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Using pressuremeters - worked examples

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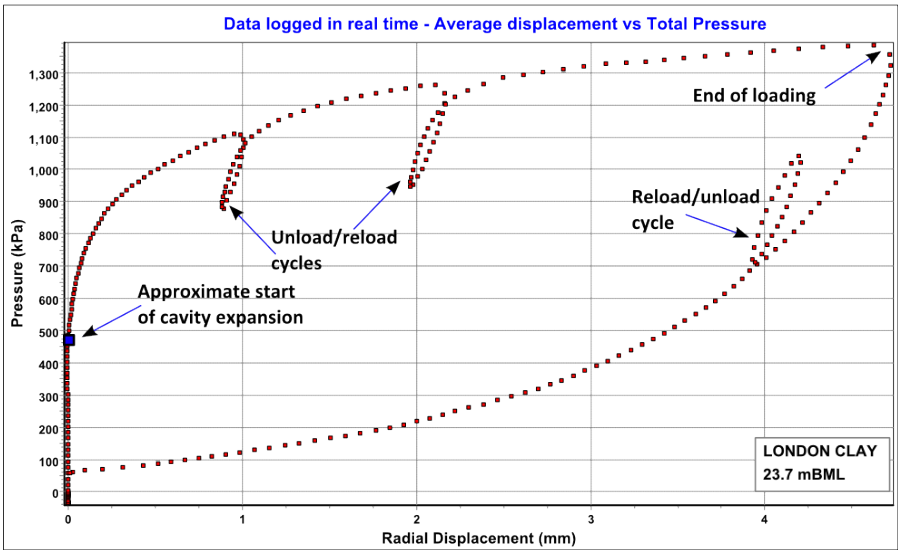
Using pressuremeters – worked examples

This technical reference document provides examples of pressuremeter tests from a range of materials with illustrations of how engineering parameters can be derived.

CASE A.
Analysis of a self bored pressuremeter test in London Clay

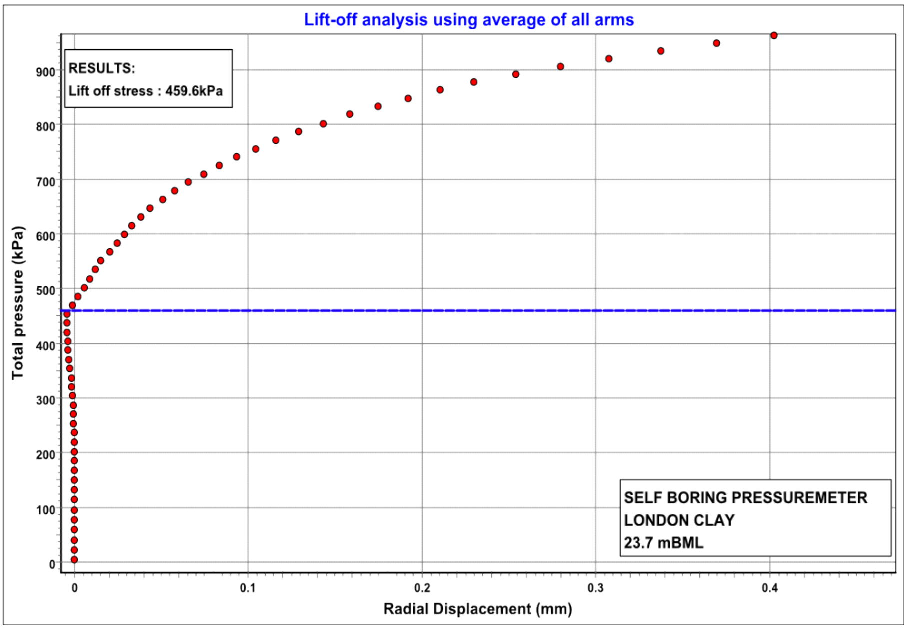
The most straightforward test to analyse is an undrained cavity expansion and contraction in clay, where a self boring pressuremeter has been used. The insertion disturbance is likely to be small and the undrained path means it is easy to calculate radial and circumferential stresses and strains directly from the displacement and pressure measurements made by the instrument. There are a number of analyses that can be applied; what is described here is one approach. The test itself was over water so depth is referred to bed level.

