Association of Geotechnical & Geoenvironmental Specialists

# AGS Guide to the Selection of Geotechnical Pressuremeter Testing

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## Definitions

Like many other technical disciplines, pressuremeter testing uses multiple acronyms and has some specific terminology. The table below outlines definitions of the more common terminology used.

| | |
|---|---|
| DMT | Flexible Dilatometer |
| Equipment | An entire pressuremeter system including measuring system, probe, and pressure control system |
| HPCP | High-pressure control panel, used to control the flowrates and regulate the pressure of fluid with certain pressuremeter types |
| HPD | High-pressure dilatometer |
| In situ | Used to describe testing undertaken in the original position, actually within the ground |
| Loops | Unload / reload cycle, used to determine linear and non-linear stiffness in soils and rocks |
| Membrane | Flexible cylinder, typically made of wrapped or extruded nitrile, sometimes reinforced at either end with Kevlar strands |
| MPM | Ménard pressuremeter |
| PMT | Pressuremeter test |
| Pressuremeter | All pressuremeter types |
| Probe | Downhole instrument which is inflated or actuated using a compressed fluid |
| Radial stress | Stress applied perpendicular to the central axis of a cylindrical instrument |
| RPM | Reaming pressuremeter |
| SBP or SBPM | Self-boring pressuremeter, sometimes called a self-bored pressuremeter |
| Test Pocket | The cavity formed within the ground created with specific dimensions as required for the insertion of a pressuremeter |

# 1 Introduction

Pressuremeter testing (PMT) is a recommended in situ testing technique for ground investigation, referenced in Eurocode 7 (EN 1997-2). "The objective of a pressuremeter test is to measure the in situ deformation of soils and rocks by the measured expansion of a cylindrical pressurised membrane" (EN 1997-2).

Pressuremeters are typically used to provide in situ stress, strength and stiffness parameters of soils and rocks. This type of testing can provide high quality information since disturbance to the in situ ground state is minimised, particularly when compared to samples removed for geotechnical laboratory testing.

The acronym 'PMT' covers a range of equipment types which vary in complexity and sophistication that can operate in different ground conditions, providing information on ground properties. The testing procedure and instrumentation is generally complex and operated by specialist engineers and contractors. Testing is carried out in accordance with the relevant sections of BS EN ISO 22476, and procedures vary depending on the type of equipment deployed.

All pressuremeters are deployed downhole and a test is undertaken by applying a load to generate radial displacement at the borehole wall (except for flat dilatometers). Both the load and displacement are recorded throughout the test. The varying load is dictated by the pressure within the probe itself.

The change in pressure and resulting movement at the borehole wall illustrate a cavity expansion with an increase in cavity strain. Solutions of varying complexity can be applied to determine engineering parameters, such as stiffness and strength. It is possible to avoid empiricism, depending on the specific pressuremeter used. The type of test itself may vary depending on factors such as number of unload/reload cycles, and the addition of creep holds. Furthermore, the insertion technique, as well as the approach to applying the load, dictate the quality of the test.

## 1.1 Types of pressuremeter

This guide covers a variety of pressuremeter types which are commonly used in the United Kingdom. These include:

- Volumetric techniques, such as Ménard pressuremeters. This equipment measures change in volume (where the digital or analogue instrumentation is typically located at the surface).
- Direct strain techniques such as manufactured by Cambridge Insitu, RocTest pressuremeters and Oyo Instruments. This equipment is different to volumetric pressuremeters as they measure radial movement, typically across three axes. The instrumentation in these instances are commonly downhole, at the test depth.
- Flat dilatometers such as Marchetti DMTs. This equipment records the load required for a fixed amount of linear movement (typically at 0.1mm and 1.1mm).

Dependent on the equipment selected, PMT can be undertaken in materials ranging from a soft clay to competent rock, however, not all tools are suitable for all ground conditions. Section 2 describes the different types of equipment in detail.

A pressuremeter can be inserted into the ground through several different methods, depending on the equipment employed. Pre-bored pockets, into which the probe is lowered, can be created using rotary drilling. Self-boring pressuremeters are lowered into an existing cased borehole and then self-bore down to create a pocket. If the ground is soft enough, certain probes can be pushed, this includes directly pushing into virgin ground, pushing into an existing CPT pilot hole, or placing the probe in a pocket created by SPT tooling. These are discussed in more detail in Section 2.

## 1.2 Relationship with wider investigation

Pressuremeter testing is usually carried out as part of wider ground investigations. Most pressuremeters require heavy plant such as a rotary rig, cable percussive rig, or cone truck to allow for borehole advancement at depth. Each type of instrument will have specific plant requirements, as described in Section 4.

It is typical for pressuremeter testing to be undertaken by a specialist contractor, engaged either by the ground investigation contractor, or consultant. Prior to designing a testing programme, it is useful to understand the desired parameters and the expected ground conditions. This will help inform equipment selection and allow the PMT specialist to determine the most appropriate test procedure. It is common therefore for PMT specialists to be involved in early discussion with the investigation supervisor and ground investigation contractor. Section 6 contains more detail on pressuremeter test results and data used in design.

Due to the specialism of PMT techniques, communicating the analysis to the end user must be conducted carefully, to ensure that both the value of the data and their limitations are understood.

Pressuremeter testing may be an alternative and/or a common complementary technique to sampling and laboratory testing. The results obtained through PMT are less likely to be influenced by disturbance; in situ testing eliminates disturbance associated with sampling, handling, transportation, and core preparation. However, there is still disturbance associated with drilling; this can be almost fully eliminated through high quality self-boring. It is advantageous that PMT applies a load to a significant quantity of material; an SBP affects approximately 0.167$m^2$, thus enabling large scale effects to be measured. This allows the reality of natural variations within a specific stratum to be considered in situ.

It is common for pressuremeter testing and the acquisition of suitable samples used for laboratory testing to be undertaken in a complementary fashion, as part of the same borehole. During pre-bored PMT, laboratory testing can be undertaken on core obtained during pocket formation, allowing for the option of the direct comparison. See Section 4.1 for more information on suitable coring options for pre-bored PMT.

## 1.3 Framework of experience

As with all ground investigation techniques, it is necessary that all main parties involved have an awareness of in situ testing, so as to ensure there is adequate experience prior to engaging in the works. The end users of the test results should ideally have a framework of experience such that they are able to recognise if the results are plausible. Anyone interacting with PMT data should be able to assess results and recognise gross errors or unusual variations in the ground profile and should be able to check against known observed behaviour. Specialist PMT analysts should be able to justify analytical decisions based on a framework of experience and knowledge and be able to identify and communicate any oddities in the data.

## 1.4 Engineering parameters for design

All types of pressuremeter can provide stiffness results when testing in soil or rock. If a pressuremeter fails the test material, a value for a strength parameter can be given. Dependent on the equipment type, in situ horizontal stress can either be observed, calculated, or correlated using empirical methods.

PMT is a useful technique for determining the stiffness of a material. If the equipment type and test procedure allow, this should include an assessment of the variation of stiffness with strain and stress level. (See Section 6.)

If the equipment has the capacity to measure direct pressure and direct displacement, it is simple to convert these measurements into stress and strain. From here, the pressuremeter data can be analysed to produce key engineering parameters for geotechnical design, without the need for empirical methods. This procedure requires careful categorisation of the data. Transparent data processing and appropriate analysis is vital to ensure accurate determination of geotechnical parameters.

If the equipment is reliant on measuring volumetric change to determine the quantity of displacement, there will be a reliance on empirical corelations.

Some of the parameters that can be directly derived from pressuremeter data include the following:

| | |
|---|---|
| In situ horizontal stress | $\sigma_{ho}$ |
| Yield stress | $P_f$ |
| Limit Pressure | $P_{lm}$ |
| Undrained shear strength | $c_u$ |
| Frictional strength properties[1] | $\phi_{cv}$ , $\phi_{pk}$ , $c'$ |
| Shear modulus (linear and non-linear) | $G$ |
| Rigidity index | $i_r$ |

With supporting information or estimated values such as Poisson's ratio, unit weight or ambient pore water pressure, it is possible to derive other engineering parameters indirectly, including the following:

| | |
|---|---|
| Earth pressure co-efficient at rest | $K_0$ |
| Over consolidation ratio | $OCR$ |
| Young's modulus | E |

The parameters obtained are useful to input directly into design or simply convert to relevant modelling specific input parameters. Section 6.1 has more detail on determining parameters from pressuremeter test data.

## 1.5 Challenges with processing pressuremeter data

Both volumetric and flat dilatometer techniques rely on empirical methods to determine engineering parameters. This means that the results are only as good as the empirical correlation and the material these relate to. However, both techniques are simpler than direct strain techniques, so if the confidence in the applied correlations is high, or design sensitivity is low, then they are an effective option. Furthermore, volumetric pressuremeters provide a very specific output (such as the Ménard modulus), which might be of key importance to the investigation.

[1] An estimate of the ambient pore water pressure is required to understand effective stress.

Though accuracy is likely to be higher when testing with direct strain pressuremeters, there are time and result complexity elements that must be considered. Therefore, this may not be the most appropriate technique in some circumstances.

Equipment with low resolution sensors, or a slow data read-rate will provide obvious challenges when the time comes to analyse the datasets produced by this equipment. This can limit confidence, and draw a contrast when compared to other high resolution pressuremeter types. Additionally, there can be difficulties identifying which data is influenced by drilling disturbance if low resolution instrumentation is deployed.

Pressuremeters with a flexible cylindrical membrane have the potential for membrane ruptures to occur during testing. Ruptures can result in loss of pressure, early test termination and loss of required data for analysis. It is not possible to retest the same zone if a membrane rupture occurs and inadequate data is obtained.

**Figure 1: A direct-strain pressuremeter test that has suffered a membrane rupture resulting in catastrophic and sudden loss of pressure**

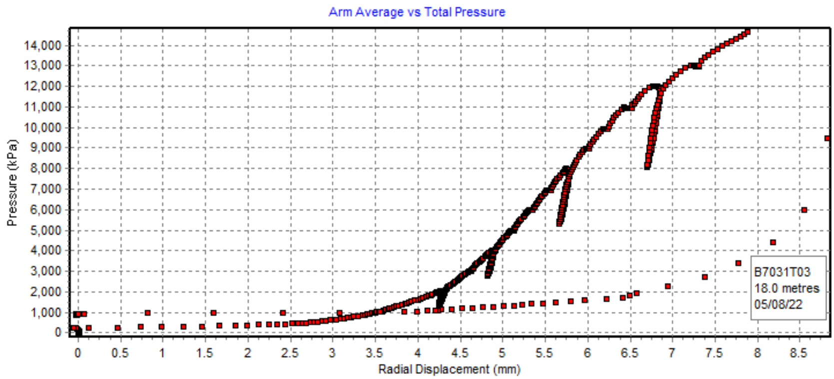



*Image by Cambridge Insitu Ltd, 2022.*

It can sometimes be challenging to tell if a test was sufficiently successful on-site prior to full analysis, however operator experience will help gain an early understanding.

A further fundamental challenge to good quality parameter determination is that PMT requires high quality drilling to be conducted to form a pocket for instrument installation. If drilling is inadequate, or the pocket is allowed to collapse, then the ground will be too disturbed to give representative results. (See Section 4 for details on drilling and borehole preparation.)

## 1.6 Relevant industry standards

Pressuremeters are discussed in general terms in BS 5930 (2015) Section 43. Specific standards for each technique discussed in this document are provided in the following:

- Volumetric pressuremeter: BS EN ISO 22476-4:2021.
- Flat dilatometer: BS EN ISO 22476-11:2017.
- Direct strain self-boring pressuremeter: BS EN ISO 22476-6:2018.
- Direct strain full displacement pressuremeter: BS EN ISO 22476-8:2018.

