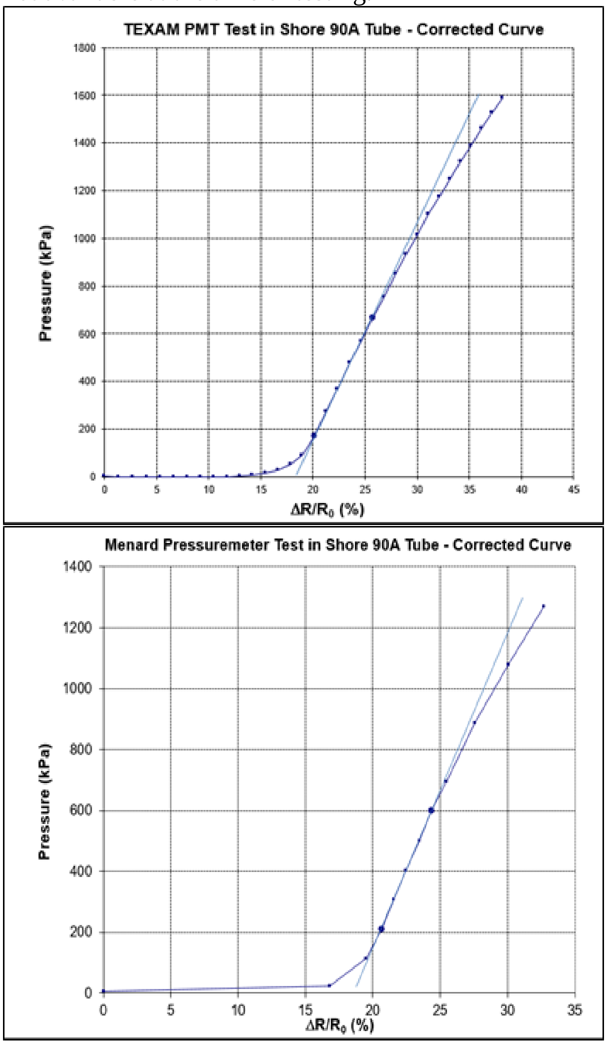

Figure 4. Typical test results in the Shore 90A TST obtained with N-size MC and TC Menard-type pressuremeters

The main observations we can make from these tests are : that there is a systematic difference between the moduli measured with the MC and the TC probes, and that this difference varies directly with the stiffness of the TST. More specific observations are presented below.

The MC-VR probe gives moduli lower than those obtained with the TC probe. This difference increases directly with the stiffness of the TST, from -13% to -19.9%.

The MC-MR probe gives moduli higher than those obtained with the TC probe. This difference gradually decreases with the increasing stiffness of the TST, from +13.8% to -0.1%.

The MC-MR probe gives moduli higher than those obtained with the MC-VR probes. This difference decreases gradually with the increasing stiffness of the TST, from +30.8% to +23.6%.

Regarding the Pl measurements, we see that the differences are small (+/-10% or less), and that they are not clearly correlated with TST stiffness. Thus, no significant differences in Pl were found between MC and TC probes. However, considering the difference between failure modes of soil and polyurethane, caution should be used before concluding that TC and MC pressumeters produce equivalent values of Pl.

Table 1. Typical test results with N-size probes

TST	PMT Type	Rings	E			Pl	
			(MPa)	Diff (%) MC vs TC	Diff (%) MC-MR /VR	**(MPa)**	Diff (%) MC vs TC
Shore 85A	TC	VR	**12.3**			**1.9**	
	MC	VR	**10.7**	-13.0		**1.94**	+2.1
		MR	**14.0**	+13.8	+30.8	**2**	+5.3
Shore 90A	TC	VR	**17.0**			**2.39**	
	MC	VR	**14.5**	-14.7		**2.49**	+4.2
		n.a.	**n.a.**	n.a.	n.a.	**n.a.**	n.a.
Shore 95A	TC	VR	**44.0**			**5.38**	
	MC	VR	**35.7**	-18.9		**4.96**	-7.8
		MR	**45.3**	+2.9	+26.9	**4.84**	-10
ABS	TC	VR	**136.9**			**n.a.**	
	MC	VR	**109.7**	-19.9		**n.a.**	n.a.
		MR	**135.6**	-0.1	+23.6	**n.a.**	n.a.

