THE PENCEL PRESSUREMETER: A USEFUL TOOL FOR ROUTINE SITE INVESTIGATION

LA JAUGE DE PRESSION APPELE PENCEL: UN OUTIL PRATIQUE POUR LES INVESTIGATIONS DE ROUTINE AU CHANTIER

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SYNOPSIS: The paper compares elastic moduli obtained from a 22.5mm diameter pressuremeter (the PENCEL) inserted horizontally into the sides of large diameter boreholes, with those derived from lateral plate-jacking tests. The PENCEL is relatively simple and inexpensive to use and seems to give appropriate measures of moduli. Due to the relatively simple nature of the apparatus it has promise for use in routine site investigation. Using the PENCEL pressuremeter in situ implies that the amount of undisturbed samples required for laboratory testing is reduced, and so lowers investigation cost. In addition, being by nature an in-situ test, in-situ moisture conditions and stress states are automatically taken into account. Details are given of preliminary tests carried out at two sites where plate bearing and oedometer test results were also available for comparison. Results indicate a closer agreement for unloading moduli than for loading moduli. Recent findings indicate that unload-reload loops are often the most applicable moduli to be used in design.

BACKGROUND

In South Africa extensive use of large diameter (750 mm) auger holes for soil profiling and sampling is made, especially where geotechnical investigations for larger structures are carried out. Investigations typically involve inspection and sampling of materials for laboratory testing. This is possible over most of the interior of the country where permanent water tables are relatively deep, ie typically below 20 m depth. Areas where large diameter boreholes would not be used include soil profiles where seepage is present from shallow perched watertables, as well as in coastal areas where mainly estuarine and beach deposits are associated with shallow permanent water tables. The only other important constraint to using this method is suitability of the soil profile for augering. For soils and very soft rock, virtually the only significant problems are when large boulders in transported soils or corestones in residual soils are encountered.

Using large diameter boreholes for investigation has the advantage of obtaining a first hand chance of evaluating the soil profile in terms of some of its primary properties, ie moisture content, colour, consistency, structure and origin. It also allows "undisturbed" block samples to be cut from the sides of these holes. Although good quality samples are relatively easy to obtain for laboratory testing, the effects of changes in stress and moisture content are difficult to quantify and avoid.

Consequently, laboratory tests conducted on samples obtained from large diameter holes are often augmented by in-situ tests. Typically this may comprise lateral plate jacking tests within the holes or possibly pressuremeter testing in smaller diameter holes. Despite being fairly popular, lateral plate bearing tests are often difficult to carry out satisfactorily due mainly to the awkwardness of handling the apparatus inside a large diameter borehole and preparing suitable bearing surfaces. These surfaces should be parallel to each other and smooth, necessitating plaster of paris or a similar rapid hardening seating agent. This increases the time taken for the test to be carried out and introduces more complexity to the test procedure and analysis.

Pressuremeter testing is traditionally carried out within predrilled vertical boreholes or with the self boring pressuremeter. Soil moduli are measured in the horizontal direction since expansion of the pressuremeter probe imposes a lateral stress on the surrounding soil inducing plane strain conditions. Anisotropy and stress dependency may mean that the vertical modulus of the soil differs from the horizontal modulus, thus rendering test results inappropriate to the design situation.

Comparisons of plate and pressuremeter test results have been carried out in various instances, for example Powell and Uglow (1985), Windle and Wroth (1977), Wroth et al. (1979), Walker and Jewell (1979) and Marsland et al. (1983). The correlation between pressuremeter and plate moduli varies according to a number of factors such as material type, the technique employed to derive moduli from test results, and the stress or strain ranges over which moduli are measured. The aim therefore when deriving material parameters from test results should be to ensure that values are compatible with design techniques to be employed. With this in mind, the ideal situation is where parameters are backcalculated from full-scale structural behaviour and compared to those derived from pressuremeter curves. The most appropriate parameters should then be identified. An example of this can be seen where the unload-reload moduli from a Cambridge self-boring pressuremeter have been compared to values obtained from analysis of the settlement of a reactor (Wroth et al., 1979).