Fig. 1 – Field Curve



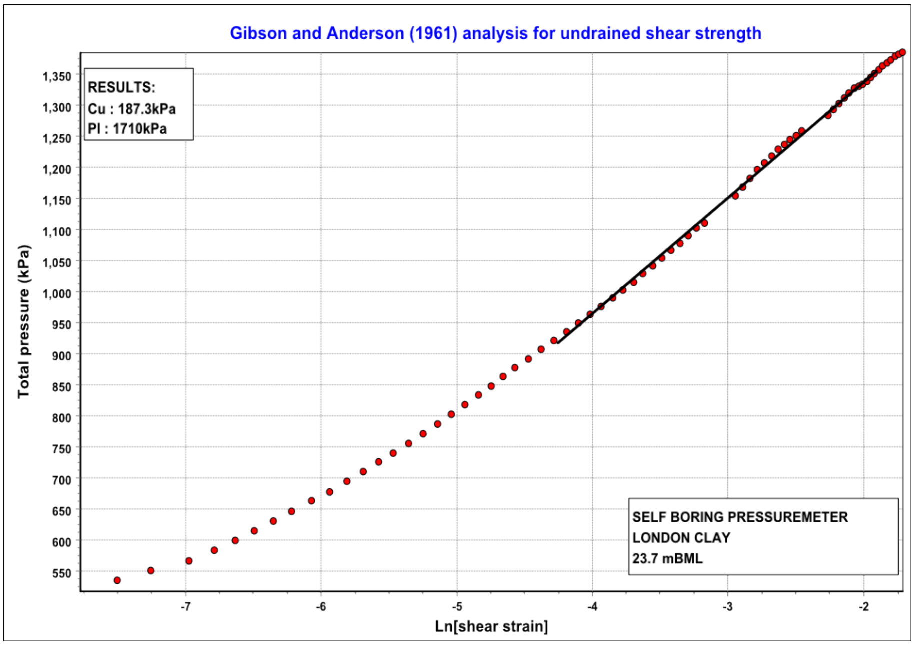
The test is logged as a set of readings of pressure and displacement. At intervals the loading is interrupted to make a small unload/reload cycle. These cycles can also be taken on the final contraction.

Fig. 2 – Lift-off



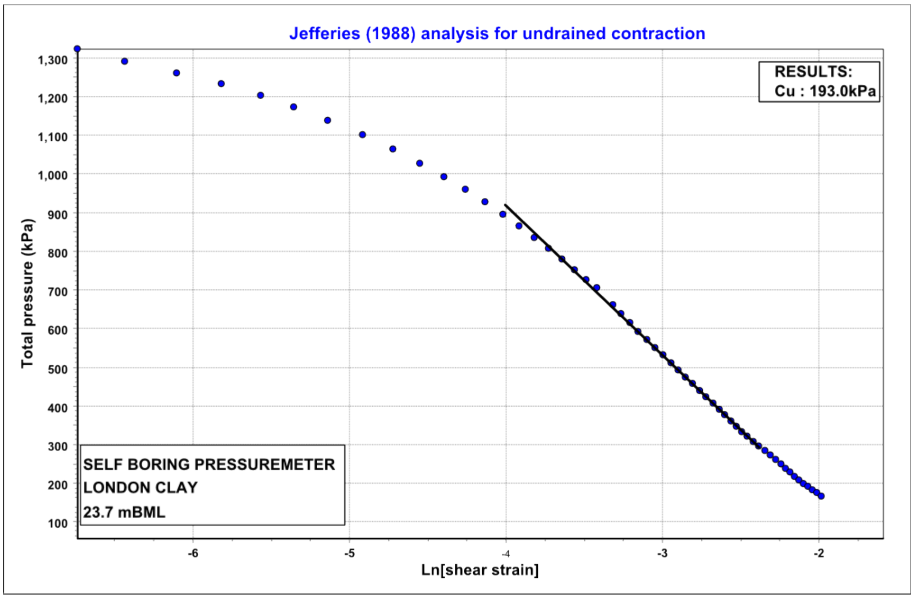
The first action when analysing the data is to select a plausible co-ordinate of stress and displacement that represents the origin for the cavity expansion. The stress value is the point where some movement is apparent. The displacement ordinate is close to zero, a feature of self boring.

Fig. 3 – Shear strength (a)



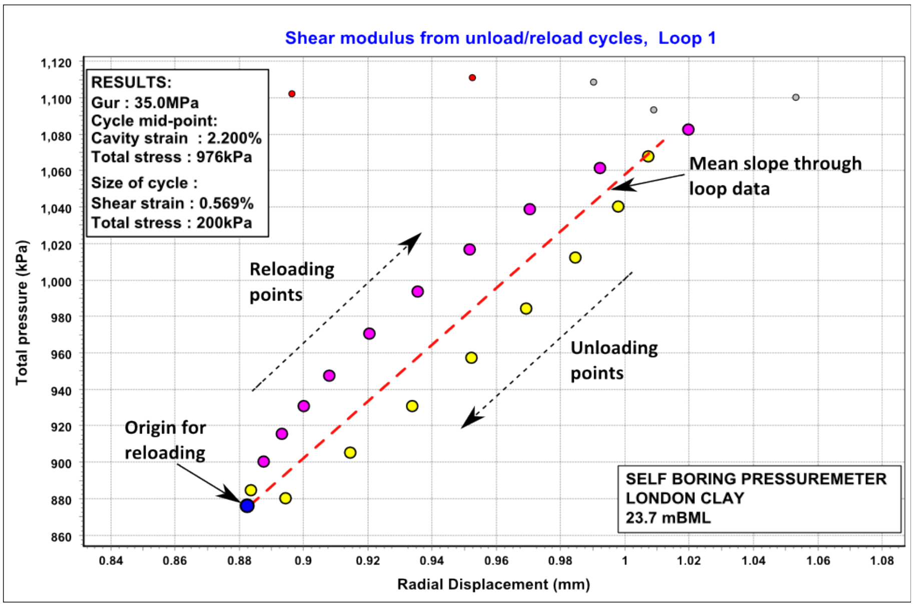
Having selected an origin, displacement can be converted to strain and the data analysed. This figure shows the result of plotting the loading data on semi-log scales and identifying the ultimate slope and intercept. These give shear strength and limit pressure [Reference 49].

