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INFLUENCE OF EQUIPMENT AND TEST PROCEDURES ON INTERPRETATION OF PRESSUREMETER TESTS

by
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SYNOPSIS

Factors affecting pressuremeter test results are discussed. Specific aspects of equipment design and tolerances, installation method and test procedures are addressed. It has been shown that volume change strain measurements in mono-cell instruments should be used with caution, possible hysteresis effects during unload-reload cycles and arm-membrane interaction should be checked for, tolerances in instrument dimensions are critical especially for small diameter instruments and rate effects can affect results in sands and clays.

INTRODUCTION

1. Much of the early development of pressuremeter (PM) testing occurred in France with the pioneering work of Menard. The Menard PM has a tri-cell construction and must be placed in a pre-bored hole. Considerable experience has been gained in France with the Menard pre-bored pressuremeter (PBPM) and good quality foundation design is possible by using standard testing techniques and correlations.

2. In the last 20 years, as a result of extensive research primarily in France (Ref. 1) and the U.K. (Ref. 2) significant advances have been made in installation techniques, probe design, control of membrane expansion and interpretation of the PM data. Many commercial models now exist.

3. During the last ten years, experience has been gained at the University of British Columbia (UBC) with many different pressuremeters. It has become clear that, although there has been considerable debate on the influence of equipment and test procedures on results obtained, most of the existing pressuremeters still have design features and test procedures that influence the measurements and, hence, the interpretation. This paper briefly discusses some of the important features of PM equipment and test procedures.

EQUIPMENT

Cell Design

4. X-rays have been used (Ref. 3) to compare the mode of expansion of mono and tri-cell PMs in dense sand. Both types inflated approximately as right cylinders. In studies at

UBC, a PM with a length to diameter ratio of 6 equipped to measure both volume change and strain-arm displacement was used to carry out tests in various soil types. The results are summarized on Figure 1.

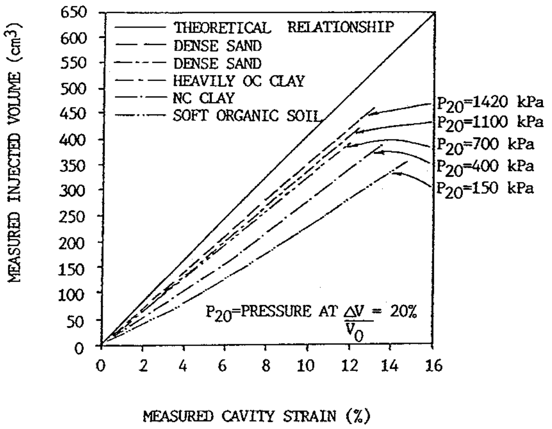


Figure 1:

Comparison of volume change and strain arm measurement of membrane expansion.

As the stiffness of the soil decreased, the measured deflection at mid-height of the membrane departed further from the theoretical relationship between deflection and volume change calculated assuming expansion as a cylindrical cavity. When the PM was inflated in air, it expanded like a rugby ball. From this data, it is apparent that no unique relationship exists between volume increase and radial displacement. Consequently, tests using mono-cell PMs will give different results depending on the method of measurement employed.

5. An advantage of volume measurement for membrane expansion is that the overall volume change of the probe may be more representative than localized displacement measurement (Ref. 1) In addition, individual strain arms rarely give identical pressure expansion curves, and so some method of averaging is required. However, no consensus exists on the method of averaging.

Strain Arms

6. An attractive feature of self-boring pressuremeter (SBPM) tests is the opportunity to measure in situ stress. Interpretation of lateral stress around the PM is generally done by examining the results of the early stages of the expansion data plotted to a large scale (Ref. 4). This is frequently complicated by features of the strain-arm design which can result in changes in strain-gauge output indicating apparent movement prior to lift-off (Ref. 5). Recent experience at U.B.C. during the development of the seismic cone pressuremeter (SCPM) (Ref. 6) has indicated the sensitivity of strain-arm performance to design details. Figure 2(a) shows the lift-off behaviour of an initial strain-arm design for the SCPM. As inflation began, the arm appeared to move inwards prior to lift-off. The behaviour was most noticeable in clay where high pore pressures existed around

the membrane due to the full displacement installation of the probe. The problem was traced to bottoming out of the cantilever spring arms.