Clough (1990) notes that unload-reload moduli from pressuremeter curves seem to give the most appropriate values for design, and in addition, these values are relatively unaffected by drilling disturbance, which is often a large consideration, especially in sands.

THE PENCEL PRESSUREMETER

The PENCEL pressuremeter is a small diameter pressuremeter initially developed for use in airport and highway design in North America in the 1970s and 80s, principally by Briaud and Shields (1979), Briaud (1979), Briaud et al. (1982) and Briaud et al. (1987). The Division of Roads and Transport Technology (DRTT) of the CSIR in South Africa also applies this pressuremeter to pavement evaluation and design (Sanders, 1991). In particular, the pressuremeter is being used to measure in-situ pavement layer material stiffnesses and being applied to the South African Mechanistic Pavement Design Procedure (Freeme, 1983).

Two pressuremeters have been used at DRTT: 32 and 22,5mm diameters, with active lengths of 225 and 150mm respectively, thus maintaining a length-diameter ratio of around 7 which is comparable with a typical ratio of between 6 and 6.5 used for general commercial pressuremeters. Ideally the length-diameter ratio should be as large as possible in order to simulate ideal radial expansion over as much of the length of the membrane as possible, thus reducing end effects to a minimum.

The smaller pressuremeter was developed principally to test pavement layers down to 150mm thick where holes are quite easily predrilled in materials with an electric power drill. The holes are drilled deeper than the length of the pressuremeter probe to provide relatively equal confining stresses within the zone of influence of the pressuremeter. A schematic representation of the pressuremeter test is given in Figure 1.

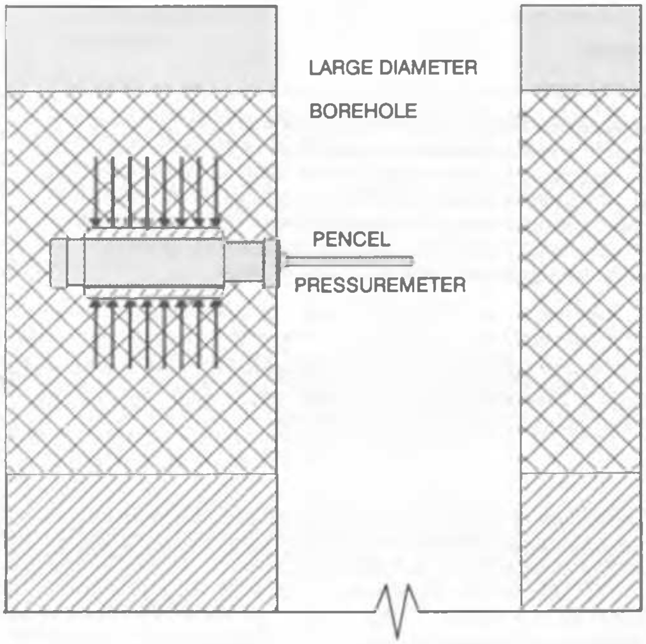


Fig. 1 : PENCEL pressuremeter - horizontal insertion.

Before testing, the pressuremeter is calibrated by measuring the membrane resistance to expansion. The expansion of the entire apparatus when pressurised is also measured for calibration purposes. After drilling, the hole is cleared of all drilling spoil, the probe inserted to the required depth and the test conducted by adding increments of approximately 2,5% of the initial probe volume. Unload-reload cycles are carried out where required during testing to obtain elastic moduli, the amplitude of which should be restricted to twice the undrained shear strength (C_u) in cohesive materials and for non-cohesive materials, the pressure difference between the passive and active failure conditions (Wroth, 1982):

$$\Delta p = \left(\frac{2\sin\phi'}{1+\sin\phi'}\right)*(p-u_0)_{max}$$

where Δp represents the allowable pressure difference, ϕ' the angle of shearing friction and $(p-u_0)_{max}$ the effective radial pressure at the wall of the cavity at the start of the unloading cycle.

