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ABSTRACT

An experimental study of the effects of various components of soil disturbance. The tests were carried out using the Cambridge self boring pressuremeter at a site in Ottawa, Ontario. The results are compared with others recorded in the literature and some guidelines are suggested.

RÉSUMÉ

Étude expérimentale des effets de perturbation du sol par divers composants. Les essais ont été réalisés avec un appareil de mesure des pressions Cambridge autoforeur sur un chantier si[illegible] Les résultats sont comparés à ceux d'[illegible]ons sont form[illegible]

EFFECTS OF SOIL DISTURBANCE IN PRESSUREMETER TESTS

by

K.T. Law* and W.J. Eden*

INTRODUCTION

Successful design and construction of foundations require a thorough understanding of the engineering behaviour of soil as it exists in the field. In situ tests treat the soil as is and thus remove the uncertainty that arises from sampling and approximating field conditions during laboratory tests. Of the many in situ test devices, the pressuremeter probably has the best potential for studying the important aspects of soil behaviour since the total in situ horizontal stress as well as the stress-strain relationship can be obtained. Like other test equipment, however, the pressuremeter produces results that are influenced by factors such as disturbance, stress path, anisotropy and rate effect. This paper deals with the disturbance aspect.

There are two components of disturbance. The first causes a change in the in situ stress, hence modifying the starting stress reference. This stress modification may change the soil behaviour and as a result true behaviour is not measurable. The second component generates a mechanical softening of an annular zone of soil around the pressuremeter probe. This may also lead to results that do not reflect the true behaviour. Considering undrained strength, theoretical work (Baguelin et al. 1975 and Prevost 1979) shows that both disturbance components lead to an overestimation of the undrained strength. This overestimation derived from disturbance is in contrast to other test experience and leads to unsafe design if the results are taken at face value.

An ordinary pressuremeter, such as the Menard type, requires a predrilled borehole and disturbance is therefore unavoidable. The self boring pressuremeter, considered superior to the ordinary type, does not completely eliminate disturbance either. As there is a growing use of pressuremeters the need to study disturbance effects is quite evident.

An experimental study of the effects of both disturbance components is reported in this paper. The tests were carried out using the Cambridge self boring pressuremeter at a site in Ottawa, Ontario. The results are compared with others recorded in the literature and based on this some guidelines are suggested.

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SOIL CONDITIONS

The site studied is located in an open field within the grounds of the National Research Council of Canada (NRCC). The subsoil profile consists of Champlain Sea clay and is shown in Figure 1. The surface fissured crust is about 7 m thick. Underlying it is a layer of medium grey clay of high sensitivity. It is overconsolidated with an overconsolidation ratio of about 2.2. All the pressuremeter tests reported here were conducted in this layer.