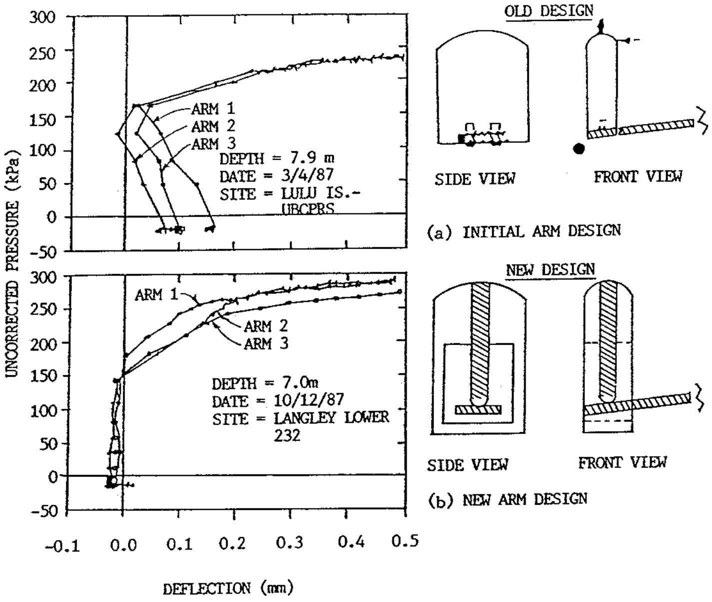


Figure 2:

Effect of arm design on lift-off pressure.

High differential pressures acting on the membrane resulted in the head of the strain-arm being pressed against its seat. As the pressure differential across the membrane decreased, the flexing relaxed. The arm appeared to move inwards until apparent lift-off when internal and external pressures balanced. A change in head design led to the improved behaviour shown in Figure 2(b).

7. A further problem which has been observed with strain arms is that of hysteresis. This is of great importance in the measurement of unload-reload modulus. In stiff soils, unload-reload cycles usually result in a strain increment of the order of 0.2 percent. For a SBPM with a diameter of 80 mm, this requires precise measurement of about 0.16 mm, and for the new 44 mm diameter full displacement pressuremeters (FDPM), (Ref. 7) it requires measurement of 0.088 mm. As several points are required on the unload-reload loop, resolution of the order of 1×10^{-2} mm is required. Any hysteresis of the strain arm will become more important for smaller diameter probes. Experience at UBC with a Cambridge type strain arm design, (Ref. 8) has shown that the frictional contact between the cantilever spring and the strain arm can lead to hysteretic response of the arm. The calibration factor applicable to an unload-reload cycle of 0.088 mm varied with the current degree of arm deflection as shown in Figure 3. Improvements in strain arm design are urgently needed to eliminate such effects and to improve estimates of in situ stress, with elimination of compliance of prime

importance. The use of non-displacement transducers would be a significant advance.

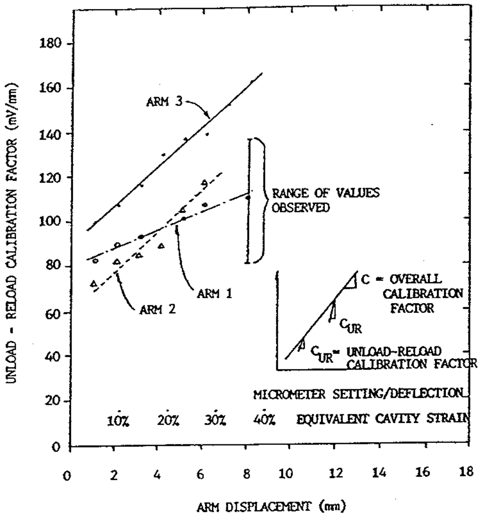


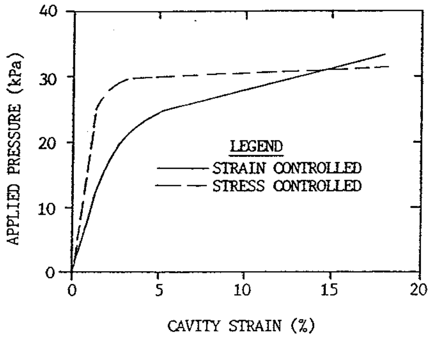
Figure 3:

Variation of calibration factor with deflection.