On completion of the test the membrane stress calibration is again carried out using the same increments of volume as used during the test.

Following the manufacture of the small pressuremeter the possibility of using the device for horizontal insertion in large diameter boreholes was considered. In this way vertical soil stiffness parameters, as opposed to horizontal parameters obtained via plate bearing and conventional pressuremeter testing, should be obtained. Another percieved advantage was that as the apparatus is small and light, tests would be carried out more easily than lateral plate bearing tests for instance. Equipment required to insert the probe is a brace and bit or a power drill to drill the horizontal hole and a tubular reaming tool to smooth the sides of the hole and to remove drilling spoil. The PENCEL pressuremeter is then inserted and the test conducted.

TRIAL SITES

Two sites were selected for trials with the PENCEL pressuremeter. One site is situated in Pretoria and is underlain by andesites. The soil profile comprises, apart from some fill, redbrown clayey silt and silty clay which is ferruginised to a varying extent over the top 2 to 2,5 m. Below this depth the profile consists of a clayey silt that grades into silt and eventually very soft rock at about 8 m depth. A typical soil profile is shown in Figure 2.

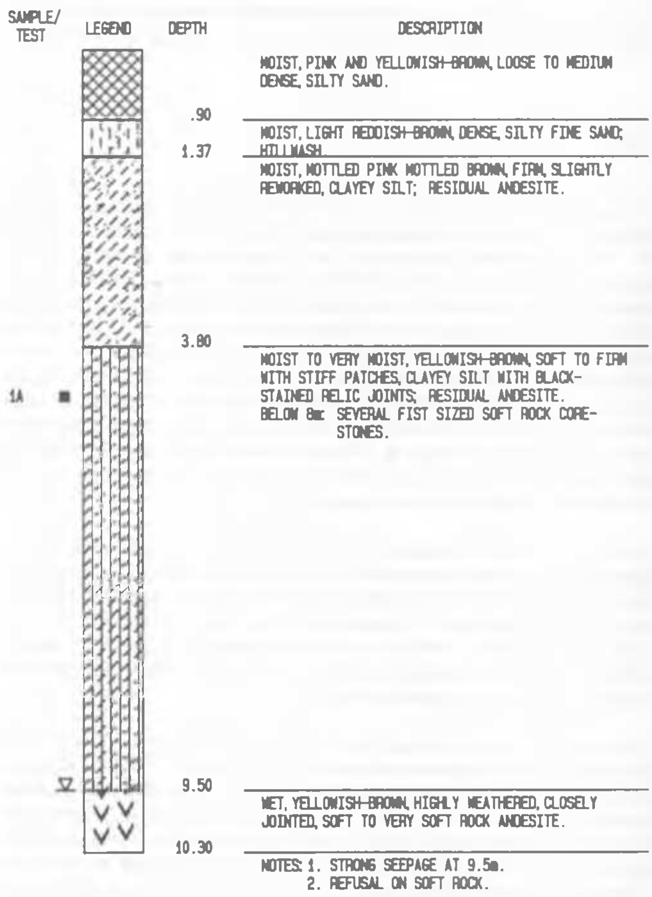


Fig. 2 : A typical soil profile of the Pretoria site.

The second site is situated in the Johannesburg area and is also underlain by andesitic lava weathered to depths of between 11 and 18 m. The soil profile differs somewhat from that of the second site, particularly over the top 6 m.

The surface material consists of a silty fine windblown sand with minor clay to depths of 3 to 3,6 m. Below this depth the profile becomes ferruginised with depth to the extent that it can be described as a dense nodular ferricrete in some holes, while in other holes it can be described as a highly ferruginised silt. Below approximately 6 m depth the profile grades into a soft to firm clayey silt and at 10 to 12 m depth becomes very soft rock. A typical profile also appears in Figure 3.

