EVALUATION OF CONE PRESSUREMETER TESTS IN SOFT COHESIVE SOILS

by

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SYNOPSIS. A comparison is presented of data obtained using three types of pressuremeters at three different clay sites in the Lower Mainland of British Columbia. The factors affecting the results are considered in relation to instrument and soil characteristics. Methods for determining the undrained shear strength are evaluated. Finally, the rigidity index based on unload-reload cycles and vane shear strengths are compared to established modulus reduction curves.

INTRODUCTION

1. Of the many recent advances in equipment for use in in-situ testing of soils, the pressuremeter (PM) is generally considered to be the most promising for providing a rational basis for the interpretation of soil parameters for geotechnical design. Equipment design and characteristics have developed rapidly resulting in a variety of insertion methods and test procedures. Interpretation methods developed for one particular type of equipment are often applied to other situations where the initial assumptions of the method are invalidated by test conditions. This paper examines the application of methods derived for interpreting self-boring PM tests to the results of full-displacement PM data.

2. The PM test is carried out by expanding a cylindrical instrument radially against the soil and recording the pressure applied and the resulting expansion. Insertion of the pressuremeter may be effected by prebored (PBPM), self bored (SBPM) or full displacement (FDPM) methods. Methods of interpretation of the results obtained commonly rely on the assumption that the test models the expansion of an infinitely long cylindrical cavity in an isotropic homogeneous medium, for which a closed form solution exists. The test results are interpreted to give in-situ stress, stiffness and strength.

3. Little validation of the FDPM has yet been undertaken, particularly in cohesive soils. This paper presents and discusses results obtained in soft clays with a self-boring and two full-displacement pressuremeters as part of the in-situ testing research at the University of British Columbia (UBC). The SBPM tests at McDonald Farm were performed by Hughes (10). The equipment was on loan to UBC for subsequent tests. A cone

pressuremeter of 15 sq.cm cross sectional area was initially made available to UBC by Fugro B.V., Holland for preliminary evaluation. Subsequently, a seismic cone pressuremeter (SCPM) also 15 sq.cm was developed at UBC (8).

EQUIPMENT

4. The characteristics of the three pressuremeters used in this study are summarized in Table 1. The development of the seismic cone PM, SCPM, has been described by Campanella and Robertson (3). During penetration the SCPM allows the simultaneous measurement of cone bearing, sleeve friction, pore pressure at two locations, slope and temperature. During pauses in the penetration, the shear wave velocity can be evaluated using the downhole technique and a computer controlled PM expansion curve can be obtained.

5. The instrument supplied by Fugro B.V. was a prototype equipped with a solid steel conical tip instead of an instrumented cone. Further details on the characteristics of the instruments are given by Withers et al. (16) and Howie (8).

Table 1. Pressuremeter Characteristics

PM	Hughes PM (SBPM)	Fugro Cone PM (CPM)	Seismic Cone PM (SCPM)
Installation Method	Jetted-Self Boring	Full Displacement	Full Displacement
Diameter (mm)	74	43.7	44
L/D Ratio	6	10.3	5
Inflation Method	Gas from Surface	Gas from Surface	Downhole Pressure Developer - Oil
Strain Measurement	Strain Arms	Strain Arms	Strain Arms
Maximum Cavity Strain	20%	50%	27%
Additional Instrumentation	-	Dummy Cone	Seismic Piezocone

DETAILS OF TEST SITES

6. SCPM tests were performed at three soft clay sites in the Lower Mainland area of British Columbia, namely: McDonald Farm, Lulu Island Pile Research Site and Lower 232nd Street, Langley.

7. The McDonald Farm and Lulu Island sites are situated in the Fraser River Delta. The stratigraphy at McDonald Farm consists of approximately 2 m of soft compressible silts and clays underlain by about 13 m of fine to medium sand. After a 2 m transition zone the soil is a soft normally consolidated clayey silt which extends to great depth.

