Analysis of DMT Results and Comparison with Other In Situ Tests in a Sensitive Clay of Eastern Canada

Vincenzo Silvestri[1] and *Claudette* Tabib[2]

[1] *Professor, Polytechnique Montréal, Civil Engineering, Postal Box 6079, Station Centre-Ville, Montréal, Québec, Canada H3C 3A7*
[2]*Consultant, Polytechnique Montréal, Civil Engineering, Postal Box 6079, Station Centre-Ville, Montréal, Québec. Canada, H3C3A7*
[#]*Vincenzo Silvestri: vincenzo.silvestri@polymtl.ca*

ABSTRACT

This paper presents a re-evaluation of test results obtained from an extensive series of in-situ tests carried out in a lightly overconsolidated sensitive clay of eastern Canada. The geotechnical investigation involved self-boring pressuremeter tests (SBPMTs), flat dilatometer tests (DMTs), hydraulic fracture tests (HFTs), and vane shear tests (VSTs). The first surprising result is that the in-situ coefficient of lateral pressure at rest, K_0, deduced from DMTs, SBPMTs, and HFTs is much higher than expected. Second, the values of the overconsolidation ratio, *OCR*, computed from DMT data are also much higher than oedometer-deduced values. Third, undrained shear strengths obtained from SBPMT expansion curves are higher than both DMT- and VST- deduced values, with the latter tests yielding very similar results.

Keywords: flat dilatometer tests; K_0; overconsolidation ratio; undrained shear strength.

1. Introduction

The flat dilatometer test (DMT) was introduced by Marchetti (1975, 1979, 1980) as a new in-situ test. Marchetti (1980) combined the corrected pressures p_0 and p_1 with the pre-insertion pore water pressure u_0 and the effective overburden pressure, σ_{vo}', and proposed the following indices and modulus:

$$I_D = \text{Material index} = (p_1 - p_0)/(p_0 - u_0) \quad (1)$$

$$K_D = \text{Lateral stress index} = (p_0 - u_0)/\sigma_{vo}' \quad (2)$$

$$E_D = \text{Dilatometer modulus} = 34.7(p_1 - p_0) \quad (3)$$

The Lateral stress index is of major importance in clays for it allows estimation of a) the in-situ coefficient of lateral pressure at rest, K_0, from the expression

$$K_0 = (K_D / \beta_k)^{0.47} - 0.6 \quad (4)$$

with $\beta_k = 1.5$; b) the overconsolidation ratio, *OCR*, from the relation

$$OCR = (0.5\, K_D)^{1.56} \quad (5)$$

and c) the undrained shear strength, S_u, on the basis of the SHANSEP approach (Ladd and Foott 1974), leading to

$$S_u = 0.22\,(0.5\, K_D)^{1.25} \quad (6)$$

The SHANSEP approach applies to insensitive clays that are either normally consolidated or have been rendered overconsolidated by unloading, but are neither cemented nor sensitive (Ladd and Foot 1974; Marchetti 1979, 1980; Marchetti et al. 2001).

Although *OCR* values predicted from Eq. 5 are greatly overestimated compared to oedometer-deduced values in the sensitive clays of eastern Canada (Silvestri and Tabib 2015, 2016), undrained shear strengths computed from Eq. 6, which follows directly from Eq. 5, are nevertheless quite similar to field vane results (Lutenegger and co-workers 1986, 1988, 1990, 2006, 2015; Silvestri and Tabib 2015, 2016; Silvestri 2018). A better agreement between oedometer-deduced *OCR* values and DMT predictions in the sensitive clays of eastern Canada was obtained from the expression (Lunne et al. 1989, 1990)

$$OCR = \delta_k\,(K_D)^{1.17} \quad (7)$$

with δ_k = 0.35-0.45. Moreover, in spite of the observations that K_o values predicted from Eq. 4 with β_k = 1.5 compare well with values found from SBPMT lift-off pressures and HFT closure pressures (Silvestri and Tabib 2015, 2016), the computed exceptionally high values are difficult to explain in these lightly overconsolidated cemented clays (Lefebvre et al. 1981, 1991; Hamouche 1995; Hamouche et al. 1995). In addition, the data reported in Fig. 4 show that K_0 values obtained from the expression (Mayne and Kulhawy 1982, 1990)

$$K_0 = (1 - \sin\phi') \, OCR^{\sin\phi'} \tag{8}$$

where the *OCR* corresponds to the oedometer-deduced value and ϕ' is the effective friction angle of the normally consolidated clay, which equals approximately 30° for the sensitive Champlain Sea clays, are much lower than those deduced from both SBPMTs and HFTs. Hammouche et al. (1995) also found that a better agreement was obtained by replacing the exponent $\sin\phi'$ by *0.98*. This result also agrees with the value of *0.95* found by Lefebvre et al. (1991) from a series of HFTs in five Champlain Sea clays.

