Dilatometer Tests in Sensitive Champlain Sea Clay: Stress History and Shear Strength

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ABSTRACT: Dilatometer tests were conducted at nine sites in northern New York and southern Ontario in Champlain Sea clay with sensitivity ranging from about 10 to 500. The results are compared with laboratory one-dimensional consolidation tests on undisturbed samples performed to evaluate the stress history (OCR) and overconsolidation difference (OCD = $\sigma'_p - \sigma'_{vo}$) and field vane tests performed to evaluate the undrained shear strength. Results from the sites are shown collectively to develop specific correlations for these deposits and are compared with other previously reported results in sensitive clays and with reported correlations between DMT results and reference stress history and shear strength results. The results show strong trends with several DMT pressure readings and provide the possibility of obtaining redundant estimates of stress history. Undrained shear strength from field vane tests also show good comparison with DMT results.

1 INTRODUCTION

The Marchetti Flat Dilatometer (DMT) has gained popularity within the geotechnical profession for in situ evaluation of geotechnical parameters of soils. This may be partly in view of the fact that the test equipment has proven to be rugged and easy to operate and the test may be conducted in a wide range of materials; from very soft clays and waste materials to dense sands. However, this may also be attributed to the surprisingly good accuracy with which the test is capable of predicting certain pertinent soil parameters and more importantly, field performance of full-scale structures.

Like all in situ tests, the DMT may have limitations to its breadth of applicability. In this paper the applicability of the test in sensitive marine clays in North America was evaluated. These soils may present special problems for any in situ test because of the high sensitivity which they may exhibit and the structural dependence of measured engineering parameters. Unlike unstructured or rather soils which possess massive structure and therefore lend themselves to normalized behavior, sensitive clays may undergo dramatic changes in structure during testing, which in turn leads to unique behavior. These behavioral problems are well documented for the sensitive Champlain clays of southern Canada, and need not be elaborated on here.

The purpose of the work described herein was to determine the degree to which the DMT could be successfully used in Champlain clay deposits to provide meaningful results of basic soil engineering parameters of interest to engineers, i.e., stress history and undrained shear strength. Field tests were conducted at five test sites in northern New York along the St. Lawrence River and at four sites in southern Ontario. Samples were obtained at each of the New York sites to provide a laboratory data base for comparing field test results. Results from the sites investigated in Canada were compared with field and laboratory data available in the literature for each of the sites. Previous DMT tests conducted in Leda clay were presented by Tanaka & Bauer (1998) who investigated the upper stiff fissured clay at a single site in Ontario.

The results of the work indicate that the current empirical correlations used for data reduction do not give satisfactory predictions of stress history. Suggestions are made for alternative techniques to evaluate data.

2 TEST SITES

The invasion of the Late-Pleistocene Champlain Sea into the St. Lawrence River Valley left deposits of clay along both sides of the river and accounted for a large majority of the surficial materials in the St. Lawrence lowlands of northern New York. In New York, four of the sites investigated are located in the general area around the village of Massena, NY while the fifth is located near the village of Ogdensburg, NY. The sites in Canada are located in the St. Lawrence lowlands from Gloucester, near Ottawa, Ontario to Louiseville in Quebec. These sites have been extensively investigated previously by other researchers in Canada. Only a brief description of each of the test sites and geotechnical conditions will be presented.

2.1 *Northern New York Sites*

The sites in northern New York are considered typical of Champlain clay in the region and show the diversity of geotechnical properties of the materials. Four of the five New York sites have a weathered surficial crust which is overconsolidated, presumably as a result of desiccation or freeze-thaw. Conventional test borings were conducted at each of the sites and traditional soil parameters were determined from undisturbed (76 mm dia. piston) and disturbed samples.

2.1.1 *Massena High School (MHS)*

The site is located along N.Y. State Route 37, directly across from the Massena High School. Test borings indicate about 1 m of very stiff brown silty clay, 3 m of stiff gray-brown mottled silty clay overlying about 9 m of soft gray and bluish-gray clay. These cohesive materials overlie glacial materials, primarily sand and gravelly till. An overconsolidated crust extends to a depth of about 5 m. While the ground water level at the time of field investigations varied from 1 to 2 m below the surface, larger fluctuations have apparently occurred during the past. The undrained shear strength, measured from Nilcon field vane generally show a decrease in undrained strength with depth.