- Direct strain flexible dilatometer (including tools such as the High-Pressure Dilatometer): BS EN ISO 22476-5:2012.

Clause 9.5 of the third edition of the UK Specification for Ground Investigation (2022) covers pressuremeter and dilatometer tests. The project requirements will be specified in S1.16.10 to 13 and the interpretative approach specified in S1.24.4.

Digital data requirements are specified in AGS documentation (current format 4.1.1) using headings PMTG, PMTD, and PMTL.

## 2 Equipment description

Several types of pressuremeter exist, suiting different applications and ground conditions. However, most pressuremeters have a cylindrical flexible membrane which expands when pressure is applied by compressed air or oil via an umbilical. This expansion causes a reaction on the borehole wall resulting in a deformation.

### 2.1 Volumetric pressuremeters

Volumetric pressuremeters (such as those developed by Louis Ménard in the 1950s) measure ground displacement via a change in fluid volume injected into the pressuremeter, as opposed to direct measurement of radial displacement using strain arms. The test is performed using a cylindrical probe, containing a central measuring cell positioned between two guard cells (see Figure 2, below). The probe is inserted into a pre-bored test pocket on the end of rods, with a connecting line linking the cells to the surface. Once in the test pocket, fluid is injected under pressure into the central measuring cell, and compressed gas into the guard cells. This expands the probe to induce displacement of the ground. The pressure applied and associated volume expansion of the measuring cell are measured and recorded, to obtain the stress-strain relationship of the ground under test. The sensors for measuring the pressure and volume change are in equipment on the surface, as opposed to being downhole, as with direct-strain radial pressuremeters discussed elsewhere.

**Figure 2: Annotated diagram of Ménard pressuremeter**

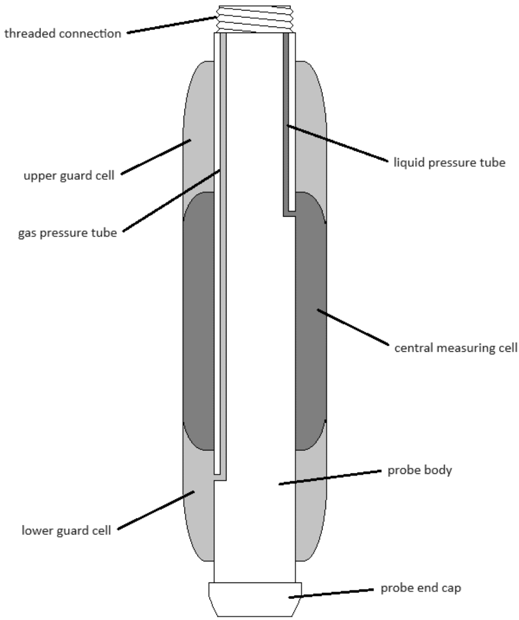



*Image by In Situ Site Investigation Ltd, 2024*

Typically, volumetric pressuremeters are rated to a maximum pressure capacity of 5MPa, although higher pressure equipment (up to 10MPa) is available. The most common pressuremeter used is 60mm in diameter, with a volumetric expansion capacity of up to 700cm$^3$. There are also 76mm and 44mm diameter volumetric pressuremeters that can be used to suit different borehole sizes, see Table 1 for further details. Testing can be carried out in most types of homogenous superficial deposits and weaker rock, depending on the equipment used.

The most commonly used volumetric pressuremeter is the Ménard device, manufactured by, for example, Apageo in France, and Roctest in Canada. Testing in the UK is covered under BS EN ISO 22476-4, relating specifically to the Ménard procedure. These types of instruments are also referred to as pre-bored pressuremeters, based on the method of insertion into the ground, but note that there are also direct-strain reading pre-bored pressuremeters (e.g. HPD) as discussed later.

The test method is described in BS 5930, which also notes that Ménard-style tests can be carried out using other types of equipment, these being referred to as "emulated Ménard tests".

### 2.1.1 Calibrations

Two different calibrations are carried out to allow corrections to be made for:

- the effect on the measured pressure due to the inherent stiffness of the measuring cell's rubber membrane.
- the effect on the measured volume change due to the expansion of the connecting pressure hose.

These are referred to as the pressure loss and volume loss calibrations. The pressure loss calibration is carried out in free air and is undertaken to measure the resistance to expansion of the rubber membrane (see Figure 3, below). This resistance is then subtracted from the pressure values acquired during the test, for each recorded volume expansion.

**Figure 3: An example of a pressure loss calibration**

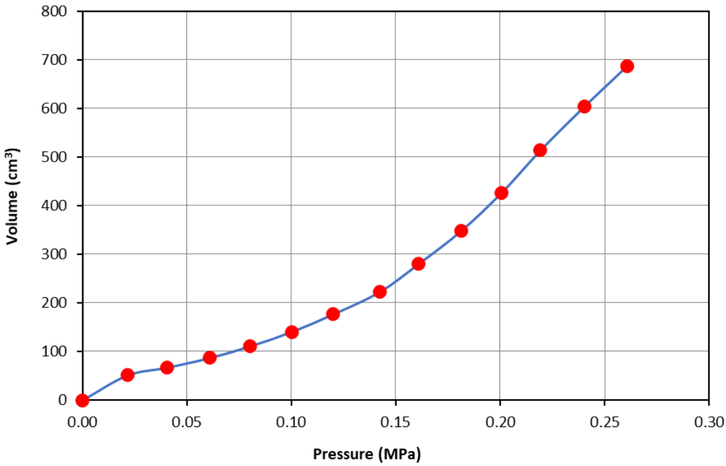



*Image by In Situ Site Investigation Ltd, 2024*

The volume loss calibration is carried out with the instrument enclosed in a rigid steel cylinder which prevents expansion of the cells. The calibration measures the expansion of the water injection hose at increasing pressure stages, up to the maximum pressure of the tests to be performed. The volume loss calibration coefficient is derived from the slope of the linear points of the calibration. This can then be subtracted from the total water volumes recorded during the course of a test.

**Figure 4: An example of a volume loss calibration undertaken within a steel cylinder.**

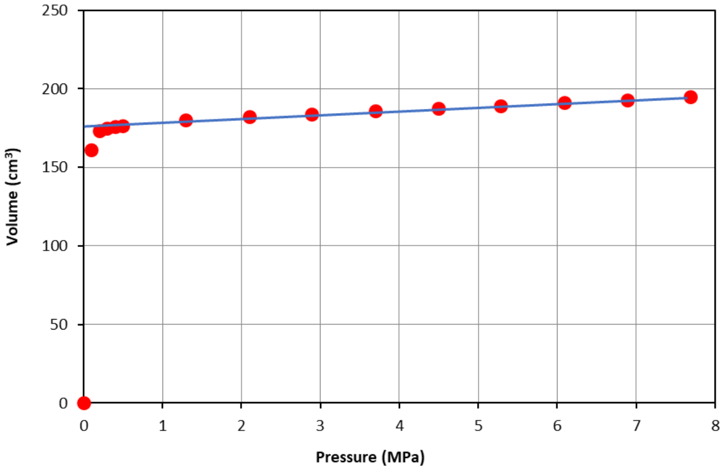



*Image by In Situ Site Investigation Ltd, 2024*

### 2.1.2 Probe insertion details

Details of the available instruments are given below in Table 1 and Table 2.

**Table 1: MPM instrument sizes**

| Instrument size | MPM | | |
|---|---|---|---|
| | **44mm** | **60mm** | **70mm / 74mm** |
| Minimum test pocket length (m) | 1.20 | 1.00 | 1.00 |
| Test pocket diameter (range in mm) | 46 to 52 | 60 to 66 | 74 to 80 |
| Minimum casing diameter ID (mm) | 75 | 75 | 125 |
| Location of test centre (m above PMT base) | 0.40 | 0.30 | 0.30 |

*Table by In Situ Site Investigation Ltd, 2022*

**Table 2: MPM installation details**

| Installation method | MPM | | |
|---|---|---|---|
| | 44mm | 60mm | 70mm / 74mm |
| Rotary | ✓ | ✓ | ✓ |
| Sonic (without vibration function) | ✓ | ✓ | ✓ |
| Cable percussion | ✓* | × | × |
| CPT truck | ✓** | × | × |

*Extended Standard Penetration Test used to create pocket
**Depending on ground conditions to be tested

*Table by In Situ Site Investigation Ltd, 2022*

### 2.1.3 Description of test

Tests using volumetric pressuremeters are generally carried out as stress-controlled tests with incremental cavity expansion where pressure is increased in steps and held constant for a short time.

The test is controlled by the operator at the surface and commences by injecting fluid into the cells of the instrument, via the hose line. The pressure and volume within the measuring cell is monitored and controlled throughout the test period. Pressure steps are carried out at designated intervals during the test, depending on the expected maximum pressure, with each step held constant and typically maintained for 60 seconds. These steps are carried out throughout the loading stage of the test to completion.

The equipment used to control the test can be either manual (operator controlled), automatic (computer controlled), or a combination of both. The test will be classified based on the type of pressure and volume control unit used:

A - pressure and volume control = Manual; reading and recording = Manual

B - pressure and volume control = Manual; reading and recording = Automatic

C - pressure and volume control = Automatic; reading and recording = Automatic

During each pressure step, the fluid pressure and volume within the measuring cell are read a number of times: for Type A tests, readings are taken at 15, 30 and 60 seconds once the step pressure is reached; for Type B and C tests, the readings are recorded every 1 second and reported at 1, 15, 30 and 60 seconds. An example volumetric pressuremeter test curve is shown below in Figure 5. These time related readings are used for the assessment of material creep.

**Figure 5: A theoretical volumetric pressuremeter test curve.**

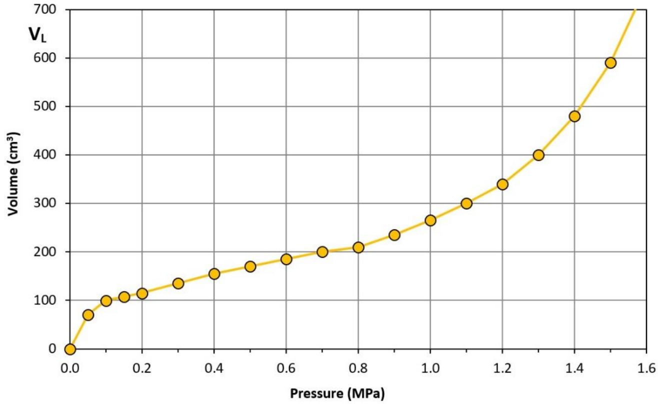



*Image by In Situ Site Investigation Ltd, 2022*

### 2.1.4 Terminating the test

The test is ideally terminated when sufficient data points are obtained to define a test curve from which the material parameters can be calculated, see section below. However, tests may be terminated early when the maximum pressure or volume capacities of the instrument are reached, or in the event of a membrane burst or other equipment failure.

### 2.1.5 Assessment and presentation of test results

Analysis of tests using Ménard-type volumetric pressuremeters is carried out to provide parameters specific to the test method, unlike for direct-strain devices which are generally analysed to derive fundamental soil parameters.

Interpretation of the test curve is carried out to determine the following parameters:

| | |
|---|---|
| Ménard pressuremeter modulus | $E_M$ |
| Ménard pressuremeter limit pressure | $P_{lm}$ |
| Ménard pressuremeter creep pressure | $P_f$ |

A theoretical volumetric pressuremeter curve is shown below, Figure 6, to illustrate the derivation of these parameters. The plot shows the corrected volume-pressure data, i.e. after corrections have been made for membrane stiffness and fluid line expansion (yellow points), and the creep at each pressure increment (blue points). The creep represents the increase in volume measured during each test pressure increment between 30 and 60 seconds. The data used to present the overall volume-pressure response during the test is based on the final reading at each increment.