TST : Test Simulation Tube / TC : Tricell / MC : Monocell / VR : Vulcolan rings / MR : Metal rings

3.2. Tests with B-size (58 mm) probes

A few tests were also run using B-size probes. Those tests were done with MC-VR and TC probes put in a 63x155x500-mm, Shore 90A, polyurethane TST. The test results are similar to those obtained with the N-size probes in that : no significant difference was found between limit pressures, while the modulus obtained with the MC-VR probe was lower than the one obtained with the TC probe. In fact, the difference in moduli was greater between B probes than between the N probes, i.e. about 30% instead of 15%. We have not investigated to find out the reason for this difference. But it might come from the difference in the length / diameter ratio between the two MC-VR probes, which is 6.6 for the N probe (46 cm / 7 cm), but only 5.7 for the B probe (33 cm / 5.8 cm).

4. Factors that might explain the difference in moduli

Various elements might explain the difference between the E values obtained with the MC and the TC probes. Four elements were identified and analysed below.

4.1. Variations in the loading sequence

The tests performed with the TC probes are always pressure-controlled (i.e. with equal steps of pressure). Those performed with the MC probes are generally volume-controlled (i.e. with equal steps of volume). In order to evaluate the potential effect of this difference, tests with the MC probes were repeated following equal steps of pressure. No significant differences were observed. Considering that and the results from previous tests [6], it would seem that this element has no significant effect on the results.

The duration of each test was approximately 10 minutes.

4.2. Data reduction method

The method used for reducing the data was identical with both pressuremeters. Only the ranges over which E and 'a' (the deformation factor of the equipment) were measured, varied slightly. Verifications and modifications of these ranges were made. No significant impact that would explain the differences in the moduli were found.

4.3. Length relationship between the probes and the TST

The length ratios of the TST versus the TC probe (including the guard cells) are different from those between the TST and the MC probes. In order to see if this could affect the results, a few tests were repeated in ABS TSTs of different lengths. No significant differences were found.

4.4. End effects of the probe

The change in length of the measuring cell during the test was analysed in order to evaluate the end effects of the probe. It is assumed that this change occurs only with the MC probe, not with the TC probe because of the guard cells on this one, which were designed for preventing that. Therefore, only the longitudinal change of the measuring cell of the MC probe was measured. This was done with an N probe fitted with VR rings, and then repeated with the same probe but assembled with MR rings.

The assumption that the measuring cell expands radially in a uniform way all along its length would mean that the contact length (**CL**) between the TST (or the soil) and the membrane remains constant throughout the test. We therefore measured the evolution of CL during pressurization of the probe. The procedure described below was followed.

4.4.1. Testing methodology and results

The N probe was put in the 76-mm inner diameter steel pipe and gradually pressurized. The location of the last point of contact between the membrane and the steel pipe was estimated at each pressure step using a thin curved steel strip as shown on Figure 5. The averages of three readings, spaced 120 degrees at the periphery of the probe, were used for evaluating CL.

Then, we compared CL to **L0**, which is the theoretical length of the measuring cell. L0 is used for evaluating the volume of the probe, which in turn is used for calculating the modulus E. L0 was originally set by the manufacturer at 46 cm for the VR probe, and at 49 cm for the MR probe [7].

The results are shown in table 2 and figure 6.

Figure 5. Measuring CL with a steel strip

Table 2. Measurements of contact lengths

MC-VR probe				
Vol (cm^3)	P (kPa)	CL (cm)	L0 (cm)	Diff L0/CL (%)
0	0	0		
205	100	45.3	46	+1.4
278	200	50.7		-10.2
294	400	51.5		-11.9
306	600	52.8		-14.9
314	800	55		-19.5
320	1000	56.7		-23.2
331	2000	57.7		-25.4
339	3000	57.9		-25.9
347	4000	58.3		-26.8
351	5000	58.4		-26.9
356	6000	58.4		-27.0
366	8000	58.6		-27.4
373	10000	58.6		-27.4
MC-MR probe				
Vol (cm^3)	P (kPa)	CL (cm)	L0 (cm)	Diff L0/CL (%)
0	0	0		
225	100	42.8	49	+12.6
255	200	44.8		+8.5
275	400	46.7		+4.8
283	600	47.5		+3.1
287	800	47.8		+2.4
291	1000	48.3		+1.5
300	2000	48.4		+1.2
306	3000	48.5		+1.0
312	4000	48.5		+1.0
318	5000	48.5		+1.1
322	6000	48.5		+1.1
331	8000	48.5		+1.0
339	10000	48.6		+0.8