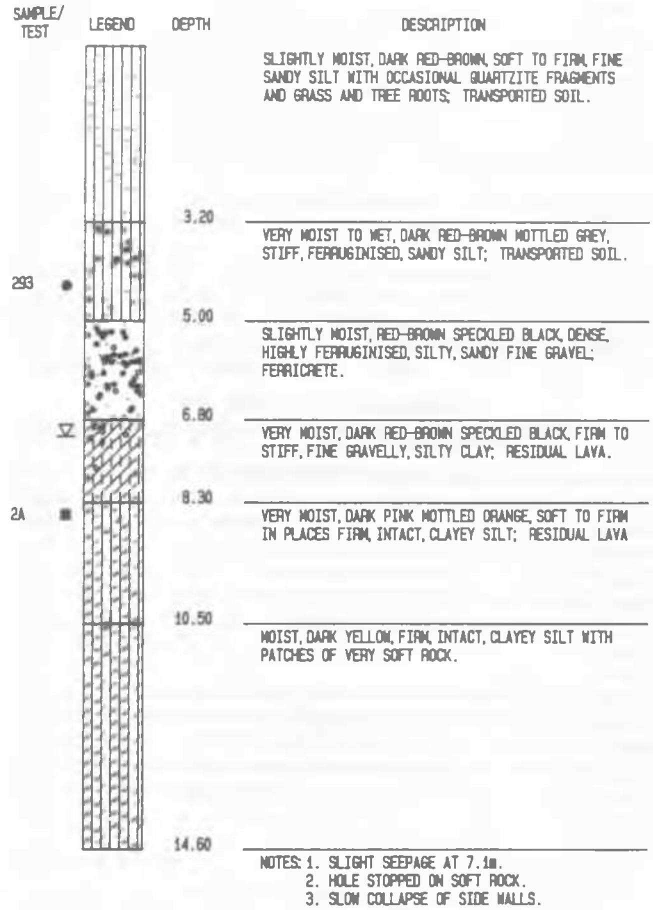


Fig. 3 : A typical soil profile of the Johannesburg site.

Test procedures followed at the two sites included the following:

* Horizontal PENCEL pressuremeter tests were conducted in three holes at about 4 m depth at both sites.

* In the same holes and at similar depths lateral plate bearing tests were carried out.

* In the holes at the Pretoria site and at the same depths as the in situ tests, undisturbed samples were cut and subjected to oedometer confined compression tests. The soil at the Johannesburg site was too friable to obtain undisturbed samples for such tests.

In addition, vertical insertion PENCEL pressuremeter tests were conducted at the Pretoria site in the same three holes at slightly shallower depth (3,3 m) but in essentially the same type of material.

The aim of the tests was twofold:

* To establish whether PENCEL tests could be conducted practically and on a routine basis inside large diameter exploration holes,

* To establish whether the results obtained from the tests agreed with the results obtained from plate bearing and consolidometer tests, and the consistency of the soil recorded during profiling.

TEST CHARACTERISTICS

General

It is important to be aware that the different test modes used to derive moduli vary significantly, hence the liklihood of differences in test results. These differences are reflected in the load-deformation characteristics measured in each test. It should be appreciated that different stress paths and boundary conditions are present in each case and influence the analysis of test results. These aspects are discussed briefly since it is not the intention of this paper to present detailed analyses on the specifics of each type of test. The typical features of each of the test types are highlighted in turn.

Plate Bearing Tests

Horizontal plate bearing tests were conducted by jacking against the opposite walls of the auger holes. Surfaces were prepared to be as smooth and parallel as possible and the stress increased in increments of about 60 kPa. Virgin loading was conducted up to contact stresses of the order of 400 to 600 kPa, followed by a cycle of unloading and reloading to pressures between 1600 and 1800 kPa. Loading was done at such a rate as to allow plate deflection to stabilise after each load increment (i.e. less than 0.001 mm movement in two minutes).

Oedometer tests

Where test samples are cut, prepared and correctly inserted into oedometer test rings, the sample experiences zero lateral strain once bedded in. The ratio of lateral stress to vertical stress is K_0, ie the coefficient of lateral stress at rest corresponding to zero lateral strain. Although the sample is subjected to both shear and compressive strain, the soil is prevented from failing in shear and therefore compressive strain predominates.

