AN EVALUATION OF THE
FULL DISPLACEMENT PRESSUREMETER

by

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BASC, The University of British Columbia, 1982

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
DEPARTMENT OF CIVIL ENGINEERING

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
July, 1985

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ABSTRACT

The self-boring pressuremeter which is inserted into the ground without disturbing the surrounding soil has two drawbacks. Skilled operators are needed to insert the probe into the ground without disturbing the soil, and the self-boring process requires a jetting action or a rotating cutter and drilling mud. One method of simplifying the pressuremeter installation procedure is to install the probe in a full displacement manner. A solid tip is placed on the end of the probe and then the pressuremeter is pushed into the ground in the same manner as a cone penetrometer.

This research project was performed to examine the suitability of using the full displacement pressuremeter for determining shear modulus, in situ horizontal stresses, and undrained shear strength. The variables examined were: the type of pressuremeter, whether the pressuremeter was run in a stress or a strain controlled manner, the size of the tip pushed in front of the pressuremeter, and whether time was allowed for the dynamic pore pressures to dissipate. Tests were conducted in sand, silt, and clay.

When the shear moduli measured with the full displacement pressuremeter were adjusted to account for the differences in strain level, and mean effective stress they compared very well with the dynamic shear moduli measured with the seismic cone. The attempts to determine the in situ horizontal stress by examining the liftoff pressure were unsuccessful. The undrained shear strengths of clay determined using cavity expansion theory compared very well with undrained shear strengths determined using the field vane.
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ACKNOWLEDGEMENT

I would like to thank my advisors, Dr. P.K. Robertson, and Dr. R.G. Campanella, my colleagues and the Civil Engineering technical staff for their assistance with this research project.

The financial support of the Natural Sciences and Engineering Research Council of Canada is also gratefully acknowledged.

This presentation is dedicated to my wife Sue, my family, and all my friends who provided unstinting support when I needed it most.
Chapter 1.
Introduction

1.1 History of the Pressuremeter

The self-boring pressuremeter was developed in the early 1970's as a method of inserting the pressuremeter into the ground without disturbing the surrounding soil. This presented two major advantages over the traditional Menard-type pressuremeter; the tests were conducted on undisturbed soils, and the analysis could be carried out using fundamental principles developed with cavity expansion theory.

The self-boring pressuremeter has two drawbacks; skilled operators are needed to insert the probe into the ground without disturbing the soil, and the self-boring process requires a jetting action or a rotating cutter and drilling mud. The complicated installation procedure is of particular significance if the test is to be conducted at considerable depth offshore.

Reid et al, 1982 developed an open-ended push-in pressuremeter (PIP) as one alternative to overcome the installation problems associated with the self-boring pressuremeter. The PIP was designed to be pushed a short distance into the ground with soil passing through the cutting shoe and into the hollow core of the instrument. The disturbance can be minimized somewhat with an appropriate cutting shoe design but the instrument is a thick walled tube and some disturbance is
inevitable. One advantage of this design is that the probe is withdrawn after each test and the sample obtained in the core of the instrument can be examined. The corresponding disadvantage is that the instrument must be withdrawn after each test to allow the soil in the core to be removed.

The Full Displacement Pressuremeter (FDPM) is a further step in the process of simplifying the installation procedure. A solid tip is placed on the end of the probe and the FDPM is then pushed into the ground in the same manner as a cone penetrometer. The soil around the probe is fully disturbed. However, research by Robertson, 1982 with the self-boring pressuremeter (SBPM) showed that the moduli derived from unload-reload cycles were insensitive to soil disturbance. This has important implications if the major parameter that is to be derived from the pressuremeter test is the soil stiffness. The FDPM could be combined with an electronic piezometer-friction cone to form a cone pressuremeter. The cone could provide a continuous log of the soil. The penetration could be stopped at regular intervals or in layers of specific interest and pressuremeter tests could be conducted. The addition of good stiffness measurements from the pressuremeter would allow better correlations to be developed for obtaining soil parameters from the cone penetration test.

This research project continues previous work conducted with the FDPM in sand by Hughes and Robertson, 1984.
1.2 Thesis Outline

Chapter 2 lists the soil parameters that can be estimated with the pressuremeter. The methods of deriving these parameters are discussed in detail.

Chapter 3 describes the equipment used in this research project. The test procedures and the methods of data acquisition are explained. Considerable attention is given to the calibrations that are required.

Chapter 4 presents the results of the tests at the three research sites. The pressuremeter curves are examined, the shear moduli are compared with results from the UBC seismic cone, the undrained shear strength is compared with results from the field vane, and the measured horizontal stress is compared to the vertical effective stress.

Chapter 5 presents the conclusions that were drawn from this research and presents recommendations for further research.
Chapter 2
Parameter Interpretation

2.1 Parameters determined with the pressuremeter

There is a long list of soil parameters that can be measured with the pressuremeter. They include the undrained shear strength, the angle of internal friction, the shear modulus, the insitu horizontal stress, and the horizontal coefficient of consolidation. The stress strain curve can also be derived, and attempts have been made to use pressuremeter data to investigate the susceptibility of a soil to liquefaction. Pressuremeter curves can also be modified to give pressure-displacement curves for use in a beam spring analysis of laterally loaded piles.

This paper will be confined to determination of the shear modulus (G), the undrained shear strength (Su), and the insitu horizontal stress.

Research with the full displacement pressuremeter has also been directed at the design of laterally loaded piles. The development of pressure-displacement curves from the pressuremeter curves and the comparison of predictions with actual pile test results is presented in Robertson et al, 1985a.

Hughes and Robertson, 1984 showed that the angle of internal friction could not be determined from the full displacement pressuremeter using analysis developed for the self-boring
pressuremeter. This does not however preclude the development of an empirical correlation. Since the eventual goal is to pair the full displacement pressuremeter with a cone penetrometer where good correlations for the angle of internal friction have already been developed it does not appear to be necessary to follow that line of research at this time.

2.2 Shear Modulus

Throughout the history of the pressuremeter a variety of deformation moduli have been determined. When the Menard pressuremeter test is being interpreted a modulus corresponding to the slope of the approximately linear portion of the pressuremeter curve is measured. With the self-boring pressuremeter a range of secant moduli are sometimes measured at strains corresponding to positions such as 0.5 of the limit pressure or 0.5 of the peak stress. For these moduli to be used in design, it is necessary to determine whether they are appropriate to the soil model being used.

Small strain cavity expansion theory says that if the soil is unloaded and then reloaded, the slope of the resulting line on a pressure versus circumferential strain plot would be twice the elastic shear modulus, ie. 2G. The shear modulus is a parameter that has been well researched and can be used directly in design.

In their 1984 paper, Full Displacement Pressuremeter Testing
in Sand, Hughes and Robertson showed that the method of installing the pressuremeter into the ground should not significantly alter the slope of the unload-reload cycle (see Figure 2.1). This is based on the assumption that soil that is unloaded beneath a yield surface will behave elastically. Wroth, 1982 shows that there are limits on the size of the unload-reload loop within which the soil can be expected to be remain elastic. For a clay, the maximum allowable size of the stress cycle is $2\sigma_u$ and, for a drained cohesionless soil, the maximum size of the stress cycle is:

$$\frac{2 \sin \phi'}{1 + \sin \phi'} \frac{\sigma'_{e}}{\sigma}$$

$\phi'$ is the angle of internal friction

$\sigma'_{e}$ is the effective radial stress

Janbu, 1963 established that shear modulus is proportional to the mean effective stress raised to the $n$th power, where $n$ is typically 0.5 for cohesionless soils. This means that as the mean effective stress increases so does the measured shear modulus.

$$G = K_g \times \sigma_{e}^n$$

where:

$K_g$ = shear modulus number

$\sigma_{e}^n$ = mean effective stress

$\sigma_{e}$ = reference stress

A pressuremeter test run in a clay is generally considered to be undrained. If that is the case, the total stress is increasing
Figure 2.1 Summary of Stress Paths and Pressure Expansion Curves as a Function of Pressuremeter Installation (After Hughes and Robertson, 1984)
during the test, but the effective stress is remaining approximately constant. Shear moduli measured at various times during a pressuremeter test (PMT) in clay should therefore be equal. In reality there are very high pore pressure gradients generated during a pressuremeter test in clay and some drainage almost certainly occurs. This results in the effective stress rising during the test, causing the shear moduli measured at later stages of the test to be higher than those measured at the initial stages (see section 4.2.2.1).

During a PMT in free draining material the mean effective stress rises constantly and this must be accounted for if measurements of $G$ at various times during the PMT are to be compared. Robertson, 1982 showed that the mean effective stress around a self boring pressuremeter in sand could be estimated as a function of the effective radial stress. The stresses around a full displacement pressuremeter in sand are much more difficult to estimate because of the residual stresses caused by insertion of the probe. As a comprehensive understanding of the stresses around the full displacement probe was lacking, it was decided to use the same approximate approach developed for the self-boring pressuremeter where the mean effective stress is taken to be 0.5 times the effective radial stress.

