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Measuring Properties of Rock with a High Pressure Pressuremeter

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1. INTRODUCTION

A new pressuremeter has been developed for the insitu determination of the strength and deformation parameters of rock. Shear strengths greater than 7 MPa have been measured in the Kings Park Formation underlying Perth and the instrument should be capable of initiating failure in rocks with shear strengths in excess of 10 MPa. Test data is collected in the field on a microprocessor data acquisition and control system (DACS). The raw data is digitized and stored on floppy discs from which it can be calibrated and printed or plotted out in any required form. The analysis and interpretation of the test data is discussed and compared with conventional methods of determination of strength.

2. NOTATION

E	Young's modulus
G	shear modulus
G_I	initial tangent modulus
G_{UR}	modulus obtained from unload-reload loop
r	current borehole radius
r_0	initial borehole radius
S_u	undrained shear strength
V	current borehole volume
V_0	initial borehole volume
ψ	cell pressure
ε	observed strain
μ	Poisson's ratio

3. DESCRIPTION OF EQUIPMENT

The High Pressure Pressuremeter developed at the University of Western Australia in conjunction with Golder Associates Pty Ltd has a nominal 20 MPa pressure capacity. Designed for use in NQ size diamond-cored boreholes (76mm nominal diameter), the probe consists of a thick reinforced rubber membrane clamped onto a solid steel body. The membrane is expanded under gas pressure and displacement is measured directly by LVDT transducers located around the probe centre line.

Being gas operated there is no head correction with depth as is the case with pressuremeters inflated by fluid pressure. At present the high resolution pressure transducer is connected into the gas line at the surface for safety and convenience. There are no limits to operating depth other than the length of the coaxial gas/signal cable attached to the probe. However it could be that with a cable in excess of say 200m the pressure transducer would need installation within the probe rather than at the surface to eliminate pressure lag.

There are 4 displacement transducers equally spaced around the pressuremeter which can either be treated individually or averaged. The travel of each is limited to about 9mm at present which limits the size of borehole and/or the amount of expansion which can be handled. A limit of an 84mm diameter cavity corresponds to about 10.5% expansion from the nominal borehole size or 20% expansion from the 70mm initial probe diameter.

The length to diameter ratio of the expanding section of the sheath is about 6 which is adequate to ensure plane strain expansion at the mid height of the expanding borehole. The probe may be lowered on drill rods or wirelined down the prebored hole. In general, wirelining is not favoured where there is any danger of material from the borehole sides falling in and jamming the probe as could occur in soft or fractured rocks.

Test data may be recorded by hand from the signal display box (Fig. 1). This box contains signal conditioning circuitry which enables the transducer outputs to be displayed as direct displacement (in mm) and pressure (in MPa)

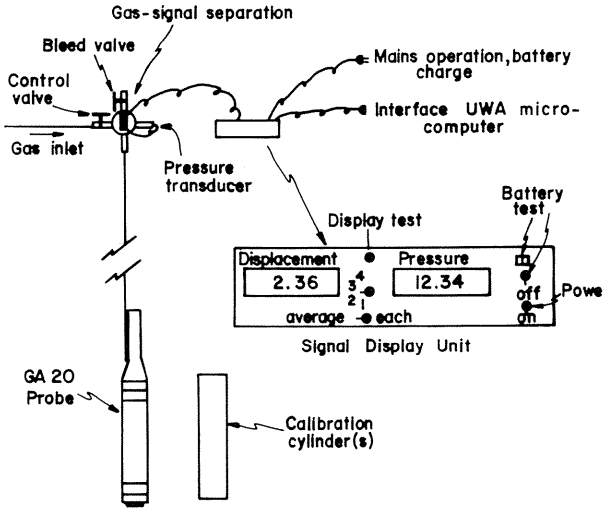


Figure 1. Schematic Setup of High Pressure Pressuremeter and Associated Equipment.

readings on the LCD displays. The transducer outputs can also be fed into the microprocessor DACS and this powerful facility enables many more data to be recorded and analysed to obtain the desired rock parameters than when recording by hand.