Pressuremeter tests

The test method used for the tests here described were strain-controlled, i.e. the probe was expanded with a fixed increment of volume throughout the test. Unload-reload cycles were performed at selected times during the test to obtain the stress-dependence of moduli. A typical corrected pressure-volume change plot is given in Figure 4. It should be noted that although the pressuremeter test may appear to compress the surrounding soil as the test progresses, radial and circumferential stresses are equal and opposite, implying a shearing process, hence the derivation of the elastic shear modulus (G) from test results and not the elastic (Youngs) modulus.

Detailed descriptions of pressuremeter equipment, test procedures and test analysis appear in a number of references, two of which being a CIRIA ground engineering report (Mair and Wood, 1987), and the recent book authored by Briaud (1992).

In addition to the pressuremeter test performed using a horizontal insertion into the sides of boreholes at the Pretoria site, vertical insertion tests were also carried out at this site.

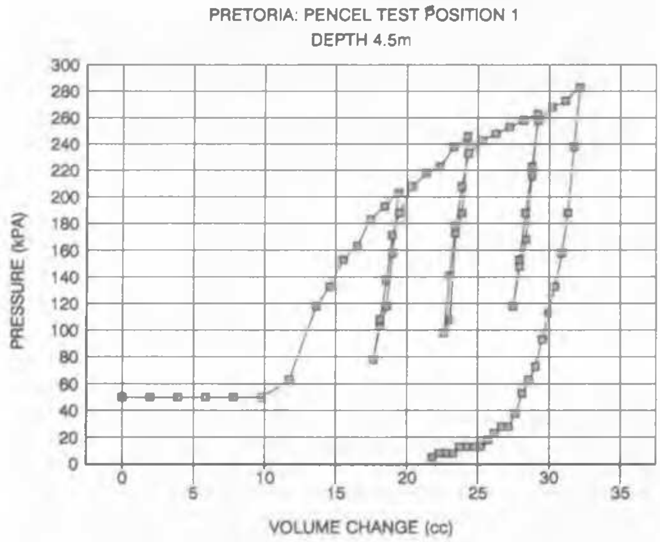


Fig. 4 : Typical stress-volume change plot of the PENCEL pressuremeter.

DISCUSSION

General

When assessing test results, the overall object of the investigations should be remembered, i.e. to investigate the practical use of the PENCEL for foundation investigation and design. In addition, comparison between results of the different tests is still very much in the preliminary phase. A fuller analysis comparing more representative stress and strain distributions induced by the test types will follow in later publications.

For an initial comparison of test results the relationship between moduli at similar soil-plate and soil-pressuremeter interfaces has been compared, as well as moduli at different vertical stress ranges in the oedometer (for the Pretoria site). "Average" stresses are simply the midpoint of the stress interval over which the moduli are calculated.

Note that due to the different test modes (dissimilar boundary conditions, load rates and magnitudes and volume of material tested), different means of test analysis and direction, a one-to-one correlation of parameters is not considered appropriate. With this in mind, consistancy in the differences between tests results was thought to be more important for practical use of the different methods.

Test results are presented in graphical form for ease of comparison. It is appreciated that horizontal insertion pressuremeter moduli are being compared with horizontal plate values at the Johannesburg site (through necessity). Results of the Pretoria tests on the other hand are presented in two formats: one giving all test results and the other only the plate versus pressuremeter (horizontal insertion) for comparison between the two sites.

Primary Loading Moduli

Typical test results for the two sites are given in Figures 5 and 6.

It is immediately apparent that there are considerable differences in moduli at similar contact stresses between test types. Considering all test results obtained from both sites, moduli obtained from the initial (or virgin) loading cycles are highest for the plate, followed by pressuremeter moduli obtained from the vertical insertion pressuremeter tests. The oedometer moduli are seen to be greater than those obtained from horizontal insertion of the pressuremeter, but lower than values from the standard (vertical) pressuremeter test mode.