8. At Lulu Island a soft organic compressible peat grading to a clayey silt extends from the surface to approximately 15 m, being underlain by a fine to medium sand.

9. The third site is located in Langley where a typical profile consists of soft silty clay of medium plasticity to depths in excess of 30 m. At depths between 10 and 15 m the clay is interbedded with thin layers of silt and sand. As a result of desiccation the silty clay is overconsolidated at the surface becoming normally consolidated at approximately 5 m depth. Only data for the upper 15 m of this deposit are considered here.

10. Table 2 summarizes the relevant index parameters for the soils in which PM tests have been performed.

Table 2. Soil Properties

Site	McDonald Farm	Lulu Island	Langley (Lower Site)
Soil Description	Clayey Silt	Organic Clayey Silt	Glacio-marine Silty Clay
W_n %	35	69	45
LL %	35	64	40
PI %	11	21	19
S_t(FV)	5	11	7-10
OCR	1	1	1-6
$(S_u/\sigma_v')_{nc}$	0.33	0.4	0.26

FACTORS AFFECTING INTERPRETATION OF PM DATA

11. As with any other field or laboratory test method, the data obtained from PM testing are influenced by several factors. Of these, the most important and those over which the operator has some degree of control are

- the effects of disturbance caused by insertion;
- the period of relaxation allowed after insertion prior to conducting the expansion of the probe;
- test procedures;
- instrument characteristics.

All factors are interdependent to some extent.

Effects of Disturbance

12. Interpretation of PM tests in clay using analytical methods conventionally requires the assumption that all points in the deforming region follow a unique stress path, that the deformation is equivoluminal and that the initial stress state is isotropic in the horizontal plane. Conditions approximating these can be obtained by self-boring installation methods. The full-displacement method, however, results in large strains and a substantial pore pressure gradient around the installed probe. It has been suggested (16) that if the PM is capable of sufficiently large expansion, a condition can be

attained where the majority of the soil affected by expansion experiences stresses larger than those caused by insertion. If this were the case, it is possible that existing interpretation methods may be applicable to FDPM tests. This hypothesis requires verification.

13. Research performed at UBC and elsewhere indicates that the total stress measured during penetration is dominated by the pore pressures generated during full displacement installation (1,4,11,14). Furthermore, it also appears that total stress/pore pressure are dependent on the exact location of the measurement in relation to the cone shoulder (14). Soil type characteristics will further modify any initial stress/pore pressure distribution induced by undrained or partially drained penetration.

Effects of Relaxation

14. It follows from the above, that the FDPM lift-off pressure in clay will be dominated by pore pressures generated during insertion and their subsequent degree of dissipation during relaxation/consolidation. Lutenegger (11) has shown this to be true for the dilatometer (DMT) lift-off pressure (P_0). The contribution of pore pressure to P_0 was shown to be dependent on the stress history of the clay.

15. The effect of variations in relaxation time on lift-off pressure was examined at the Lulu Island site with the SCPM. Quick tests were performed 1.5 minutes after insertion while similar tests were performed with relaxation times varying between 7 and 13 minutes. As would be expected, the lift-off pressure decreases as the relaxation time increases. For the time periods used, an average reduction of 15% in lift-off pressure was measured. The steeper pressure expansion curves and higher limit pressures for the tests with longer relaxation periods suggest the importance of consolidation on measured data. Since the effect of a given relaxation time will vary with soil characteristics and probe diameter, it is not possible to select a "standard" relaxation period in order to achieve a consistent degree of consolidation prior to expansion.

16. Cavity expansion theory suggests that the PM pressure-displacement curve is a function of both soil stiffness and shear strength, i.e., of both elastic and plastic properties. Clarke and Wroth (5) suggested that the DMT pressure-displacement relationship would be similar to that for expansion of a FDPM and found that a relationship existed between ($P_1 - P_0$) and ($P_L - \sigma_h$) where P_L is the SBPM limit pressure and σ_h is the total horizontal stress. Campanella and Robertson (4) confirmed the similarity between expansion curves obtained with the SBPM, SCPM and DMT and indicated the importance of pore pressures to the limit pressures and overall shapes of the curves. It seems reasonable to expect, therefore, that despite the effect of disturbance and relaxation, the FDPM pressure-expansion curve should provide similar information about soil properties to that from the SBPM.