This notwithstanding, Mayne and Kulhawy (1990) found that Eq. 8 yielded good predictions in a large number of either sensitive or insensitive clay deposits, even though the best results were obtained in clays that had been overconsolidated by unloading. In addition, Lunne et al. (1989, 1990) indicated that accurate K_0 values in young soft clays could be determined from the expression

$$K_0 = 0.34 \, (K_D)^{0.54} \tag{9}$$

However, this equation gives results quite similar to those obtained from Eq. 8.

The contradictory results reported in the literature for K_0, *OCR*, and S_u predictions in the sensitive clays of eastern Canada, and as well as the exceptionally high K_o values found by Jefferies et al. (1987) in the Beauport Sea clays, incited the authors to carry out a re-evaluation of the data obtained by Hamouche (1995) by means of DMTs, SBPMTs, HFTs, and VSTs at the experimental site of Louiseville (Quebec).

2. Field test results

As detailed test results obtained by Hamouche (1995) may be found in a number of publications (see, for instance, Hamouche et al. 1995; Silvestri 2003, 2018; Silvestri and Tabib 2015, 2016), the present section summarizes briefly the findings.

The soil profile at the experimental site of Louiseville (Quebec) consists of a 60m thick deposit of sensitive Champlain Sea clay of average plasticity index of 45% and a natural moisture content slowly decreasing with depth, from 90% at 2 m to 65% at 14 m. The field vane undrained shear strength increases linearly with depth, from 20 kPa at 1.8 m to 55 kPa at 14 m. The overconsolidation ratio decreases from 5.6 below the 1.7 m thick oxidized crust to 2.4 at 14 m.

2.1. DMT pressures and indices

DMT pressures p_o and p_1 are compared in Fig.1a with effective overburden pressure σ_{vo}' and pre-insertion pore water pressure u_0. Computed values of I_D and K_D are shown in Figs. 1b and 1c, respectively. Figure 2 presents a comparison between K_0 values deduced from SBPMT lift-off pressures and HFT closure pressures, and those computed from Eq. 4. It appears that Eq. 4 with $\beta_k = 1.5$ provides a satisfactory agreement with SBPMT and HFT - deduced values. Figure 3 compares the *OCR* determined from oedometer tests with corresponding values found from Eqs. 5 and 7. While Eq. 7 with $\delta_k = 0.35$ provides an excellent agreement with oedometer- deduced values, those based upon Eq. 5 result in a severe overestimation.

2.2. Undrained strengths and limit pressures

Undrained shear strengths were determined using the data obtained from SBPMTs, DMTs, and VSTs. The results are reported in Fig. 4. Examination of the data shown in this figure indicates that SBPMT-deduced values are much higher than those found from VSTs. The SBPMT-deduced values were obtained from the constant slopes of the radial pressure-tangential strain expansion curves in the SBPMTs, following the procedure suggested by Marsland and Wroth (1977). As for the DMTs, Fig. 4 indicates that the values of S_u are practically equivalent to those deduced from the vane shear tests.

DMT pressures p_0 and p_1 are compared in Fig. 5, first, with both the lift-off pressure p_{oh} and the maximum radial pressure p_l reached in the SBPMTs and, second, to the theoretical limit expansion pressure p_L reached in the expansion of a cylindrical cavity in an ideally elastic perfectly plastic material. The theoretical limit pressure p_L, which is reached at an Almansi strain of 50%, was found from the expression (Gibson and Anderson 1961)

$$p_L = p_{oh} + S_u \, (1 + G/S_u) \tag{10}$$

where p_{oh} is the lift-off pressure and G is the shear modulus found from the pressuremeter tests. Concerning the experimental maximum radial pressures reached in the pressuremeter tests, the Almansi tangential strain at failure ranged between 8% and 10%, as reported by Silvestri and Tabib (2016) and Silvestri (2003).