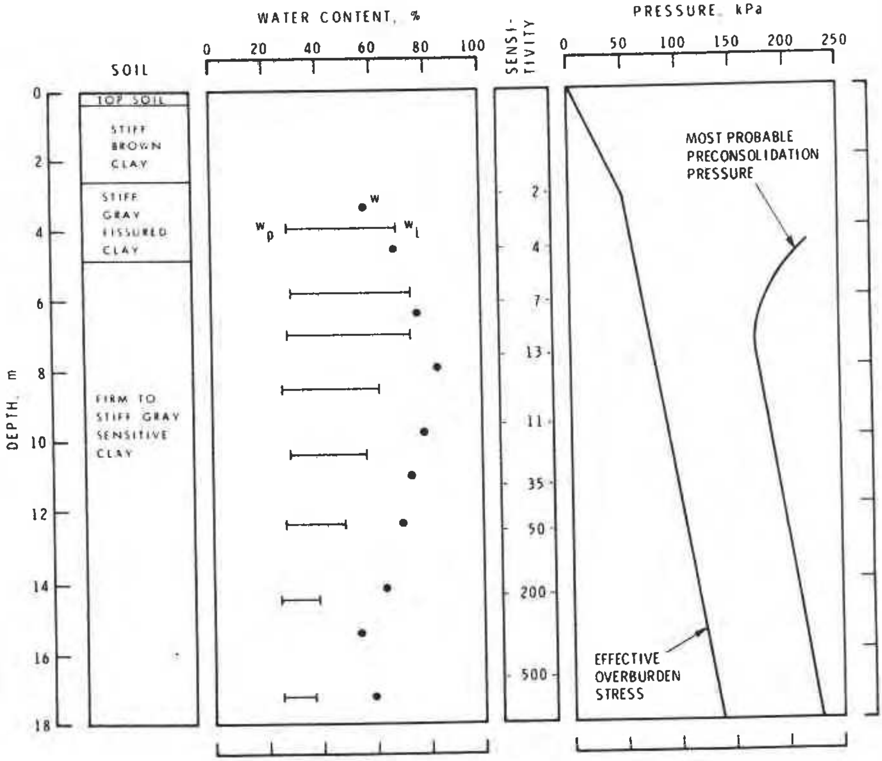

Figure 1 Geotechnical Profile at National Research Council of Canada, Ottawa, Canada

TEST DESCRIPTION

Equipment

The Cambridge self boring pressuremeter was used in this study. Its operating principle was described in detail by Wroth and Hughes (1973, 1974). Some modifications were made so that the equipment could be adopted to a hydraulic-powered, truck-mounted drill rig. The details were given by Eden and Law (1980).

The pressuremeter probe was 80 mm in diameter and 0.90 m long. It has a rotating cutting blade inside the cutting shoe. Above the shoe is the membrane portion, which is about 0.61 m long. The original cutting shoe was replaced by a removable hardened tool steel shoe the same size as the membrane section. A Kaye System 800 data logger was used to record test data and a Texas SR-52 programmable calculator was employed for preliminary data analysis. Figure 2 shows the setup in a covered service truck.

Tests with different cutting shoe sizes

In this test series, three borehole sizes were studied. They are defined by R, the ratio of cutting shoe (hence borehole) diameter to the membrane section diameter. The values of R are 1.011, 1.00 and 0.995 and the cutting shoes used are called oversized, matched and undersized respectively.

The test procedures generally consisted of the following: 1) measurement of membrane resistance before inserting the probe into the ground; 2) self boring to depth; 3) waiting for the pore pressure

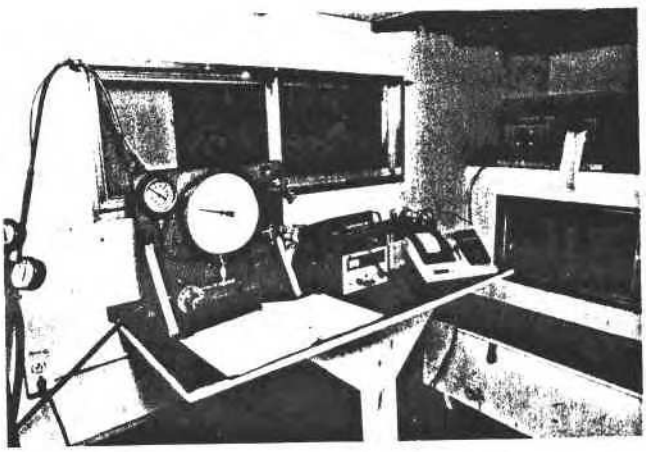

Figure 2 Monitoring equipment for the probe

to come to equilibrium; 4) inflating the membrane incrementally at a rate of 9.8 kPa/min until the circumferential strain reached 7 per cent; and 5) complete unloading.

Tests with different degrees of softening

Softening of the soil around the probe was introduced in this test series by subjecting the soil to a certain strain before the test. To do so a procedure of loading, unloading and reloading was used. After the probe was self bored to the appropriate depth and the excess pore water pressure dissipated, the membrane was inflated to 1 per cent and then unloaded. At this point excess pore water pressure was generated and after waiting for its dissipation, reloading to 3 per cent was carried out. This process of unloading, waiting and reloading was repeated with maximum strain reaching 7 and 9 per cent respectively. For each location, therefore, four loading curves were obtained, each being subject to a different prior strain.

Throughout this test series, a matched cutting shoe was used. A constant strain rate of 0.16 per cent/min was used in the loading stage and a constant load decrement of 50 kPa was applied every half minute in the unloading stage. Three depths were studied, i.e., 8.78, 10.30 and 11.82 m.