The DACS is a modified Obsorne 1 micro computer built into a rugged carrying case for use in the field. The modifications include the addition of an 8 channel 12 bit analogue to digital converter with real time clock and calendar and 12 Volt D.C. battery operation. The system was built by T.A. Brown Electronics under contract to the University of W.A. specifically for the Self Boring Pressurementer (Camkometer) and for that instrument controls the test in addition to providing a data acquisition and processing facility. It has been adapted to provide a data acquisition and processing facility for the high pressure probe simply by the writing of dedicated software for the purpose.

For both Camkometer and HPP operations a dot matrix printer provides a printout facility. Robustly cased for field work and provided with 240 Volt AC power, the printer permits printout of data in plotted or tabulated format. Examples of the plots have been reduced and used for the figures in this paper.

4. TEST PROCEDURE

Two types of pressuremeter test are routinely performed. The practice of increasing the pressure in increments and determining the "creep" that occurs at each pressure setting over a specific time span is the traditional test method used with Menard type pressuremeters. The second type of test involves increasing the pressure at a rate set to achieve either a constant stress increase or a constant rate of strain. Such tests are routinely undertaken with the Camkometer.

Most of the tests carried out with the new probe have been of the latter type. However the results of both types of test are presented in this paper in order to illustrate several points relating to the analysis of results. The use of the computer which is set to take a complete set of transducer readings every 5 seconds enables a comprehensive set of data to be stored for manipulation and analysis by a variety of methods. For example at a constant pressure increase of 10 kPa/second a test to 18 MPa requires 30 minutes for the loading stage without unload-reload cycles and the final unloading. In that 30 minute period 360 sets of data are obtained.

When a constant rate of pressure increase is maintained, the rate of displacement is observed to increase after failure is initiated in an annulus adjacent to the membrane. It has been our practice to continue the test in a strain controlled manner after that stage to ensure that the expansion is slow enough to "control" creep.

5. INTERPRETATION OF TEST RESULTS

5.1 Test Results

The output of the displacement LVDT's can be individually plotted against pressure or they can be combined and averaged. It has been observed in calibrating cylinders that the body of the probe can move relative to the cylinder with increasing pressure. Because of this and other effects it is normal practice to consider only the average of the LVDT outputs.

Figures 2 and 3 present data from two tests undertaken in the dark grey siltstone which comprises the upper strata in the Kings Park Formation underlying Perth. The tests were taken in two boreholes approximately 3 metres apart and where the top of the siltstone was encountered at a depth of approximately 15 metres. Figure 2 presents data from a test undertaken at an approximately constant rate of pressure increase while the test presented in Figure 3 was undertaken at a constant rate of pressure increase up to approximately 4.5 MPa and then in increments of stress of approximately 0.5 MPa. On both figures each dot represents a separate recorded data point.

5.2 Reduction of Data

Data reduction involves applying a sheath correction to each displacement reading and converting it into a "cavity strain" (ε) where:-

$$\varepsilon = \frac{\Delta r}{r} = \frac{r - r_0}{r} \qquad (1)$$

The pressure required to expand the sheath to the sides of the borehole is a function of the stiffness of the sheath and of the initial borehole diameter. The sheaths in use require a pressure of the order of 200 kPa for "lift off" and a further increment to reach the borehole sides. With a prebored hole, in which there has been stress (and strain) release, a further pressure increment is required to reconstitute the insitu stress to the stage where the initial linear pressure - deformation relationship is established (Fig. 2(a)).

It is possible to obtain a value of r_0 by an examination of a pressure - LVDT deformation plot as was initially undertaken. For materials with a shear strength exceeding about 1 MPa and initial hole sizes up to about 80 mm it is our practice to define r_0 as the displacement reading when the cell pressure reaches 1 MPa. This criterion, which is justified later in the paper is very convenient for use with the computer.

A thick walled rubber cylinder expanded in plane strain exhibits decreasing wall thickness with expansion. By expanding the probe in a number of calibrating cylinders of known internal dimensions to a constant pressure (1 MPa say) it has been found that the relationship between LVDT readings and cylinder diameter is linear. Further, when the pressure is increased in any particular cylinder an additional reduction in sheath thickness occurs. These calibration factors must be applied to LVDT output in determining deformation of the borehole sides.