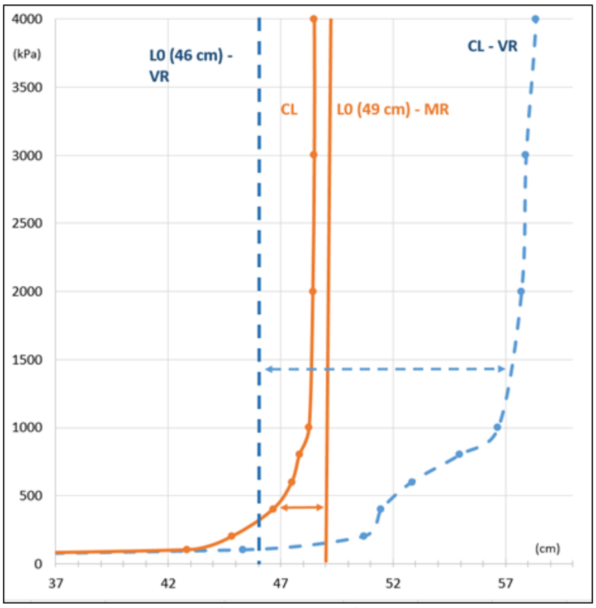

Figure 6. Evolution of CL versus L0 for MC - VR / MR probes

4.4.2. Evaluation of results

Three main observations were made.

First, we see that, for both types of probes, CL increases as the probe is being pressurized. This is not surprising considering that because of the gap between the TST and the probe, the unconfined ends of the latter are free to expand longitudinally.

Second, we see that CL becomes more stable over 2000 kPa, which means that the elongation of the membrane slows down significantly at this point. This may be due to the steel strips covering the rubber membrane. These steel strips are glued to the flexible membrane in such a way that they allow radial expansion of the rubber membrane, while limiting its longitudinal elongation.

Third, we note that the difference between L0 and CL, and the difference between the moduli E obtained with the MC and TC probes, evolve in a very similar way.

More specifically, we see that for the MC-VR probe, the difference between L0 and the CL increases from -10.2% to -25.4% between 200 kPa and 2000 kPa (see Table 2). This evolution is similar to the difference between the E measured with the MC-VR and the TC probes, which gradually increases with the stiffness of the TSTs from -13% to -19.9% (see Table 1).

We also observe such similarity with the MC-MR probe i.e. we see that the difference between L0 and CL decreases from +8.5% to +1.2% between 200 kPa and 2000 kPa. This evolution is similar to the difference between the E obtained with the MC-MR and the TC probes, which gradually decreases with the stiffness of the TSTs from +13.8% to -0.1%.

Considering the foregoing, it would seem that the difference in E between the two types of pressuremeters would be explained to a large extent by the discrepancy that was observed, for the MC PMT, between CL and L0. It would also appear that this difference comes from the fact that the value of Lo was not initially set in a fully representative manner, and from the fact that CL does not remain constant as the probe is pressurized.

5. Modification of L0

The test results above suggest that L0 was originally set too low for the MC-VR probe, and too high for the MC-MR probe. If L0 is increased from 46 to 51 cm (+10.9%) for the VR probe, and reduced from 49 to 45 cm (-8.2%) for the MR probe, the difference in the moduli between the MC and TC probes would be reduced as shown on table 3 and figure 7. These suggested values of L0 correspond to CL measured with the probe pressurized at 200 kPa in a 76-mm steel tube.

6. Evaluation of the effects of the stiffness and inner diameter of the TST

Some tests were also undertaken to give an overview of the effects of the stiffness and inner diameter of the TST over CL. These tests consisted in gradually pressurizing the probe and measuring CL in a 76-mm steel tube, a 76-mm polymer (Shore 85A) tube, and in a 82.5-mm steel tube. The results of these tests, presented in the figure 8, show that CL does not appear to be significantly affected by the stiffness of the TST. However, it would more affected by the inner diameter of the tube : CL is 3% smaller on average in the 82.5-mm steel tube compared to CL measured in the 76-mm steel tube. These comparisons were done between 200 and 1100 kPa.