2.1.2 *Racquette River Cemetery (RRC)*

This site is located about 2 km south of the Massena airport adjacent to the Racquette River. Numerous small landslides have occurred near the site in the past. Test borings and DMT tests were conducted in a stable upland landscape position, however the site drops off rapidly about 15 m toward the river which is located about 80 m away. The site is capped by about 2 m of loose to medium dense mixed silty sand which overlies the marine clay. The clay extends to a depth of about 12 m and is underlain by coarse glacial sediments. It appears that because of the close proximity of the Racquette River, and the rapid change in slope, the groundwater at the site has been depressed in the past throughout the thickness of the marine clay. During investigations, the groundwater level was about 3 m below the ground surface. In general, the entire profile of marine clay is overconsolidated as indicated by oedometer tests.

2.1.3 *St. Lawrence Seaway (SLS)*

This site is located about 1 km north of the Snell Lock on the St. Lawrence Seaway. The upper 1.5 m contains highly stratified clay and sand seams overlying the marine clay. The clays at this site only extend down to a depth of about 10 m and are again underlain by gravelly glacial materials. A thin sand seam containing abundant shells is present at about 5 m throughout the site. The groundwater level encountered during field investigations was consistently at a depth of 0.4 m and appears to represent static conditions.

2.1.4 *Industrial Development Agency (IDA)*

This site, located about 2 km south of the Racquette River, directly south of Massena appears to be more characteristic of the classical Champlain clay deposits described in Ontario and Quebec. The site is located in a broad lowland position between glacial uplands and is capped by 1.5 m of loose fine sand. The marine clay has been investigated by in situ tests down to a depth of about 25 m. The groundwater throughout the year is located about 0.3 m above the ground surface and only fluctuates to a depth of about 0.3 m below the surface. This site generally shows the highest sensitivities and lowest undrained strengths measured by the field vane than any of the five N.Y. sites. The characteristics at this site appear to be most similar to the sensitive Leda clays in Canada.

2.1.5 *Ogdensburg (OGB)*

This site is located adjacent to Route 37 just north of the village of Ogdensburg. The site is adjacent to a railroad overpass which has experienced considerable movement in the past 20 years. The soils consist of very stiff brown and gray brown silty clays which extend to a depth of about 3 m. These materials are underlain by gray and blue gray silty clays to a depth of 19 m.

2.2 *Canada Sites*

The sites in Canada were selected as typical of Champlain Sea deposits in Ontario and Quebec. Each of the sites has previously been used and evaluated extensively in terms of the geotechnical characteristics. Published data from each of the sites were used in evaluating the results of DMT tests. DMT tests were performed at each of the sites by the author using the same equipment used at each of the New York sites.

2.2.1 *Gloucester, Ontario*

The location for tests near Gloucester, Ontario was near the site of the NRC test embankment. Because of site limitations near the test embankment, dilatometer tests were conducted about 500 m northwest of the embankment area. Site characteristics and geotechnical properties of marine clays at the location of the test embankment have been presented in detail elsewhere by others (e.g., Bozozuk & Leonards, 1972; Lo et al. 1976).

2.2.2 *St. Albans, Quebec*

The St. Albans site is about 80 km west of Quebec City. The clay extends to a depth of about 13 m and has a thin upper stiff crust of about 1.5 m thickness. The site has previously been used to investigate the failure of an embankment constructed on the soft sensitive clay (LaRochelle et al. 1974) and has also been used to investigate the behavior of driven piles in soft sensitive clay (Roy et al. 1981). Properties of the clay at the site have also been described by Tavenas et al. 1975.