The initial part of the test comprises the readings obtained during probe expansion up to the point of contact ($P_1$) between the outer surface of the probe and the test pocket wall. From $P_1$ to $P_2$, the readings represent the pseudo-elastic section of the test curve, where the probe is expanding against the deforming ground. The Ménard modulus ($E_M$) is obtained from the slope of a best fit line to this section. The Ménard limit pressure ($P_{lm}$) is defined as the pressure where the original cavity volume is doubled, for instance when the corrected volume of the probe's central measuring cell is doubled. The limit pressure is at the point where:

$$V_L = V_c + 2V_1$$

where $V_c$ is volume of the measuring cell and $V_1$ is the volume at $P_1$

The creep pressure ($p_f$) is estimated from the creep curve as the pressure at the inflection point along the creep curve, and should lie between $p_2$ and $p_{lM}$. The creep pressure generally corresponds to the end of the linear pseudo-elastic section, and represents the onset of plastic yielding of the ground.

**Figure 6: A theoretical volumetric pressuremeter curve to illustrate the derivation of the fundamental parameters.**

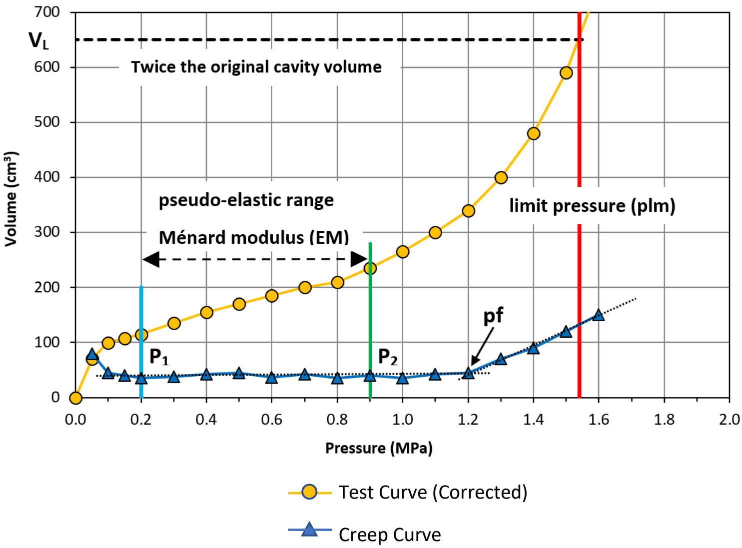



*Image by In Situ Site Investigation Ltd, 2022*

## 2.2 Flat dilatometers

The Flat Dilatometer (DMT) equipment consists of a steel blade that has a circular steel membrane on one side. The DMT blade is inserted into the ground vertically on a series of rods. At fixed depth intervals (generally 0.20m) the penetration is stopped and the membrane is pressurised with compressed gas (generally nitrogen or compressed air) which induces displacement of the material. The test procedure is detailed in BS EN ISO 22476-11:2017, with additional recommendations contained in ASTM D6635-15 and the ISSMGE publication TC16: 2001 & 2015.

The DMT blade and the gas bottle are both connected to a control unit in the rig. The pneumatic-electrical cable that connects the DMT blade to the control unit runs through the insertion rods to transmit gas pressure and test readings. Due to the compact nature of the DMT blade the test can be quasi – continuous, taking measurements typically every 20cm, or carried out at greater intervals.

The DMT blade is 95mm wide and 12mm thick, with a cutting edge, as illustrated below in Figure 7. The circular steel membrane is 60mm diameter and 0.20 to 0.25mm thick, depending on the material to be tested.

**Figure 7: Flat Dilatometer - Front and side view.**

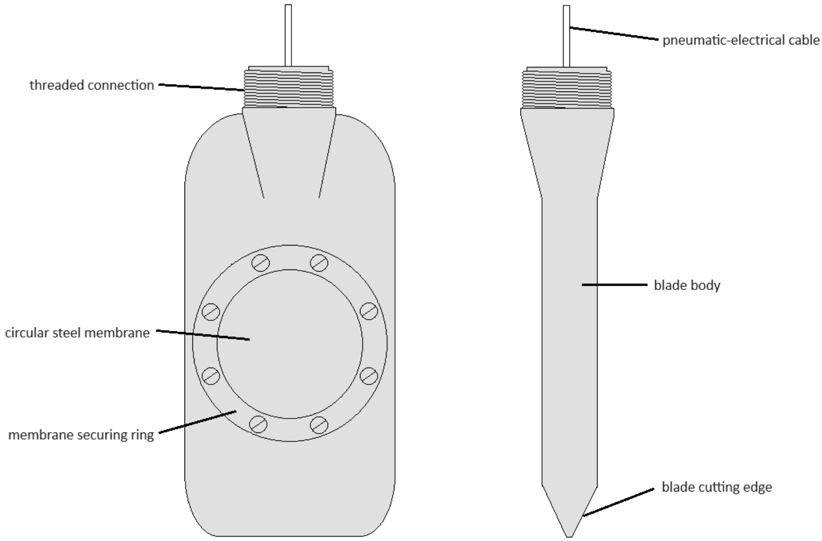



*Image In Situ Site Investigation Ltd, 2024*

### 2.2.1 Calibration

The membrane of the DMT requires a calibration so that its influence on the test results can be accounted for. The calibration procedure consists of inflating the DMT membrane with no external loading, ‘free air’. The pressure that is required to inflate the membrane is recorded and corrections are then derived, which can be applied to test data.

### 2.2.2 Insertion requirements and test procedure

DMT test requirements are noted below in Table 3.

**Table 3: DMT test requirements**

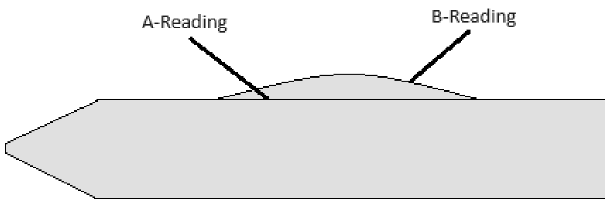
| Property | Value | Remarks |
|---|---|---|
| Length of test zone (m) | 0.30 | |
| Minimum casing diameter ID (mm) | 125 | Larger casing diameter required for clearance during insertion |

| Property | Value | Remarks |
|---|---|---|
| Location of test centre (m above DMT base) | 0.10 | |
| Rotary | ✓ | Pushed in using rotary head from base of borehole |
| Sonic (without vibration function) | ✓ | Pushed in using rotary head from base of borehole |
| Cable percussion | ✓ | Drive in using SPT hammer |
| CPT truck | ✓ | |

*Table by In Situ Site Investigation Ltd, 2022*

At each test depth, the penetration of the blade is stopped and the operator starts the test either manually or using a computer. Pressure is built up inside the circular steel membrane using compressed gas, which is delivered from the control unit. The first reading is the A-reading, taken approximately 15 seconds after starting the test. The A-reading is the pressure at which the membrane is inflated to 0.1mm and first starts to move against the tested material, called the 'lift off'. The inflation is then continued and the B-reading reading recorded, in another approximately 15 seconds. This B-reading is the pressure required to expand the membrane a further 1mm (1.1mm total inflation) into the material (illustrated in Figure 8). The gas is then slowly vented, the C-reading is taken at the point the membrane deflates back to where the test started, and the test is complete.

**Figure 8: Flat Dilatometer - Side view during test.**




*In Situ Site Investigation Ltd, 2024*

The blade is then advanced into the ground to the next test depth and the procedure for taking A, B and C-readings is repeated.

### 2.2.3 Terminating the test

A flat dilatometer test is ideally terminated when the test is completed successfully and the membrane deflated. Other reasons for termination would be; that the circular steel membrane bursts or is damaged, or the ground conditions are such that the DMT blade cannot be inserted into the ground.

### 2.2.4 Data interpretation and presentation of test results

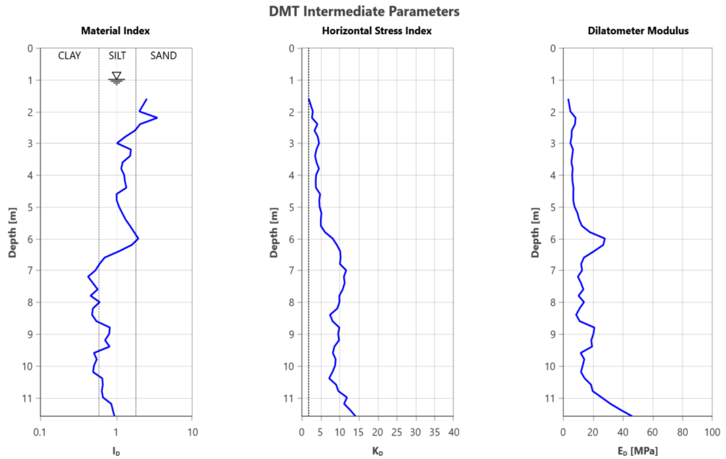
The test data can be used to determine a range of geotechnical parameters. Firstly, the test data is used to calculate intermediate parameters. It is these intermediate parameters that are then used to derive geotechnical parameters, such as stress, strength and compressibility characteristics, and to classify the soil type (clay, silt or sand). The tables and graphs below show the various parameters that can be calculated, depending on the type of material the tests are carried out in. The methods are also detailed in the Report of the ISSMGE Technical Committee 16 on *Ground Property Characterisation from In-situ Testing* 2001.

**Table 4: Intermediate parameters**

| | |
|---|---|
| Material index | $I_D$ |
| Horizontal stress index | $K_D$ |
| Dilatometer modulus | $E_D$ |

*Table by In Situ Site Investigation Ltd, 2022*

**Figure 9: Variation of DMT intermediate parameters with depth**




*In Situ Site Investigation Ltd, 2022*

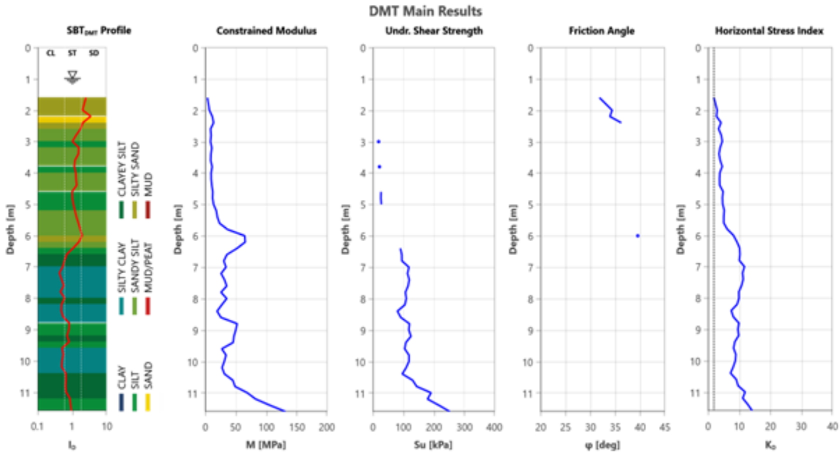
**Table 5: Geotechnical parameters derived from intermediate parameters**

| | |
|---|---|
| Earth pressure co-efficient at rest (clay) | $K_0$ |
| Over consolidation ratio (clay) | $OCR$ |
| Undrained shear strength (clay) | $c_u$ |
| Friction angle (sand) | $\phi$ |
| Coefficient of consolidation (clay) | $c_h$ |
| Coefficient of permeability (clay) | $k_h$ |

| | |
|---|---|
| Unit weight and description (all soils) | $\gamma$ |
| Vertical drained constrained modulus (all soils) | $M$ |
| Equilibrium pore pressure (sand) | $u_0$ |