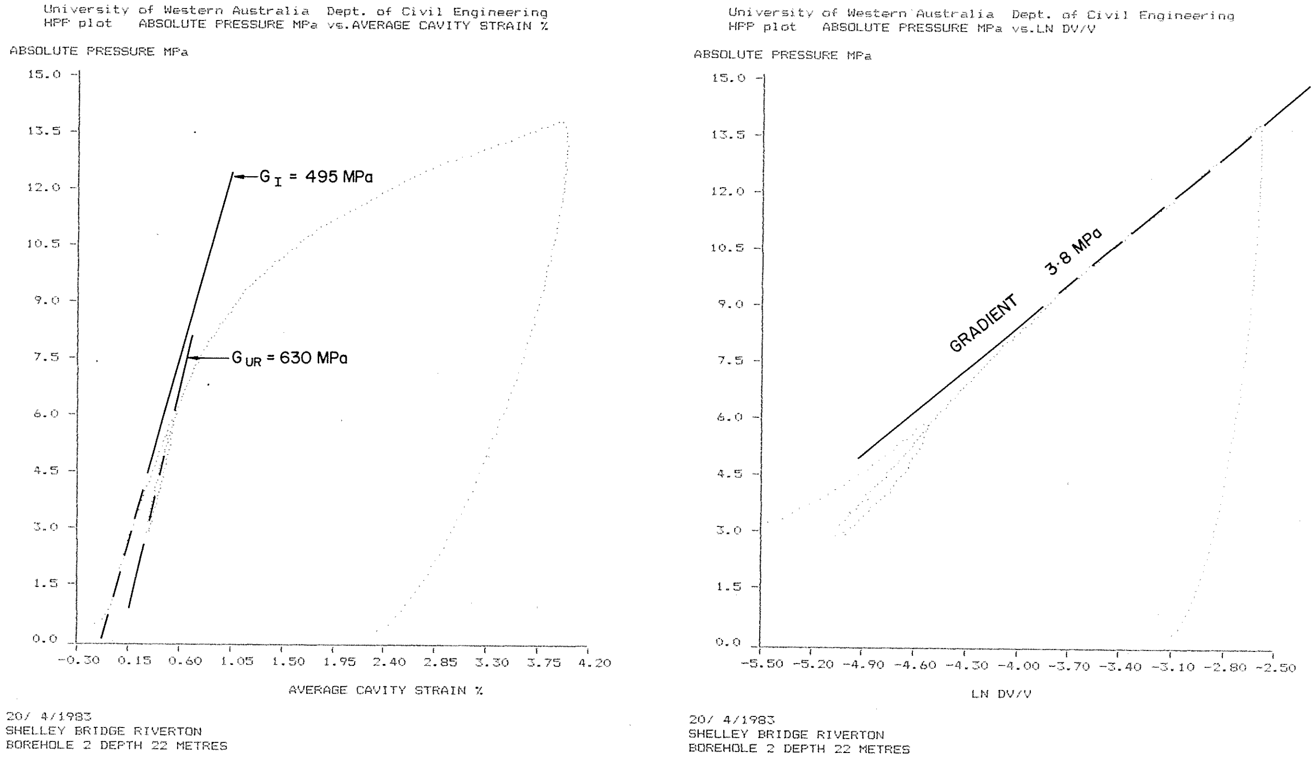
5.3. Determination of Engineering Parameters

5.3.1. Shear modulus (G)

When the test results are plotted as pressure versus cavity strain as in Figures 2(a) and 3(a), the gradient of the curve at small strains is twice the shear modulus (Palmer 1972).

$$\text{ie:-} \quad \frac{d\psi}{d\varepsilon} = 2G \qquad (2)$$

The shear modulus may be evaluated from the initial linear tangent to the curve (G_I) or from



(a) (b)

FIG. 2: TYPICAL CONTROLLED STRESS TEST RESULTS

an unload-reload cycle undertaken during the test specifically for the purpose. The unload-reload modulus (G_{UR}) is evaluated from the gradient of a line which bisects the hysteresis loop of the unload-reload cycle.

Two points must be kept in mind in assessing a shear modulus evaluated in this manner. Firstly it is obtained from a test conducted in a horizontal plane and hence is a horizontal modulus. Secondly it is a "shear"modulus and in order to derive a value of Young's modulus (E), it is necessary to adopt an appropriate value of Poisson's ratio.

ie. $E = 2(1 + \mu)\ G$ (3)

The pressuremeter test is conducted at a rate such that in cohesive material the test is probably measuring the undrained parameters and even in sand some pore pressure increase has been measured with the Camkometer. As such the appropriate value of μ will likely fall within the range of 0.25 to 0.5. This means that the value of Young's modulus will range from 2.5 to 3 G.

i.e.

drained

$E' = 2(1+\mu')\ G = \text{say } 2.5\ G$ (4)

undrained

$E_u = 2(1+\mu_u)\ G = 3\ G$ (5)

The value of G_{UR} can be obtained graphically from the ψ - ε plot as previously described and can also be obtained directly from the computer from a least-squares regression analysis on the data points in the unload-reload loop.