TEST RESULTS

Several methods exist for interpreting the pressuremeter data. Some yield the shear stress-strain relationship from the measured pressure-expansion curve (Baguelin et al. 1972; Palmer 1972 and Ladanyi 1972). Others require an assumption of the stress-strain relationship (Gibson and Anderson 1961; Prevost and Hoeg 1975 and Denby 1978). The first approach is used here because of its simplicity and generality.

There are also a number of ways to determine the in situ horizontal stress σ_{ho}. Wroth and Hughes (1974) suggested that σ_{ho} is the pressure when the excess pore pressure starts to develop during the inflating stage. Denby (1978) used the pressure corresponding to the early movement of the membrane with correction by inserting an initial strain in the governing pressuremeter equation. Lacasse et al. (1981) took the pressure at the start of the linear variation of radial strain with time. The σ_{ho} reported in this paper corresponds to the pressure required to just lift the membrane off the probe. This point can be identified easily by plotting the pressure against the logarithm of the strain as shown in Figure 3. The pressuremeter in this case was lowered

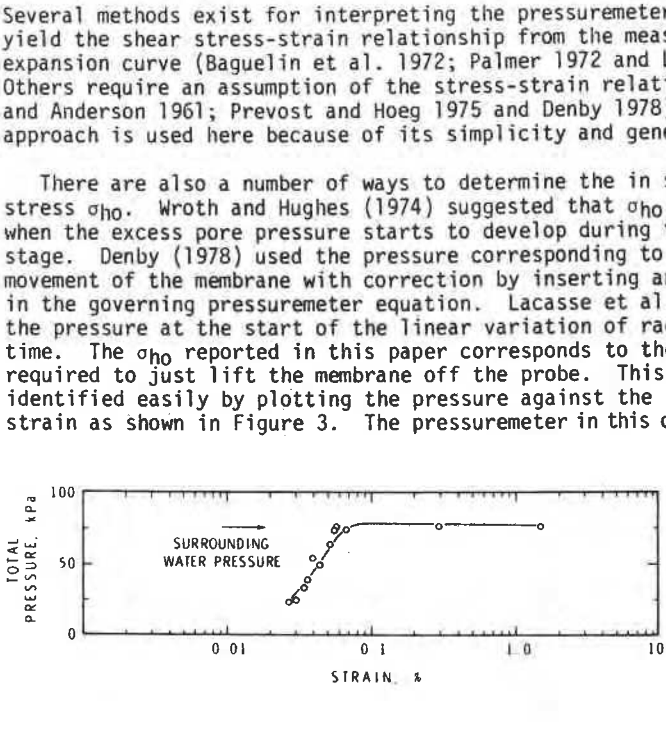

Figure 3

Measuring a given total stress using pressuremeter to the bottom of an oversized predrilled borehole and filled with water. The horizontal pressure was known and equal to the hydrostatic pressure which corresponds to the sharp kink followed by a relative flat section. When a test is performed in soil, the kink is less sharp but is still readily identifiable.

An initial modulus is commonly reported from the pressuremeter results. For some soils, the Champlain Sea clay in particular, the initial pressure-expansion curve rises steeply, leading to considerable scatter in the deduced stress-strain relationship. The initial modulus reported here corresponds to the secant modulus at the point where the relationship begins to be well defined.

<u>Tests with different cutting shoe sizes</u>

Different pressure-expansion curves (Figure 4) were obtained from tests with different shoe sizes at the same depth. The derived engineering quantities are summarized in Table I. For the oversized borehole