In order to compare the shear moduli from PMT's in sand a base or standard mean effective stress must be established. The values of shear modulus are also to be compared to those obtained
from the UBC seismic cone so it was decided to normalize all the 
moduli to the insitu mean effective stress which is approximately 
the stress at which seismic cone tests are conducted. A full 
description of the UBC seismic cone and the technique of downhole 
seismic testing is presented in Robertson et al, April 85.

The unload-reload loops are not truly elastic even within the 
range described by Wroth, 1982. They exhibit some hysteresis and 
the shear modulus attenuates with increasing shear strain. 
Figure 2.2 presents typical shear modulus attenuation curves for 
sand and for clay. The shear modulus decreases with increasing 
shear strain or, in the case of PMT, the unload-reload loop size. 
Therefore the loop size was standardized as much as possible in 
order to decrease the number of variables. 2cm$^3$ and 5cm$^3$ loops 
predominated the tests with the Pencel probe. 1.5 cm$^3$ loops 
predominated the tests with the Hughes pressuremeter.

2.3 Undrained Shear Strength (Su)

There are two approaches to determining undrained shear 
strength from pressuremeter tests. Undrained strength can be 
interpreted in an empirical manner or by cavity expansion theory 
employed in conjunction with a soil model. It was the object of 
this research project to examine the possibility of using present 
cavity expansion theory methods to determine the undrained shear 
strength.

Gibson and Anderson, 1961 modeled clay as an elastic /
Figure 2.2 Shear Modulus Attenuation Curves
perfectly plastic material and derived a method for determining $Su$. Several other more recent analyses were published in 1972 which are not restricted to this stress strain model of the soil. Wroth, 1982 states that from experience gained with the Cambridge pressuremeter the extra sophistication of the 1972 analyses are not required and that for design purposes the Gibson and Anderson analysis is adequate for most clays. The Gibson and Anderson approach was used in this research project.

There are two methods of determining the $Su$ that come out of the Gibson and Anderson analysis. Both methods were employed during this project to see if either or both would work with the full displacement pressuremeter.

The first method of determining the undrained shear strength uses the pressuremeter curve directly. The Gibson and Anderson analysis leads to the equation:

$$Su = \frac{(Pl - Po)}{1 + \ln \left( \frac{G}{Su} \right)}$$

As is demonstrated in Figure 2.3, the limit pressure, $Pl$, and the liftoff pressure, $Po$, are determined directly from the pressuremeter curve. $Su$ can be determined from an initial estimate of the stiffness ratio, $G / Su$, and then an iterative process is followed. The problem is then whether to use the dynamic shear modulus ($G_{max}$), a value of $G$ corresponding to the strain level at failure, or some other value for $G$. During the analysis in this paper, it was decided to use a value of $\ln \left( \frac{G}{Su} \right) = 6.5$. If
Figure 2.3 Determining Undrained Shear Strength from the Pressure Expansion Curve

\[ (1 + \ln \left( \frac{G}{S_u} \right)) S_u \]
for example, Gmax was used to calculate the stiffness ratio at a depth of 8m at Langley, the stiffness ratio would be:

$$\ln \left(\frac{G_{\text{max}}}{S_u}\right) = \ln \left(\frac{150}{0.25}\right) = 6.4 \sim 6.5$$

Gmax in the above example was determined with the seismic cone and Su was determined with the field vane. It can be seen that this method of calculating Su depends heavily on the value of Po, and Pl. Because of the logarithm function the value of the stiffness ratio is less important.

The second method of determining undrained shear strength using the Gibson and Anderson analysis is demonstrated in Figure 2.4. Applied pressure is plotted versus the logarithm of volumetric strain. This should be a linear relationship once failure has been reached and if natural logarithms are used, the slope of the line is equal to Su. The prime advantage of this approach is that no estimate of the stiffness ratio is required, nor do Po or Pl need to be measured. Pl can sometimes be a problem to measure if the test is not carried to a high enough strain level.

These analyses are based on the assumption that the clay is undrained during the pressuremeter test. As was already mentioned in section 2.2 high pore pressure gradients are created during the test and some drainage does occur. This will cause the clay to consolidate and thus the undrained shear strength increases. This is one of the reasons why undrained shear strengths determined from the PMT are generally higher than those determined by other conventional tests (see Wroth, 1984). Some of the other reasons
Converting to natural logarithms

\[ Su = \text{Slope} / 2.303 \]

Figure 2.4 Determining Undrained Shear Strength from the Pressure vs Log Volumetric Strain Plot
are; strain rate effects (PMT's are usually run much faster than other conventional tests and many cohesive soils have strain rate dependent shear strengths), and the fact that a pressuremeter expansion is actually somewhere between a cylindrical and a spherical cavity expansion, not a truly cylindrical expansion as assumed in the analysis.

The undrained shear strengths derived from the pressuremeter were compared to undrained shear strengths obtained with the Nilcon field vane. A description of the Nilcon field vane is given in Greig, 1985.

2.4 Insitu Horizontal Stress

The pressuremeter presents the possibility of measuring the insitu horizontal stress, a parameter required for detailed computer analysis. The self-boring pressuremeter which is supposed to be installed without disturbing the soil is the ideal tool for measuring the insitu horizontal stress. However, when the probe is self-bored into the ground there is still a small amount of disturbance. In sand this small disturbance can lead to significant errors in measuring the insitu horizontal stress. When the probe is installed in a full displacement manner the soil is fully disturbed. Hughes and Robertson, 1984 examined the stress path followed by the soil near a full displacement probe. They suggest that although the soil is subjected to very high stresses during the insertion of the probe, the lateral stresses then
relax and return to somewhere near the initial lateral stress.

Lacasse and Lunne, 1982 point out some of the difficulties in determining the liftoff pressure from self-boring pressuremeter tests. The simplest method is to visually determine the point on the pressure versus circumferential strain plot where the membrane first begins to move. An allowance for the compliance of the system must be made and there is considerable room for judgment. Lacasse and Lunne have shown that this method usually yields slightly lower estimates of the insitu horizontal stress than the best estimates predicted by methods other than the pressuremeter. Visual inspection was considered to be a sufficiently accurate estimate of the liftoff pressure during this project.

One of the problems encountered when examining measurements of insitu horizontal stress is what should they be compared to. The liftoff pressure represents the total horizontal stress acting around the probe. The liftoff pressure minus the equilibrium pore pressure (Uo) represents the effective horizontal pressure. If the measured effective horizontal pressure is plotted together with the vertical effective stress the measured value of Ko can be observed directly.
Chapter 3
Equipment & Test Procedures

3.1 Introduction

The two most common methods of inserting the pressuremeter into the ground are to self-bore it or to place the probe in a pre-bored hole. There is, however, an alternative method and that is to install the probe in a full displacement manner. The pressuremeter is fitted with a solid cone tip and then pushed into the ground in the same manner as a cone penetrometer. This chapter examines the equipment used in this study during the full displacement pressuremeter tests, the procedures needed to prepare the equipment, the type of data obtained and how it is obtained. The procedures used to run the tests and how different procedures and equipment affect the data will be examined and discussed.

Two types of pressuremeter probes were used during the course of this research program. They were: a) the Roctest Pencel and b) the Hughes Pressuremeter. The pressuremeters were installed using the UBC Insitu Testing vehicle which is described in detail in Campanella and Robertson, 1981.

3.2 Roctest Pencel

The Pencel probe has a deflated diameter of 32mm. The main advantages of this small pressuremeter are that the pushing force required to install the probe is reduced and that the probe can be
placed behind an electronic cone penetrometer. However a standard 10 sq.cm. electronic cone has a diameter of 36mm. Thus the Pencel probe is smaller than a standard electronic 10 sq. cm. cone.

An important aspect of this research project was to evaluate the effect of varying the diameter of the solid tip in front of the probe. The alternative to a 10 sq. cm. tip is a 32mm diameter tip, which is the same diameter as the probe. The use of a 36mm tip is similar to the situation where the probe is placed in a pre-bored hole and the soil is allowed to relax.

3.2.1 Description of the Pencel Probe

The Pencel probe differs from previous Roctest pressuremeters, such as the Menard G-Am probe, in that it has only one cell rather than three. The mono cell approach is the one that has been adopted with self-boring pressuremeters.

The Pencel pressuremeter unit shown in Figure 3.1 consisted of four components; the probe and fittings, a membrane, the flexible tubing and a control unit. The core of the probe was a 22mm diameter hollow steel cylinder with threads on either end. Extending from either end of the probe was a short piece of steel tubing. The flexible tubing from the control box attaches to one piece of steel tubing and the other piece of steel tubing, which is normally sealed, can be opened to aid in the saturation process. Each piece of steel tubing was connected to a small passageway in the wall of the probe that ran to a point just past
Figure 3.1 Pencil Probe
the retaining lip. The two retaining lips were centered on the probe and were 390mm apart. The membrane was sealed against these retaining lips by tapered metal rings which were held in place by lock nuts.