5.3.2 Shear strength (S_u)

When the test results are plotted as pressure against the natural logarithm of the volumetric strain ($\Delta V/V$) the gradient of the linear portion of this plot represents the undrained shear strength of the material under test.

This method was proposed by Gibson and Anderson (1961) assuming a linearly elastic, perfectly plastic soil model and no volume change with shearing. After failure is initiated the value of Su is obtained from the expression:-

$$\psi = \psi_\ell + S_u\ \ell n\ \{\frac{\Delta V}{V} - (1- \frac{\Delta V}{V})\ \frac{\sigma_h}{G}\} \qquad (6)$$

where ψ_ℓ and σ_h represent the limit pressure and insitu lateral stress respectively.

If the reference state for strain is taken at the volume at which the pressure is equal to σ_h then this expression reduces to :

$$\psi = \psi_\ell + S_u\ \ell n(\frac{\Delta V}{V}) \qquad (7)$$

and the undrained shear strength may be obtained as the value of the tangent to the plot of ψ versus $\ell n\ (\Delta V/V)$ after the initial elastic phase. Accurate determination of r_o may not be possible. However if r_o is overestimated, the value of s_u derived will be an underestimate of the true value. This justifies our criterion for determination of r_o used for calculation.

With this method of analysis, obtaining volumetric strain is an additional step in the necessary calculations. While this is of no consequence for the computer it is tedious when recording and reducing data manually.

Since:

$$\varepsilon = \frac{r-r_o}{r} \text{ and } \frac{\Delta V}{V} = (\frac{r^2 - r_o^2}{r^2}) \text{ (for unit length)}$$