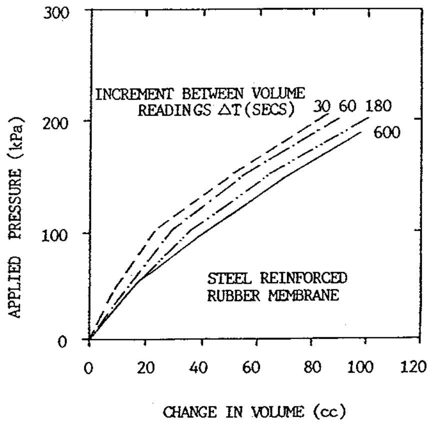
Membrane and Membrane Protection

8. The inflation pressures recorded during membrane expansion include an amount to overcome the membrane resistance. To allow correction of the pressures for this effect, the membrane is inflated in air. In soft soils, this correction can form a substantial portion of the total recorded inflation pressure. Many pre-bored PM devices have highly non-linear and rate-dependent membrane correction curves. Consequently, the membrane correction will depend on the inflation method. Figure 4(a) shows the difference between a stress controlled and strain-controlled membrane calibration in air for a 75 mm diameter urethane membrane.

Figure 4: Rate effects on membrane calibration curves



a) Comparison of stress and strain controlled membrane calibration curves - urethane membrane.



b) Effect of holding time on membrane calibration.

Figure 4(b) shows the influence of rate effects on a stress-controlled membrane calibration in air for a 32 mm diameter steel-reinforced rubber membrane. This figure clearly shows that the membrane correction can be very large for small diameter pressuremeters and that rate effects can be significant. In stiff soils and weak rocks, the membrane calibration can be critical as deformation of the membrane may be of similar magnitude to that of the soil or rock (Ref. 8).

9. Insertion of the SBPM and FDPM can result in large friction forces on the membrane. To prevent damage, a protective covering or reinforcement of the membrane is required. This is mainly achieved by using a steel sheath or "Chinese Lantern" made up of butting or overlapping steel strips placed longitudinally against the membrane. This introduces a further correction which must be minimized by good design and must be accounted for by accurate calibration. Since test data is often presented in terms of cavity strain (ΔR/R), the absolute magnitude of the correction is more significant for smaller diameter probes.

10. Potential designs of protective sheaths include:

a) Butting steel strips bonded to the membrane or to a second outer membrane;

b) A thin steel casing with slots;

c) Overlapping strips with the degree of overlap sufficient to prevent gapping between strips even at maximum deflection. Option (a) has a tendency to increase the magnitude of the membrane stiffness correction and has the potential disadvantage of allowing soil to become lodged between strips when the membrane is expanded, hence preventing deflation to its original diameter. Option (b) will certainly result in soil becoming lodged between the lantern and the membrane. During evaluation of Option (c) for the UBC SCPM, several problems were encountered. The steel strips were curved in order that the cavity would be circular at full expansion. However, in a deflated position and during the initial stages of inflation, some compression of the steel strips occurred, resulting in an error in the measured expansion. The required correction was evaluated by inflating the PM and sheath in a rigid steel cylinder. The correction was difficult to apply as the compression of the steel strips was a function of the effective soil stress on the sheath. Hence, a knowledge of the pore pressures was required. The correction was important at lift-off and during unload-reload cycles with corrections of up to 50% of the measured strain increment being required.