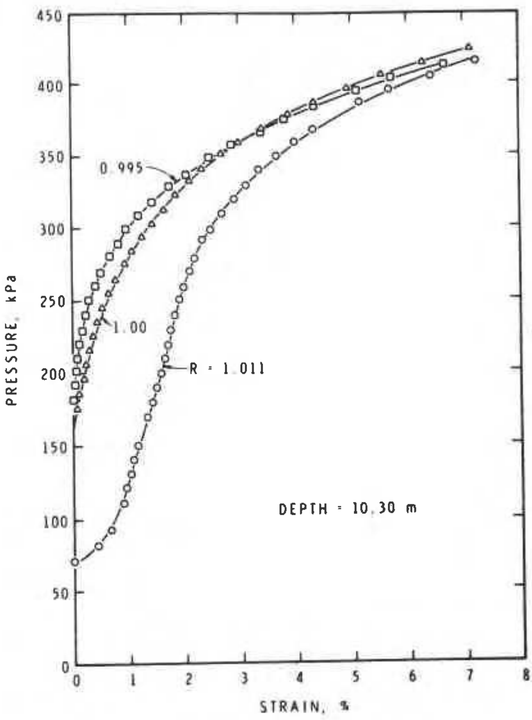

Figure 4 Pressure-expansion curves with different cutting shoe sizes

(R > 1.0), a gap was created between the soil and the probe. This caused a reduction of horizontal stress in the soil around the probe, hence this test registered a lower value than the matched shoe. For the undersized borehole (R < 1.0), the soil was pushed laterally by the membrane section leading to an immediate rise of horizontal stress in the soil. This stress rise, however, was partly removed by the stress relaxation process in the ensuing waiting period.

The deduced shear stress-strain relationships are shown in Figure 5. A pronounced peak is found in the oversized case with the undrained

TABLE I

RESULTS OF PRESSUREMETER TESTS WITH DIFFERENT SIZE RATIO OF CUTTING SHOE TO MEMBRANE

Test No.	Depth m	Size ratio of cutting shoe to membrane, R	Total horizontal stress σ_{ho} kPa	Initial shear modulus, G MPa	Undrained strength, S_u kPa
77-4	8.78	1.011	76.5	10.1	139.3
78-2	8.78	1.00	88.3	7.1	85.3
77-11	8.78	0.995	111.8	3.7	83.9
77-5	10.30	1.011	78.5	7.0	135.3
77-10	10.30	1.00	82.4	5.9	78.5
77-12	10.30	0.995	88.2	4.7	69.6

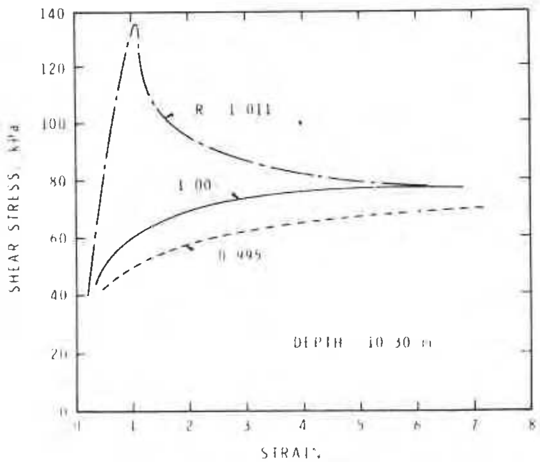

Figure 5 Shear stress-strain curves with different cutting shoe sizes

shear strength exceeding that of the soil because a stress release and deformation had taken place before the test. This condition has been shown in theory (Prevost 1979, Law and Eden 1980) to produce an apparent peak much higher than the real strength of the material. Such being the case, the shear strength deduced from the pressuremeter test in an oversized borehole, particularly in one predrilled, will lead to unsafe design.

Tests from an undersized borehole also yield a shear stress-strain relationship different from the matched case (Figure 5). The resistance is lower at small strains and beyond a moderate strain (~ 5 per cent) the difference is small.

The initial modulus is highest in the case of R > 1.0, again due to the stress release effect while the modulus from the undersized borehole is lower than from the matched case.

Tests with different degrees of softening

Figure 6 shows a typical set of pressure-expansion curves for this test series and the results are summarized in Table II.