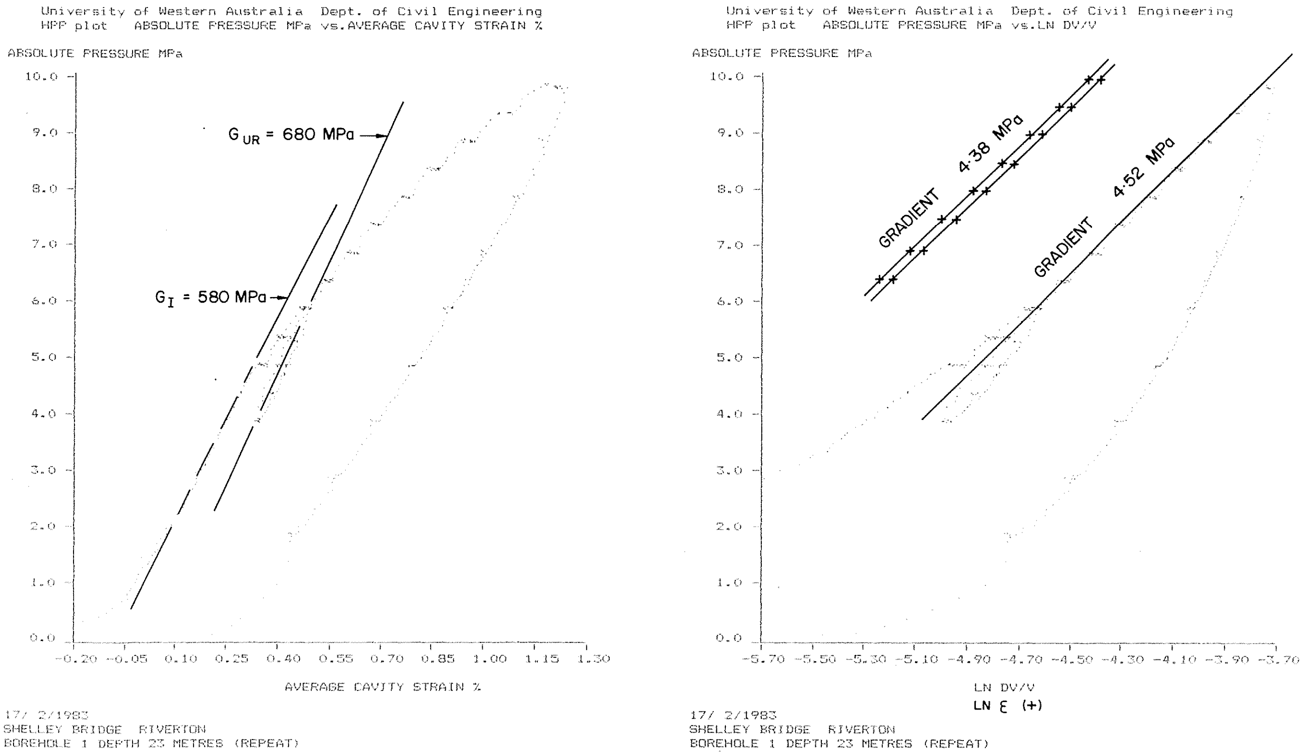
then

$$\frac{\Delta V}{V} = 2\varepsilon + \varepsilon^2 \qquad 2\varepsilon \text{ for small strains}$$

and

$$\psi = \psi_\ell + S_u\ (\ell n\ 2 + \ell n\ \varepsilon) \qquad (8)$$

Therefore a plot of ψ against $\ell n\ \varepsilon$ should be linear after the initial elastic phase with the



(a) (b)

FIG. 3: TYPICAL INCREMENTED STRESS TEST RESULTS

gradient of this plot providing a very similar value of S_u to that obtained from the plot of ψ against $\ell n\ (\Delta V/V)$. On Figure 3(b) the data has been plotted as ψ against both $\ell n\ (\Delta V/V)$ and $\ell n\ \varepsilon$ for comparison.

6. DISCUSSION

The sheath correction includes two components: firstly that caused by the reduction of the sheath thickness with increasing hole size, and secondly the correction for reduction of thickness with increasing pressure. The correction due to increasing size of hole is linear and in the worst combination of extreme expansion and pressure consists of greater than 99% of the total sheath correction. This is an accurately defined and reproducable correction.

The correction for increasing pressure varies with borehole size from values between 0.003 to 0.006mm/MPa. It has been determined that the difference between these values is not of significance in the context of the total corrections to be applied and a value of 0.004mm/MPa is used in practice.

Of the two values of shear modulus determined G_{UR} is consistently higher than G_I and it is derived and presented for a number of reasons:

> The initial linear tangent is not always easily identifiable and this is especially so in weak and/or disturbed material. On the other hand the G_{UR} value is easily identified and repeatable and to a large extent the value obtained is not greatly affected by the value of strain at which the loop is undertaken. Wroth (1982) has discussed this issue in some detail as it relates to both cohesive and granular materials.
>
> At present it is believed that G_{UR} provides a better estimate of the elastic modulus of soil and rock than the initial tangent modulus.
>
> The issue that the designer must resolve is whether he wants an "elastic" modulus or a deformation parameter that reflects the condition likely to be encountered on first loading.

The G_{UR}/G_I ratio for the two tests presented in Figures 2 and 3 is of the order of 1.2. The ratios determined from all the tests conducted at this location varied from 1.2 up to 1.6. However, in other locations where the rock encountered was more weathered and variable ratios up to 7 have been recorded. This may well be due to any number of factors but it is clear that the determination of a clearly defined and reproducable deformation parameter such as G_{UR} will be of more value for design than G_I.

Existing formula for settlement calculations may need to be adapted to make use of raw G_{UR} values. Where they are higher than normally adopted values, low calculated settlements could result. Resolution of this situation will only be reached with further work involving back analysis from field data. Programs involving a complete profile of pressuremeter data followed by monitoring of deflections throughout the profile would be the ideal approach to further work and hopefully these will be initiated in the near future.

The values of shear strength determined have been made on the basis of zero volume change during shearing. It is uncertain if this assumption is correct for rock or whether some form of dilatent behaviour should be considered. The siltstone under test contains a considerable quantity of sand sized quartz particles in a silt sized matrix and the volume change characteristics of the material have yet to be determined. Nevertheless the linear form of the semi logarithmic plot in Figure 2(b) suggests that the siltstone conforms to the Gibson and Anderson assumptions of perfect plasticity and zero volume change at strains in excess of 1.2% at the rate of shearing undertaken in these tests.