The membrane was a 2.5mm thick rubber sheath with sixteen 13mm wide stainless steel strips glued to the outside. The metal strips extended to within 25mm of the end of the 410mm long membrane and were only glued along one edge so that they did not prohibit the membrane from expanding. The ends of the metal strips were held underneath the tapered metal rings which caused increased end constraints. Increasing the end constraint decreased the ability of the probe to expand as a right cylinder, an assumption made in the interpretation of the data. This is discussed more fully in section 3.3.2.3.

The 20m length of flexible tubing used during this study had an outside diameter of 6.35mm and an inside diameter of 2.0mm. The tubing was found to have a very small compliance for the range of pressures used in this study (0 to 20kpa).

For the purposes of this research project it was decided not to purchase the control unit supplied by Roctest but rather to develop control units that would be versatile enough to handle future research needs. The control units used are discussed in the following subsections.
There was a problem encountered assembling the Pencel probe. When the tapered rings were put in place to seal the membrane against the retaining lip, the membrane also sealed the fluid inlet. To overcome this problem a groove was cut in the core of the probe that allowed the fluid to flow farther along the probe before it entered the area behind the membrane. New probes supplied by the manufacturer have this modification already incorporated.

The Pencel has been designed so that it can be combined with an electronic cone penetrometer. The inside diameter of the Pencel probe is such that a shielded 14 conductor cable such as used with the UBC electronic cones can be passed through the probe but the probe is not large enough to allow the slightly larger connectors at the end of the cable to pass through. This necessitates the cone cable being rewired each time the Pencel probe is to be strung onto the cable. The adapter that is required between the probe and the cone penetrometer, however, does not have sufficient clearance inside to accept the cable. The steel tubing used during the saturation must fit inside this adapter and when it does there is insufficient room to thread the cone cable. This could be overcome if the method of sealing the passageway was altered. Instead of sealing the passageway by attaching a piece of steel tubing and then sealing the piece of tubing with a nut, a small screw could be threaded directly into the core of the probe to seal the passageway.

The method of attaching the membrane to the probe appears to
limit the type of soil in which the test can be performed. It was found that whenever the CPT qc value exceeded about 150 bar, the membrane was torn off the probe during penetration. This severely limited the depth to which the probe could be installed. The failure of the membrane appears to originate from the high friction force pulling the membrane out from between the lower tapered ring and the retaining lip. This appeared to be a self perpetuating problem since once a membrane had been pulled from between the retaining lip and the tapered ring, the tapered ring would become slightly enlarged and would not hold the next membrane as tightly, therefore the next membrane pulled out more easily.

3.2.2 Test Procedure and Data Acquisition

3.2.2.1 Stress Controlled Test

The pressuremeter test has traditionally been carried out in a stress controlled manner. That is, a certain pressure is applied and, after a specified time interval, the corresponding strain is recorded. The control unit from a Menard G-Am pressuremeter, shown in Figure 3.2, was used to perform the stress controlled test. The Pencel probe has a much smaller volume than the G-Am probe so it was necessary to read the volume more accurately over a smaller range. Therefore a solid brass cylinder was inserted into the water reservoir to decrease the cross sectional area. The scale was then recalibrated to reflect the new
Figure 3.2  Modified Menard G-Am Control Box
volume / length relationship. This allowed a more accurate determination of the volume and still maintained adequate volume range for the Pencel.

The pressure and strain readings were recorded manually during this test. The strain readings were recorded as changes in volume in the fluid reservoir. In order to compare these tests with those done with the Hughes pressuremeter the changes in volume were converted to circumferential strain. This was done using the assumption that the membrane expands as a right cylinder. The validity of this assumption is discussed in section 3.3.2.3.

One of the prime problems with analyzing stress controlled tests is attempting to understand the drainage conditions. During the initial portion of the test the soil around the probe may be strained slowly enough that the soil is fully drained. As the soil approaches failure, the strain rate greatly increases and the soil may become undrained. In the middle of the test the drainage conditions are even more complex.

One of the problems with using the Pencel probe in a stress controlled manner is determining which value should be used for the initial volume in the calculations. After performing a pressure expansion test, the membrane is allowed to collapse back to the closed position. The membrane cannot be drawn back to any specific position unless a vacuum source is attached to the control box. This leads to the question of whether the initial
volume should be taken as the volume at the start of each test or should it be taken as the totally collapsed volume so that it can be consistent from test to test. If the latter is the case then most of the tests will start with some initial circumferential strain, since the membrane tends to remain slightly inflated even after the probe has been pushed to the next test depth. The effect of choosing different initial volumes on the pressuremeter curves is shown in Figure 3.3. An additional curve is shown for the situation where the initial volume was chosen to be the size of the opening created by the 36mm tip. For ease in comparing with other tests it was decided to use the volume at the start of each test as the initial volume, thus the initial circumferential strain was zero at the start of each test, as it was with the other types of tests.

When the stress controlled test was initially described it was stated that the pressure increment was applied and then after a specified time interval the volume reading was recorded. If the volume reading was recorded continuously a curve such as shown in Figure 3.4 would be delineated. As shown in Figure 3.4 the pressure reading taken at the surface increases immediately but time is required for the fluid to flow into the probe. In the stress controlled test there is no correction made for the head loss in the tubing therefore sufficient time must be allowed for the pressure in the probe and at the surface to equalize. This is discussed further in the following section.
Figure 3.3  Pencil: Curves determined with various initial volumes
Figure 3.4  Pencil: Type of curve generated by a stress controlled test
3.2.2.2 Calibrations for the Stress Controlled Test

Data readings from the Pencel probe must be adjusted to account for the system compliance, the membrane stiffness and the hydrostatic pressure caused by the fluid in the flexible tubing. Before the adjustments can be made two calibrations must be performed; a system compliance calibration and a membrane calibration.

The system compliance is a measure of how much the control unit and the tubing expand under pressure. The system compliance of the Pencel probe was relatively low and was approximately constant. The system compliance does not depend on whether the test was run in a stress or strain controlled manner. When the system compliance is known, the volume injected into the probe can be calculated.

\[ V_{pr} = V_{sur} - V_{com} \]

where:

- \( V_{pr} \) = actual volume injected into the probe
- \( V_{sur} \) = volume change recorded at the surface
- \( V_{com} \) = volume attributed to system compliance
- \( V_{com} = P \times \text{System Compliance} \)
- \( P \) = Pressure applied to the system

The pressure measured at the surface must be adjusted in two ways to reflect the pressure exerted by the probe on the soil. The hydrostatic head of water above the probe in the flexible tubing must be added to the pressure measured at the surface and the
resistance of the membrane to expansion must be subtracted from the measured pressure.

The adjustment for the hydrostatic head is straightforward and is a procedure that has always been required with the Menard type pressuremeter.

The membrane stiffness was difficult to determine as it depended on several factors. The first factor that must be considered before calibrating the membrane is that it softens with use. This was especially noticeable when the membrane was new. It was recommended by the manufacturer that the membrane be inflated in air to maximum volume and then deflated to zero volume a total of five times. This should be considered a minimum whereas twenty inflation / deflation cycles would appear to be a better recommendation. The effect that softening has on the membrane calibration is shown in Figure 3.5. After inflating and deflating the membrane a number of times the probe no longer returns to the same initial volume at zero pressure. The membrane can however, be deflated back to the initial volume but for this to occur an external pressure is required. This pressure is small but is important when trying to calculate the liftoff pressure. In order to measure this part of the membrane calibration curve, a vacuum source was applied to the control box.

Under constant pressure the membrane creeps. Therefore, as shown in Figure 3.6, the membrane calibration curve is dependent on the time between pressure increments. Figure 3.7 shows that the
Figure 3.5  Pencel Membrane Calibration: Effect of cycling
Figure 3.6  Pencel Membrane Calibration: Effect of varying the time increment
size of the pressure increment also affects the membrane calibration curve. The question then arises as to which pressure and time intervals should be used for the calibration. One possible approach would be to use the same pressure and time intervals that are used during the tests. Take, for example, a typical test performed in medium dense sand. One bar pressure increments were applied every 30 seconds until a limit pressure of 11 bars was reached. An unload-reload loop was also performed. The total time of the expansion part of the test was 10 minutes. If the calibration curve was generated in the same way only two data points would be obtained since three bars would generally exceed the limit pressure for a membrane expanded in air. The total time required to inflate the probe would have been less than one and a half minutes. Since it has been established that the membrane exhibits time dependent creep, using a curve that was generated quickly by the above approach does not appear to be correct. Another approach would be to increase the time interval between pressure increments during the calibration so that the total time to run the calibration approximates the total time to run the test in the field. Alternatively, the total time for expansion during the test could be duplicated by using the same time intervals but smaller pressure increments during the calibration. A close look at what is happening when a pressure increment is applied to the probe during a PMT shows that the pressure increment is not carried entirely by the membrane nor is the portion that is carried by the membrane consistent. The pressure increment is carried mostly by the soil with the portion carried by the
Figure 3.7  Pencil Membrane Calibration: Effect of varying the size of the pressure increment
membrane dependent on the amount of strain corresponding to the increment.