11. Another disadvantage of the design was that soil was able to penetrate the sheath, resulting in an increase in probe diameter. For both the SBPM and FDPM, changes in the outside dimensions of the probe can have a significant influence on the subsequent pressure expansion data, especially on the measured lift-off stress. During recent field evaluation of different instruments, a clear trend was observed between the geometry of the probe and the measured lift-off pressures. Figure 5 shows a summary of results obtained in the sand deposit at the McDonald Farm site using a Marchetti flat dilatometer (DMT), a 44 mm constant diameter cone pressuremeter and a 44 mm diameter cone pressuremeter with a slightly undersized (43.6 mm diameter) expanding section.

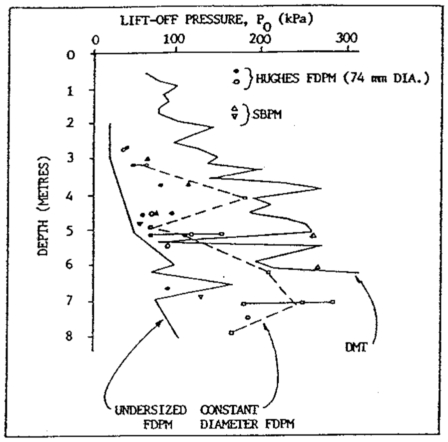


Figure 5:

Effect of probe geometry on lift-off pressure, McDonald Farm site.

The measured lift-off pressure decreased with an increase in the degree of unloading behind the cone tip. The importance of stress relief behind the penetrating cone in sand was discussed by Hughes and Robertson (Ref. 9). A tolerance of only 0.2 mm in the probe diameter represents a cavity strain increment of almost 0.5% for a 44 mm diameter PM. In a stiff soil, such an imposed strain increment during installation could result in a large lateral stress change.

PROCEDURES

12. Except in France, where PM testing is conducted by a standardized stress-controlled procedure, there appears to be a trend towards strain-controlled PM testing. Typical rates of inflation are 1% per minute. This is generally believed to be a suitable rate of expansion to ensure that tests in clay remain undrained (Ref. 10). However, this rate of expansion primarily refers to tests using 80 mm diameter self-

boring pressuremeters. The use of constant rate of strain tests poses difficulties in that the rate of pressure increase is very fast at the beginning of a test, often resulting in insufficient data points to define lift-off stresses. Similar problems will be encountered during unload-reload cycles and final unloading, especially in stiff soils. Generally, stress-controlled procedures are preferred during lift-off, unload-reload cycles and unloading. A disadvantage of stress-controlled inflation with modern data acquisition systems is that all data points can be recorded, resulting in stepped test curves where each stress increment is clearly visible. This can pose a difficulty for analysis methods involving differentiation of the test curve.

13. It is known that consolidation and creep affect PM test results in clays. For a given rate of strain, a range of strain rates is applied to the soil, since strain rate varies with radius from the probe. The initial size of the cavity has an influence on the inferred shear strength: the smaller the probe, the greater the effect of consolidation for a given rate of expansion (Ref. 11). This is in agreement with theoretical solutions which show that consolidation rate varies inversely with the square of the radius of the cavity. Hence, to maintain approximately undrained conditions during a pressuremeter test in clay, the strain rate should get faster for smaller diameter probes. However, this can introduce further strain rate effects. For tests in one soil, the derived parameters would vary with test procedure (Ref. 12). Tests in different soils with a common test procedure would be influenced differently, depending on the creep and consolidation characteristics of a given soil, e.g. one test may be undrained while another may be partially drained. This makes the specification of a standard test procedure difficult if tests are to be interpreted analytically.

14. Recent work at UBC has shown the importance of creep in sands (Ref. 13). Laboratory tests on angular and rounded sands have shown an influence of stress ratio, confining stress, angularity, relative density and mineralogy on creep characteristics. In drained FDPM tests in clean sands performed at McDonald Farm, and in Leidschendam, Holland (Ref. 14), large time-dependent strains were observed, the magnitude of which increased with stress level. A typical result for a stress-controlled test is shown in Figure 6. Figure 6 illustrates that a family of different pressure-expansion curves can be generated through points of equal strain rate. Different curves are obtained depending on the imposed strain rate. In stress-controlled tests, strain decayed with time at constant pressure. In strain-controlled tests, the inflation pressure drops at a decreasing rate when the cavity strain is held constant. This observed behaviour is consistent with the concept of a stress-strain-strain rate behaviour.