Fig 4. – Shear strength (b)



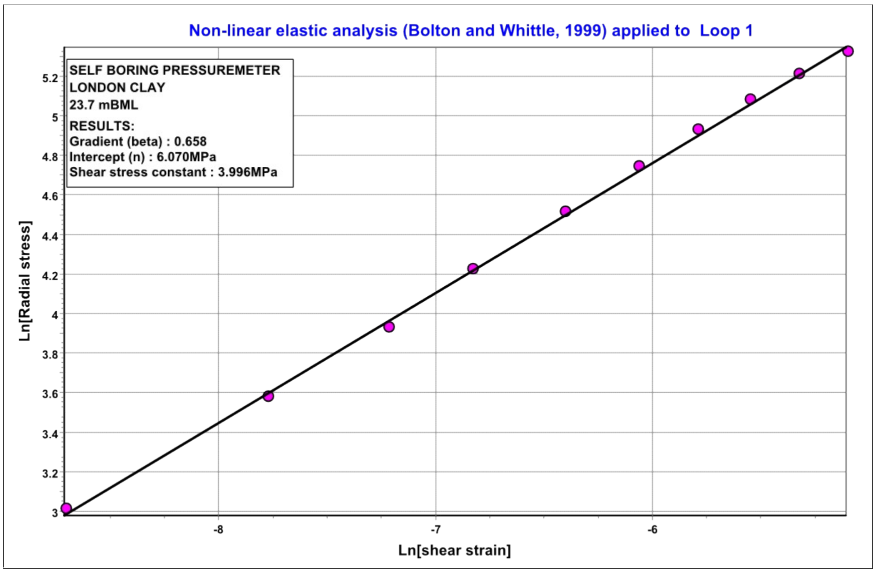
This is a similar procedure but applied to the final contraction data. It is of special interest because the origin at the start of unloading is an observable point – the origin used for the initial loading is always uncertain due to disturbance [Reference 60].

Fig 5. – Shear modulus (a)



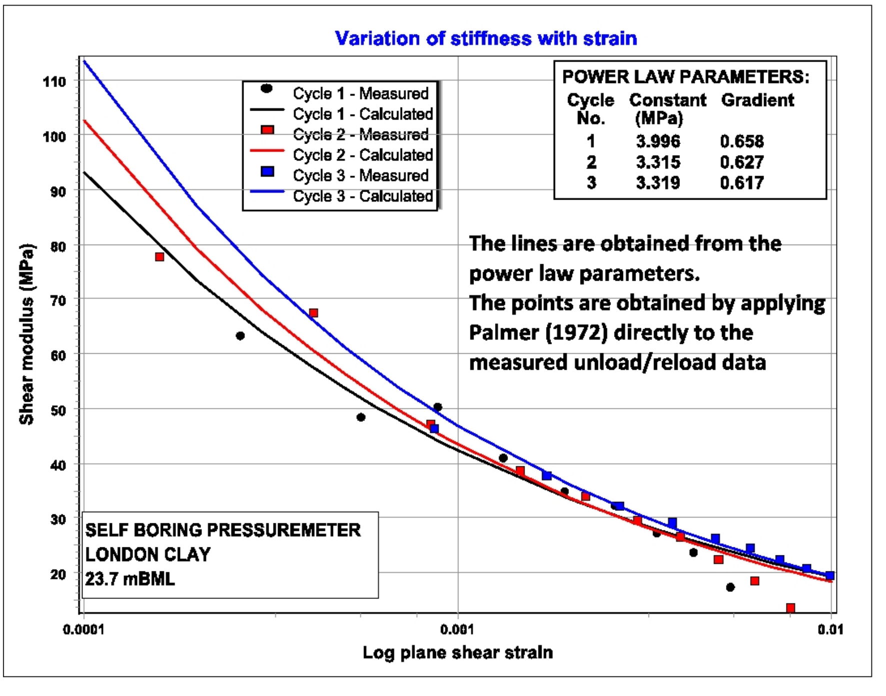
This is a simple approach to derive an estimate of the shear modulus, by taking the slope of the chord bisecting a cycle of unloading and reloading. In a linear elastic material the unloading and reloading data would coincide. Here the cycle appears hysteretic, indicating that modulus varies with strain.

Fig 6. – Shear modulus (b)



This non-linear stiffness behaviour can be represented by a power law. Here the reloading data from the previous plot are redrawn on log-log scales and the slope and intercept identified. These two parameters allow the current shear stress to be predicted at any strain [Reference 29].