2.2.3 *Berthierville, Quebec*

The Berthierville site is located between Quebec City and Montreal. Close to the surface, an upper layer of soft silty clay of about 3 to 5 m thickness is covered by a few meters of sand and is underlain by sand. This upper layer is the zone of clay investigated in the current work. The liquidity index is between 1.5 and 2. The site was previously used to evaluate in situ stress strain behavior under a small test embankment. Details on the site and the soil properties were presented by Kabbaj et al. 1988.

2.2.4 *Louiseville, Quebec*

The Louiseville site is located about 30 km east of Montreal. According to Leroueil et al. (1983) the site is typical of the clay deposits in the basin of the Champlain sea in this area. Site characteristics have been presented by Hamouche et al. (1995). DMT investigations at the site extended to a depth of 14 m.

3 STRESS HISTORY FROM DMT

Engineers are interested in evaluating the stress history of soils at a site for a variety of reasons; typically for estimating consolidation settlements but often for evaluating other soil parameters from stress history, e.g., undrained shear strength or in situ lateral stress. For the past thirty years the Dilatometer has proven to be a robust in situ tool for evaluating soil characteristics for wide range of soil deposits from very soft clays to very dense sands and generally for providing accurate estimates of a number of soil parameters.

In the initial presentation of the Dilatometer, Marchetti (1980) had proposed a simple empirical relationship for clays between the DMT Index K_D and OCR determined from oedometer tests of the form:

$$OCR = (0.5K_D)^{1.56}$$

The general form of this expression has been confirmed by others, e.g., Powell & Uglow 1973; Lacasse & Lunne 1988; Chang 1991; Kamei & Iwasaki 1995, but it appears that some local correlations using different constants provide a better fit to laboratory data.

The calculation of both OCR and K_D require an estimate of the in situ vertical effective stress, σ'_{vo}, at each test location which may be obtained from a measure (or estimate) of both the total unit weight of the soil and the in situ pore water pressure. Figure 1 shows the relationship between K_D and OCR for the nine sites investigated. The preconsolidation stress values at each site were interpreted from results of oedometer tests on undisturbed samples and unit weights were measured at each site.

The data in Fig. 1 show some scatter but in general they support a strong relationship between OCR and K_D as has been observed by others. The determination of K_D makes use of only one pressure measurement obtained from the DMT, the lift-off pressure, P_o, which is a total stress measurement. The empirical correlation suggested by Marchetti (1975) is shown in Fig. 1 for reference and it will be noted that this correlation tends to overpredict the OCR as compared to the laboratory database of these clays. Fig. 2 shows the same results of Fig. 1 but on a log-log scale.

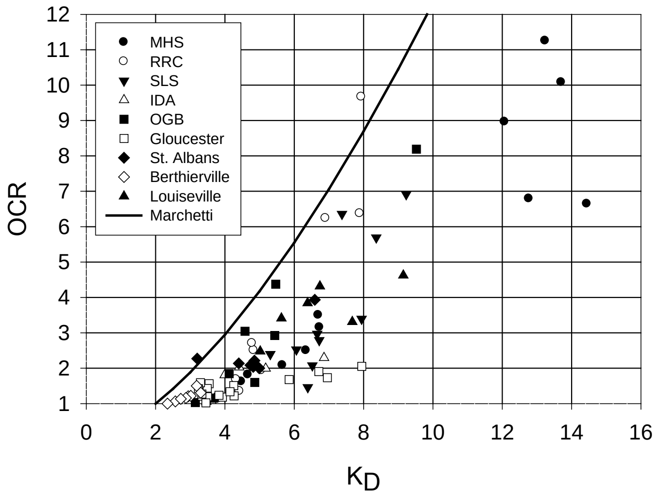

Fig. 1. Relationship between OCR and DMT K_D.