3. Discussion of test results

3.1. Coefficient of lateral pressure at rest, K_0

Examination of the results reported in Fig. 2 indicates that K_0 values computed from Eq. 4 with $\beta_k = 1.5$ compare well with SBPMT and HFT - deduced values. Values predicted from Eq. 8 which are also shown in Fig. 2 clearly indicate that this equation fails to give reasonable results in this sensitive clay. The results obtained from Marchetti's Eq. 4 are rather surprising since this relationship was thought to apply only to normally consolidated clays and overconsolidated clays for which overconsolidation is caused by unloading. As the overconsolidation of the sensitive clays of eastern Canada is also due to cementation bonding and delayed consolidation (Silvestri 1980; Hamouche et al.1995), it appears that Eq. 4 might have a wider application.

In addition, although predictions shown in Fig. 2, based upon Eq. 8 are less representative of the lateral geostatic stresses found in the sensitive clays of eastern

Canada, this equation was found to yield reasonable estimates of K_0 in a large number of clay deposits (Mayne and Kulhawy 1982, 1990). Indeed, a review of data summarized by these authors for 56 different clay sites tested by means of the self-boring pressuremeter demonstrated that although the stress history was a predominant factor, the development of the lateral stress might have also included, for example, geologic origin, mineralogy, pre-shearing, cementation, and delayed consolidation. Concerning the exceptionally high K_0 values reported by Jefferies et al. (1987) in the Beaufort Sea clays, Mesri and Hayat (1993) attributed the cause to post-depositional folding and shearing deformation, and showed that Eq. 8 was not applicable in that case. However, as overconsolidation for the Louiseville clay is in part due to unloading and cementation bonding (Hamouche et al. 1995), it was expected that Eq. 8 would give reasonable K_0 estimates. But it appears at first sight that this is not the case. Let us examine in detail the field tests.

3.1.1. Hydraulic fracture tests

Consider first the HFTs. There exist contradictory opinions on the use of such tests for the indirect determination of in-situ K_0. For instance, Jamiolkowski et al. (1985) indicated that such tests are hampered by several difficulties and that the method may actually be restricted to K_0 values less than one, as suggested by Bjerrum and Andersen (1972). On the other hand, Lefebvre et al. (1981, 1991) indicated that such tests may be used in clay deposits characterized by K_0 values greater than one, provided that the piezometers used are characterized by a length-to-diameter ratio, *L/D*, greater than 6 to 8. As the *L/D* ratio of the piezometer used at Louiseville was equal to 11.5, HFTs should give accurate results. However, as the insertion of the piezometer probe is similar to the penetration of full-displacement pressuremeters, which are known to induce either a plastic state or destructuration in soft clays (Campanella et al. 1985; Mayne 1987; Mesri and Hayat 1993; Lutenegger and co-workers 1986, 1988, 1990, 2006,2015; Robertson et al.1988), it is difficult to imagine that such tests would give reasonable estimates of lateral pressures in these soils. Indeed, cracks and fractures may develop in the radial direction following the insertion of the piezometers when the effective tangential stress becomes zero for uncemented clays or equal to the negative value of the tensile strength of cemented clays (Marchi et al. 2014; Mitchell and Soga 2005). Macroscopically, the failure mode for fracture initiation is considered to be either tensile failure (Andersen et al. 1994; Bjerrum and Andersen 1972) or shear failure (Mori and Tamura 1987; Atkinson et al.1994).

3.1.2. DMT results

Concerning now DMTs in sensitive clays, it has been postulated that the insertion of the dilatometer blade might cause partial destructuration of the soil and expansion of a vertical cavity, inducing failure of the clay and causing an increase in deduced K_0 values during installation of the probe (Campanella et al. 1985; Mesri and Hayat 1993; Lutenegger and co-workers 1986, 1988, 1990, 2006; Robertson et al. 1988).

In view of conflicting results reported in Fig. 2, the present authors believe that reasonable estimates of K_0 values in the sensitive clays of eastern Canada still elude geotechnical science and that additional studies are needed for a better understanding of the physico-chemical mechanisms responsible for the development of lateral geostatic stresses in such soils.