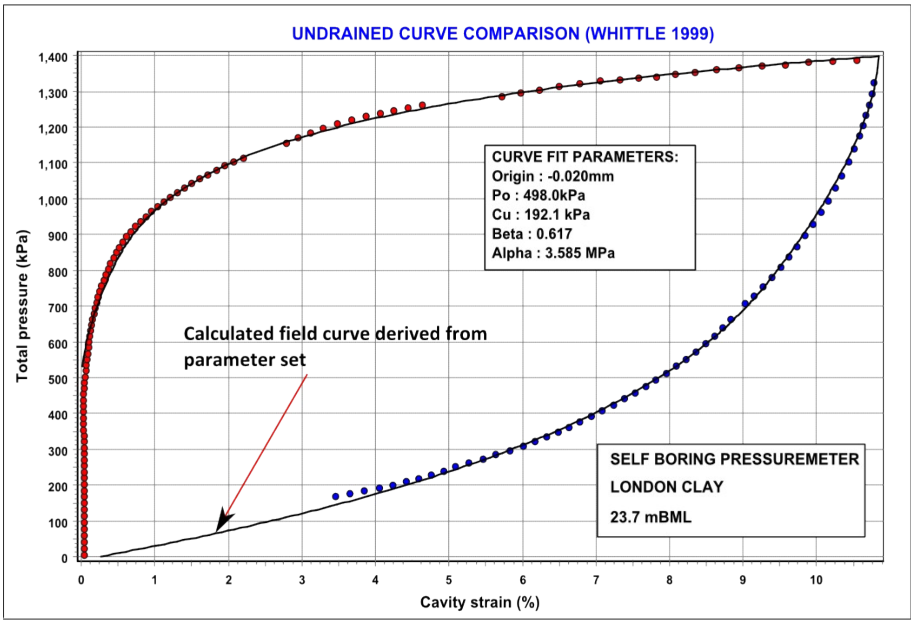
Fig 7. – Stiffness/strain



The trend of declining stiffness with strain is drawn here for each cycle. Because the test is virtually undrained the three cycles give almost exactly the same result. The lines come from the power law results, the data points from applying Palmer (1972) directly to the data [Reference 72].

At this stage of the process the analyst has a set of parameters describing the strength and stiffness of the material, and the insitu stress state. There are differing levels of uncertainty in these values. One method for resolving this uncertainty is to see if the parameter set can reproduce the measured field curve. Every measured data point could be calculated if the underlying stress:strain curve was known. The soil model used here assumes a non-linear elastic/perfectly plastic stress:strain curve for which there is a closed-form solution. The essence of such solutions is to define the stress and strain required to make the material yield, then integrate this condition between known boundaries. In the implementation shown here only the insitu horizontal stress is treated as a free variable.

Fig 8. – Curve comparison

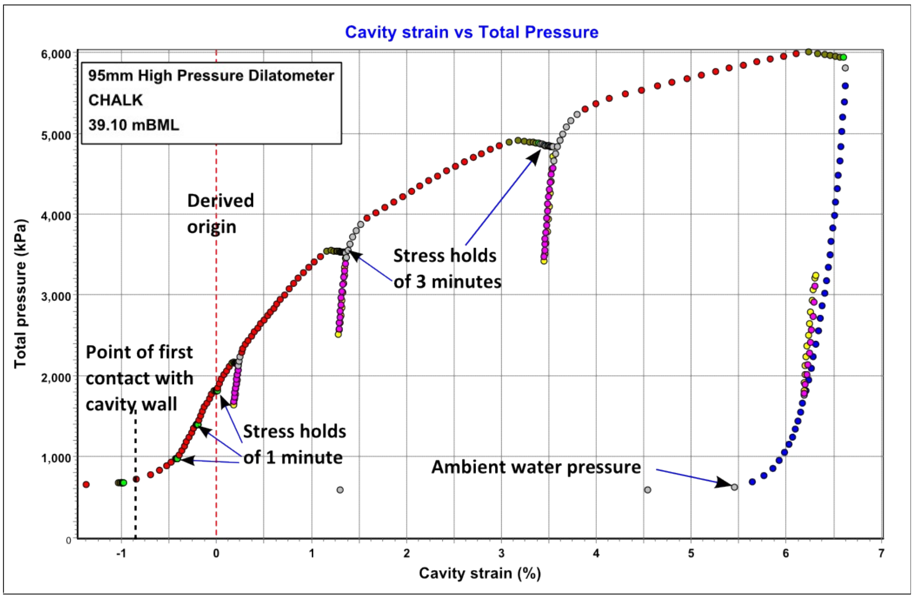


The parameters produced so far are used to calculate a pressure/strain curve for comparison with the measured data. The non-linear stiffness parameters are assumed correct. A tiny alteration to the origin reconciles loading and unloading shear strength. Finally, the initial reference stress is chosen for best fit [Reference 83].

CASE B.
Analysis of a pre-bored pressuremeter test in Chalk

A more difficult test to analyse is now described. This is a test in weak chalk made with a pre-bored pressuremeter. The pocket for the probe was made by rotary coring. The analysis is harder because the disturbance caused by pre-boring and the complete unloading of the cavity prior to the probe being placed means that little can be gleaned from the initial response. It is also complicated because the material is highly permeable and therefore the test is a drained loading. This means that it is not so easy to derive radial strain and circumferential stress from measured pressuremeter co-ordinates of pressure and displacement. Account has to be taken of dilatant properties, possible cohesion and the ambient pore water state.