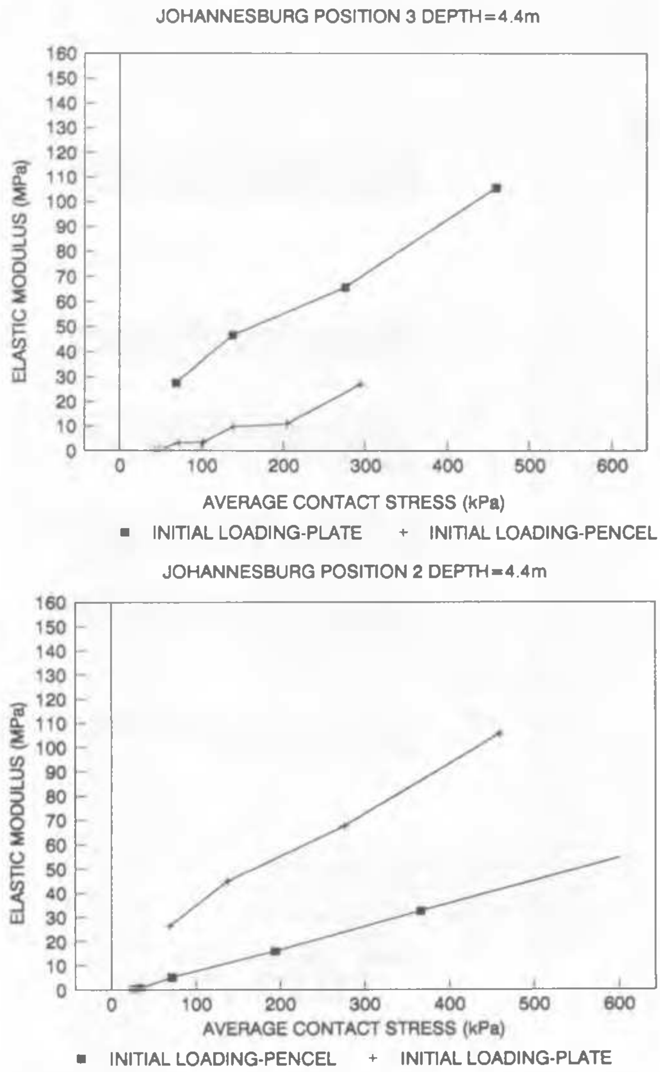
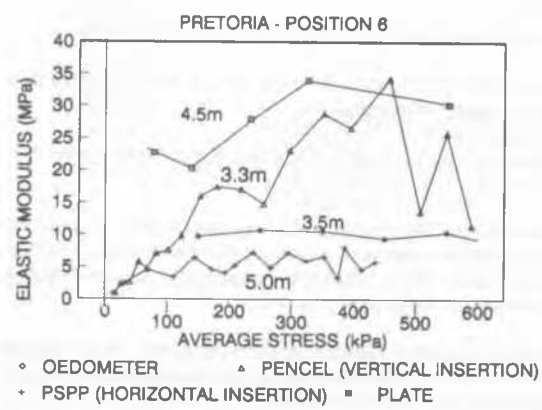


Fig. 5 : Loading moduli vs. contact stress: Johannesburg site



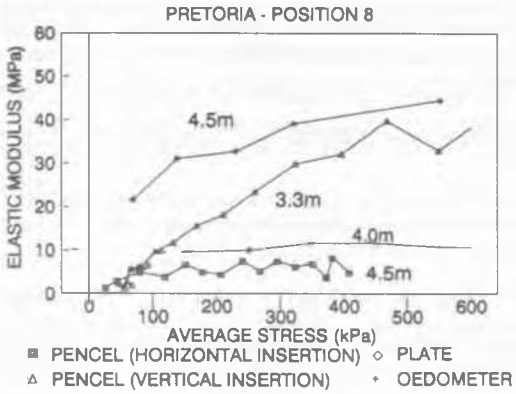


Fig. 6 : Loading moduli(including odoemeter and vertical insertion pressuremeter) vs. contact stress: Pretoria site.