3.2. Overconsolidation ratio, *OCR*

Examination of the data reported in Fig.3 shows two important observations: first, predictions based on Eq. 5 are too high compared to oedometer-deduced values and, second, predictions made using the relationship proposed for young soft clays by Lunne et al. (1989, 1990) with δ_k = 0.35 provide a satisfactory agreement with laboratory-deduced values. The reason for the high *OCR* values computed from Eq. 5 is due to the corresponding high values of the Lateral stress index shown in Fig.1c. This particular behaviour, which was shown several years ago by Marchetti (1979) in the case of the cemented Santa Barbara clay, is also caused by cementation bonding in the case of the sensitive Louiseville clay.

As a consequence, *OCR* values predicted by means of Eq. 5 are unreasonably high and should be regarded as "extended" values (Marchetti 1979, 1997).

3.3. Undrained shear strength, S_u

S_u values predicted from Eq. 6 agree extremely well with field vane values, as shown in Fig. 4, even though the OCR values, which are based upon Eq. 5, are largely overpredicted. According to Marchetti (1997), the original expression proposed in 1980 was generally confirmed for many soft clays, including sensitive clays (Lacasse and Lunne 1988). The reason for such an apparent contradiction lies in the choice of the value of *0.22* retained by Marchetti (1980) for the stress ratio $(S_u/\sigma_{vo}')_{nc}$, where the subscripts "*nc*" refer to the clay in the normally consolidated state. Thus, by combining such a low value for the stress ratio with the high *OCR* values given by Eq. 5 results in S_u values that are practically equivalent to field vane results. The latter are also approximately equal to $0.3\sigma_p'$, where σ_p' is the preconsolidation pressure (Bjerrum 1973; Mesri 1975, 1989; Mesri and Wang 2017). For instance, as K_D = 9.19 at a depth of 3.05 m in Fig. 1c, application of Eq. 6 yields S_u = 28.5 kPa compared to $S_u = 0.3\sigma_p'$ = 29.5 kPa for σ_p'= 98.4 kPa.

As a consequence, the agreement between DMT- and VST-deduced values is purely accidental. It should be also recalled that the field vane S_u must be corrected for anisotropy and time effects, as shown by Bjerrum (1973). In addition, the undrained shear strength, S_u, based upon the expression $0.22\sigma_p'$ (Mesri 1975, 1989; Mesri and Wang 2017) refers to the minimum value mobilized in the field for the design of fills and footings in soft clays and should not be compared directly to uncorrected field vane-deduced values.