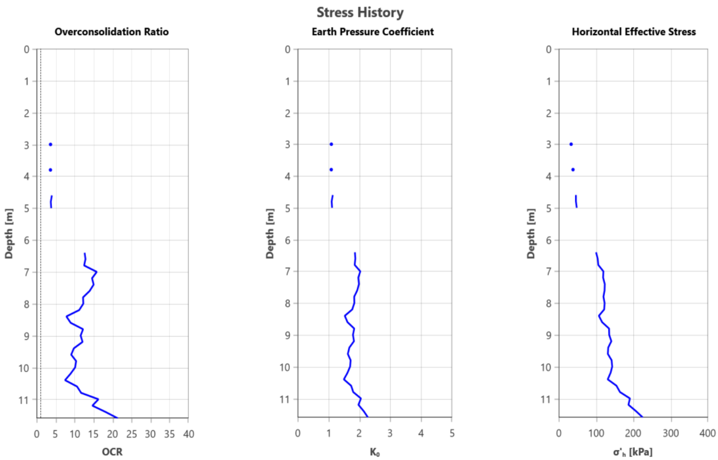
*Table by In Situ Site Investigation Ltd, 2022*

**Figure 10: Variation of geotechnical parameters from DMT with depth**




*In Situ Site Investigation Ltd, 2022*

**Figure 11: Variation of stress history parameters from DMT with depth**




*In Situ Site Investigation Ltd, 2022*

## 2.3 Direct strain pressuremeters (Cambridge style pressuremeter)

Direct strain pressuremeters, sometime called radial displacement pressuremeters or "Cambridge type pressuremeters", are instrumented probes where down-hole measurements are taken directly via strain gauge transducers spaced evenly around the probe. These strain gauges measure the displacement of the membrane continuously during a test. A further transducer measures the internal pressure of the probe during the test. Combined, the transducers provide precise and reliable data for pressure (stress) and displacement (strain). Transducer resolutions can equal to as little as 0.1 kPa and 0.3 microns. The output of these instruments appears as a live data stream on a graph viewed via software.

There are three main classifications of Cambridge type pressuremeter. All are based on the same concept as outlined above, as they all have capacity to measure stress and strain during a test. It is worth noting that some of these instruments can be configured to include a digital electronic compass to measure and record magnetic field. This can allow some insight to the anisotropy of the data collected during a test.

**Figure 12: CAD renders of four variations of Cambridge Insitu manufactured direct strain pressuremeter. From top to bottom: 95mm High-Pressure Dilatometer (95HPD), 95HPD Short, Self-Boring Pressuremeter, Reaming Pressuremeter.**

*Image by Cambridge Insitu Ltd, 2022*

### 2.3.1 Pre-bored direct strain pressuremeter

A pre-bored pressuremeter is one where the "pocket" (the cavity created via drilling, for the instrument to be inserted into) is created by removing the material from the ground. Commonly this is done by rotary coring, or by destructive drilling. An example of an instrument that is deployed in this routine is a 95mm High-Pressure Dilatometer (95HPD). This instrument has a high maximum working pressure and as such can be used in materials ranging from rock, such as mudstone or chalk, to soft clays.

### 2.3.2 Push-in pressuremeter / full-displacement pressuremeter

"Push-in" describes the way the pressuremeter is inserted into the ground. Simply put, this technique refers to a direct push style of insertion, not dissimilar to how a CPT is installed. The only Cambridge type pressuremeter used in this way is a 47mm Reaming Pressuremeter (47RPM). It is worth noting that the 47RPM is a small and quite versatile instrument, used in any material from soft clays to weak/ weathered rock. It is often installed in either a pushed or pre-bored fashion (a recent technique in suitable geology is to create a pocket using a modified SPT (modified by increasing the nominal length of the drive to >0.6m). SPT pockets result in a pushed style test, despite the manner of installation being more logically described as pre-bored). Additionally, this type of pressuremeter can be configured with a digital 15cm$^2$ CPT, to be used concurrently with the pressuremeter. In this format this instrument is renamed a Cone Pressuremeter (CPM).

### 2.3.3 Self-boring pressuremeter

A self-boring pressuremeter can (when operated correctly) provide constant support for the ground during insertion, thus minimising stress relaxation or concentration of the material. This is undertaken by steadily removing material from the ground via a cutting shoe and a drag bit, and then instantly replacing that excavated material with the body of the instrument. The drilling mechanism for this instrument can involve using a rotating drag bit, rock roller or full-face cutter. In some specialist cases a non-rotating lance can be used (sometimes called a jetting bit), which utilises pressurised water flush from a backwards-facing flush-hole to remove cuttings from the face of the instrument.

A Cambridge Self-Boring Pressuremeter (SBPM) is predominantly used in soils. The two pore water pressure cells located 180 degrees from one another on the membrane measure the pore water pressure response both during insertion (drilling), and during the live test. Measuring the pore water response during drilling gives the analyst some indication as to the drilling conditions during insertion and how much the drilling has impacted the ground, which is essential for some analysis techniques.

**Figure 13: A Cambridge Self-Boring Pressuremeter cutting shoe, configured with a drag bit**

*Image by Stuart Pearce, 2021.*

# 3 Calibrations

The requirements for pressuremeter calibrations are set out in the instrument specific standards, as listed in Section 1.6. Additionally, calibrations should be undertaken in accordance with the instrument manufacturer's recommendations and/or as instructed in the GI specification. It is the pressuremeter testing contractor's responsibility to ensure that the instrumentation has been suitably calibrated prior to any testing.

Calibrations are undertaken for instrument reliability and repeatability, which ensures maximum data accuracy. Most calibrations of pressuremeters can be spilt into two different categories:

- Calibration of the measuring systems (displacement, pressure or volumetric).
- Measurement of the instrument's mechanical properties. Sometimes referred to as a 'calibration' of the membrane stiffness and the system stiffness of the instrument itself.

Calibration certificates should be provided by the pressuremeter contractor at the same time as or before reporting and should not be more than six months old.

Additionally, the straightness of the pressuremeter should be checked regularly, especially for all self-boring pressuremeters. This specific requirement is important because the SBP's high test quality comes from minimised disturbance upon insertion. If the instrument has become bent over time and use, its ability to undertake this fundamental task will be compromised, simply due to the impossibility of drilling a clean, straight, cylindrical hole with damaged (bent) tooling. There are no set tolerances in standards yet, but it is a check that the supplier of the pressuremeter testing should be carrying out.

## 3.1 Calibration of the measuring system

To provide the measurements of pressure, displacement or volume that are key to a pressuremeter test, the instrument in question must possess sensors (either digital or analogue) to make these important measurements.

These sensors in some cases have very fine precision (sub-micrometre) over very large ranges (20mm). This highlights the importance of regularly calibrating the sensors, specifically for their linearity and hysteresis, against known quantities such as suitable verified third-party pressure gauges and vernier gauge micrometers, such as illustrated below in Figure 14.

**Figure 14: A micrometer set up on an RPM, used for calibrating the strain gauge transducers for measuring displacement**

*Image by Kyle Clarkson, 2022.*

## 3.2 Measurement of the instrument's mechanical properties

Direct strain measuring pressuremeters will deform due to the pressure being internally applied – simply put, the probes stretch. Because the displacement measuring system uses the body of the instrument as a reference, movements of the body are seen as apparent displacements of the membrane; some ingenuity is needed to isolate the displacement measuring system from this problem. This system compliance has implications for the measurement of shear modulus, and it can become a significant source of error when measuring very high modulus values.

The Cambridge type set of pressuremeters are placed inside a metal calibration cylinder of known stiffness and inflated to the maximum working pressure for that tool. The pressure is then released gradually to give a plot such as shown below in Figure 15, where the average system stiffness is calculated.

**Figure 15: An example of a system stiffness calibration undertaken within a steel cylinder of known properties**

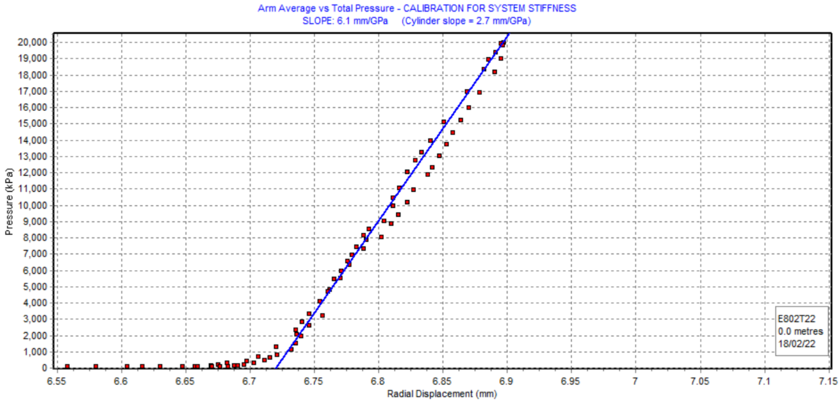



*Image by Cambridge Insitu Ltd, 2022*

## 3.3 Calibration of the membrane and the finite stiffness of the instrument

The pressuremeter membrane is expanded in free air, and having its own initial tension it requires an unknown pressure to move it. The membrane is inflated (whilst freely positioned in air), and this initial tension is determined to remove this value from the overall pressure in a test to understand the true stress applied to the ground.

During a membrane calibration the average arms plot is used to determine a zero and slope from the best fit of the tool's maximum strain displacement, as shown in Figure 16.

**Figure 16: An example of a membrane stiffness calibration undertaken on a high-pressure dilatometer**

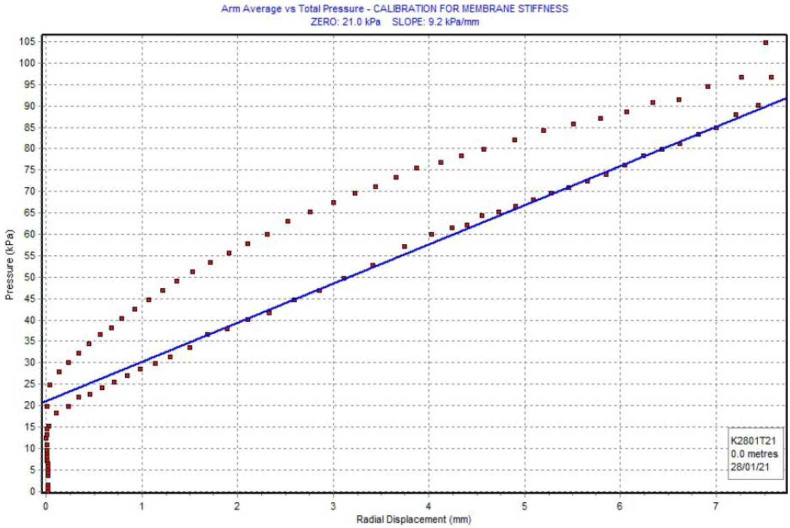



*Image by Cambridge Insitu Ltd, 2022.*

# 4 Drilling requirements and test procedure

This section provides a description of the testing procedure, from the drilling requirements to the termination of the test and retrieval of the pressuremeter.

A discussion at enquiry/planning stage with PMT companies is advisable to determine which pressuremeter technique is likely to be most suitable, largely based on what ground conditions are expected to be encountered on site. The estimated ground conditions and desired engineering parameters determine the best pressuremeter for the intended use, and therefore, the required insertion method. These measures will avoid mobilising inappropriate equipment to site.