Table 3. Effects over E of L0 adjustment

TST	PMT Type	Rings	E 1 (with current L0 values)			E 2 (with adjusted L0 values)		
			(MPa)	**Diff (%) MC vs TC**	Diff (%) MC-MR /VR	(MPa)	**Diff (%) MC vs TC**	Diff (%) MC-MR /VR
Shore 85A	TC	VR	12.3			12.3		
	MC	VR	10.7	**-13.0**		11.8	**-4.1**	
		MR	14.0	**+13.8**	+30.1	12.9	**+4.9**	+9.3
Shore 90A	TC	VR	17.0			17.0		
	MC	VR	14.5	**-14.7**		16	**-5.9**	
		n.a.	n.a.	**n.a.**	n.a.	n.a.	**n.a.**	n.a.
Shore 95A	TC	VR	44.0			44.0		
	MC	VR	35.7	**-18.9**		39.3	**-10.7**	
		MR	45.3	**+2.9**	+26.9	41.9	**-4.8**	+6.6
ABS	TC	VR	136.9			136.9		
	MC	VR	109.7	**-19.9**		120.7	**-11.8**	
		MR	135.6	**-0.1**	+23.6	125.0	**-8.7**	+3.6

E 1 : Moduli with L0 currently set at 46 cm for the MC-VR and at 49 cm for the MC-MR

E 2 : Moduli with L0 adjusted at 51 cm for the MC-VR and at 45 cm for the MC-MR

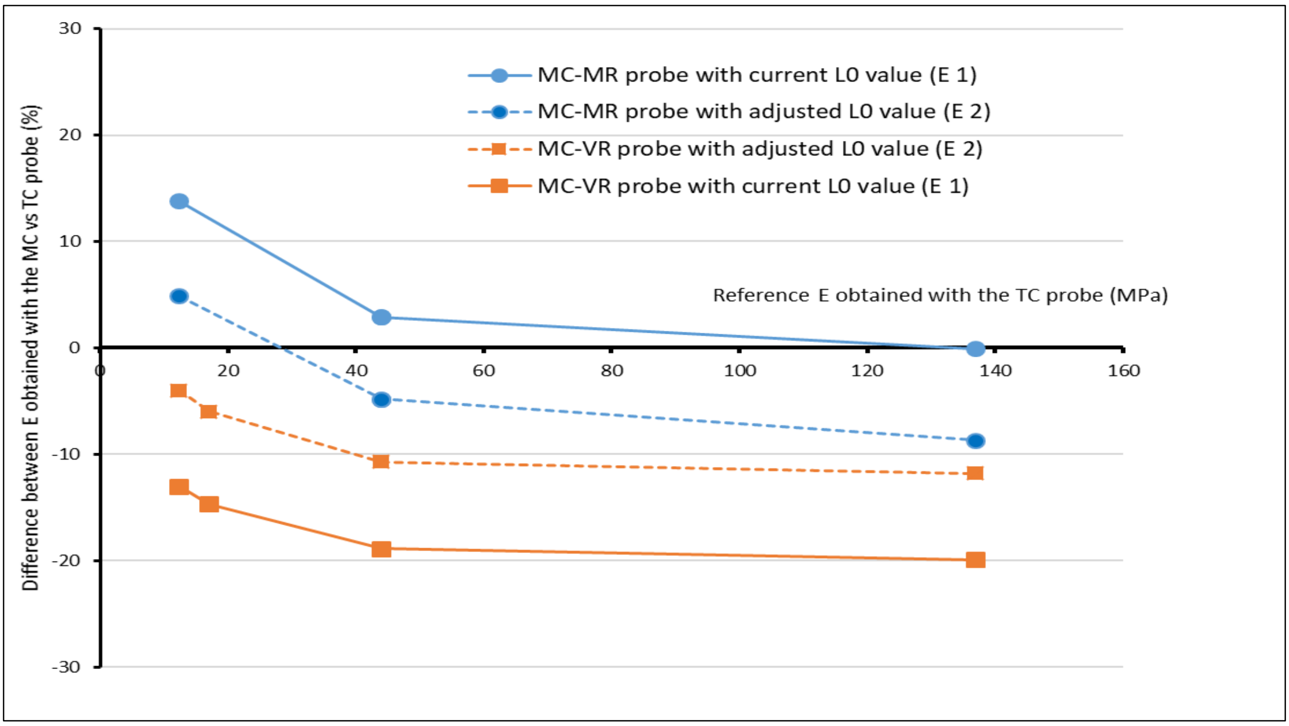

Figure 7. Difference in % between E obtained with MC vs TC probes before (E 1) and after (E 2) adjustment of L0