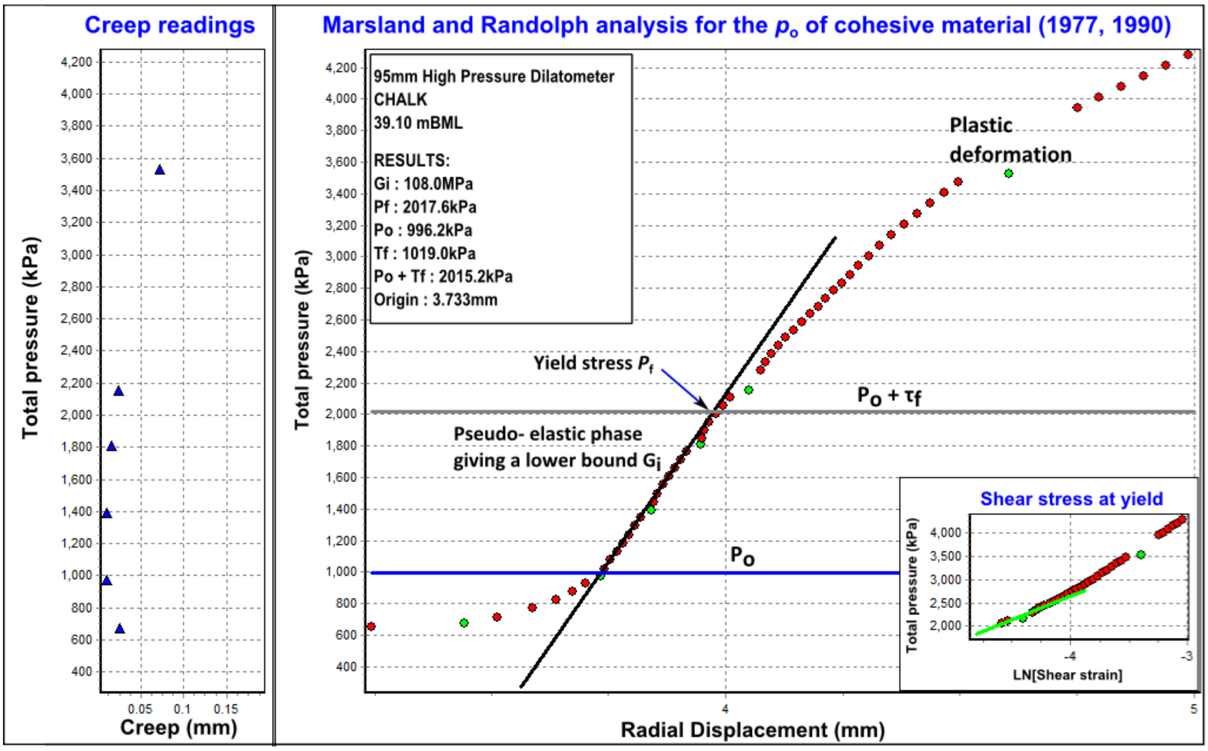
Fig 9. – Test in chalk



The picture is slightly misleading because it shows the final output of the analysis. The additional features of this test compared with the self boring example in clay are:

- The cavity wall is not pressed against the instrument at the start of the test.
- There is an appreciable difference between the point of first contact and cavity strain zero. This is a consequence of unloading the cavity prior to the test.
- The initial part of the expansion contains short duration stress holds, to see if the material 'creeps'.
- There is a longer stress hold before the start of each unload/reload cycle.
- Less evidence of hysteretic behaviour in the cycles, so they appear more linear than the clay.
- The membrane collapses at the head of water pressure at the end of the test, a feature of a drained expansion.