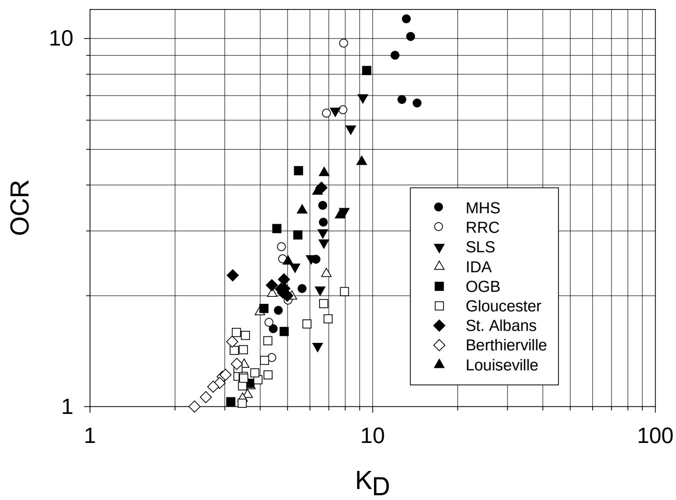

Fig. 2. Relationship between OCR and DMT K_D.

It has previously been shown (e.g., Mayne 2006) that in soft, near normally consolidated clays, the value of the DMT lift-off pressure, P_O, is dominated by excess porewater pressures; i.e., immediately after insertion of the DMT blade into soft clays the effective horizontal stress is very low. A measure of the approximate effective horizontal stress acting on the face of the blade after insertion may be obtained by using the recontact pressure, P_2, obtained after obtaining the 1 mm expansion pressure, P_1 in combination with the lift-off pressure, P_O. In this way, two of the DMT test pressure measurements are used and it is then possible to calculate the "Initial Lateral Stress Ratio", $K_i = (P_O - P_2)/\sigma'_{vo}$. DMT recontact pressures were obtained at eight of the nine sites but were not obtained during the testing at Gloucester. Fig. 3 shows the relationship between K_i and OCR at the eight sites.

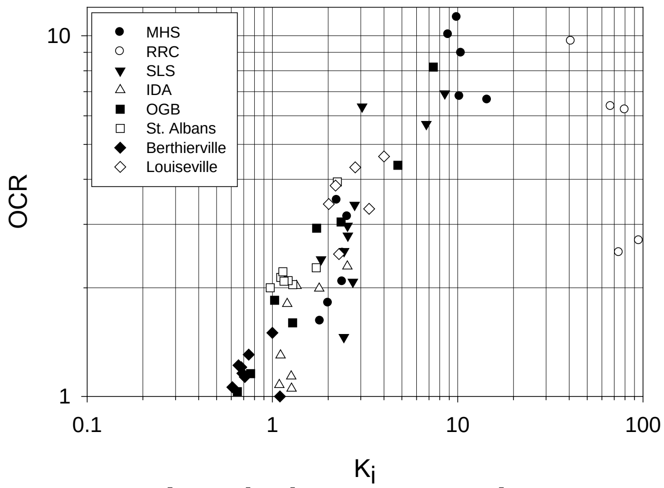

Fig. 3. Relationship between OCR and DMT K_i.

The general trend suggested by these results is very strong but it may be noted that five data points shown in Fig. 3 do not follow the general trend of the rest of the data. These points were all obtained at the same site in New York (RRC) in the upper fissured clay crust and where the DMT tests were performed above the water table in unsaturated conditions, as previously noted. Figure 3 provides an alternative approach to estimating the stress history which may be statistically stronger since it uses two DMT pressure measurements, but naturally suffers from the requirement of obtaining the recontact pressure P_2. The author is a strong advocate of obtaining the recontact pressure and has made this part of routine DMT practice for the past 25 years. The author suggests that OCR estimates be made by both methods for comparison and to identify possible errors in data. This is no different than using both the tip resistance and pore water pressure measurements from a piezocone to provide redundant estimates of OCR, e.g., Demers & Leroueil (2002).

A more direct comparison between the DMT pressure measurements and the interpreted vertical oedometer preconsolidation stress values may be made by comparing the net P_O value directly to the lab values of σ'_P. Fig. 4 presents results from the nine sites. Some of the scatter indicates in Fig. 4 may be related to assumptions related to values of the in situ pore water pressure at each test location.