The question still remains as to what pressure and time increment should be used. For the purposes of this research program it was desired not to have to generate a separate calibration curve for each test of different duration. Therefore, the pressure increment was standardized at 0.5 bar and a time increment of 30 seconds was used for both the test and the calibration. This was a small enough pressure increment to allow the calibration curve to be defined and corresponded to the pressure increment used during tests in clay, silt, and loose sand. The manufacturer's recommendation for the Menard G-Am probe, which was also designed to be performed in a stress controlled manner, is to use standardized 0.25 bar increments applied at 60 second time intervals for both the test and the calibration.

It was very difficult to determine the correct membrane stiffness correction for the unloading part of the pressuremeter curve. The membrane stiffness during unloading was a function of the maximum volume to which the probe had been expanded. The initial portion of the unloading curve was very steep and small differences in the volume reading corresponded to large differences in the pressure correction. This was especially important when unload-reload loops were being analyzed. A membrane calibration curve that included a unload-reload loop starting at the same volume as the loop being analyzed was required. Since the test was performed in a stress controlled manner it was very
difficult to match the volumes at the start of the unload-reload loops. A family of calibration curves was therefore required. This was less of a problem with the strain controlled test. In a strain controlled test, the volume was controlled so the unloading during the test and during the calibration could be carried out at specified volumes.

The other two components that required calibrating were the graduated cylinder and the pressure gauges. The cylinder was calibrated using standard laboratory techniques and the pressure gauge was calibrated with a dead weight pressure tester.

3.2.2.3 Strain Controlled Test

The strain controlled test differed from the stress controlled test in that the volume of fluid injected into the tubing was controlled rather than the pressure. This allowed the test to be performed at a constant rate of strain rather than at the variable rates caused by pressure increments.

There are many reasons for wanting to run the pressuremeter test in a strain controlled manner. The fact that the strain rate can be held constant for the duration of the test and varied from test to test is important in dealing with soils that are known to have rate dependent properties. Equally as important with the Pencel probe was the fact that membrane calibrations performed in a strain controlled manner are dependent on fewer variables and
are more repeatable. This is discussed in detail in the following section.

The strain control unit was developed and built at UBC to accommodate the needs of this research program as well as the expected needs of future programs. The unit which is shown in Figure 3.8 is simple, versatile, and easy to use. The main components are a screw jack which is attached to a piston inside of a brass cylinder. Attached to the unit is a filler cylinder, a LVDT to measure displacement, and a pressure transducer. The screw jack is turned by a hand crank but there are facilities for an electric motor to be used instead. The use of the LVDT and the pressure transducer allowed the measurement of pressures and volumes more accurately than was possible with the stress controlled test equipment. The data was recorded by connecting the LVDT and the pressure transducer to an XYY chart recorder.

One advantage of the strain control device was that it was possible to apply a vacuum to the probe so that the membrane could be drawn back to the same starting volume after each test. This was a great aid in standardizing the test and may have also reduced membrane damage because the probe was not being pushed to the next depth in a partially expanded state, a common occurrence during the stress controlled test.
the pressure transducer is located behind the screw jack and is located within the pressure cylinder.

Figure 3.8  Strain Control Device
3.2.2.4 Calibrations for the Strain Controlled Test

When the pressuremeter test was performed in a strain controlled manner a unique relationship between membrane calibration pressure and volume was established for any given strain rate, as shown in Figure 3.9.

The major difference between the calibration curve for the strain controlled test and the calibration curve for the stress controlled test was that the strain controlled curve included a component that corresponded to the head loss in the tubing. The reason different strain rates produced different calibration curves (Figure 3.9) was because the head loss varied with the rate of flow of fluid in the tubing. There may be some difference in the membrane stiffness due to strain rate but this was not examined thoroughly. The stress controlled calibration curve did not have a head loss component because there was generally an adequate time lapse between the time the pressure increment was applied and the time that the volume was recorded during which the pressures throughout the system equalized.

Figure 3.9 also shows that observation of the pressure drop when the inflation was stopped allowed the head loss component of the calibration to be identified. However, it was not necessary to identify this component because the head loss during the test was the same as the head loss during the calibration provided the strain rates were the same.
Figure 3.9  Pence Membrane Calibration: Effect of varying the strain rate
Calibrating the LVDT was simply a matter of recording the volume of liquid expelled from the cylinder corresponding to a voltage increment. The pressure transducer was calibrated with the same dead weight pressure tester used to calibrate the pressure gauge in the Menard G-Am control box.

3.3 Hughes Pressuremeter

The Hughes pressuremeter is of interest because it allows direct comparison between pressuremeter tests where the probe was inserted by a self-boring action with those inserted in a full displacement manner. The only differences between self-bored tests with this instrument and full displacement tests is the manner of installation. With the Pencel probe the diameter, membrane type, and method of data collection are all different from those employed using the self-boring pressuremeter.

3.3.1 Description of Hughes Pressuremeter

The Hughes pressuremeter (HPM) is patterned after the one developed by Hughes and Wroth at Cambridge in the early 1970's. This particular model has been constructed with a slightly smaller diameter of 76mm so that it can be lowered through a smaller drill casing, a concern on commercial projects.

The probe which is shown in Figure 3.10 is generally inflated with pressurized nitrogen gas which is controlled by a pressure
Figure 3.10 Hughes Pressuremeter (HPM)

(After Hughes and Robertson, 1984)
regulator at the surface. The expansion of the membrane is measured by strain gauges attached to three arms at the center of the membrane. These arms measure radial displacement which is easily converted to circumferential strain. This is in contrast to the Pencel probe where changes in volume are measured and then converted to volumetric strain. The electronically monitored strain arms are more sensitive and can detect smaller movements than the Pencel measuring system. The pressure is measured by a total pressure cell inside the probe. The membrane on the HPM is considerably more flexible than the membrane used on the Pencel probe. One important influence of the flexible membrane is the smaller membrane stiffness corrections. The protective stainless steel sheath is not attached to the membrane but is attached directly to the probe in such a way that it is free to slide at one end.

The expandable portion of the membrane is 456mm long with a resulting 1/d ratio of 6. This is slightly smaller than the 1/d ratio of 7.5 for the Pencel probe.

3.3.2 Test Procedures and Data Acquisition

The HPM test (HPMT) was performed in two different formats. Tests were performed in the stress controlled format because that was how the locally available self-boring tests were performed and the object was to compare the self boring results to the full displacement results as directly as possible. The HPMT was also
performed in a strain controlled format for the same reasons as were listed in section 3.2.2.3.

3.3.2.1 Stress Controlled Test

The control box shown in Figure 3.11 was normally used for performing the HPMT when self-bored into the ground and was also used when the HPM was installed in a full-displacement manner. No modifications were necessary. The control box required an electrical power supply because it was used to power the strain gauges and transducers in the probe. A pressurized nitrogen bottle was attached to the control box. The control box included a pressure regulator and a flow control valve which regulated the supply of gas to the probe. The signals from the probe were received and amplified in the control box, and could be read with a digital voltmeter. The signals could also be recorded on a chart recorder. The fact that gas rather than a liquid was being used to inflate this probe meant that the pressure applied at the surface was approximately the same pressure that was measured in the probe. There was no hydrostatic pressure head. There was a small head loss in the tubing but it was negligible, especially at the shallow test depths studied in this research project (ie. < 20m).

3.3.2.2 Calibrations for the Stress Controlled Test

There are four components that must be calibrated for this test; the membrane, the total pressure cell, the strain arms, and the system compliance.
Figure 3.11  HPM Control Box
The HPM membrane was much softer than the Pencel membrane. The membrane calibration which is shown in Figure 3.12 was considered to be a constant. An initial pressure of approximately 0.35 bar was required to cause the membrane to start inflating and it continued to inflate to the maximum allowable volume at this pressure.

The strain arms were difficult to calibrate individually once the membrane had been installed. Prior to the membrane being installed a voltage reading was recorded when the arms were fully compressed and the amount of expansion corresponding to subsequent voltage readings was measured directly. This yielded different calibration factors for each strain arm. Once the membrane had been installed it was difficult to determine how much an individual arm had expanded. However, the electrical cable connecting the probe to the surface was subject to a lot of abuse and often needed to be repaired. Whenever the electrical cable was repaired the calibration changed. Since the membranes are expensive ($66 each) it was desirable not to have to remove and replace them every time a strain arm calibration was required. The strain arms could be calibrated with the membrane on by inflating the probe inside a steel cylinder of known diameter and making the assumption that all three arms expanded the same amount.

The total pressure cell was easily calibrated in the same manner as the pressure transducer in the strain control device.
Figure 3.12  HPM Membrane Calibration Curve
The system compliance was measured and found to be very low and was generally taken to be insignificant within the pressure range used during this study (i.e. < 20 bar).

3.3.2.3 Strain Controlled Test

The main problem encountered using the HPM in a strain controlled manner was the size of the head loss through the tubing. Due to its larger size, the volume of fluid required to expand the HPM to a given circumferential strain was much greater than that required for the Pencel probe. Therefore, if the strain rate was to be the same as was used during the Pencel tests, more fluid must flow through the tubing resulting in even greater head losses than with the Pencel probe.