Fig 10. – Estimates of cavity reference stress and displacement

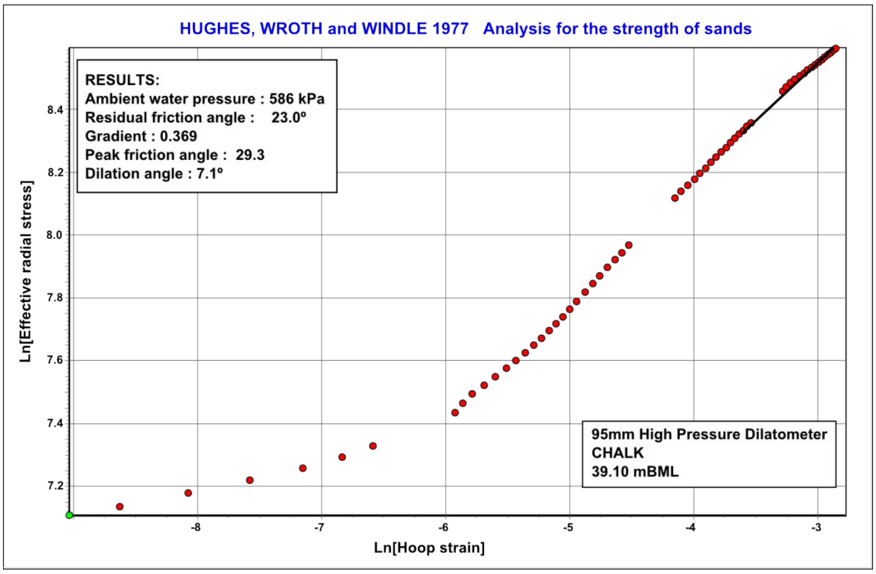


It is not possible to discover the initial stress state by inspection, so a method is used whereby estimates are back-calculated from the yield stress. The plot above consists of three views. The main display shows about 2mm of the initial expansion. The slope of the stiffest part has been used to estimate initial shear modulus. The onset of plasticity is where the data points move away from the slope line. Initially the reference stress is guessed, the displacement ordinate of that stress giving an origin for calculating strain. An analysis for mobilised shear stress near failure is carried out, and a calculated failure stress derived. This should coincide with the observed value. If not, the guess of cavity reference stress is adjusted and the cycle repeated until a match is found.

The chart on the left shows the creep displacements from the holds included in the expansion phase of the test. Creep seems to fall to a minimum in the vicinity of the cavity reference stress estimate and increases again near the yield stress estimate.

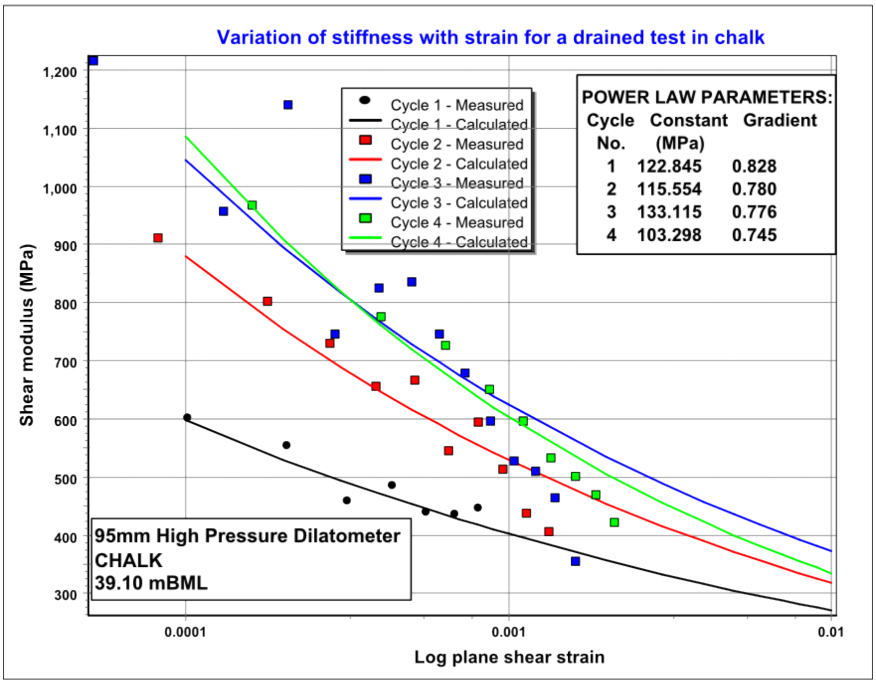
This analysis is used regardless of whether the loading conditions are drained or undrained. It is expected to give a higher bound estimate for reference stress but a lower bound value for the strain origin [References 67, 51].

Fig 11. – Friction angle



Because the expansion is drained a different analysis for strength is required. The gradient of a log-log plot of effective stress and strain is used to produce a value for the internal angle of friction and dilation. Ambient water pressure and the residual friction angle have to be known or estimated [Reference 56].