Effects of Test Procedures

17. Field and laboratory studies by various researchers have examined the importance of rate effects in the interpretation of PM tests (2,9,15). In order to prevent consolidation, rapid rates of expansion are required resulting in strain rates many times larger than those applied in laboratory testing. In addition, strain rate varies with radius. However, it would appear that appreciable changes in strain rate are required before SBPM data are significantly affected. Due to the disturbance effect caused by the full-displacement probes, it is not certain whether strain rate effects for the SBPM and the FDPM will be similar. A standard range of cavity strain rates of 5-10% per min. has been used throughout this study.

Instrument Characteristics

18. PM tests cannot model the expansion of an infinitely long cylindrical cavity due to its finite length. Table 3 shows the calculated ratio of the radius of the plastic zone around the cavity, R_p, to the length of the expanding section L_p, when the PM is fully expanded. At maximum expansion, it is questionable whether cylindrical analysis is appropriate for any of the instruments. Spherical theory may be more appropriate especially for the SCPM. Houlsby and Withers (7) suggest that the expansion limit pressure is somewhere between the cylindrical and spherical values.

Table 3. Effect of Insertion Method on the Radius of the Plastic Zone for an Elastic Perfectly Plastic Soil ($I_r = G/S_u = 200$; $R_p = r_0(I_r)^{0.5}$)

PM	PM Radius r_0 (mm)	PM L/D	PM Length L_p (mm)	Assumed Cavity Strain (%)	Max.Radius of Plastic Zone R_p (mm)	R_p/L_p
UBC SCPM	22	5	220	25	389	1.77
FUGRO CPM	22	10	437	25	389	0.88
HUGHES SBPM	37	6	444	15	298	0.67

COMPARISON OF PRESSUREMETER DATA

19. A typical comparison plot of the expansion curves for the three different pressuremeters used is shown in Fig. 1. The SBPM curves in general are more rounded and fatter as opposed to the shallow flat-lying CPM and SCPM curves. For good quality SBPM tests at low strains, the expansion curves are significantly steeper than for the CPM and SCPM tests, and show lower lift-off, and higher limit pressures. As expected, lower limit pressures are obtained for the CPM (L/D = 10) than for the SCPM (L/D = 5).

UNDRAINED SHEAR STRENGTH (S_u)

20. Mair and Wood (12) indicate that the method least affected by disturbance for obtaining S_u from PM test data is either:

- to measure the ultimate slope of the pressure vs. ln($\Delta V/V$) curve where ΔV is the volume increase in the cavity and V is the current volume, i.e. Windle and Wroth (15) method (WW method);
- alternatively, the expression

$$S_u = \frac{(P_L - \sigma_h)}{N_p} \qquad (1)$$

may be used where $N_p = f(G/S_u)$. Because of the variation in σ_h expected due to disturbance and relaxation effects, the total overburden stress σ_{vo}, was substituted into equation (1) and an empirical value of Np was calculated from S_u(FVT).

21. Houlsby and Withers (7) recently proposed a method for determining S_u which utilizes the unloading portion of a FDPM test (HW method).

22. The S_u profiles at Langley obtained by applying the WW and HW methods to SCPM data are compared in Fig. 2 to the range of field vane (FVT) data obtained over a 5-year period. The WW method gives strengths approximately double the FVT strength. This ratio concurs with published FVT/PM undrained strength ratios evaluated for SBPM tests. It appears that the Windle and Wroth analysis may be used successfully with FDPM results to obtain S_u values comparable to those from SBPM data. The HW method, on the other hand, agrees well with the vane data at Langley. At other sites the HW method consistently underpredicted S_u (FVT).