The larger the softened zone created prior to the expansion of the probe, the greater the deformation at a given pressure. The direct consequence is, therefore, an underestimation of the in situ horizontal stress and the initial shear modulus as indicated by the test results. The apparent shear strength, however, increases with increased degree of softening. Such a phenomenon is contrary to other strength tests that yield decreasing strength with increasing softening. Theories have been put forth (Baguelin et al. 1975 and Prevost 1979) to explain this

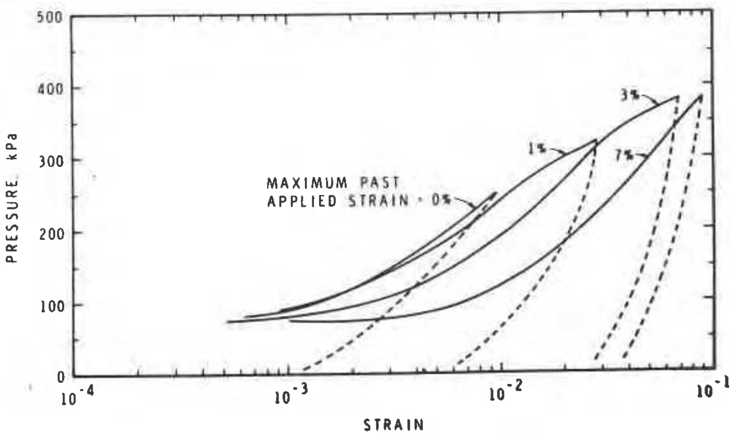

Figure 6 Pressure-expansion curves for tests with different degrees of softening

contradiction. Essentially, the reason lies in the assumption of homogeneous material used in the conventional theory of interpretation. This assumption is not compatible with the presence of a softened annulus zone of material around the probe.

TABLE II

RESULTS OF PRESSUREMETER TESTS WITH DIFFERENT DEGREE OF SOFTENING

Test No.	Depth m	Previously applied strain before expansion %	Total horizontal stress, σ_{ho} kPa	Initial shear modulus, G MPa	Undrained strength, S_u kPa
81-A1-A	8.78	0	90	13.1	-
81-A1-B	8.78	1.0	85	9.5	107
81-A1-C	8.78	3.0	75	6.0	120
81-A1-D	8.78	7.0	72	3.0	160
81-A2-A	10.30	0	112	15.0	-
81-A2-B	10.30	1.0	95	9.7	123
81-A2-C	10.30	3.0	90	6.1	170
81-A2-D	10.30	7.0	81	3.4	201
81-A3-A	11.83	0	110	16.5	-
81-A3-B	11.83	1.0	110	11.2	110
81-A3-C	11.83	3.0	100	6.7	185
81-A3-D	11.83	7.0	98	4.2	203

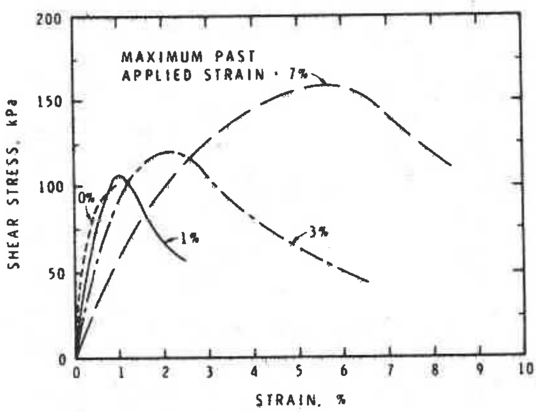

Figure 7 Shear stress-strain curves for tests with different degrees of softening

Figure 7 shows the apparent shear stress-strain relationships deduced from the pressure-expansion curves. As the degree of softening increases, the soil becomes more compressible and reaches failure at a higher strain with higher shear strength. There is also a more pronounced decrease in the post-peak shear strength.

DISCUSSION

Based on the foregoing experimental results, it is evident that disturbance significantly affects the engineering quantities measured using the pressuremeter. Table III summarizes qualitatively the results based on comparison with the case of a matched cutting shoe and without deliberate introduction of soil softening. In the following each quantity is discussed separately.

Total horizontal stress

The measured total horizontal stress σ_{ho} is reduced by stress release involved in an oversized hole and by mechanical softening. This view is consistent with several pieces of work recorded in the literature. Marsland and Randolph (1977) carried out tests in stiff fissured London clay by means of the Menard pressuremeter. The borehole was oversized and mechanical softening was inevitable. The resulting σ_{ho} values from conventional interpretation are smaller than those drawn from the vast experience on this clay. Tavenas (1975) conducted Menard pressuremeter tests in a soft sensitive clay and reported that the results were scattered but appeared to be lower than the more reliable