A comparison of the test data on Figures 2 and 3 suggests that similar values of the strength and deformation parameters will be obtained regardless of whether the pressure is applied at a steady rate or applied rapidly in increments and stabilized for specific periods while measuring "creep". With the methods of analysis suggested it is not necessary to define the pseudo-elastic phase by means of monitoring the rate of creep and that form of test is not recommended. Even when recording manually the average displacement and pressure readings can be read simultaneously at prescribed pressure settings without halting the rate of pressure increase.

Figure 4 presents shear strengths calculated as half the unconfined compressive strength obtained from tests conducted on core samples recovered while boring the holes for the pressuremeter tests. Superimposed on these data are the shear strengths obtained from the pressuremeter results. Both sets of data present the same trend of shear strength increasing with depth. However the pressuremeter values are of greater magnitude.

The microprocessor data acquisition system developed for field use with the pressuremeters is invaluable in data handling and processing. The quantity of data which can be collected and processed enables a complete pressure-deformation relationship to be obtained. This eliminates any possible need for curve fitting techniques to "fill in the gaps" in a limited number of data points. It is now possible therefore to accurately compare field data with trends predicted by conventional methods of analysis. The system will enable an accurate comparison of data from tests conducted at different rates of loading for example and in due course the influence of that and other factors on the test and parameters obtained may be evaluated.

When used in the field in conjunction with a printer it is possible to produce a printout of data as the test progresses if desired. It is also possible to produce report quality plots of the calibrated data and to evaluate the strength and deformation parameters immediately after the test. This can be a significant improvement on the practice of recording and reducing a limited number of data points manually.

7. CONCLUSIONS

The new high pressure pressuremeter has proved to be a convenient and satisfactory instrument for the insitu determination of strength and deformation parameters for rock. For oversize holes and softer material it will be desirable to extend the range of the displacement transducers and that modification will be incorporated shortly.

It has been shown that both strength and deformation parameters are obtainable using conventional methods of pressuremeter test analysis. When the pressuremeter is used in conjunction with the microprocessor data acquisition system both parameters can be evaluated by the computer.

The shear modulus obtained from an unload-reload loop (G_{UR}) has better repeatability than that obtained from the initial pressure-deformation relationship and is not affected by initial disturbance. G_{UR} is believed to be the appropriate value for design purposes even if its use requires a rethink of current methods of settlement determination. Further work is required to relate pressuremeter derived parameters to design.

Although not reported here, the pressuremeter has been successfully used in much softer material than the siltstone. The capacity for both low and high pressure work together with the simplicity of operation and the greater accuracy means that the new instrument has the Potential to supersede the Menard Pressuremeter.

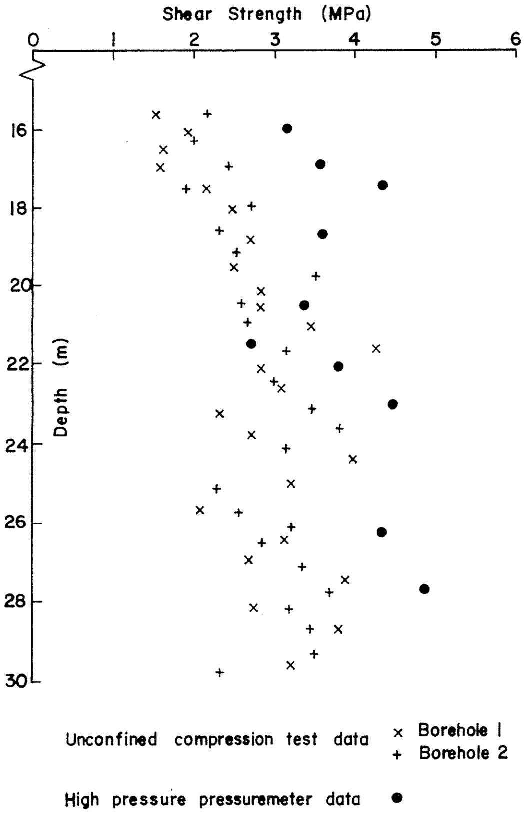


Figure 4. Shear Strength Profile For Kings Park Formation Siltstone

8. ACKNOWLEDGEMENTS

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