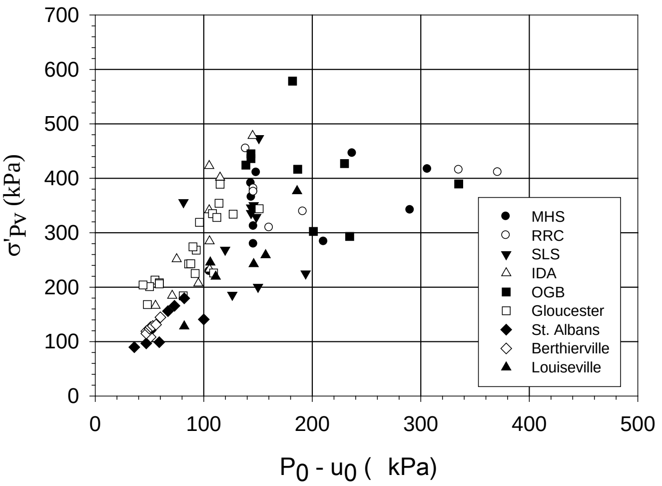

Fig. 4. Relationship between σ'_{PV} and $P_O - u_O$.

In similar fashion as was previously indicated (Fig. 3), it is possible to consider the relationship between laboratory values of σ'_P and the approximate horizontal effective stress using the recontact pressure P_2. These results are shown in Fig. 5. The advantage of this approach is that no assumptions regarding the initial in situ pore water pressure are required. It appears that for these clays there is less scatter in this approach as compared to Fig. 4.

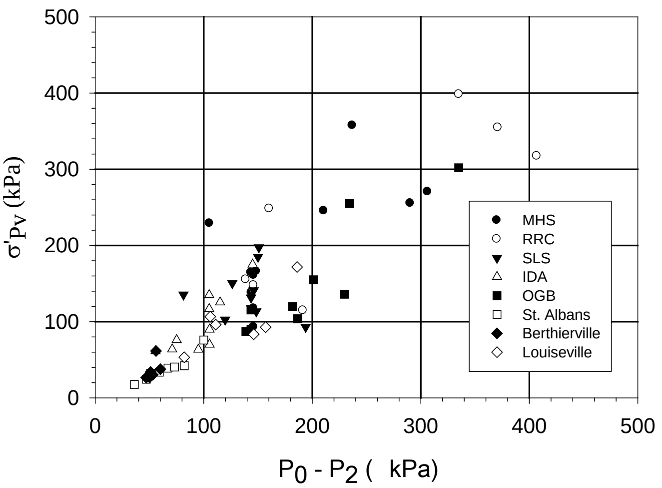

Fig. 5. Relationship between σ'_{PV} and $P_O - P_2$.

The insertion of a penetrating probe into soft and very soft clays represents a large strain problem and therefore is it logical to expect that the probe has created a failure in the soil immediately surrounding the blade. The preconsolidation stress is a yield point that separates small strain behavior from large strain behavior and therefor it is logical that the value of $P_O - P_2$ would provide a reasonable estimate of the vertical oedometric yield stress.

In clays it might also be argued that the DMT 1 mm expansion pressure could be used to estimate the preconsolidation stress, either in conjunction with the in situ pore water pressure or in conjunction with the lift-off pressure, P_O, since previous analyses have shown that P_1 may be used to estimate undrained shear strength in clays. Figures 6 and 7 show the trend in preconsolidation stress with net P_1 pressure and $P_1 - P_O$ and suggest reasonably good fits of the data.

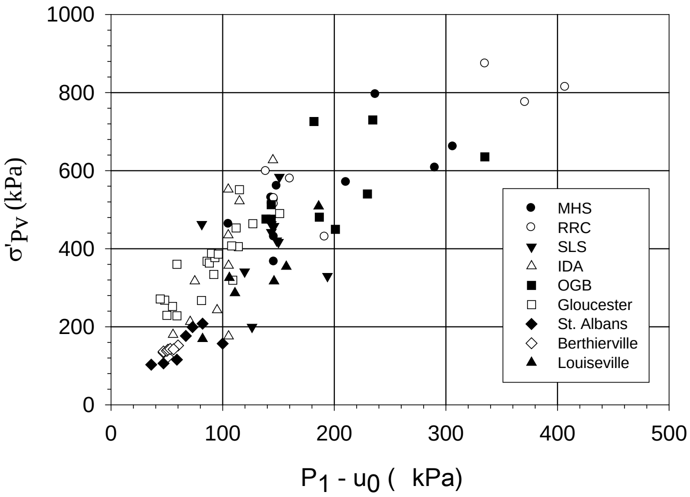

Fig. 6. Relationship between σ'_{PV} and $P_1 - u_O$.