As it was desired to run the strain controlled test with the same control unit used with the Pencel probe, a non-compressible fluid was required. The presence of electronics in the instrument meant that the fluid used must be non-conducting, unlike the Pencel probe where water was used. The fluid originally chosen was a light hydraulic oil. However, this proved to be too viscous and the head losses with the 20m of tubing were such that the fluid that was injected into the probe could not be drawn back into the reservoir even under a full vacuum. The fluid that eventually proved to work was WD-40, a commercially available mixture of light oil and solvent. The only major drawback to the use of this fluid was the tendency for the membrane to stretch considerably when the WD-40 was left sitting in the probe. This problem was
easy to control since the ends of the membrane could be unclamped and the fluid drained from the probe when it was not in use. The ends of the membrane were reclamped without damaging the membrane.

The strain control device used with the Pencil probe was used for the HPM strain controlled test in conjunction with the control box normally used with the HPM. The strain control device allowed the rate at which fluid was injected into the probe to be controlled.

There were two big advantages to having both control systems operating on one probe. The first was the opportunity to compare the total pressure in the probe to the pressure measured at the surface. This allowed an opportunity to directly measure the head loss in the tubing and to observe that pressure fluctuations at the surface were not present in the probe (see Figure 3.13).

The second advantage to having the two control systems was the opportunity to examine the difference between the volumetric strain calculated from measuring the amount of fluid injected into the probe with the circumferential strain measured by the strain arms at the center of the membrane. The results of the comparison are shown in Figure 3.14. The volumetric strain is the change in volume divided by the original volume. The original volume was calculated using the original diameter of the probe. The circumferential strain is the change in radius measured by the
Figure 3.13  HPM: Comparison of pressure reading at the surface and at the probe
strain arms divided by the original radius of the probe. If the assumption is made that the probes expand in the form of a right cylinder the volumetric strain should be approximately twice the radial strain. Suyama et al, 1983 used X-ray radiography in model experiments and showed that pressuremeters employing the mono-cell design expand very close to a right cylinder when expanded in sand. The exact formula relating the two types of strain is shown on Figure 3.14.

The fact that the membrane is constrained at each end means that it can never expand as a true right cylinder but as the $1/d$ ratio increases the effect of the end constraint diminishes. The HPM has a softer more flexible membrane, and less end constraint because the protective steel sheath is not clamped at both ends as it is with the Pencel probe. However, the HPM has a smaller $1/d$ ratio (6.0 vs 7.5) than the Pencel probe. The final result is that the HPM probably expanded in a shape closer to a right cylinder than did the Pencel probe. The purpose of previous pressuremeters having a tri-cell design rather than the mono-cell design was to reduce the effect of the end constraint.

The results shown in Figure 3.14 indicate that the strain measured by the arms at the center of the probe was always greater than the strain calculated from the volume measurements. This is to be expected because of the end constraint. The results also show that the volumetric strain agrees much more closely with the circumferential strain in stiffer material. To understand this it is helpful to consider the expansion of the probe in air. In this
Figure 3.14  HPM: Comparison of volumetric strain and circumferential strain measurements
The expanded probe is shaped somewhat like a football. When the probe is expanded in a stiff material the amount of constraint in the center of the probe is going to be proportional to the amount of expansion. Therefore when the center of the probe begins to expand more than the ends of the probe it meets more resistance and the membrane expands along the path of least resistance which is closer to the ends. The stiffer the material the less significant the end restraints become. Figure 3.15 illustrates the effect of calculating the strain in different ways on the various pressure expansion curves. One curve is shown with strain calculated from the injected volume and the other from measured strain at the center of the probe. If the Pencel probe expands less like a right cylinder than the HPM than the ratio of strain at the center of the membrane to the average strain calculated from the volume increase would be higher than it is with the HPM.

The question that arises is that if the membrane is not expanding as a right cylinder then what is the correct circumferential strain. Should the measured strain at the center of the membrane be used or the one calculated from the volumetric increase which represents some sort of an average over the entire length of the membrane.
Figure 3.15  HPM: Comparison of curves generated with volumetric strain and those generated with circumferential strain.
3.3.2.4 Calibrations for the Strain Controlled Test

The calibrations were basically the same as those for the stress controlled test. The major exception was the membrane calibration.

When the test is strain controlled it became apparent that the membrane calibration shown in Figure 3.12 was a nearly linear relation between pressure and strain as was to be expected from a linear elastic material. Note this is in contrast to the behaviour observed in the stress controlled test. In the stress controlled test the membrane behaved like a balloon in that it took a certain initial pressure to begin the inflation and very little extra pressure to continue the inflation.
4.1 Introduction

Field tests with the full displacement pressuremeter were conducted at three research sites in the lower Fraser River Valley. One site consisted primarily of sand, another primarily of organic silt, and the third primarily of clay. These sites were chosen because they reflected the three soil types and because of the other insitu tests which had been or were being conducted there.

The first site was in Langley, just off the Trans Canada Highway. The soil consists of normally consolidated clay with a layer of over consolidated material at the surface. The second site was at Boundary Road on Lulu Island in the Fraser River. The soil profile consists of organic silt over dense sand with a layer of peat near the surface. The third site was at McDonalds Farm on Sea Island in the Fraser River delta. The McDonalds Farm site has been well documented in many UBC research publications. The soil profile at McDonalds Farm consists of 13m of sand of varying density overlying silt and clay.
Figure 4.1  Site Location Map
4.2 Langley

Langley was chosen as a research site because the soil profile contains a fairly uniform clay layer at a readily accessible depth. This site was also one of the locations used in a research program involving determination of the undrained shear strength from the field vane and the cone penetrometer. As a result of the other research program, several cone profiles were already available at this site as well as several Nilcon field vane profiles.

4.2.1 Site Description

The site is located on the approach to the 232nd Street overpass, just off the Trans-Canada Highway in Langley, B.C. The piezometer-friction cone profile shown in Figure 4.2 gives a good indication of the soil stratigraphy. The upper 6m consists of two distinct layers of overconsolidated clay, with a very stiff layer located at 2.75m. Below 6m is a uniform layer of normally consolidated clay. Interbedded silt layers begin at 14m and continue below that depth. The water table is between 3 and 4 meters below the surface.

4.2.2 Results

The table shown in Figure 4.3 lists all the insitu tests that were conducted at Langley and used in this research program.
Figure 4.2  Langley cone profile
### TESTS CONDUCTED AT THE LANGLEY TEST SITE

<table>
<thead>
<tr>
<th>Test Designator</th>
<th>Instrument</th>
<th>Test Date</th>
<th>Comments</th>
<th>Depths at which PMTs were conducted</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Pencil Probe</td>
<td>06/09/84</td>
<td>Stress controlled 32mm tip</td>
<td>2.75, 6, 8, 10, 11.5, 15</td>
</tr>
<tr>
<td>Lanr2</td>
<td>Pencil Probe</td>
<td>06/09/84</td>
<td>Stress controlled 36mm tip</td>
<td>2.75, 6, 8, 10, 11.5, 15</td>
</tr>
<tr>
<td>Lanr3</td>
<td>Pencil Probe</td>
<td>16/11/84</td>
<td>Strain controlled 36mm tip</td>
<td>3, 6, 7, 8, 9, 10, 11</td>
</tr>
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<td>16/11/84</td>
<td>Strain controlled 32mm tip</td>
<td>3, 6, 8, 9, 10</td>
</tr>
<tr>
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<td>HPM</td>
<td>18/07/84</td>
<td>Stress controlled</td>
<td>3, 6, 8, 10, 12</td>
</tr>
<tr>
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<td>HPM</td>
<td>19/07/84</td>
<td>Stress controlled</td>
<td>3, 6, 8, 10, 12</td>
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</tr>
<tr>
<td>CPT #1</td>
<td>Seismic cone</td>
<td>02/10/84</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nilcon Field Vane Profile

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**Figure 4.3** Insitu tests conducted at Langley
Typical curves from each of the various types of tests obtained using the Pencil probe at a depth of 6m are shown in Figure 4.4. Examining Figure 4.4 several similarities are seen; the curves tended toward the same limit pressure, and the closing pressure was almost identical with all four tests. The liftoff pressures varied considerably and this will be discussed in section 4.2.2.2. The strain controlled test yielded a very erratic pressuremeter curve, which was a function of the hand cranking of the strain control device. This is discussed further in section 4.3.2.

Figure 4.5 compares the Pencil tests conducted with the 32mm diameter tip to the stress controlled HPMT. Again the pressuremeter curves all tended towards the same limit pressure. Note that all three of the tests had the same closing pressure.

4.2.2.1 Shear Moduli

Figure 4.6 is a profile of the shear modulus determined at the Langley site with the Pencil probe. The results shown are those obtained during the strain controlled tests. It was not possible to determine shear moduli from unload-reload loops performed with the stress controlled Pencil at any of the sites. There were two reasons for this. 1) The calibration corrections were a very significant factor in the calculation and the corrections were a function of so many variables that the appropriate corrections were very difficult to determine. 2) The
Figure 4.4: Pencil: Typical Curves at Langley
Figure 4.5 Comparison of Pencil curves with HPM curves: Langley
Figure 4.6  Profile of Shear Modulus at Langley: Pencil
control unit used for the stress controlled tests was not capable of accurately registering the small volume changes involved with unload-reload loops.