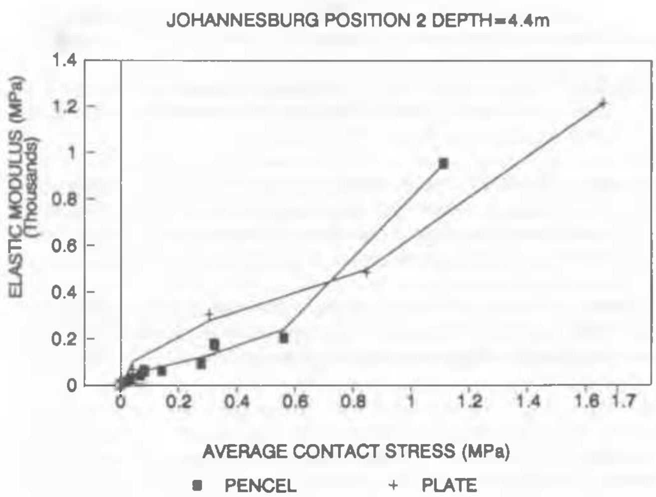
A general trend of increased moduli with stress is seen for both sites, with the relationship derived from test results being particularly linear for results from the Johannesburg site. Stress dependency of moduli seems to indicate that the material is partly-saturated and/or has limited cohesion which was borne out by in-situ observations.

In addition, the range of elastic (Youngs) modulus cited for silts is between 2 and 20 MPa and for dense sands between 50 and 80 MPa (Hunt, 1986). This is in reasonable agreement with the results depicted in Figures 6 and 5 for the Pretoria and Johannesburg sites respectively, bearing in mind that the moduli in the above figures are not elastic moduli in the true sense of the word. It is also interesting to note that the soil profile descriptions reflect the consistencies measured. The values in Figures 5 and 6 are in good agreement with the soil profile description which was rated generally as firm over the depths of testing and sampling at the Pretoria site and stiff at the Johannesburg site.

As the overall purpose of in-situ testing is to obtain design parameters, it is clear that great care must be exercised in using any moduli from a given test. The differences of moduli seen in Figures 5 and 6 are significant for design purposes, as excessive settlement or expensive over-design could result from the use of inappropriate values.

Unloading Moduli

Figures 7 and 8 reflect elastic moduli-contact stress relationships for the two sites analysed.



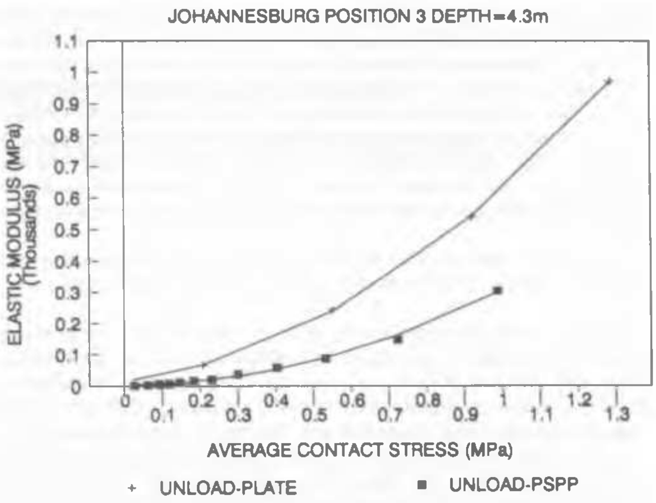
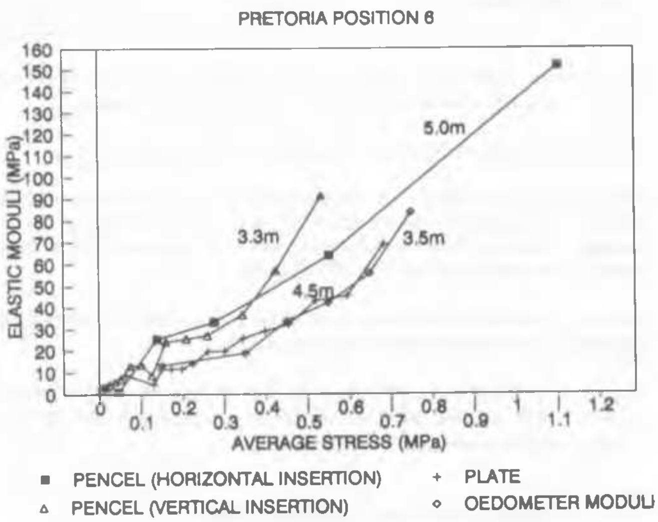