Table 6, below, lists different pocket dimensions and plant requirements for different direct strain pressuremeters. It should be noted that the 47RPM is one instrument type, with three different methods of insertion possible.

**Table 6: Installation details for different types of pressuremeter**

| Instrument type | 95HPD | 73HPD | 47RPM – Pre-bored | 47RPM – SPT pocket | 47RPM – Direct push | SBPM |
|---|---|---|---|---|---|---|
| Pocket length (m) | 1.50 to 3.00 | 1.50 to 3.00 | 0.70 | 0.70 | 0.70 | 1.00 |
| Pocket diameter (range in mm) | 98 to 101 | 76 to 78 | 47 to 50 | 50.8 | n/a | n/a |
| Minimum casing diameter ID (mm) | 125 | 125 | 75 | 75 | 75* | 125 |
| Location of test centre (m above PMT base) | 0.65 | 0.73 | 0.30 | 0.30 | 0.30 | 0.50 |
| Rotary *** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Sonic (without vibration function) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Cable percussion | × | × | × | ✓ | ✓ | ✓** |
| CPT truck | × | × | × | × | ✓ | × |

Notes:

*If the 47mm RPM is deployed on rods of the same diameter or larger, provided the umbilical is routed within the rods, then casing is not required.

**Specialised rams and powerpack required to undertake test.

***Rotary drilling with a coring and casing system is regarded as best practice, though in specific cases open hole drilling may be permissible depending on the soil/rock type.

## 4.1 Borehole preparation

Prior to pressuremeter testing being undertaken the borehole requires some preparatory measures. A stable, well-formed borehole is essential before the formation of the test pocket. If there is any indication of borehole instability at this stage, it is highly unlikely that a suitable pocket for testing can be created. Whenever possible, casing that covers the full length of the borehole, down to the top of the test pocket is advised to ensure that the borehole remains open and stable for the entire duration of pocket formation and testing. It should be noted that it is very common for a wireline rotary drilling system such as Geobor S to be employed to provide a fully cased hole, although this specific system is but one example.

An accurate measurement of the borehole depth is essential prior to the formation of any pocket, as this will ensure accurate test depth measurements. Furthermore, it is advised that measurements and records be kept of the depth of casing as well as the head of water within the borehole.

The above is regarded as best practice; however, the reality may not be as easy to achieve as in theory. Therefore, it is important for the driller to liaise with the pressuremeter operator as well as the site engineer/manager to mitigate any potential problems, so as to acquire sufficient data.

#### 4.1.1 Pocket formation

Whichever pocket formation method is used, it is preferable to target zones of homogeneous material (where possible) and aim to ensure that these zones cover the full length of the inflatable membrane. This will ensure a more reliable test with fewer terminations due to membrane rupture caused by cavity expansion into heterogeneous material. With pre-bored pockets, inspection of the retrieved core and/or reviewing televiewer plots can aid in positioning the pressuremeter correctly within the pocket, avoiding areas that could cause damage to the pressuremeter.

- **Pre-bored**

It should be ensured that there is sufficient rotation and flush used to create the pocket, but not an excess of either since this can affect the pocket quality. This scenario would have a subsequent effect on the quality of the test. Once the barrel has been drilled to depth, flush the hole sufficiently to remove fines and cuttings from suspension to avoid these settling during the test and potentially causing the pressuremeter to become stuck. In larger diameter holes where the pocket diameter is comparatively small, the use of sludge pots may be considered. The depth of the pocket should be measured to ensure the pocket is viable to test prior to deploying the pressuremeter.

- **SBP**

Drillers with experience in SBP insertion are typically preferred. The drilling in of the SBP is carried out by the drilling contractor under the supervision of the PMT operator ensuring that rotation and flush are sufficient but not excessive. It is crucial to liaise with the PMT operator during pocket formation. If the correct drilling technique is not used, certain data acquisition could be compromised.

- **SPT pocket**

A specialised, oversized (with respect to length) SPT spoon is used to create a pocket of 0.6m length (a normal SPT is less than this and therefore too short). An SPT hammer can be used to drive the SPT sampler/cone down to the desired depth. This is the quickest pocket formation method and is only suitable in material that can remain open unsupported long enough to remove the SPT sampler and rods and then insert the pressuremeter.

- **Direct push**

This technique is typically employed when an RPM is fitted with a digital cone. This technique is effective where ground conditions are soft enough to allow a safe push with a CPT ram set or pushed using a rotary head.

### 4.1.2 Timing of pocket formation

Pressuremeter testing should be undertaken as soon as is reasonably practicable after the pocket has been formed. Best practice would be for the elapsed time to be less than 60 minutes. Pockets created overly prematurely may result in excessive stress relaxation at the borehole wall, which may affect the test and results. In extreme cases, a stress-relaxed pocket may deform over time, eventually obstructing PMT insertion. It should be noted that more sensitive materials (for instance a soft clay) will be more susceptible to the influence of elapsed time, when compared to a more competent material such as mudstone. The only excpetion to this is when testing in a material capable of supporting itself (in other words, where no casing is used as the material is particularly competent, such as intact rock), this is mentioned in Section 4.2.

### 4.1.3 Cleaning the pocket

All pockets formed with rotary drilling require effective flush (for best results use water or polymer/mud) to be used to remove cuttings from the pocket. Excessive cuttings within the pocket will affect the test.

### 4.1.4 Flushing mediums

To ensure good quality pocket formation, choosing the correct flush medium for the material is important; however, this is likely already to have been determined by the drilling contractor or the location of the borehole. Media such as water, mud and air-mist are common, and discussing with the contractor prior to arrival will give a more favourable outcome to pocket formation. When drilling with a self-boring pressuremeter, water or a thin mud/polymer are typical flushing media and are recommended even if these are not used for the main borehole advancement.

## 4.2 Pocket dimensions

A range of lengths for the pocket are provided in Table 6, above. A longer length allows for scope to move the pressuremeter within the pocket to target a preferred depth, or avoid an area as seen via the core sample or televiewer data recovered. The additional length also may allow for cuttings from drilling to settle in the bottom of the pocket, with the probe then positioned above.

The diameters provided as target values for the pocket formation are intended to optimise the performance of the different instruments. It is obvious that if a pocket is too small for a pressuremeter then installation will not be possible, but likewise a pocket that is too large in diameter will negatively affect the pressuremeter’s ability to achieve the desired strain. This is particularly critical in more competent materials where larger values of stress and strain may be necessary to achieve a full dataset where shear failure of the ground is included.

In situations where the borehole is formed in a material capable of supporting itself (in other words, where no casing is used as the material is particularly competent, such as intact rock), then it may be possible to drill the entire borehole in a constant diameter, conducting pressuremeter testing from the bottom of the borehole and working up towards the surface. This methodology may provide a very efficient workflow but is not without risk, since a collapse within the unsupported borehole (whilst the pressuremeter is installed) may result in the loss of the instrument.

## 4.3 Probe insertion

Having reviewed the recovered core (in the scenario of pre-bored testing) or televiewer data, all pressuremeters utilise drilling rods to insert the pressuremeter into the ground, regardless of which pocket formation type is used (for example, as shown below in Figure 17). It is essential to use drilling rods and not simply lower the pressuremeter down via wireline for several reasons, namely:

- It provides a stable mass to tape the umbilical to, which will prevent sagging which can lead to damage and/or the loss of the instrument downhole.
- In the event of a borehole collapse (even if only minor) whilst the pressuremeter is installed in the ground, it can be difficult to retrieve it with the limited tension applied via wireline and winch.
- The utilisation of drilling rods allows for a greater reaction to ease the pressuremeter out of the pocket.
- It is useful to measure the exact depth of the test by measuring the drilling rods and subtracting the stick-up.

There are very few exceptions to this best practice, the most notable case being in the event of offshore testing from dynamically positioned drilling vessels, where custom and specialised wireline systems may be utilised.

**Figure 17: Photograph showing a 95HPD being lowered into a borehole via a rotary drilling rig**

*Photo by Stuart Pearce, 2022.*

In the case of the SBPM, a twin rod system is attached to the top of the pressuremeter, which in turn is attached to the drilling rig. Using a bearing system (known as a Hughes Hardware), the inner rod can spin whilst keeping the outer casing still. The material is removed to surface by the flush passing through the annulus between the rods and casing, allowing the operator to observe the cuttings from the material that the pressuremeter is drilling into. When using a cable percussion rig, which does not have a rotating head, the SBPM can still self-bore to depth by utilising a custom set up which attaches to the existing casing and is drilled in by the PMT operator.

## 4.4 Description of test

A direct strain pressuremeter test involves a cavity expansion phase, and a cavity contraction phase, essentially that is to say it has a “loading” stage and an “unloading” stage.

As the engineer increases the pressure in the instrument, they will typically take two or three unload/reload cycles (sometimes referred to as “loops”) during this cavity expansion phase. A further unload/reload cycle is undertaken on the contraction/unloading phase. It is recommended as best practice that each pressuremeter test should have a minimum of three unload/reload cycles.

Although an experienced pressuremeter operator will have an idea of the likely outcome of the test based on material and ground conditions; it is important to remember that all tests are dynamic, and the operator is reacting in real time to what they are seeing on the live output on screen. Ultimately, the test characteristics are dictated by the material.

Examples of test data returned from tests undertaken using different types of PMT and in different materials are shown below in Figure 18 to Figure 22 inclusive.

**Figure 18: A graph showing the individual arm displacement values vs pressure for a typical pushed test undertaken in soil with a Reaming Pressuremeter**

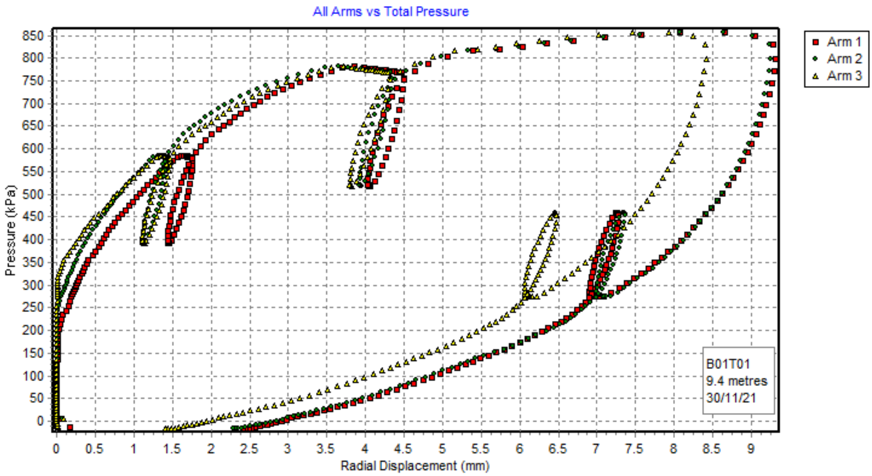



*Image by Cambridge Insitu Ltd, 2022.*

**Figure 19: A graph showing the individual arm displacement values vs pressure for a typical pre-bored test undertaken in soil using a High-Pressure Dilatometer (HPD)**