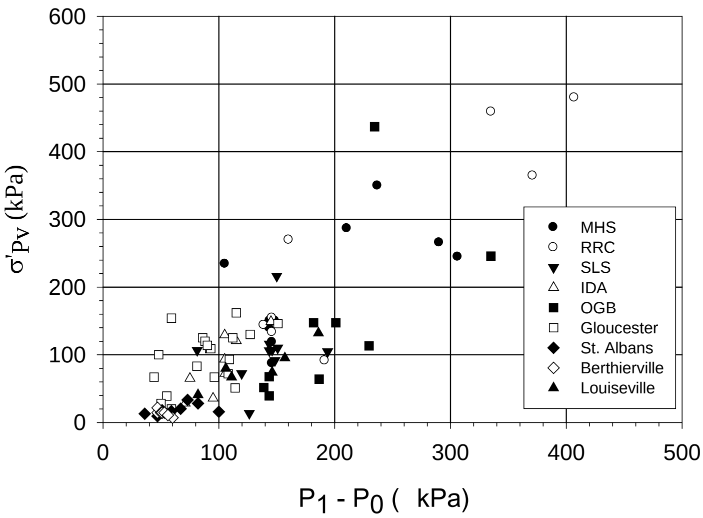

Fig. 7. Relationship between σ'_{PV} and $P_1 - P_O$.

All of the trends indicated in the previous figures appear to be independent of clay sensitivity. No correlations are presented for any of the previous data since the interest in the tests was to evaluate only trends in results in this deposit relative to other less unique clays.

Laboratory values of preconsolidation used in Figs. 1-5 were obtained by the traditional approach of trimming tube samples in the upright position so that the values represent the traditional vertical preconsolidation stress. The DMT measurements are obtained from soil which responds largely to stress conditions in the horizontal direction and so it may be of some interest to compare measurements with the horizontal yield stress. At the five New York sites oedometer tests were conducted on vertically trimmed specimens immediately adjacent to the horizontally trimmed specimens to give loading in the horizontal direction. While the stress field is not strictly correct for in situ stress conditions, the results of these tests provide a close approximation to the in situ horizontal yield conditions. Laboratory data on vertically trimmed specimens from the Canada sites were only available from St. Albans.

A comparison between $P_O - u_O$ and the horizontal yield stress (denoted with a subscript σ'ph) is shown in Fig. 8. Fig. 9 shows the variation in horizontal yield stress and $P_O - P_2$. These data show more scatter than trends with vertical preconsolidation stress which may be related to the natural structure in these deposits but may also be a result of the laboratory confinement conditions as compared to the field.

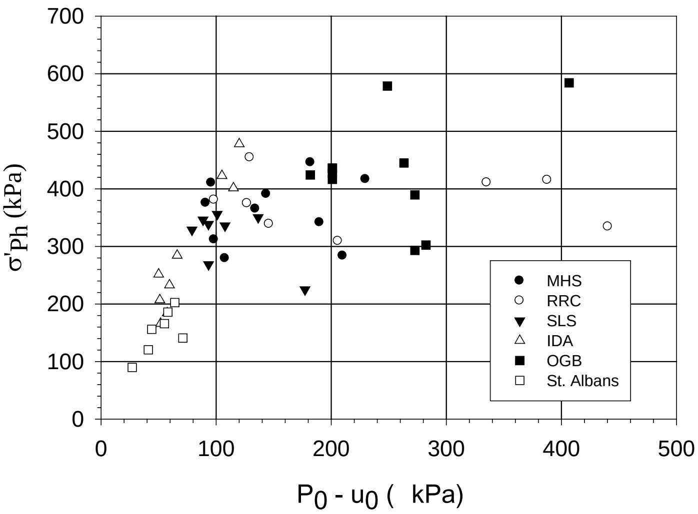

Fig. 8. Relationship between σ'_{Ph} and $P_1 - u_O$.