23. Interpretation of the PM data to evaluate N_p by means of eqn. (1) gave average factors of 4 to 4.5 in the normally consolidated clays at McDonald Farm and Lulu Island. At Lower 232 the N_p factor was clearly subject to the influence of stress history.

SHEAR MODULUS FROM UNLOAD-RELOAD CYCLES (G_{ur})

24. The performance of unload-reload cycles during PM expansion provides information on the stress and strain level dependent shear modulus of soils. To obtain a shear modulus corresponding to the in situ effective stress state it is necessary to perform this cycle rapidly. This particular definition of shear modulus is advantageous since it appears to be the least affected by soil disturbance. The Houlsby and Withers (7) method also permits evaluation of G from the unloading portion of the PM curve. This latter analysis gave shear moduli slightly higher than those from unload-reload loops. It is difficult to ascribe a strain level to the Houlsby and Withers modulus.

25. Figure 3 presents the G_{ur} normalized with respect to S_u (FVT) as a function of the shear strain increment at the

cavity wall over which G_{ur} was measured. The average relationship for cohesive soils by Seed and Idriss (13) is also indicated for comparison. It would appear that G_{ur} is relatively insensitive to disturbance in clays as has been previously found for sand, provided the effects of stress and strain level are taken into account. In addition, the results suggest that it may be possible to derive analytically G_{max} from PM unload-reload moduli and that modulus degradation with strain level can be examined with the PM. Measured values of G_{max}/S_u from the seismic cone penetration test and FVT indicate a ratio as much as 2 to 3 times lower than that suggested by Seed and Idriss (13).

STRESS HISTORY

26. Various empirical formulations exist for evaluating stress history in cohesive deposits. Figure 4 compares two empirical factors which are sensitive to stress history, one based on CPTU data and the other derived in a similar fashion from FDPM data (6). The value P_{20} is the pressure at 20% strain in the UBC SCPM. The results are presented for the Lower 232 Street site. Also shown is the calculated variation with OCR for the CPT approach assuming a constant value of 12.5 for N_{kT}. If N_{kT} is taken as inversely dependent on OCR as has been shown (17), the upward concave line flattens out and gives better agreement with the field data. Also, the cone bearing relationship in Fig. 4 appears to be much more sensitive to OCR than the SCPM relationship. This observation needs further study.

CONCLUDING COMMENTS

27. The foregoing has evaluated and commented on factors affecting full displacement PM tests in cohesive soils by means of comparison testing. Similarly, interpretation methods have been briefly reviewed where relevant. The observations made can be summarized as follows:

- the stress conditions around the probe are very dependent on probe geometry and soil characteristics. Furthermore, relaxation phenomena around the probe may signifcantly affect the soil response. This would suggest that some degree of standardization of test procedure is required to enable the development of improved methods of analysis;
- the shape of the pressure expansion curve obtained with FDPM's is flatter and shallower than that with SBPM's and reflects the dominance of the pore pressures induced during insertion;
- the initial response of the FDPM appears to be modified by the remoulding of soil close to the probe. Total stress cell data indicate that a rational interpretation of in situ horizontal stress may be possible if dissipation of excess pore pressures is allowed to occur. This would, however, be impractical in most situations;

- notwithstanding the disturbance effects, the application of methods of analysis to obtain G_{ur} and S_u originally developed for the SBPM appear to provide consistent soil parameters when applied to FDPM test results; and
- FDPM testing is easier to perform and provides more consistent data due to the repeatable disturbance achieved. In the case of the SCPM the benefits of obtaining CPTU and shear wave velocity data in the same hole cannot be overemphasized, especially for an instrument which will probably rely substantially on the use of empirical correlations for determining geotechnical parameters, at least for the near future.