Fig 12. – Stiffness/strain



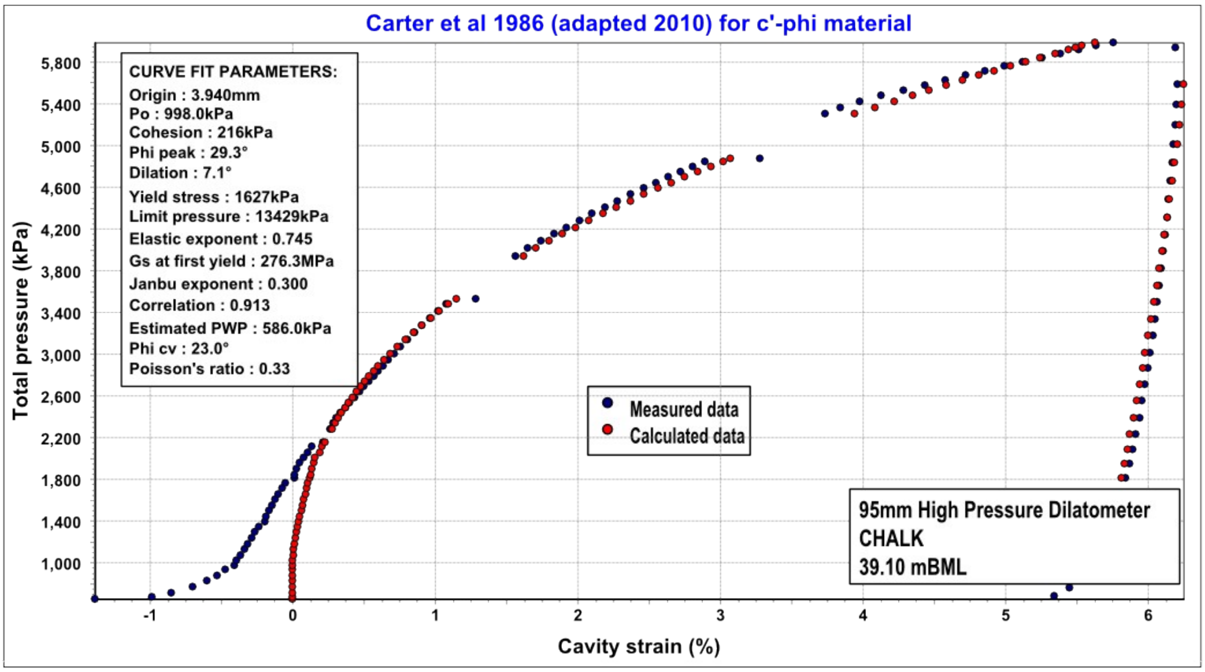
Non-linear modulus parameters are obtained in the same manner as a test in clay. Because the test is drained each cycle plots a higher trend, related to the mean effective stress. The unloading cycle shows the stiffest response because the mean stress is that which applied at the end of loading.

Fig 13. – Drained curve modelling

We have developed a closed-form solution for a drained test in a c´ - phi material based on the same non-linear elastic/perfectly plastic shear stress:shear strain curve as for the undrained case. It is less well constrained:

- Cohesion is also unknown as well as the insitu lateral stress.
- Shear modulus parameters must be adjusted for stress level.
- Poisson's ratio is required, and this probably has to be guessed.
- Ambient water pressure and residual friction angle are required.
- The solution takes no account of tensile strength which begins to be an issue as material approaches a rock like condition.

Despite these cautions the procedure is capable of producing plausible matches to the field data.

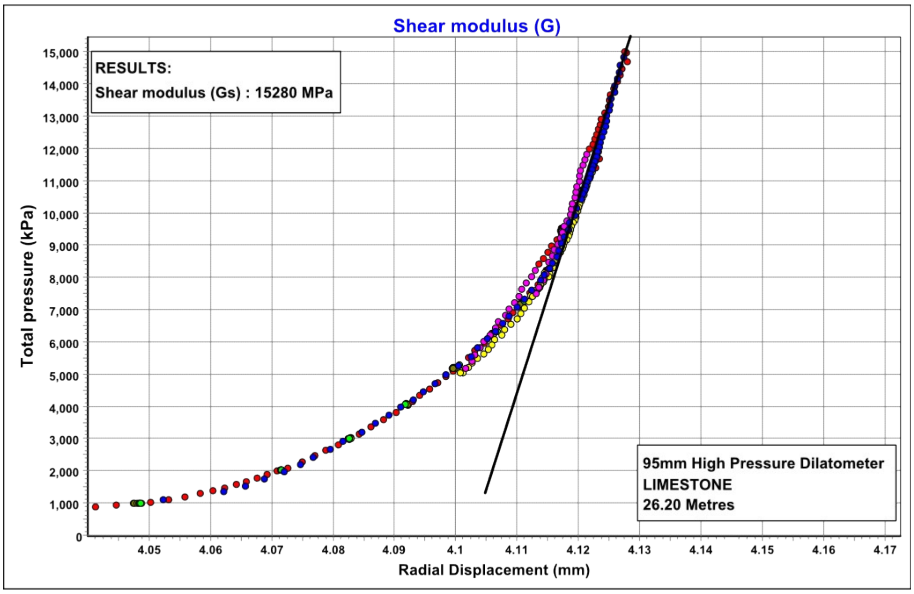


In this example the cavity reference pressure from the yield stress analysis gives the best fit curve but it has been necessary to make a slight adjustment to the origin for strain. The shear modulus at yield is nearly 3 times greater than the value provided by the initial slope, a typical result for a pre-bored test. The solution is also able to provide a value for the limit pressure of the material [Reference 106].

CASE C.
Analysis of a pre-bored pressuremeter test in competent rock

If failure in shear is an identifiable point in a pressuremeter test then it is always possible that analyses for strength and initial stress state can be carried out. In rock, the material can be so good that the probe reaches its maximum working pressure with only elastic deformation being seen. All that can be easily derived from such tests is a value for shear modulus. It it important to derive this from as late in the test as possible so that the forming of the pressuremeter cover against the rock is not confused with movement of the rock itself.