Fig. 7 : Unloading moduli vs. contact stress: Johannesburg site.



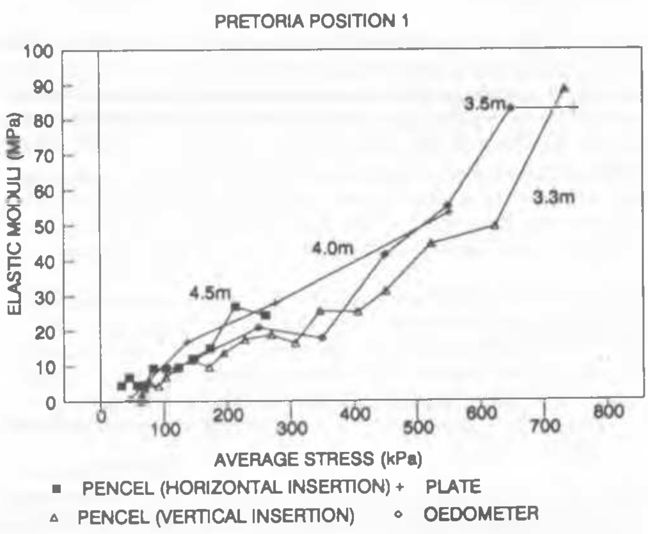


Fig. 8 : Unloading moduli vs. contact stress: Pretoria site.

The most obvious feature of Figures 7 and 8 is that there is in general a close correlation between test types, especially for the Pretoria site. This indicates that elastic unloading (or rebound) relationships are more consistent than those for initial loading. Intuitively this can be appreciated if the various test modes are considered, the soil-test equipment interaction being quite different for each test type. In addition, the test modes will induce differing amounts of plastic and elastic deformation at similar stresses during loading. Unloading on the other hand, is likely to be more predictable due to test readings reflecting elastic rebound effects with no component of plastic strain.

It is seen that values of modulus are in general higher for unloading than those derived from initial loading cycles at comparable stress levels.

One aspect of pressuremeter testing noted on both sites was the relatively good reproducibility of test results. An additional feature of the pressuremeter tests obtained to date has been the relatively good definition of pressure-volume curves (and hence of material behaviour). This allows more sophisticated analysis to be carried out allowing pressuremeter tests to be used to define relationships between *inter alia* elastic modulus and stress, strain, cyclic loading and creep loads. Shear strength values are also obtainable from pressuremeter tests using a variety of methods (Briaud et al., 1982).

CONCLUSIONS

Pressuremeter, plate-bearing and oedometer tests have been carried out on two sites, and elastic moduli compared over similar stress ranges.

There is in general an increase of modulus with applied stress.

A surprisingly good correlation between moduli was obtained when material was unloaded, especially for the site in Pretoria. Initial loading moduli on the other hand vary considerably between test types and great care needs to be exercised when using these moduli in design.

From the results obtained there seems to be a relatively good correlation between soil profile descriptions and test moduli.

The use of the PENCEL pressuremeter in large diameter boreholes seems to hold merit and promise, especially in similar materials to those tested in Pretoria and Johanessburg.

RECOMMENDATIONS FOR FURTHER WORK

Use of the PENCEL pressuremeter for integrity testing of earthworks could also be investigated, especially if a quick method of analysis is used. It may therefore be possible that the pressuremeter be used in preference to the more standard density or plate-bearing tests. Note that use of the pressuremeter to monitor the effects of deep and dynamic compaction is not new (Guyot, 1982).

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