Figure 4.6 also shows the dynamic shear modulus (Gmax) determined with the UBC seismic cone using the downhole seismic technique. The seismic cone obtains Gmax values from the average shear wave velocity over a 1m depth interval. The shear modulus measured by the Pencel probe is at a shear strain level of approximately 1%. The shear modulus measured with the seismic cone is at very small strain levels. Shear modulus attenuation curves for clay such as those shown in Figure 2.2 suggest that the shear modulus at 1% strain should be 10 to 40% of Gmax depending on the plasticity index of the clay. The unload-reload moduli values measured by the Pencel probe are between 25 and 50% of Gmax measured with the seismic cone. There seems to be no discernible difference between the unload-reload moduli measured when the probe was inserted with the 32mm tip and when the probe was inserted with the 36mm oversized tip. Note that the ratio between the measured unload-reload moduli and Gmax appears to remain constant even in the very stiff layer where Gmax was 467 bar. Thin discontinuous sand layers were apparent on some of the cone profiles. The occurrence of such a layer would explain the high unload-reload G values recorded with the Pencel probe at 11.5m.

The unload-reload shear moduli measured with the HPM at Langley are presented in Figure 4.7. With the HPM, the unload-reload shear moduli were between 15 and 50% of those measured with
Figure 4.7 Profile of Shear Modulus at Langley: HPM
the seismic cone.

The soil is assumed to be undrained during an unload-reload loop performed while the probe is in clay. If this is the case, the mean effective stress in the soil will remain constant and therefore the shear modulus should be constant regardless of when during the test the unload-reload loops are conducted. In practice, very high pore pressure gradients are created during a pressuremeter test and some drainage will be occurring. As a result of drainage, the mean effective stress increases and the measured unload-reload shear modulus at later stages in the test will be somewhat higher than those in the initial stages. The shear modulus number, Kg, will be constant but this cannot be calculated unless the drainage conditions are known and the mean effective stress can be estimated.

The unload-reload shear modulus measured with the HPM is approximately 65% of that measured with the Pencel probe. The Pencel has a much smaller diameter and the excess pore pressures would tend to dissipate much faster than with the HPM. If this is the case then the shear moduli measured with the Pencel would be expected to be higher because of the higher mean effective stress. The shear moduli measured with the HPM were however, subjected to less attenuation because the unload reload loops were smaller than those performed with the Pencel probe.

There is insufficient data to draw any conclusions about the
differences between unload-reload shear moduli measured with stress and strain controlled tests with the HPM.

4.2.2.2 Horizontal Stress

The liftoff pressure measured by a full-displacement pressuremeter inserted in clay can be expected to be between the total pore pressure (the hydrostatic + the dynamic pore pressure) and the insitu horizontal total stress. The liftoff pressure measured will depend on the time allowed for drainage between the stop in penetration and the start of the pressure expansion test. The measured horizontal effective stress can therefore be expected to be between the dynamic pore pressure and the insitu horizontal effective stress. Immediately after insertion, the liftoff pressure could be expected to be dominated by the total pore pressure. This is complicated somewhat when the soil is unsaturated, as is the case with the overconsolidated layer above a depth of 3m. After all the pore pressures have dissipated, the liftoff pressure could be expected to be a measure of the horizontal total stress. The soil, however, has undergone some consolidation during the dissipation of the excess pore pressures. Therefore, it can be expected that the measured horizontal stresses will be somewhat higher than the insitu horizontal stresses.

Figure 4.8 shows a profile of the measured horizontal effective stress. Most of these tests were quick tests; ie. where a pressure expansion test was performed immediately after the stop
Figure 4.8 Profile of Measured Horizontal Effective Stress At Langley: Pencel
in penetration and the pore pressures were not given an opportunity to dissipate. The exceptions to this are the test results shown shaded in Figure 4.8 where the pore pressures were allowed to dissipate up to an estimated 90%. The results of the 36mm tip strain controlled tests appear to show that the opportunity for the pore pressures to dissipate had little influence on the measured liftoff pressure. The strain controlled test with the 32mm tip that was allowed time for an estimated 90% pore pressure dissipation shows a slightly lower horizontal effective stress than the other tests performed during that sounding but the measured horizontal effective stress is still very much higher than the vertical effective stress.

The tests performed using the 36mm tip recorded lower horizontal stresses than tests using the 32mm tip. This is to be expected because the 36mm tip produces a cavity larger than the probe and the soil can relax in towards the probe. It is not obvious why the stress controlled tests recorded consistently lower horizontal stresses than the strain controlled tests.

The horizontal effective stresses recorded by the HPM and presented in Figure 4.9 follow the same pattern as those recorded by the Pencil. The measured horizontal effective stresses are all greater than the vertical effective stress and seem to increase proportionally to the vertical effective stress. It is interesting to note the higher horizontal stresses measured in the overconsolidated layer above a depth of 6m. The results from the
Figure 4.9  Profile of Measured Horizontal Effective Stress At Langley: HPM
dissipation tests show no particular trends. Some of the
dissipated results are higher than the results from the quick
tests and others lower as would be expected. The results from two
of the strain arms are shown for each of the HPMT's. They show
that the arms were in good agreement. The few depths where only
one data point is shown are where the liftoff pressures measured
from the two arms were identical.

4.2.2.3 Undrained Shear Strength

Figure 4.10 presents the values of the undrained shear
strength determined from the difference between the limit pressure
and the liftoff pressure which were taken from the pressure versus
circumferential strain plots of the Pencel probe results. Two
trends are apparent: 1) the 32mm tip yields slightly lower $Su$
values than the 36mm tip and 2) the strain controlled tests yield
slightly lower results than the stress controlled tests. The
limit pressures recorded by the various types of tests all tended
towards the same pressure but the 32mm tip and the strain
controlled tests consistently yielded higher liftoff pressures.
The difference between the limit and liftoff pressures is
therefore smaller during those tests. The calculated undrained
shear strength is consequently smaller.

The calculated undrained shear strengths are almost all lower
than the results obtained from the field vane. This is in contrast
to results reported by Wroth, 1984 where the determination of
undrained shear strength using the self-boring pressuremeter was
Figure 4.10 Profile of Undrained Shear Strength Determined from the Pencil Curves
generally approximately 50% higher than those measured with the field vane. However, this would depend somewhat on the value chosen for the stiffness ratio, \( G / Su \). A value of \( \ln(G / Su) = 6.5 \) was chosen for this study. If a value of \( \ln(G / Su) = 5.0 \) was used excellent agreement would have been obtained between the Pencel derived \( Su \) and the field vane values.

Figure 4.11 shows the values of \( Su \) derived from the HPM curves. They follow the same trend as the field vane profile. In the overconsolidated layer the results are lower than the field vane results but in the normally consolidated soil the HPMT results are approximately 10 to 20% higher than the field vane results. Thus the HPM is indicating higher undrained shear strengths than the Pencel probe.

The second method of deriving the undrained shear strength, where the pressure is plotted against the logarithm of the volumetric strain, eliminates the need to estimate \( G / Su \). This method is based on the assumption that the material is elastic / perfectly plastic.

The values of \( Su \) derived from the Pencel probe using the second method are shown in Figure 4.12. They are very similar to the results obtained using the previous method. This would tend to confirm the estimate of the stiffness ratio used in the previous calculation. There is, however, a much greater degree of scatter in this second set of results. The results from the 36mm tip
Figure 4.11  Profile of Undrained Shear Strength Determined from the HPM Curves
Figure 4.12 Profile of Undrained Shear Strength Determined from the Pressure vs Log Volumetric Strain Plot: Pencil
strain controlled tests are consistently about twice as high as any of the other results and no explanation has been found for this. There does not seem to be a consistent trend in the results of the stress or strain controlled test.

The undrained shear strengths calculated from the HPM using the second method are shown in Figure 4.13. They are very similar to the Su values calculated using the first method. One exception is at ten meters. The higher value of measured undrained shear strength at this particular depth is likely due to the presence of a discontinuous sand lense.

4.3 Boundary Road Test Pile Site

The test program was conducted at a site on the corner of Boundary and Dike Road in New Westminster, B.C. This location was the site of a B.C. Ministry of Highways pile load test. The pile was loaded both axially and laterally. Details of the pile test program and the insitu testing program used to predict the pile's reaction is given by Robertson et al, 1985a. Their paper also compares the prediction of axial load capacity using the cone penetrometer, and the prediction of lateral displacement using the full-displacement pressuremeter data to the measured results from the pile load test.

At this site, the soil parameters dealt with in this paper are the shear moduli and the horizontal stresses.
Figure 4.13  Profile of Undrained Shear Strength Determined from the Pressure vs Log Volumetric Strain Plot: HPM
4.3.1 Site Description

The site is covered with approximately 3m of rubble fill. In order to prevent damage to the probes, a 3m deep trench was dug, and backfilled with loose sand at the locations of the insitu tests, and at the location of the test pile. Figure 4.14 shows a piezometer-friction cone profile of the site at Boundary Road. The cone profile shows 3m of loose sand overlying 2m of peat and 10m of organic silt. Underlying the organic silt is a dense layer of sand extending to a depth of about 30m.