4 OVERCONSOLIDATION DIFFERENCE

Engineers may be interested in a more direct indication of the stress history through the Overconsolidation Difference (OCD), which is the absolute difference between the preconsolidation stress and the in situ vertical effective stress, i.e., $OCD = \sigma'_p - \sigma'_{vo}$. Of course in a true normally consolidated soil OCR = 1 and OCD = 0.

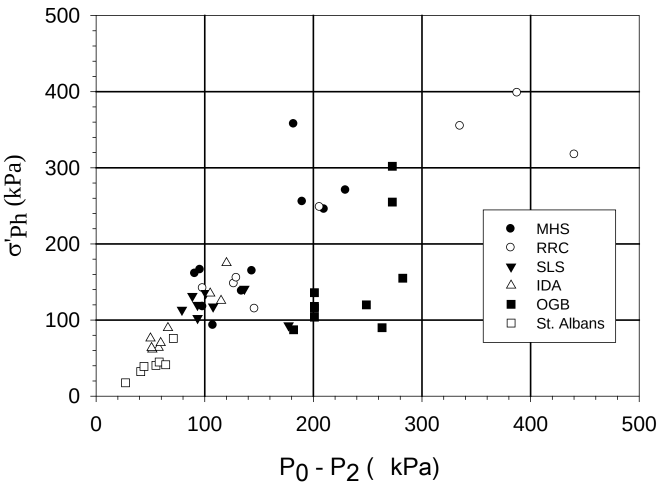

Fig. 9. Relationship between σ'_{Ph} and $P_1 - u_O$.

Since OCD depends on both the preconsolidation stress and the in situ stress, in overconsolidated soils it varies with both depth and degree of overconsolidation. The OCD allows the Engineer to quickly estimate the degree to which a soil may be loaded before large strain behavior, after the preconsolidation stress occurs. The DMT and oedometer results from the nine sites were evaluated to determine if a relationship could be established between OCD and DMT results.

Since at most of the sites the OCR decreases with depth through the upper overconsolidated zone into the lower near normally consolidated zone, the traditional approach to evaluating stress history previously illustrated has little logic, i.e., traditional stress history through either σ'_p or OCR has little merit. That is, one would not expect a relationship to exist between OCD and either P_O or K_D. On the other hand, it may be of interest to investigate whether any relationship exists between OCD and other measured values, such as the 1 mm expansion pressure. For example, Fig. 10 shows the observed trend between OCD and $P_1 - P_O$ while Fig. 11 shows the trend with normalized P_1-P_O. As can be seen, neither of these approaches provides a reliable means of estimating the OCD at these sites.

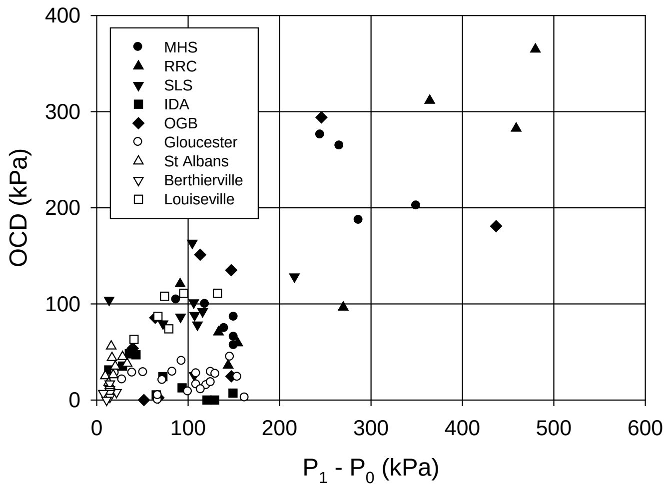

Fig. 10. Relationship between OCD and $P_1 - P_O$.