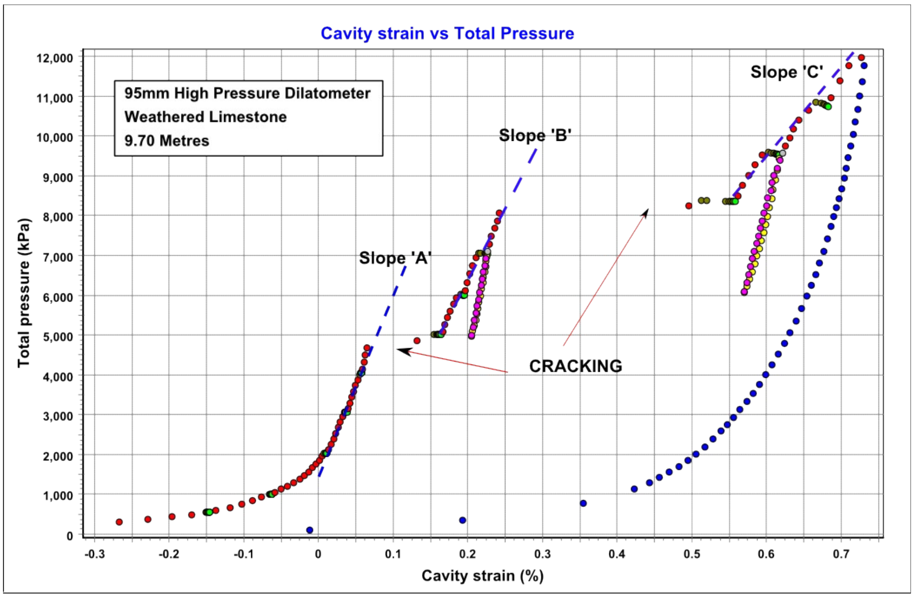
Fig 14. – Elastic deformation only



The example is from a test in intact limestone. Although not obvious there are two unload/reload cycles in this test, virtually indistinguishable from the loading path. The only parameter that is sensible to take from this test is an estimate of shear modulus from the latter part of the loading, giving a value greater than 15GPa, or in terms of Young's modulus 40GPa. The total displacement once the probe has contacted the cavity wall is only about 80 microns, so careful calibration of the probe for compliance effects is essential. A shear modulus of 15GPa is about the limit of what the probe can determine before the calibration uncertainty exceeds the apparent value.

In general it is the poorer material that is of most interest, especially those where core recovery is poor or does not produce intact samples for laboratory testing. The final example is from a test carried out in weathered limestone.

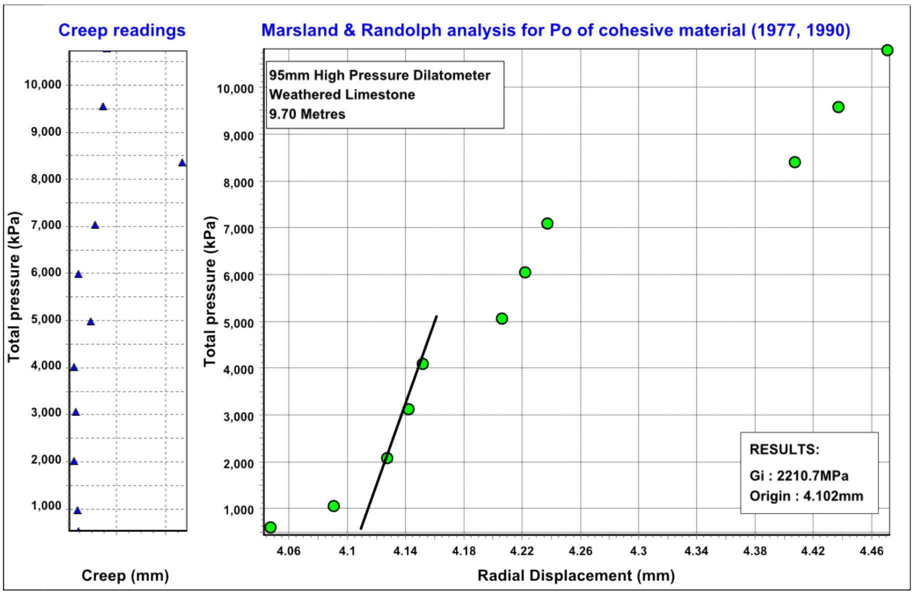
Fig 15. – Elastic deformation with tensile failure



The test shows two cracks forming, one at 4.8MPa and another at 8.1MPa. The event is too fast for any data points to be recorded so the plot shows a sudden jump at these stress levels.

The slope of the loading curve changes as a result of the tensile failure. Slope 'A' is stiffer than slope 'B' which is stiffer than slope 'C'. Not so obvious is the fact that the reload cycles have a different slope and are not representative of the properties of the intact rock – they will be under-estimates.

Fig 16. – Interpreting creep readings



In the figure above creep readings are plotted on the left and the data in the main display are ‘end of creep readings’ only. No parameters are quoted except for the initial slope and its intercept on the displacement axis. Although the material appears to have failed in shear, the loading curve is actually three lines of differing slopes with the shear failure stress not yet reached. After each crack has occurred, creep displacements reduce in magnitude.

Curiously, the one parameter that it is possible to identify with only limited uncertainty is the horizontal cavity reference pressure. The first crack appears at 4MPa total radial stress. At this point the circumferential stress must be zero or below. It follows that Po can be no greater than 2MPa, and if the tensile strength were known, could be narrowed down even further.