A list of all the various insitu tests conducted at the Boundary Road Pile Load Test site and used as part of this research program are listed in the table in Figure 4.15.

4.3.2 Results

Figure 4.16 shows typical curves from the Pencil tests. The strain control test data appears very erratic. This is a function of the method used to run the tests. The strain control device was run with a hand crank. Variations in the speed of cranking caused variations in the head loss through the flexible tubing. The head loss in the tubing at the normal expansion rate is approximately 0.4 bar, which is greater than any of the fluctuations in the curve. As the exact rate of inflation is not recorded, the head loss correction can only be based on the average rate of inflation.
Figure 4.14 Boundary Road cone profile
### Tests Conducted at the Boundary Road Test Site

<table>
<thead>
<tr>
<th>Test Designator</th>
<th>Instrument</th>
<th>Test Date</th>
<th>Comments</th>
<th>Depths at which PMTs were conducted</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBC #1</td>
<td>Seismic cone</td>
<td>05/07/84</td>
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<tr>
<td>UBC #2</td>
<td>Seismic cone</td>
<td>12/07/84</td>
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<td></td>
</tr>
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<td>10/08/84</td>
<td>Stress controlled</td>
<td>5, 7, 9, 11, 13, 3</td>
</tr>
<tr>
<td>UBC #4</td>
<td>Pencil Probe</td>
<td>06/08/84</td>
<td>Stress controlled 36mm tip</td>
<td>5, 7, 9, 11, 13, 15</td>
</tr>
<tr>
<td>UBC #5</td>
<td>Pencil Probe</td>
<td>05/08/84</td>
<td>Stress controlled 32mm tip</td>
<td>5, 7, 8, 9, 10, 11, 12, 13, 14, 15</td>
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<td>UBC #6</td>
<td>HPM</td>
<td>18/08/84</td>
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<td>UBC #7</td>
<td>Pencil Probe</td>
<td>30/10/84</td>
<td>Strain controlled 32mm tip</td>
<td>3, 5, 5, 7, 9, 11, 13, 15</td>
</tr>
<tr>
<td>UBC #8</td>
<td>HPM</td>
<td>22/01/85</td>
<td>Strain controlled</td>
<td>1, 2, 3, 5, 5, 7, 9, 10, 11</td>
</tr>
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<td>Axial Pile Load Test</td>
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<td>Pile Driven to 67m</td>
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<td>Axial Pile Load Test</td>
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<td>Pile Driven to 78m</td>
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<td>Axial Pile Load Test</td>
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<td>Pile Driven to 94m</td>
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<td>Lateral Pile Load Test</td>
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<td>Pile Driven to 94m</td>
</tr>
</tbody>
</table>

Figure 4.15  Insitu Tests conducted at Boundary Road
Figure 4.16  Pencil: Typical Curves at Boundary Road
Four important factors can be observed from Figure 4.16:
1) The limit pressure of the various tests seem to be approximately equal; 2) The strain controlled test has a higher liftoff pressure than the stress controlled tests; 3) There does not seem to be a significant difference in shape between curves using the 36mm tip tests and curves using the 32mm tip. 4) The closing pressure from all three tests was the same. No strain controlled tests were performed with the 36mm tip.

Figure 4.17 compares a typical curve from the stress controlled HPMT with typical curves from the Pencel tests with the 32mm tip. The HPM indicates a liftoff pressure in the same range as the stress controlled Pencel test but the limit pressure was much higher. The results from the strain controlled HPMT are not shown because there were equipment problems and the results were not considered representative.

4.3.2.1 Shear Modulus

The site investigation included a sounding with the UBC seismic cone. The dynamic shear modulus measured from the seismic cone was the standard to which the shear moduli measurements from the pressuremeter were compared. The seismic cone measures shear wave velocity and thus the shear modulus at the insitu mean effective stress. In the clay at Langley, it was assumed that the soil was undrained during the PMT so that the mean effective stress stayed constant. In the peat and
Figure 4.17  Comparison of Pencil Curves with HPM Curves:  
At Boundary Road
organic silt deposit at Boundary Road the drainage conditions are less certain. Some drainage may be occurring during the test and the mean effective stress may be rising. However as the pore pressures are not known during the test, no attempt has been made to estimate the mean effective stress, or what effect the variations have on the shear modulus measurements.

Figure 4.18 compares the shear moduli measurements from the Pencel probe, the HPM, and the UBC seismic cone. The Pencel measurements fall within a range of 20 to 50% of the measurements from the UBC seismic cone. The measurements are relatively consistent and do not seem to vary over a large range. At a given depth, the larger values of shear modulus were generally measured from unload-reload loops performed at later stages in the test. This is to be expected from the above discussion on drainage.

The HPM results generally show less scatter than those from the Pencel at any individual depth. The exception to this is at 1m and at 10m. Near the surface the sand was free draining and the mean effective stress increased dramatically with consequent increases in the shear modulus as the test progresses. From 9 to 11m occasional sandy silt layers were identified in the adjacent cone penetration soundings. Wherever one of these layers occurred, the soil was allowed to drain with a resulting increase in shear modulus as the test progressed. These layers were stiffer than the surrounding soil, a result which was reflected in higher shear modulus values measured by the pressuremeter. Thin stiff layers did not show up in the seismic cone profile of shear modulus.
Figure 4.18  Profile of Shear Modulus at Boundary Road:
  Pencel and HPM
because the shear wave velocity used to calculate the shear modulus was averaged over a 2m interval.

4.3.2.2 Horizontal Stresses

The horizontal effective stresses measured with the Pencil are presented in Figure 4.19. They show three significant trends. First, the values all increase at approximately the same rate with depth. This rate is similar to the rate of increase of the vertical effective stress. Second, the 36mm tip stress controlled test recorded the lowest horizontal stresses. The 36mm tip is expected to indicate the lowest horizontal stresses because it forms an oversized hole, and the soil can relax up against the probe. The third trend is consistent with that observed from the tests at Langley, namely that the strain controlled test indicates higher horizontal stresses than the stress controlled test.

Figure 4.20 shows the horizontal stresses measured from the stress controlled HPMT's. The data is shown in pairs indicating readings taken from two separate strain arms. The fact that the two arms responded similarly indicates a good test. The one set of test results at 9m that indicated a much higher horizontal stress was in a thin discontinuous sand layer, where much higher strengths were also noted.
Figure 4.19 Profile of Measured Horizontal Effective Stress At Boundary Road: Pencil
Figure 4.20 Profile of Measured Horizontal Effective Stress At Boundary Road: HPM
4.4 McDonalds Farm

McDonalds Farm has been a research site for the UBC insitu testing group since 1979. Many different types of tests have been performed at this site, and the soil profile and properties are well known. This was the site of some of the doctoral research, documented in Robertson, 1982 directly comparing the results of self-boring and full displacement pressuremeter tests. These results are presented for comparison with the results obtained from this research project.

The main difference between McDonalds Farm and the other two research sites is the drainage conditions. The pressuremeter tests at McDonalds Farm were performed in the layer of clean sand where the permeability was high enough that the sand remained drained at all times during the tests.

4.4.1 Site Description

The research site at McDonalds Farm is comprised of 2m of silt overlying 11m of clean sand. Between 13 and 15m there is a transition zone of silty sand, and below 15m, the soil consists of a soft clayey silt. Figure 4.21 shows a typical CPT profile.

The table presented in Figure 4.22 shows the insitu tests that were performed at McDonalds Farm and analyzed in this study.
Site Location: MCDONALDS FARM  
CPT Date: OCT23 1984

On Site Loc: CENTER OF PNTS  
Cone Used: 15 SQ.CM. SEIS

Fig. 4.21: McDonalds Farm cone profile
TESTS CONDUCTED AT MCDONALDS FARM

<table>
<thead>
<tr>
<th>Test Designator</th>
<th>Instrument</th>
<th>Test Date</th>
<th>Comments</th>
<th>Depths at which PMTs were conducted</th>
</tr>
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<tr>
<td>SBPM #1</td>
<td>HPM</td>
<td>03/12/80</td>
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<td>HPM</td>
<td>11/02/81</td>
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<td>HPM</td>
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<td>05/06/84</td>
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<td>Stress controlled</td>
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<td>CPT</td>
<td>Seismic cone</td>
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* The pressuremeter was self-bored into the ground
4.4.2 Results

Typical pressuremeter curves obtained with the Pencel probe at McDonalds Farm are shown in Figure 4.23. The higher liftoff pressure from the 32mm tip strain controlled results was consistent with the results from Langley and Boundary Road. It was interesting to note that the other three tests all had similar liftoff pressures, and that all four types of tests had similar closing pressures. The closing pressure is a measure of the equilibrium pore pressure for pressuremeter tests in sand. Note that with sands there is no theoretical limit pressure so the fact that the curves did not appear to converge is not surprising.