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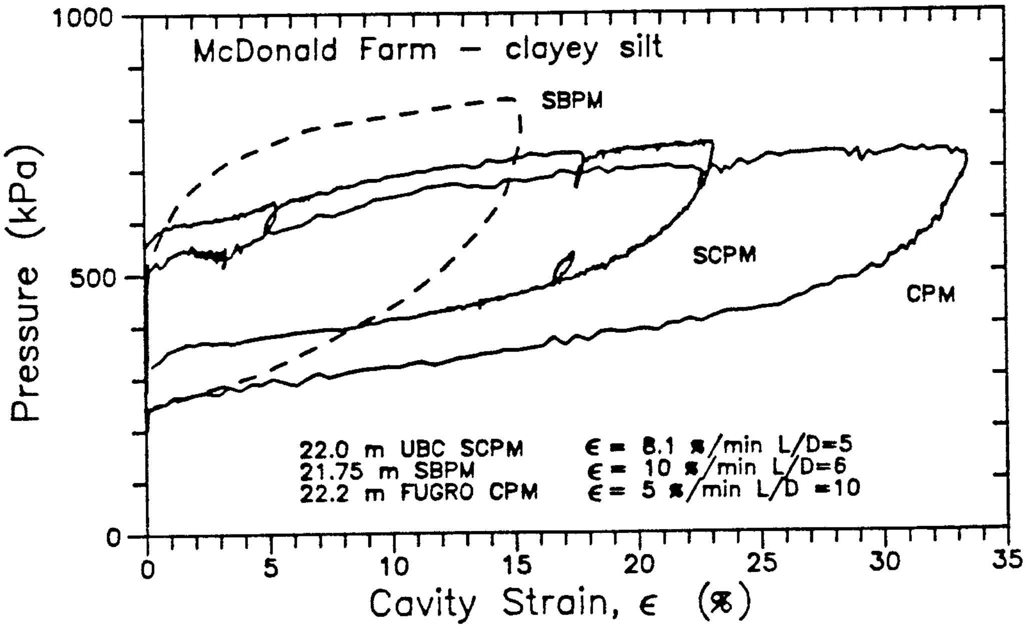

Fig. 1. Comparison of FDPM and SBPM tests at McDonald Farm.

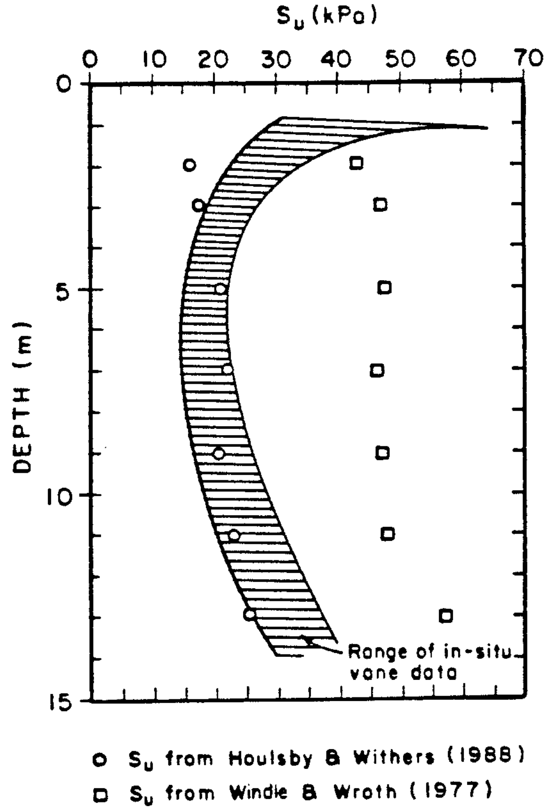

Fig. 2. Comparison of FVT and PM undrained strengths - Lower 232 St., Langley.