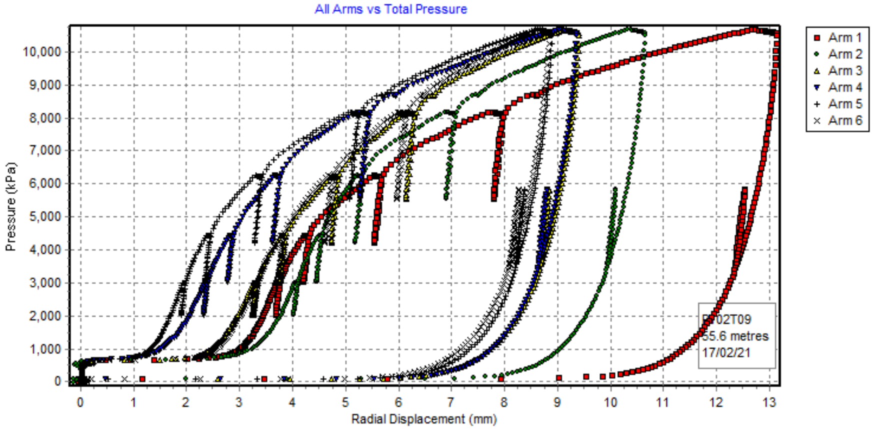



*Image by Cambridge Insitu Ltd, 2022.*

**Figure 20: A graph showing the individual arm displacement values vs pressure for a typical High-Pressure Dilatometer (HPD) test in rock**

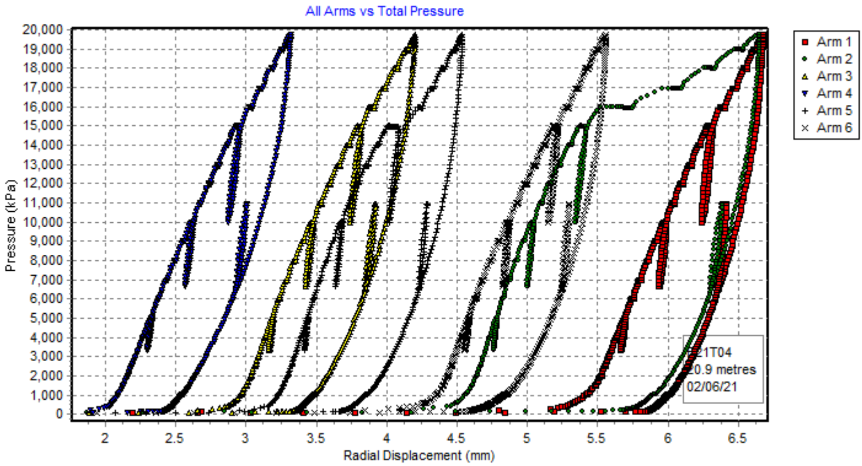



*Image by Cambridge Insitu Ltd, 2022.*

**Figure 21: A graph showing the arm pair displacement values vs pressure for a typical Self-Boring Pressuremeter (SBP) test in soil**

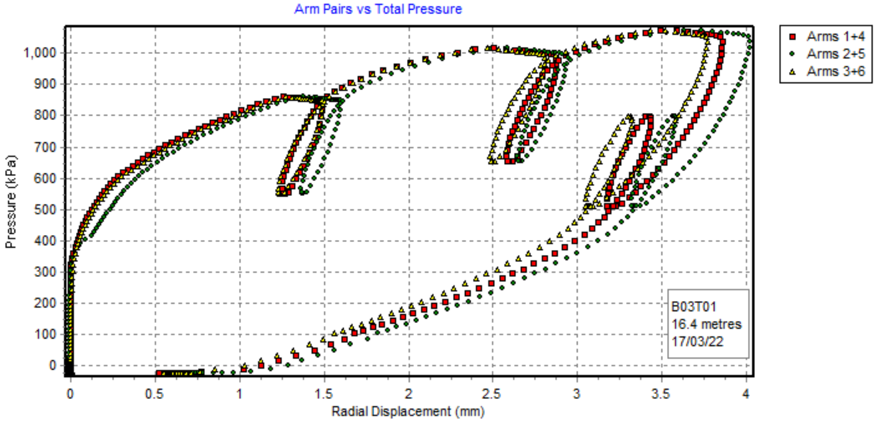



*Image by Cambridge Insitu Ltd, 2022.*

**Figure 22: A graph showing changes of ambient pore water pressure vs time for a typical Self-Boring Pressuremeter (SBP) test in an undrained soil**

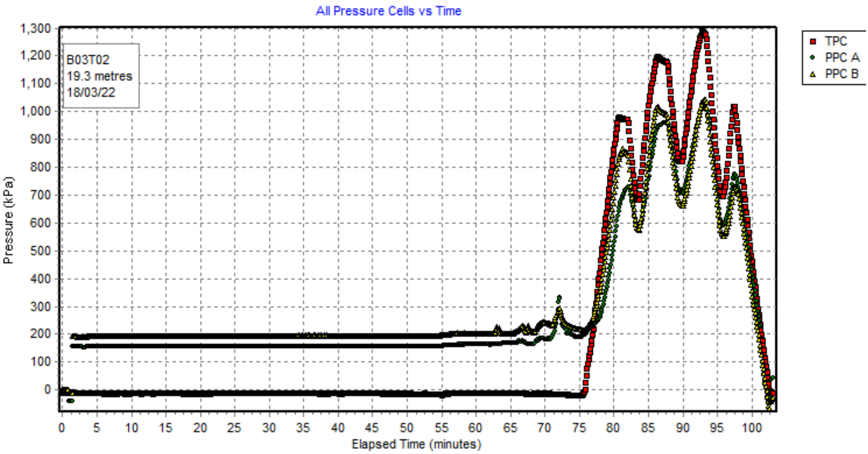



*Image by Cambridge Insitu Ltd, 2022.*

## 4.5 Terminating the test

The operator decides when to terminate a test, and this decision will take several factors into consideration. The maximum displacement or pressure capability of the instrument are obvious limiting factors. The main criterion for termination is ensuring that sufficient data has been collected to allow for the full analysis of a test. As a minimum, three unload/reload cycles and a full cavity contraction is required to consider termination. Premature termination is an indicator of poor-quality testing, often due to a lack of experience.

The exact termination point of the cavity expansion is decided based on the material response and arm movement. Behaviour such as an anisotropic expansion or pore collapse may result in an early termination. Membrane ruptures or extrusions can also occur and result in early termination of the test and loss of cavity contraction data.

# 5 The design and administration of pressuremeter testing programmes

Pressuremeter testing is generally a sophisticated in situ testing technique, and as such the design and specification of a testing regime will benefit from a technique-specific approach. Pressuremeter testing offers test at discrete intervals, and therefore it is critical that this is considered by the specification. As a rule, there is seldom any “best” technique for every occasion; only ever a “most appropriate” technique based on the anticipated geology, and the desired parameters.

It is not unusual for specifications to be written which upon scrutiny do not make complete sense. A common misconception is that a SBP is an infallible technique for acquiring all parameters, when in fact the presence of a few obstructing gravels included in the target geology has the potential to prevent the tool drilling itself to depth. Therefore, in this section there is an explanation of key factors and considerations which aim to provide a logical pathway to specifying appropriate testing techniques, for what reasons, in what material, and in what quantity.

Prior to quoting, it is useful to provide as much information as possible to enable the best possible planning for the job. This includes but is not limited to the following:

**Table 7: Required information**

| Qualitative | Quantitative | Technical | Practical |
|---|---|---|---|
| Name of project | Timescales | Specific test requirements | Drilling methods |
| Site Location | Quantity of tests | Desired parameters | Inductions |
| Description of project | Quantity of boreholes | Anticipated geology | Remobilisations |
| Type of test | Target test depths | | |

## 5.1 Client brief for the proposed structure

The desired outcome of the testing in terms of engineering parameters is the most essential part of creating a pressuremeter testing specification. The desirability of specific parameters is the starting point of the technique selection, and a specialist PMT contractor can advise with test specific requirements upon discussion. The geology must then be considered, as assessing the anticipated conditions is crucial prior to sitework. Owing to the range of pressuremeters available, each one is suited to slightly different material (as indicated below in Table 8), so it is important to consult with the specialist PMT contractor early on, to determine the most appropriate tool for use, bearing in mind the expected ground conditions and equipment limitations, so as to gather the best possible data.

**Table 8: Suitability of PMT types in different materials**

| Instrument type | 95 HPD | 73 HPD | 47RPM – Pre-bored | 47RPM – SPT pocket | 47RPM – Direct push | SBPM | Ménard | Flat dilatometer |
|---|---|---|---|---|---|---|---|---|
| Clay | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Sand | ✓ | ✓ | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Weak rock | ✓ | ✓ | ✓ | × | × | × | ✓ | × |
| Competent rock | ✓ | ✓ | ✓ | × | × | × | ✓ | × |

✓ = suitable method; x = unsuitable method

## 5.2 Fieldwork data - actual revealed ground conditions

Pressuremeter testing is a dynamic process and what is encountered on site may be different to what was previously expected. It is important to remember that scheduling of testing techniques can be changed whilst on site during a project and different pressuremeters can be mobilised to better suit the actual ground conditions. For example, SBPM is often scheduled in London Clay, however, claystone bands can be present within London Clay which will prevent the SBPM from boring through it. Mobilising an RPM as well would therefore be sensible as it requires shorter pockets and is easier to place between claystone bands.

## 5.3 Procurement

Procurement of pressuremeter testing is commonly provided via specialist contractor, though it should be noted that some ground investigation contractors, or even consultancies, may run an in situ testing department that includes pressuremeter testing capabilities. Engagement with such companies is best undertaken in a manner that permits a discussion of the project and testing specification as necessary. By providing details of the testing specification at the point of initial engagement, a more accurate and concise discussion and quoting process is permitted.

Typically, a pressuremeter contractor will provide all equipment related to the pressuremeter test, except for drilling equipment (except in the case of self-boring pressuremeter testing). Typically, the service provided will include pre-job planning/liaising with the client, fieldwork and testing services, and finally analysis and reporting. It is also desirable that the PMT contractor can perform routine maintenance and repairs in the field, to minimise downtime.

## 5.4 Scheduling

Since pressuremeter testing has a requirement for heavy plant such as drilling rigs to facilitate installation, it is understandably important to acknowledge and understand the timescales involved in the processes. This can allow for suitable planning and contract terms to minimise downtime costs, and keep realistic programme aims.

Most pressuremeter testing techniques include an “actual” test procedure ranging between 30 to 90 minutes. This varies between the two extremes depending on the type of material tested; where a test in clay might only take 30 minutes, a test in a competent rock may take up to 90 minutes or sometimes more. This obviously does not consider the time to install and recover the instrument, which is heavily dependent on the length of drilling rods, the type of the winch, and target test depth. The time taken to advance the borehole to the next target test depth should also be considered. The final consideration to the timescales and timeline of production is whether other testing or sampling regimes are to be conducted alongside the PMT in the borehole.

The only exception is a pre-drilled hole in a competent rock which will stay open without the aid of casing, where the full length of the borehole is drilled in the pocket size (e.g. 101 mm for 95HPD). In this instance, best practice is to lower the pressuremeter to the lowest target depth, complete a test, then raise to the next target test depth. This is continued until all scheduled testing is completed or a membrane rupture occurs, at which point the pressuremeter is recovered, fixed, then inserted back into the borehole to the next available test. Testing from deep to shallow means there is the least possible disturbance of the borehole wall ensuring its stability and minimising the risk of borehole collapse and inability to recover the tool.

## 5.5 Support requirements

As mentioned in Section 5.3, the pressuremeter contractor typically does not provide drilling equipment. As such, a drilling contractor is required to provide the service of creating the borehole and handling the pressuremeter during installation/recovery. Drilling plant of suitable weight and power are required based on a project-by-project basis. For more information on drilling requirements see Section 4.

To successfully conduct pressuremeter testing on site, the PMT contractor requires access to the borehole in either a commercial van or a truck. PMT equipment can weigh upwards of 500kg net, so where vehicle access is not possible, other equipment transportation arrangements will have to be made prior to quoting. Furthermore, a dry, covered working area is required for the PMT operator to conduct tests.