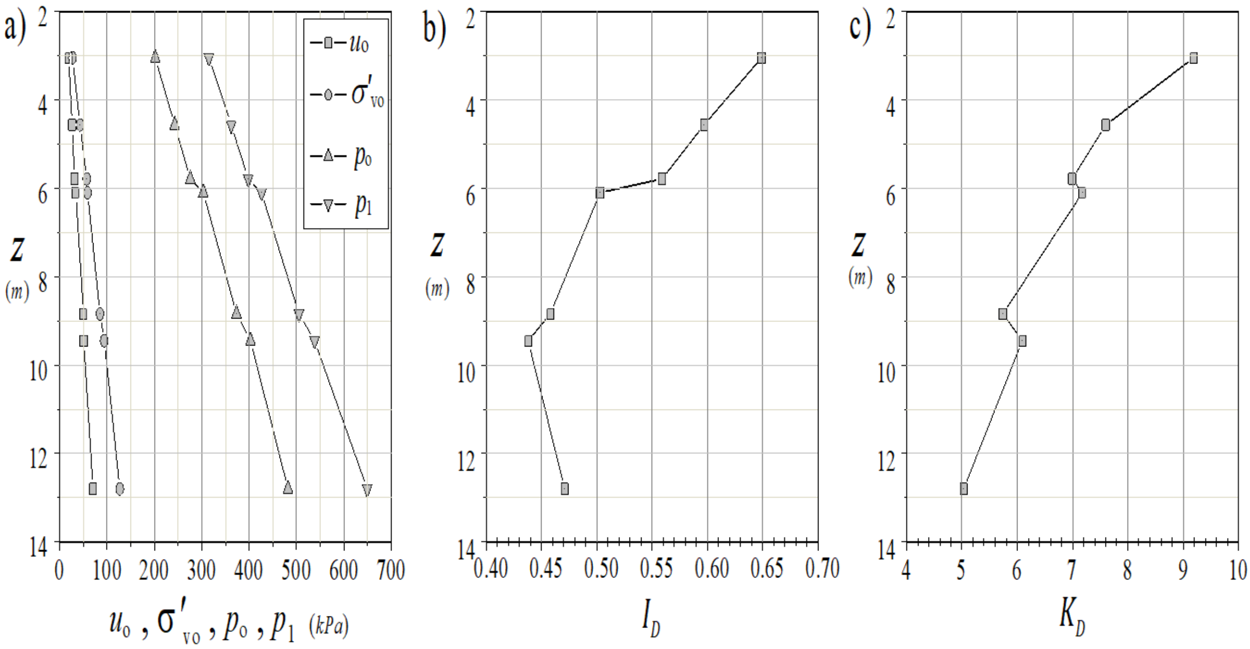

Figure 1. DMT results.

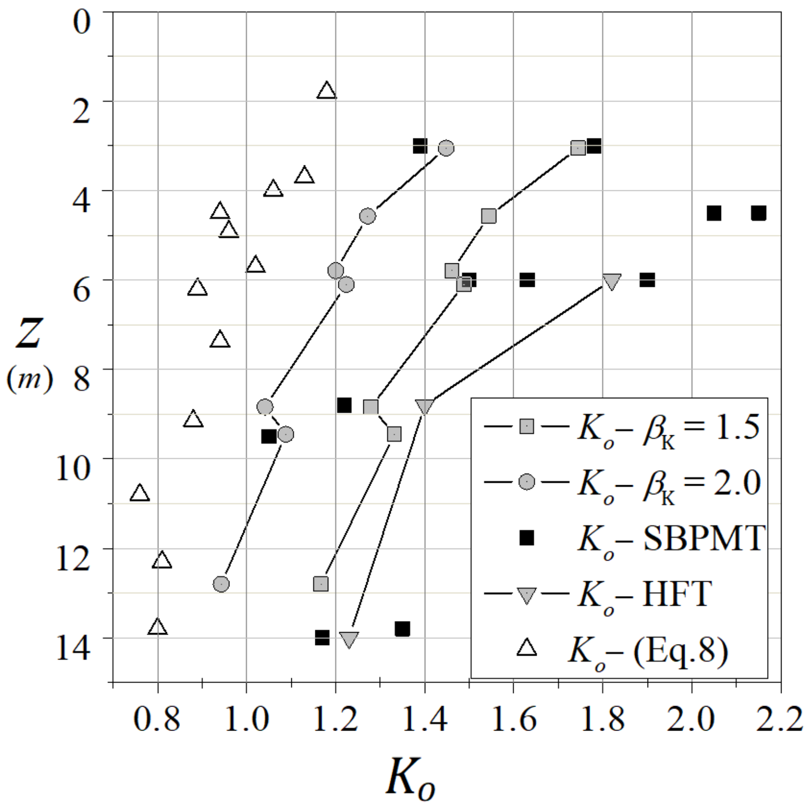

Figure 2. K_o correlations.