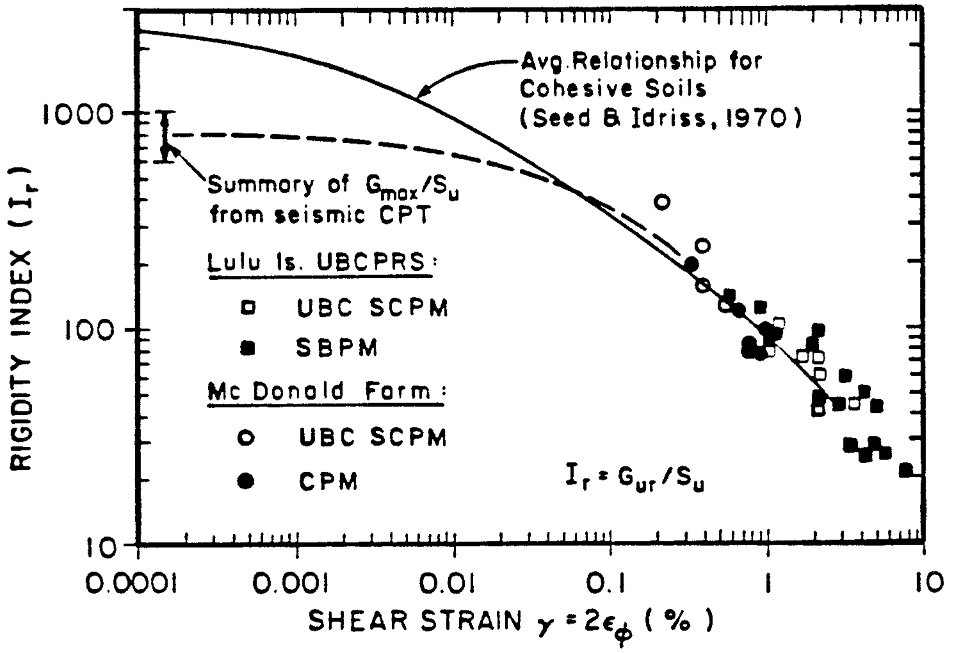

Fig. 3. Rigidity index - shear strain trends for Lower Mainland soft clays.

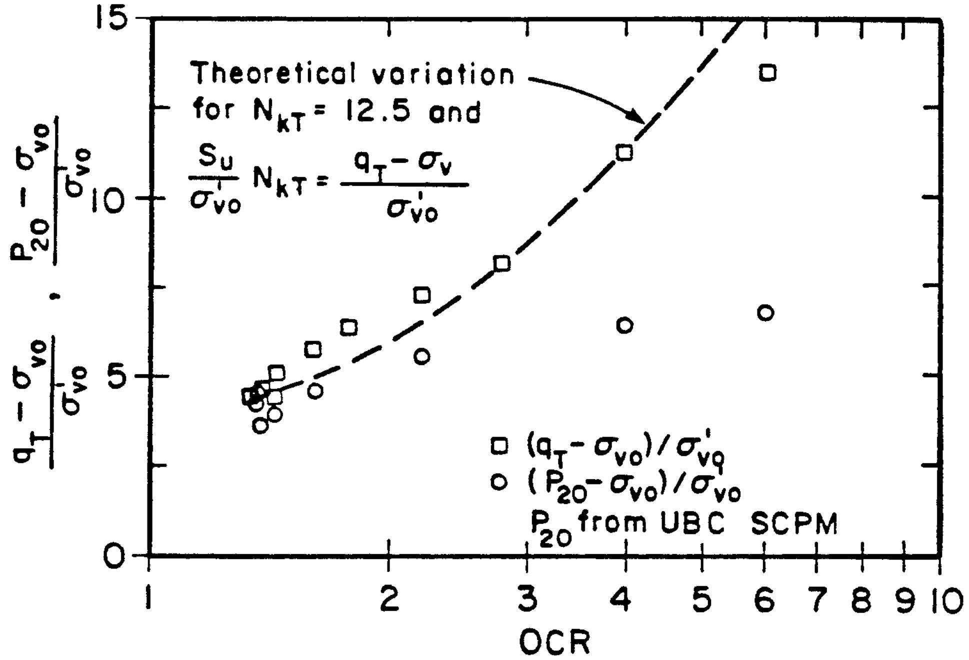

Fig. 4. Comparison of stress history indicators based on CPTU and SCPM data at Lower 232nd St. site.