# 6 Assessment and presentation of test results

Pressuremeter testing is specified and undertaken to measure specific engineering parameters, for a targeted material at a targeted depth.

This section aims to list the common parameters measured via PMT, how they are obtained, how they are presented and should be subsequently used. It is outside of the scope of this document to explain parameter derivation to a fundamental level; there are several books already in existence that explain this in detail. The information below is intended as an overview and outline of what can be provided, and how.

The process to convert the raw voltage data these instruments produce into the relevant engineering units (displacement and pressure for example), can vary depending on the type of pressuremeter used. This process needs to consider the calibration and the potential for membrane thinning. The calculation of the specified engineering parameters can be complex depending on the material response and tool used.

The quality of the test will dictate the confidence in the parameters that can be produced. To achieve the maximum return from pressuremeter testing, the desired outcomes must be considered from the start. Instrument selection, insertion technique and specific or bespoke testing procedures should be considered to match the expected geology and the desired parameters.

Once the appropriate approach to the testing has been decided, the tests must be completed in a way that provides high quality data without missing any key parts of the material response. For instance, a test that does not reach a large enough strain in a material may mean that confidence in observed strength parameters is undermined, even if the in situ stress is the primary focus of the investigation.

The actual analytical process is focussed around using directly measured techniques for each parameter. Subsequently, a curve modelling technique is utilised to provide an optimised solution to the desired parameters. This process allows both the directly measured data and modelling techniques be considered, introducing data redundancy, and providing high levels of confidence.

## 6.1 Test results, data, and common parameters

The most common parameters achieved through pressuremeter testing are linear and non-linear shear stiffness, shear strength, and in situ stress. These can be obtained via direct-strain measuring pressuremeters, since the high resolution down-hole sensors and the direct readings of pressure and radial displacement allow for simple mathematical solutions, avoiding empirical methods and permitting reliable and accurate results.

These parameters have significant value in design and are commonly compared with the same parameters acquired via other in situ testing and laboratory testing. In some cases, the pressuremeter data is used to calibrate the other results and is commonly utilised as input data for finite element modelling.

### 6.1.1 Stiffness

Generally, the fundamental purpose of PMT is to determine the shear stiffness ($G$) of the ground.

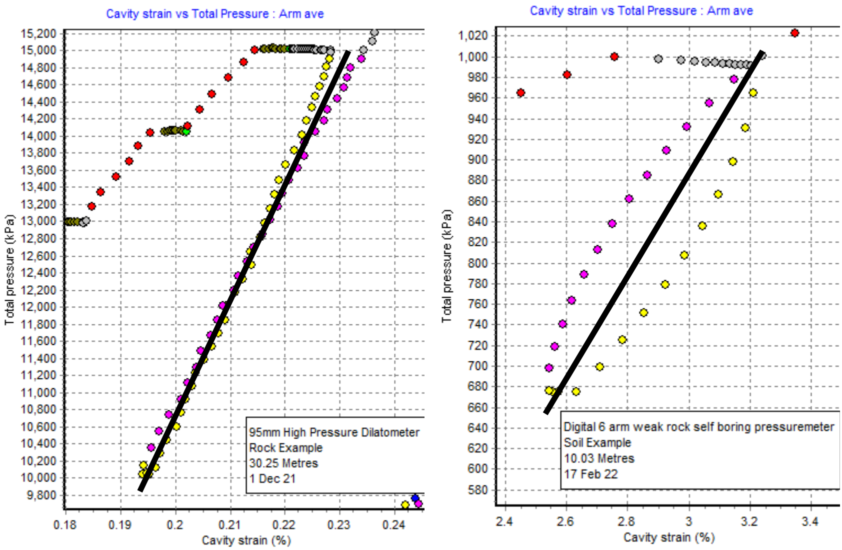
Stiffness can be determined from two parts of the pressuremeter curve. The primary source of stiffness data is the unload/reload cycles. These cycles should provide plausible, consistent, repeatable data for shear modulus. Several cycles are included in every pressuremeter tests to allow for the variation of stiffness with stress level to be understood and confirm the validity of the test.

The slope of the initial loading is also a source of modulus data. Values for modulus from this part of the test are designated $G_i$. (Initial shear modulus). However, the initial loading can be influenced significantly by drilling disturbance and relaxation. For a pushed test the meaning of the initial slope is uncertain and $G_i$ should not be used. For pre-bored tests the initial slope is likely a measure of relaxation, rather than the true stiffness of the ground.

The simplest approach to understanding the stiffness is linearly; taking a linear chord to bisect the unload reload cycle or initial slope (see example below in Figure 23). This approach is often appropriate for testing in competent rock (shear stiffness greater than 1GPa) where the “cycle” follows closely the same linear trend on the unloading and reloading phases.

In soils, a linear approach is a simplification of the true ground behaviour. The unload/reload cycles have a hysteretic form indicating a non-linear stiffness/strain relationship. By calculating a power curve on a log/ log plot (Whittle & Boulton, 1999), it is possible to derive the stiffness/strain degradation properties of the material tested. This gives secant shear modulus in the shear strain range 0.01% to the yield strain, (approximately 1% in clay). Any desired secant modulus in this range can be calculated.

**Figure 23: Variation in a linear unload/reload cycle and a non-linear unload/reload cycle**




(a) HPD in sandstone

(b) SBP in clay

At the time of measurement all modulus parameters are shear $(G)$. Shear modulus can be converted to Young’s modulus $E$ using a simple formula and Poisson’s ratio[2]. For testing in a vertical borehole,

[2] Poisson’s ratio is typically not determined by PMT and needs to be estimated or provided through alternative methods of testing.

the pressuremeter test gives values for $G_{HH}$, the shear stiffness in the horizontal plane. If $G_{VH}$ is desired (the shear moduli for transversely isotropic materials where the first suffix is the direction of loading, and the second suffix is the direction of partical movement), then further processing is required.

### 6.1.2 Strength

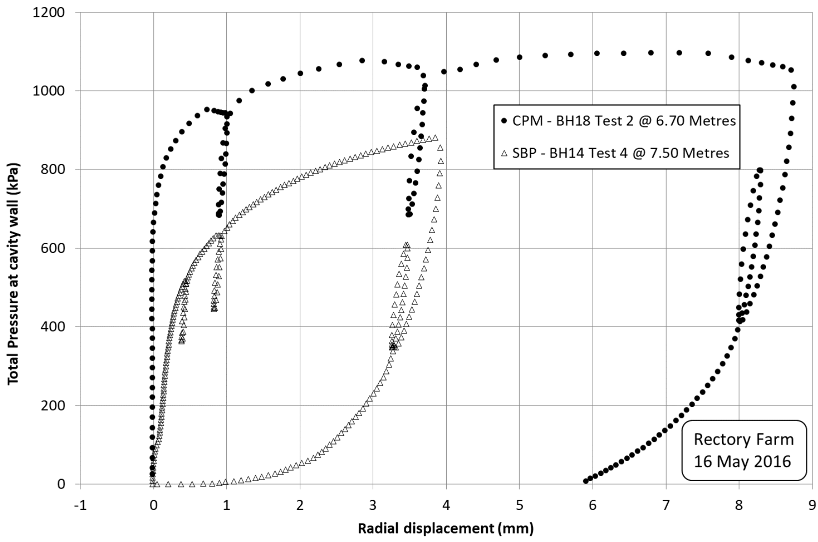
When a load is applied, soils can follow a drained or undrained path. Drained materials are typically granular (such as sands) while undrained materials are typically cohesive (such as clay).

If the material is undrained (as it might be for low permeability materials), the test rate does not permit excess pore water pressure to drain. Consequently, after failure, the mean effective stress is constant, and all unload/reload cycles give a similar response. It is generally appropriate to report an undrained shear strength from this sort of test.

If a material is free-draining, successive unload/reload cycles tend to show increasing stiffness. The dilative nature of the material should be considered, and a friction solution is required, giving a peak friction angle and dilation angle. For drained analyses, a residual friction angle must be assumed, this is typically selected by the analyst based on the material response.

For pre-bored and self-bored pressuremeter tests, both the loading and unloading parts of the curve can be used to determine strength. If a test is pushed the material has already been taken to the limit pressure: the loading data is indeterminate and only unloading data should be used to determine strength. A comparison of a pushed CPM test and self-bored test in the same location and material is shown below in Figure 24. The strength from these tests is similar, but the impact on the loading data resulting from pushing the probe is clear.

**Figure 24: Comparison of pushed Cone Pressuremeter test and Self-Bored Pressuremeter test in the same location and material (Gault Clay).**



Unless in a material with a clearly defined peak and residual, the strengths determined in an undrained test for the loading and unloading should be the same. In a material that is frictional is it common for the unloading strength to trend towards the residual friction angle, while the peak friction angle is represented by the loading strength.

### 6.1.3 Stress

PMT may determine a cavity reference pressure. For a vertical test this is assumed to be equivalent to the in situ horizontal stress. The insertion method and quality of drilling dictates the level of confidence with which the in situ stress can be estimated.

Various methods can be applied to determine the in situ stress dependent on the insertion technique. Commonly used techniques include:

- Lift off: the pressure at which the in situ stress is overcome and displacement commences.
- Onset of excess pore water pressure: the point at which excess pore water pressure begins to be generated.
- Marsland and Randolph: A back calculation of in situ stress based on an identified yield stress. (Marsland & Randolph, 1977)
- Curve fitting (see Section 6.1.4)

The applicability of these techniques is given in Table 9 below:

**Table 9: Methods for determining in situ stress**

| **Insertion technique** | **Method for determining In situ Stress** | | | |
|---|---|---|---|---|
| | **Lift off** | **Onset of excess PWP** | **Marsland and Randolph** | **Curve fitting** |
| Pushed | Dependent on very specific circumstances | | | Applicable |
| Pre-bored | | | Applicable | Applicable |
| Self-bored | Applicable | Applicable | Applicable | Applicable |

There is more stress data redundancy for SBP testing than pre-bored and pushed PMT, making SBP the preferred method for projects that need high quality stress data.

From the in situ horizontal stress, parameters such as the coefficient of earth pressure and OCR can be derived, if a unit weight of the tested soil/rock is assumed or provided.

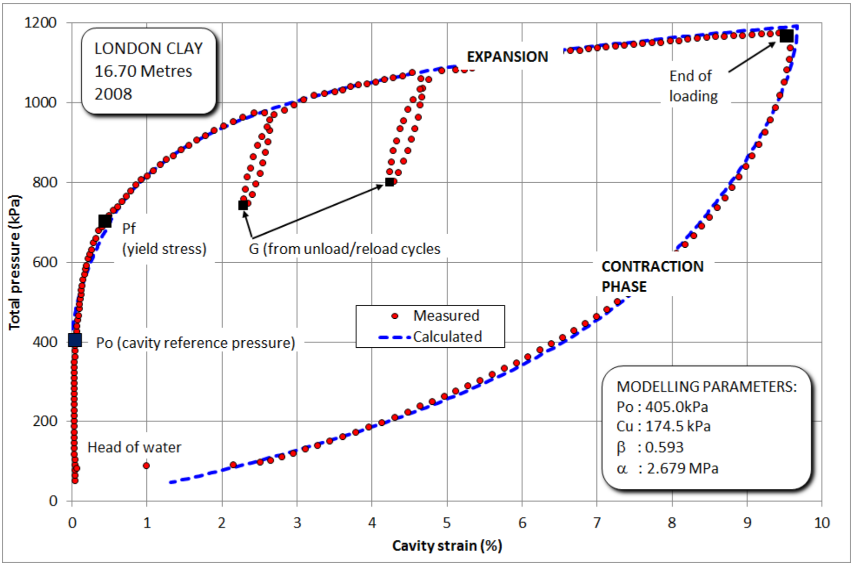
### 6.1.4 Curve fitting

Curve fitting methods are commonly applied to pressuremeter data to optimise the results.