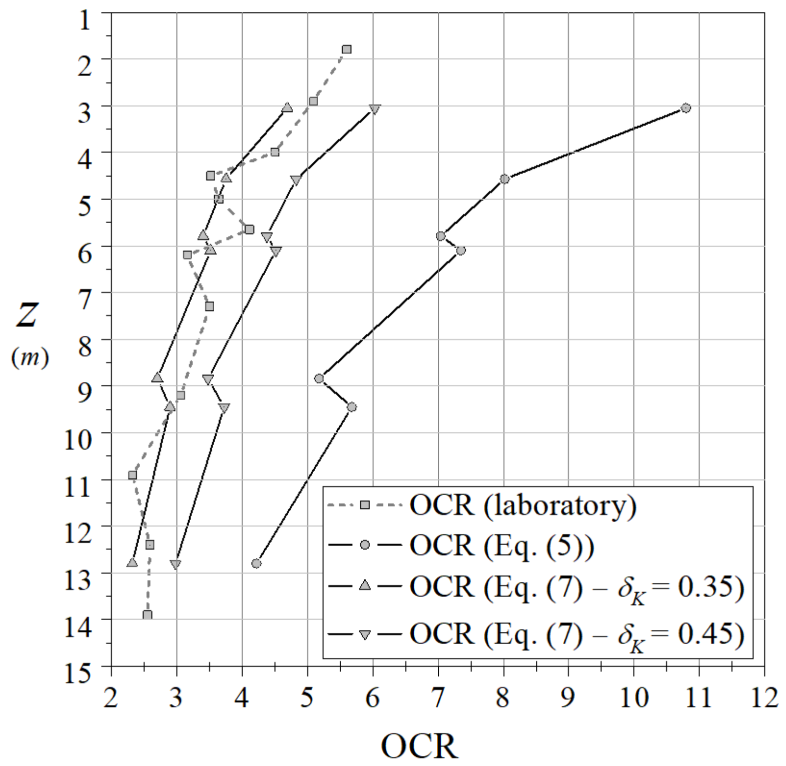

Figure 3. *OCR* correlations.

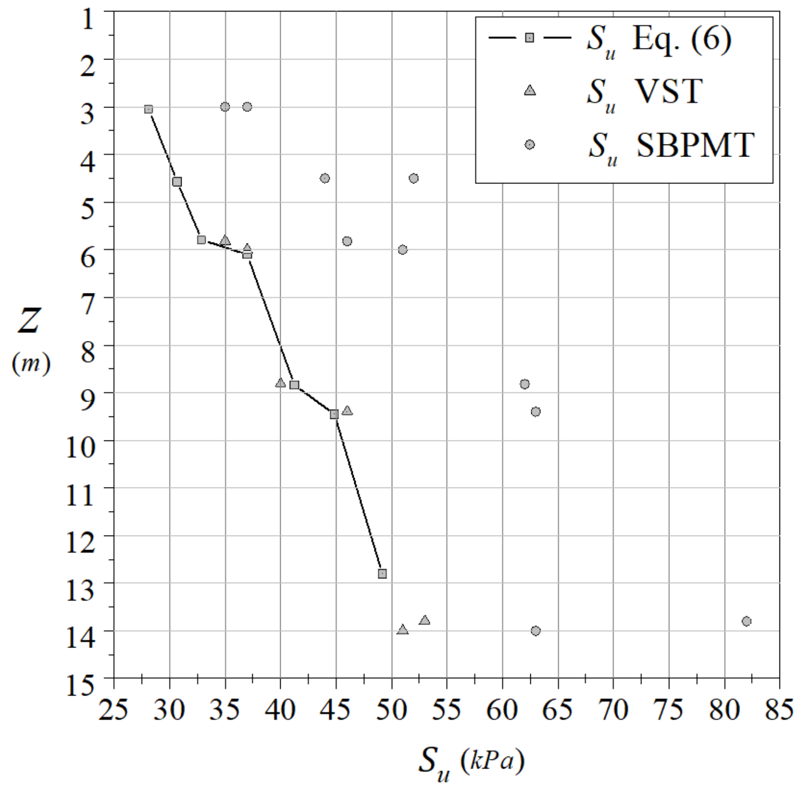

Figure 4. S_u correlations.