15. Expansion at a constant rate of strain will give a smooth loading curve which will mask creep and consolidation effects. However, during initial unloading, expansion can continue due to creep effects resulting in a rounded loop (see Figure 7).

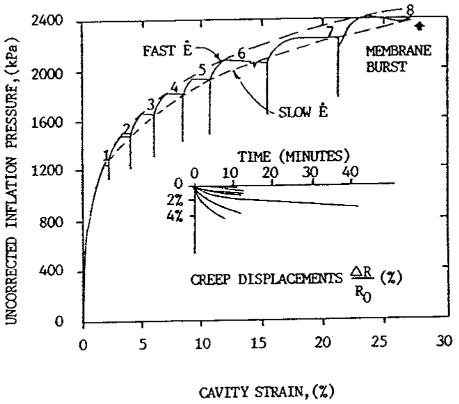


Figure 6:

Stress-controlled FDPM in clean sand, Leidschendam Site. (Ref. 14).

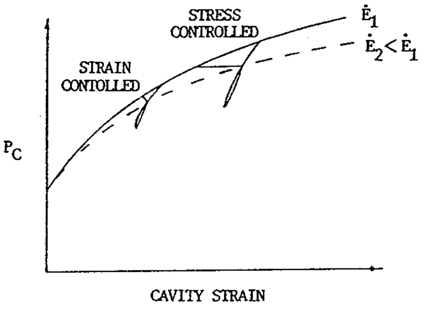


Figure 7:

Comparison of creep effects on stress-controlled and strain-controlled unload-reload cycles.

A stress-controlled test has the following advantages:

a) Better control at lift-off;

b) Elimination of creep effects prior to unload-reload cycles and final unloading;

c) Information is provided about the degree of time-dependent behaviour of the soil. This could have implications in the identification of angular or friable sands, such as carbonate sands.

16. It is clear that the shape of a PM curve and, hence, the interpreted soil parameters are affected by the test procedure. A standardized test procedure thus seems desirable. However, it is unlikely that one procedure could account for all soil behaviour characteristics for all PM designs such that direct comparisons could be made between derived soil parameters. The use of a standard instrument installed and inflated using a standard procedure would allow the development of a data base for use in the derivation of semi-empirical correlations as has been adopted with great success in France. The application of the Menard empirical correlations to data obtained using other pressuremeters is subject to much uncertainty. The uncertainty can only be removed if correlations are developed for specific designs and associated test procedures.

17. For drained PM tests in cohesionless soils, a stress-controlled test procedure should be adopted to improve the evaluation of lift-off pressure, the determination of soil moduli from small unloading-reloading cycles and to evaluate the degree of time-dependent behaviour of the soil.

18. For PM tests in fine-grained soils, either stress or strain-controlled procedures could be adopted, depending on the interpretation required. The rate of expansion should be selected to minimize consolidation of the soil. However, the combined effects of creep and consolidation are difficult to separate. If unload-reload cycles are to be performed to determine soil modulus, it would appear to be better to perform the cycle quickly to minimize consolidation, even though creep effects may influence the resulting response. The suggestion that pressuremeter tests in clay should incorporate a standard amount of creep and a maximum permissible amount of consolidation (Ref. 12) appears reasonable, provided the two processes can be distinguished.

CONCLUDING REMARKS

Interpretation of PM tests is dependent upon equipment characteristics, on installation method and test procedures. The above discussion has outlined a number of problems encountered during the development of a 44 mm diameter seismic cone PM. The main observations can be summarized as follows:

- volume change measurements in mono-cell devices should be used with caution;
- equipment tolerances, strain arm performance and the flexibility and behaviour of membranes and protective sheaths require close examination, particularly for small diameter instruments;
- test results can be sensitive to rate effects in both sands and clays;
- consideration should be given to establishment of a standard instrument and test procedures by which all tests will be run. Different standard procedures may be required for particular soil types.

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