The traditional Menard type of pressuremeter is placed in a pre-bored hole and exhibits an S shape curve upon inflation. Only in a very few of the tests with the oversized tip (36mm tip) was this ever visible with the Pencel probe. The curves shown in Figure 4.23 were typical of the curves obtained.

Figure 4.24 compares the Pencel tests conducted with the 32mm tip to the stress controlled HPMT. The liftoff pressure obtained from the stress controlled HPMT was comparable with the liftoff pressure obtained from the stress controlled Pencel test. The closing pressures were similar for the two types of tests where closing pressure was measured.
Figure 4.23  Pencil: Typical Curves at McDonalds Farm
Figure 4.24 Comparison of Pencel curves and HPM curves: At McDonalds Farm
4.4.2.1 Shear Modulus

Shear modulus is dependent on the mean effective stress. The clean sand at McDonalds Farm is fully drained so there is no excess pore pressure generated during the tests and the mean effective stress increases with radial stress. In order to compare the measured shear modulus with the shear modulus obtained from the seismic cone, or to compare values obtained at different times during the PMT the shear modulus must first be normalized to the in situ mean effective stress as was discussed in section 2.2.

A shear modulus profile obtained with the strain controlled Pencel probe is shown in Figure 4.25. The moduli measured with the Pencel were approximately 10 to 20% of Gmax measured with the UBC seismic cone. The results did not seem to differ significantly whether the 32mm tip or the oversized tip was used. These moduli were obtained from 5cm unload reload loops. This represents about 2-2.5% strain. This was within the bounds set by Wroth, 1984 where the sand will behave elastically. Although Seed and Idriss' shear modulus attenuation curves presented in Figure 2.2 do not extend to this shear strain level they would indicate that the measured shear modulus at 2% strain would be expected to be less than 10% of Gmax.

The Pencel shear moduli results obtained with 5cm$^3$ loops at McDonalds Farm appear to be more consistent than the shear moduli results obtained with 2cm$^3$ loops at Langley. The calibration corrections are quite large compared to the scale of an unload
Figure 4.25  Profile of Normalized Shear Modulus
At McDonalds Farm: Pencil
Figure 4.26 Profile of Normalized Shear Modulus
At McDonalds Farm: Stress Controlled HPM
Figure 4.27  Profile of Normalized Shear Modulus
At McDonalds Farm: Strain Controlled HPM

LEGEND

□  STRAIN CONT #1
X  STRAIN CONT #2
— GMAX (SEISMIC)
reload loop, and did not increase linearly with the size of the loop. The larger unload-reload loops have a proportionally smaller calibration correction and appear to yielded more consistent results.

Shear moduli measured with the HPM are shown in Figure 4.26. Two types of tests are shown on Figure 4.26. The self-boring pressuremeter results are plotted against the results from the three stress controlled full displacement pressuremeter tests. The self-boring tests were also run in a stress controlled manner. The moduli measured with the stress controlled HPM fall within the range of 20 to 50% of Gmax measured with the UBC seismic cone. It was expected that the results would be higher than the results from the Pencel probe because the unload-reload loops represent a smaller strain with the HPM than with the Pencel. Therefore there is less shear modulus attenuation with the HPM.

The normalized shear modulus measured with the strain controlled HPM is presented in Figure 4.27. There is a little more scatter than with the stress controlled test but the trend of the results is almost the same.

4.4.2.2 Horizontal Stresses

The horizontal effective stresses recorded by the strain controlled Pencel probe are shown in Figure 4.28 and those recorded by the stress controlled Pencel probe in Figure 4.29.
With both types of tests, those recorded with the 32mm tip have higher liftoff pressures than those with the 36mm tip. With the strain controlled tests the liftoff pressures with the 32mm tip are much higher. Comparison between the two figures indicate that the liftoff pressures from the strain controlled test are much higher than those from the stress controlled test. No explanation is readily apparent for this observation.

The horizontal stress is generally assumed to be a parameter that the self-boring pressuremeter is capable of measuring. This is however less applicable in sands where small initial disturbances can lead to large errors in determining the horizontal stresses. Figure 4.30 presents the liftoff pressures measured by the self-boring pressuremeter. Also shown in Figure 4.30 are the liftoff pressures measured with the stress controlled full displacement pressuremeter. There is actually less scatter among the full displacement results than there is with the self-boring results. Note that several tests recorded liftoff pressures less than the equilibrium pore pressure and therefore recorded negative horizontal effective stresses.

The liftoff pressures recorded with the strain controlled full displacement HPM are shown in Figure 4.31. The most significant difference when compared to the stress controlled tests is the lack of points above the vertical effective stress line. Even more often than with the stress controlled tests, liftoff pressures were recorded that were less than the equilibrium pore pressure.
Figure 4.28  Profile of Measured Horizontal Effective Stress At McDonalds Farm: Strain Controlled Pencil
Figure 4.29 Profile of Measured Horizontal Effective Stress At McDonalds Farm: Stress Controlled Pencil
Figure 4.30 Profile of Measured Horizontal Effective Stress At McDonalds Farm: Stress Controlled HPM
Figure 4.31 Profile of Measured Horizontal Effective Stress At McDonalds Farm: Strain Controlled HPM
Note that the Pencil strain controlled tests recorded horizontal stresses that were much higher than those recorded by the stress controlled test. Whereas the strain controlled HPMT's recorded horizontal stresses that were lower than the ones recorded by the stress controlled tests.
Chapter 5
Conclusions

5.1 Summary

This research study was performed with the intention of examining the suitability of using the full displacement pressuremeter (FDPM) for determining shear modulus, in situ horizontal stresses, and undrained shear strength. The variables examined were; the type of pressuremeter, whether the pressuremeter was run in a stress or a strain controlled manner, the size of the tip pushed in front of the pressuremeter, and whether time was allowed for the dynamic pore pressures to dissipate. Tests were conducted in sand, silt, and clay.

5.2 Shear Modulus

The shear modulus measured with the FDPM compared very well with the dynamic shear modulus measured with the seismic cone. Adjustments were made to account for the differences in strain level, and mean effective stress. The size of the tip in front of the instrument did not affect the results. As was expected there was no difference between shear moduli calculated from stress controlled tests with the HPM and strain controlled tests with the HPM. The shear modulus measurements from tests where the HPM were installed in a self-boring manner were very similar from the measurements from tests where the probe was installed in a full displacement manner. The shear modulus measurements from the
strain controlled Pencel probe were very similar to the HPM measurements. However, the membrane stiffness correction associated with the Pencel tests was a very significant factor in soft soils. The membrane calibration was dependent on so many variables in a stress controlled test that it was not possible to determine the correction with any degree of certainty. As a result it was not possible to determine shear modulus from any of the stress controlled Pencel tests.

5.3 Insitu Horizontal Stress

In general, the attempts to determine the insitu horizontal stress by examining the liftoff pressure were totally unsuccessful. There does not appear to be any possibility of improving this technique to the point where it would be a useful method of analysis.

The liftoff pressure was lower when an oversized tip was placed in front of the FDPM. This was to be expected as the soil was allowed to relax into the cavity surrounding the probe. Also the liftoff pressure was considerably higher when the tests were run in a strain controlled manner as opposed to a stress controlled manner. The liftoff pressures were so variable that it was difficult to determine if the liftoff pressure showed any of the expected decrease when the dynamic pore pressures were given an opportunity to dissipate before the pressure expansion test was run. The general trend of the liftoff pressures was to increase
with depth but they did not appear to hold any other relationship with the insitu horizontal stresses.

5.4 Undrained Shear Strength

The undrained shear strengths of clay determined using cavity expansion theory compared very well with undrained shear strengths determined using the field vane. The undrained shear strength calculation is dependent on the liftoff pressure and the results reflected the observations that were made about the liftoff pressure. The tests where the highest liftoff pressures were measured (i.e. the strain controlled tests and the tests with the smaller tip), were also the tests where the lowest undrained shear strengths were calculated. The HPM results were generally about 25% higher than those from the Pencel probe.

5.5 Recommendations for Further Research

The FDPM appears to be a practical way of measuring the shear moduli of many types of soil and the undrained shear strength of clay. Further research should be conducted with the FDPM with those goals in mind. The determination of insitu horizontal stresses with the FDPM was not possible and the results do not appear promising enough to warrant further research. Some specific areas of research are suggested below:

1) Further research should be conducted into the differences between the curves that are produced when the pressuremeter is run
stress controlled and when it is run strain controlled. This study indicated that there were some difference but there was insufficient data available to draw any conclusions.

2) Pressuremeters should be equipped with pore pressure measurement capability. This would be especially useful when trying to determine the mean effective stress at which the shear modulus is being measured.

3) The strain control device should be fitted with a motor drive. This would eliminate the head loss variations due to inconsistent hand cranking. A motor would make it easy to completely standardize the strain rate and the size of the stress cycle used in determining shear moduli.
REFERENCES


Hughes, J.M.O. and Robertson, P.K., 1984, "Full-Displacement Pressuremeter Testing in Sand", University of B.C., Civil Engineering Dept., Soil Mechanics Series No. 78