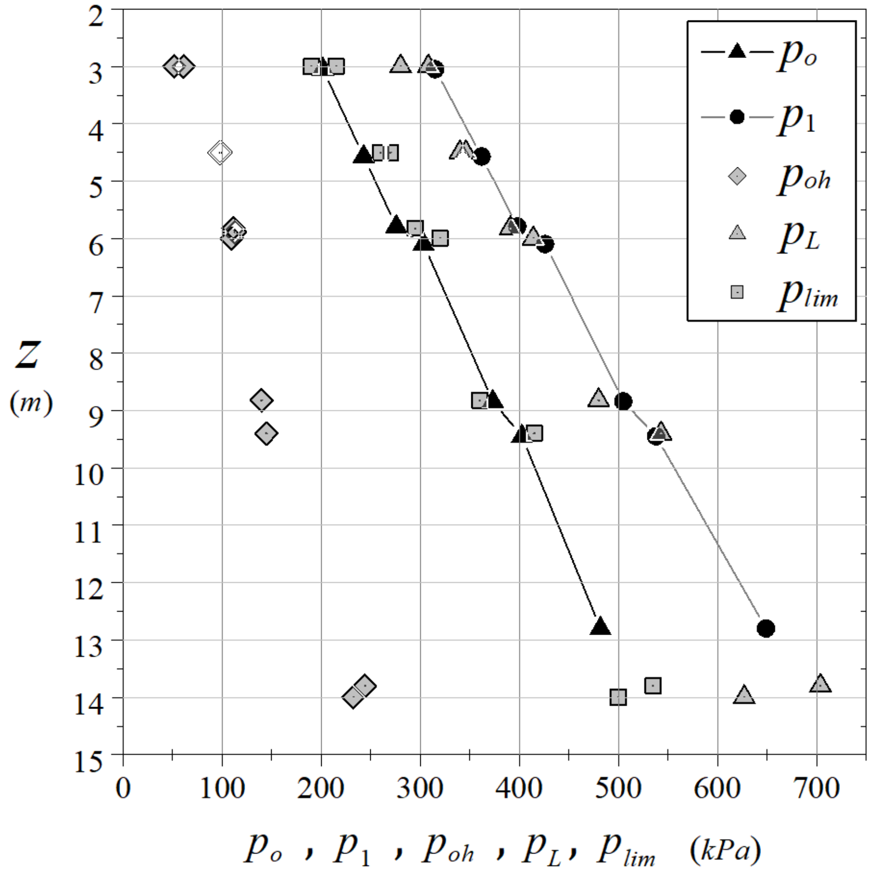

Figure 5. DMT pressures p_o and p_1 versus SBPMT pressures p_L and p_{lim}.

3.4. DMT and SBPMT pressures

Concerning the data reported in Fig. 5, Silvestri and Tabib (2015) presented a comparison between experimental radial pressure-tangential strain expansion curves obtained in the SBPMTs and theoretical relationships found by assuming that the sensitive clay obeyed the Modified Cam Clay Model. In the majority of the SBPMTs, the Almansi tangential strain at failure was reached at about 10%, while the theoretical Almansi tangential strain at failure is equal to 50%. As a result, the theoretical ultimate pressure p_L which corresponds to the value given by Eq. 10 is much higher than the pressure p_l which corresponds to a strain of 10%. As for the pressures p_0, their high values which are found to be approximately equal to the maximum radial pressures reached in the pressuremeter tests result from the computed high K_D values.

The results shown in Fig. 5 are extremely important because other investigators (see, for instance, Lutenegger and Blanchard 1990) found that the pressure p_0 is nearly identical to the initial penetration pressure measured from full-displacement probes. These investigators also found that the limiting pressure obtained from a full-displacement pressuremeter, which is inserted in a manner similar to the dilatometer blade, is more accurately predicted by the DMT pressure p_1 than pressure p_0 in soft to medium stiff clays. Moreover, Lutenegger (2006) showed that a simple cylindrical expansion model could be used to predict the undrained shear strength of soft clays using the values of both the pressure p_0 and the re-contact pressure p_2 which is measured when the probe is deflated.

4. Conclusions

The following conclusions are drawn on the basis of the contents of the present paper:

a) K_0 values deduced from DMTs, SBPMTs, and HFTs are very consistent. The values are much higher than expected, based upon the relationship, $K_0 = (1- \sin\phi') \, OCR^{\sin\phi'}$. The causes of such very high K_0 values are thought to stem from the overconsolidated nature of the sensitive clay which results from cementation bonding, delayed consolidation, and unloading.

b) Overconsolidation ratios predicted from application of the original DMT relationship were found to be extremely high. Better agreement is obtained using a more recent expression which applies to young soft clays. The cause of the very high values of the *OCR* deduced from Marchetti's original relation is possibly linked to the cemented nature of the clay.

c) The undrained shear strengths deduced from SBPMTs are too high compared with both VST and DMT data. While differences between SBPMT and VST results have been known for many years, the agreement between DMT-deduced values and vane shear test results is surprising and possibly fortuitous.

d) SBPMT- observed radial failure pressures p_l and theoretical limit pressures p_L are essentially equal to DMT pressures p_o and p_1. Such a response is linked to the large deformations induced by the insertion of the dilatometer blade.

Acknowledgements

The authors express their gratitude to Polytechnique Montréal for the financial support received in the course of the present study.

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