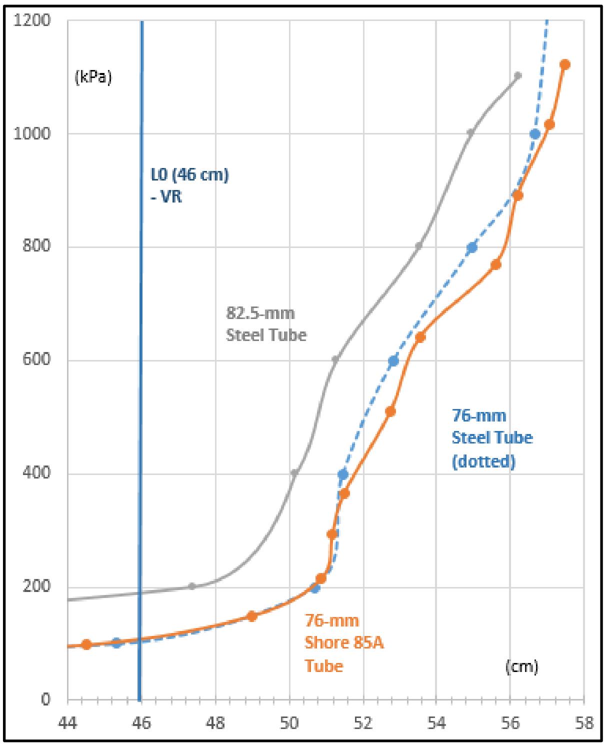

Figure 8. CL vs the stiffness and inner diameter of the TST

7. Conclusions

This study compares the results between monocell and tricell pressuremeters based on tests performed in a controlled environment (polymer tubes). The following conclusions were drawn from these tests.

First, no significant differences were found regarding the limit pressures. However, considering the differences between the failure modes of soil and polyurethane, caution must be used. We recommend validating these results with additional tests.

Second, there is a systematic difference in the moduli. This difference varies with the stiffness of the tested material. The stiffer the material is, the smaller the modulus produced with the monocell PMT is when compared to the tricell PMT, as indicated by the decreasing trend of all the curves of figure 7.

Third, the difference in moduli appears directly correlated with the difference between CL (the contact length between the membrane and the tube) and L0 (the membrane's length used for calculating E).

Fourth, this difference varies with the probe configuration. Thus, the monocell PMT fitted with polymer rings systematically gives moduli lower than those obtained with the tricell PMT (-16.6% in average). And the monocell probe fitted with metal rings gives moduli higher than those obtained with the tricell PMT (+5.5% in average).

These differences can significantly be reduced by adjusting L0 in order to better match CL. Using values that equal to CL measured at 200 kPa in a 76.2-mm steel tube would reduce the above differences to -8.1% and -2.9% respectively (table 3).

The above results apply for N probes fitted with a rubber membrane protected with steel strips, used in 76.2-mm tubes, and tested in stiff to very hard material (with E ranging from 12 to 140 MPa).

Additional tests were performed to estimate the effects of the stiffness and of the inner diameter of the test simulation tube. These tests have shown that CL would not be affected significantly by the stiffness variation of the TST but slightly more by its inner diameter.

It would be useful to validate and supplement the above results by conducting additional tests in softer simulation tubes, using other types of membranes, and ultimately in different types of soils.

Acknowledgement

We express our gratitude to Mr. Dmitry Olshansky from Toronto Transit Commission (Toronto, Canada), and Mr. Gabriel Sedran from In-Depth Geotechnical Inc. (Hamilton, Canada) for their help in the preparation of this paper.

References

[1] Hartman, J. P., "Finite Element Parametric Study of Vertical Strain Influence Factor and Pressuremeter Test to Estimate the Settlement of Footings in Sand. Ph.D. dissertation", Civil Engineering, University of Florida. 1974

[2] Briaud J.-L. "The pressuremeter". Balkema, Rotterdam, pp. 53-55, 1992

[3] ASTM (2020). "2020 Annual Book of ASTM Standards, Section 4: Construction", Vol. 04.08 : Soil and Rock (1) : D4719-20, www.astm.org

[4] Roctest, "Texam Companion" V.3.4, Copyright Roctest Limited, Saint-Lambert, Qc, 2018

[5] Roctest, "Pressio Companion" V.16.4, Copyright Roctest Limited, Saint-Lambert, Qc, 2018

[6] Marcil, L. Sedran, G., Failmezger, R. "Values of Pressuremeter Modulus and Limit Pressure Inferred from Stress or Strain Controlled PMT Testing" ISP7-Pressio 2015 pp. 173–179 Frikha, W., Varaksin, S., Gambin, M. (eds.) Soukra Ariana, Tunisia, 2015

[7] Roctest, "TEXAM Pressuremeter Instruction Manual", Roctest Ltd, E1001A-20150309, Saint-Lambert, Qc, P.15, 2015