The result of the analysis process prior to curve fitting is a set of parameters that ought to be capable of producing the measured field curve. Curve fitting is used to demonstrate this is the case and optimise variable parameters (generally the cavity reference pressure, $P_o$) in order to achieve a best fit, as illustrated below in Figure 25.

If a curve fit is not making sense, it is indicative that either the original analysis is not valid (such as modelling a drained test as undrained) or one of the key assumptions has been invalidated, for example a material that suffered structural collapse during testing.

**Figure 25: Example curve fit of an undrained test**




## 6.2 Pressuremeter results in design

The purpose of this section is to outline some considerations when using pressuremeter-derived data in civil engineering and geotechnical design. The designer should always consider the specifics of ground response and the structural interaction on a site-by-site basis.

This section will cover the estimation and interpretation of deformation characteristics with a focus on testing in weak rocks.

### 6.2.1 Application of deformation characteristics

The initial modulus is that derived from the flat portion of the initial test load phase. The value of $G_i$ will typically be affected by:

- Quality of the test pocket.
- Tensile fracturing of the rock.
- Closing of fractures.

Whilst these factors may influence the test result they would likely not be apparent in the undisturbed ground and hence not occur during loading. Therefore, it is often considered that the initial modulus, $G_i$, is not generally applicable to civil engineering design. However, care must be taken to quantify the nature of the ground before selecting the appropriate modulus value.

The ground investigation should be designed to mitigate the influence of drilling induced disturbance as far as practicably possible if an attempt is to be made to quantify the effect of closing fractures on the test result. Assuming that drilling disturbance can be minimised, an attempt may be made to quantify this by examining the ratio of $G_i/G_{ur}$ . Mair & Wood, (2013) suggest that values of this ratio in excess of 3 indicate '*moderately intact rock*'. It is recommended that these data are considered alongside an assessment of fracture intensity. This may be from logging, taking care to discount drilling induced fractures, and/or downhole telemetry such as a televiewer. If the rock quality is poor with a broken structure then the deformation parameters indicated by the initial load progression may be more applicable to design, at least for initial loading.

However, currently there are not much published data on response to loading of poorer quality, moderately fractured rock. Where the applicability of $G_i$ or $G_{ur}$ cannot be confirmed it may be necessary to consider the effects of both on the geotechnical model and select the more onerous case.

The Unload-Reload Modulus, $G_{ur}$, is obtained from the gradient of the loop. Typically, several of these will be undertaken during a test cycle, at increasing levels of stress.

The results of these tests will generally show increasing modulus with increasing test pressure. It is necessary to mitigate the effect of stress level on the interpretation of the test before applying these to the geotechnical model.

The general procedure for correcting for stress level is as follows, following Bellotti *et. al.* (1989):

- Calculate loop mean effective stress for each test loop.
- Plot loop mean effective stress against $G_{ur}$ for each UR loop.
- Derive the best fit power law curve across each complete test.
- The exponent of the curve is the Janbu number, *n.*
- Correct test $G_{ur}$ values using the following equation.

$$G_{corr} = G_{ur}\left(\frac{\sigma'_v}{\sigma'_{loop}}\right)^n$$

For the purposes of design the reference stress should be over the stress range applicable to the expected loading at a given level/location. However, particularly in weak rocks, a reference stress of in situ effective stress provides a reasonable approximation for preliminary design.

Several publications have compared predicted movement to surveyed such as Dewsbury, J. (2012), Poulous, H.G. & Bunce, G. (2008), and Polous, H.G. & Badelow, F. (2015). However, it should be noted that it is seldom stated whether a corrected value is used or any factor applied to $G_{ur}$.

The non-linear behaviour of a material is calculated from the unload-reload loops and is described by two components $\alpha$ and $\beta$. Exponent $\beta$ provides the gradient of the non-linearity, a value of 1 indicating perfectly linear behaviour, and lower values (trending to zero) indicating increasingly non-linear behaviour.

The determination of non-linear parameters is typically undertaken by the specialist PMT contractor. However, the designer should be aware that it is an interpretation, and different specialists may derive different values. The value of $\beta$ is sensitive to the selection of the return point in the UR loop and this may be difficult to determine where strain excursions are small such as in HPD testing in weak rocks.

On determination of appropriate non-linear components the shear modulus at a given strain may be calculated as follows:

$$G_{;\varepsilon} = \alpha\varepsilon^{\beta-1}$$

It should be noted that extrapolation of HPD derived modulus to strains below 0.0001% and above 0.1% is not recommended.

Based on experience in the Sherwood Sandstone (central Manchester, UK) and Bromsgrove Sandstone (central Birmingham, UK) $\beta$ values between 0.85-1.00 would normally be expected. Typical values in the Mercia Mudstone would be expected to be less, between approximately 0.75 – 0.90.

### 6.2.2 Comparison with other methods

In the absence of direct deformation testing or geophysical testing it is common to rely on correlations with Unconfined Compressive Strength (UCS) testing or laboratory based modulus testing to derive deformation characteristics.

Correlations with UCS such as that provided in CIRIA R181, *Piled foundations in weak rock*, will tend to overestimate stiffness in disturbed rocks since recovery of samples of sufficient dimensions for laboratory testing will have a tendency to be of the better quality material within the mass. Where rock quality and fracture intensity improve with depth there will be a tendency for the UCS correlation to provide lower value of stiffness when compared with corrected pressuremeter data.

### 6.2.3 Other considerations

The moduli derived from HPD testing relates primarily to the horizontal modulus rather than the vertical. However, both horizontal and vertical strains will occur in the ground under foundations and any moduli derived need to reflect this.

Past experience suggests that use of uncorrected moduli provide reasonable assessments of likely foundation performance. Published work by Meigh (1976), Thompson & Leach (1985), Clark et al. (2022) and Poulos & Bunce (2008) where comparison was made between HPD testing and methods such as plate load testing, dummy foundation with large scale load testing, and geophysical testing suggest that moduli derived from HPD testing correlates well.

More recently work by Dewsbury (2012) and Poulos & Badelow (2015), comparing calculated settlements derived from uncorrected HPD moduli with measured settlements of structures found reasonable agreement.

In rock masses, ‘structural anisotropy’ may occur within bedded deposits, where the test might be undertaken within a limited band of stronger material (e.g. sandstone bands within mudstone). In such cases the horizontal stiffness derived from the HPD would not be comparable to the vertical stiffness of the rock mass.

Any interpretation of pressuremeter data needs to consider the effect on the test result from, but not limited to, the following:

- Localised stress relief e.g. tunnel or basement construction.
- Stiffening from buried structures e.g. piled foundations.
- Increased stress from adjacent heavily loaded structures.

## 6.3 Presentation of results

It is common practice to provide preliminary results for most projects following the completion and initial analysis of each test. These preliminary results are typically a presentation of stiffness information and the logged pressure and displacement data.

A full report should be provided after all PMT testing on site has been completed. The complexity of the analysis will likely dictate the turnaround time for reporting.

The report should include a full set of results for each test, detailing strength, stiffness, and stress as appropriate. Additionally, the report should include explanatory text; referencing the analytical techniques used and detailing any deviations from standard practice. Calibrations for all instruments used should be provided. It should be clear which instrument has been used for each test and which calibrations are applicable to that test.

Alongside the technical report, it is good practice that a digital export of the results and field curves is provided. This is commonly in Excel-compatible and AGS formats. This allows for the designer to interact with the data and adjust assumed values such as unit weight and Poisson's ratio if necessary (for example upon the receipt of further lab testing).

The PMT digital AGS data should follow the format outlined in AGS guidance. Exceptions may be made if bespoke analyses, non-standard instrumentation, or atypical ground are involved.

The report should make note of any limitations that each test had. For example, a membrane rupture will reduce the confidence and reliability of the results. The report should discuss key assumptions made for the analysis, which assumptions may include:

- At the test level the material is homogeneous with isotropic properties behaving as a continuum.
- If the material is a soil, it is assumed that it is fully saturated.
- That the instrument's length to diameter ratio of the expanding section is large enough for end effects to be negligible.
- That the cavity expands as a circle and hence the results have been obtained by analysing the curve derived from the average of all displacement arms since this gives the best representation of a circular expansion. Unless the probe is an exact fit to the cavity the output from individual arms is almost meaningless. The centre of the probe is the reference for all measured displacements and is free to translate in relation to the cavity.

The results should be reported to an appropriate level of significant figures, based on the reliability, precision, and accuracy of the tool. For example, the stiffness of competent rock is often in excess of 1GPa, whereas the stiffness of weak clay can be less than 20MPa, therefore with most instrumentation it is not suitable or relevant to report these to the same number of decimal places.

## 7 Specifics of testing in soil vs rock

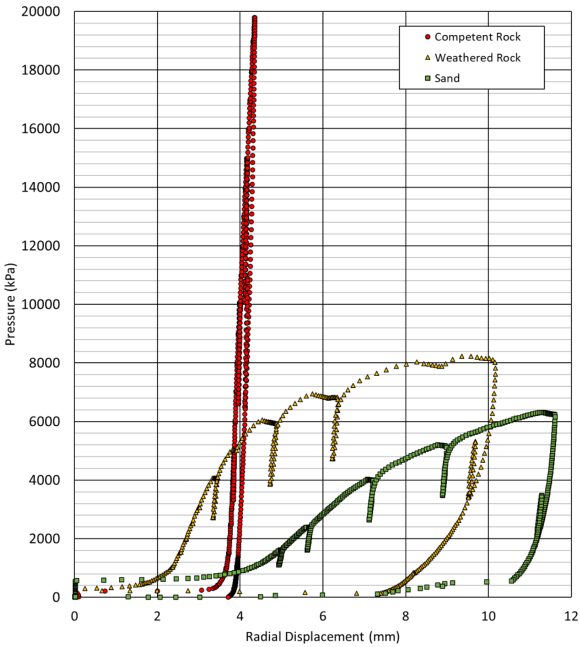
When testing in competent rock very little movement occurs over the span of the test: less than 1mm is typical. The test is therefore stress controlled, with the maximum pressure capacity of the instrument controlling the termination criteria.

This high stress and small displacement type of test means that reliable repeatable system stiffness calibrations, up to the maximum pressure of the instrument, are vital to have confidence in the results obtained. Stiffness is typically linear and in excess of 1GPa.

In competent rock, at the pressures that can be applied with commercial equipment, shear failure is unlikely to occur. However, it is typical for the tensile strength to be exceeded and multiple tensile failure to occur through the loading phase of the test.

It is not possible to determine a shear strength if shear failure does not occur. In the absence of shear failure, it is not possible to solve the boundary conditions, and curve fitting cannot be applied. To assess the in situ stress, alternative analysis methods must be applied (Byrne, 2022). These methods typically look at the differences in very small movements occurring, either if the pressure is held constant or comparing differences across the three axes of the instrument. The in situ stress anisotropy can be determined through several techniques for competent rock.

**Figure 26: Example plot of three tests, showing the difference between a test in competent rock vs a test in a highly weathered rock vs a test in sand**




Weathered rock is expected to exhibit significantly more movement than competent rock and give a field curve more comparable to one that occurs in a dense sand, as shown above in Figure 26. The shape of the curve does differ, the initial part of the loading in rock is often influenced by some tensile strength, and structural breakdown will occur in the latter parts of loading, giving the impression of a drained style shear failure. To analyse a test in weathered rock, standard frictional analysis techniques and curve modelling can be applied, with the understanding that the fit is an approximation.

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