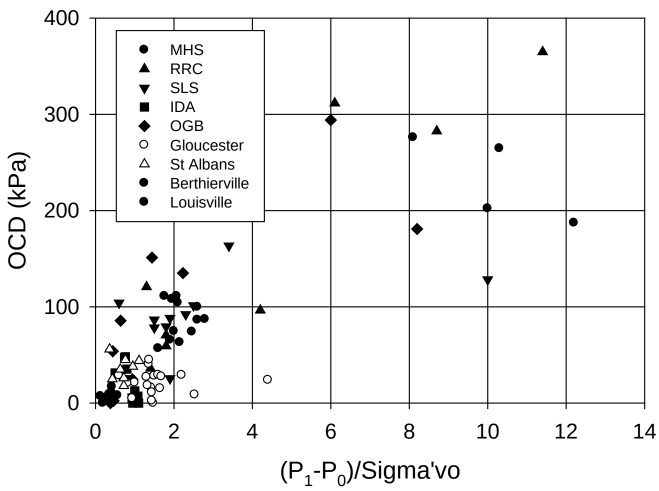

Fig. 11. Relationship between OCD and $(P_1 - P_O)/\sigma'_{vo}$.

5 UNDRAINED STRENGTH FROM DMT

Marchetti (1980) had also suggested that the DMT Horizontal Stress Index, K_D, could also be used to estimate the normalized undrained shear strength of clays. This approach has been verified by other researchers throughout the world, but as with stress history, it appears that there is a need to use local correlations for different deposits. Some of the variation in reported correlation between undrained strength and K_D may be related to the different reference tests used to establish values of s_u.

Fig. 12 shows the observed trend in normalized undrained shear strength for the five sites in New York in which reference values of s_u were obtained by the author using a Nilcon field vane test with the same vane and test procedure. In general these data also support the suggestion of Marchetti (1980) but show a slight difference between the upper more structured and fissured clays, indicated by higher values of K_D, and the lower more massive clay. The author (Lutenegger 2006) previously suggested an alternative approach using the difference $(P_O - P_2)$ and simple cavity expansion theory to estimate undrained shear strength which was shown to be applicable to these clay deposits.

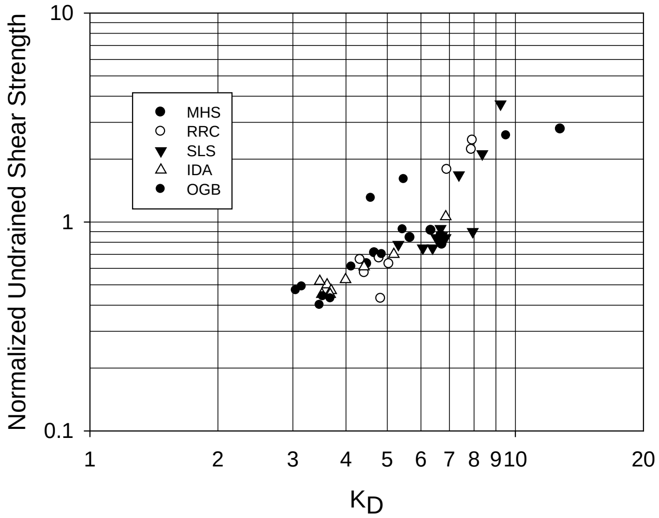

Fig. 12. Observed trend between s_u/σ'_{vo} and K_D.

6 CONCLUSIONS

Results of Dilatometer tests were compared with stress history from laboratory determined values of preconsolidation stress and OCR at a number of sites consisting of soft sensitive Champlain clay deposits in Northern New York and Southern Canada. The results show that redundant estimates of stress history are possible using the various DMT pressure readings, including the recontact pressure, P_2. The results show a slightly different relationship than was previously suggested by Marchetti (1980) but this is to be expected. The data still demonstrate that the DMT is a very useful tool for evaluating parameters of clays whose behavior ranges from insensitive to highly sensitive.

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