TABLE III

SUMMARY OF QUALITATIVE EFFECTS OF SOIL DISTURBANCE DURING PRESSUREMETER TESTS ON MEASUREMENT OF ENGINEERING QUANTITIES

Engineering quantity / Disturbance mechanism	In situ horizontal pressure	Initial modulus	Undrained shear strength
Stress released by oversized hole	-1	+1	+1
Stress induced by undersized hole	+1	-1	0
Mechanical softening of soil	-1	-1	+1

Note: -1, 0, +1 denote respectively values lower than, equal to and higher than those from using a matched cutting shoe without deliberate introduction of softening.

results from total pressure cells. Baguelin et al. (1972) performed tests using the French self boring pressuremeter with a cutting shoe slightly oversized by 1/10 mm. The measured horizontal stress was expressed in terms of the coefficient of earth pressure at rest which was found to be equal to 0.35. This value is low when compared with triaxial test results and from Jaky's equation.

As disturbance leads to a reduction of horizontal stress, the value obtained for the case of a matched shoe may also be lower than the true value prior to testing. The reason for this is that disturbance cannot be totally eliminated even in this case. Vibration from the rotating inner rod and cutter, and shearing of soil by the advance of the pressuremeter, are both possible sources of disturbance.

The use of an undersized cutting shoe will give a horizontal stress higher than that from the matched cutting shoe. At this point it is not clear if such a measured σ_{ho} will be higher than the true in situ value for three reasons. First, as explained previously, the horizontal stress measured using the matched shoe may yield a low value. Secondly, the soil on the wall of the undersized borehole is subject to shear and hence disturbance to accommodate the probe. This disturbance tends to reduce the measured σ_{ho} value. Thirdly, horizontal stress relaxation may take place during the waiting period between placing the probe and inflating the membrane.

If a choice has to be made between the three sizes of cutting shoe, it appears that the slightly undersized one is more promising. The reason is that for the other two sizes, the underestimation of σ_{ho} is unlikely to be removed or counterbalanced, because of unavoidable disturbance.

Modulus

Based on the results in Tables I and II, the oversized borehole increases the modulus by 30 per cent but mechanical softening may reduce it by four times. The net effect, therefore, will be an underestimate of the modulus. This is consistent with the experience of comparing standard and self boring pressuremeter test results by Baguelin et al. (1972), Armar et al. (1975) and Tavenas (1975).

A slight undersized borehold will also produce a lower estimate of the modulus. For the two depths studied here, the moduli are about 50 and 20 per cent less than the values with the matched cutting shoe. A similar study on a very soft marine clay (Law and Eden 1980) showed that the reduction is smaller, in the order of 15 per cent. It is believed that for clay with lower sensitivity, the underestimation may be even less. Denby (1978), for instance, found a reasonable agreement between the pressuremeter modulus (from undersized borehole) and that deduced from the finite element analysis of excavation behaviour in San Francisco Bay mud.

Ideally, a matched cutting shoe should be used for the accurate determination of modulus. It is, however, not always practicable to obtain a matched shoe as the membranes from the manufacturer do have slight size variation. In this case, a slight undersized shoe may be considered.

Undrained strength

Table III shows that stress released in an oversized borehole and mechanical softening both tend to increase the measured undrained strength. The undersized borehole produced slightly lower strength than the matched borehole. This slightly lower strength has been found to exceed that of other tests (Wroth and Hughes 1973, Eden and Law 1980 and Lacasse et al. 1981). Factors such as strain rate, disturbance and stress path have been given as part of the explanation.

It appears that with reasonable care when conducting the test, the pressuremeter will still overestimate the available undrained strength of the soil. More aggravating is the fact that with less care, the overestimation will even be higher. Caution is required, therefore, in applying the undrained pressuremeter strength for design. At this point then it is advisable to avoid an oversized hole and to minimize mechanical softening of the soil to be tested.

SUMMARY AND CONCLUSIONS

There are two components of disturbance involved in pressuremeter testing: 1) stress change due to the probe insertion and 2) mechanical softening of soil around the probe. Each component has a significant influence on the measured engineering quantities. In practice, both components are operative simultaneously. The influences have been studied individually and together for Champlain Sea clay by means of the Cambridge pressuremeter and the results, which follow, are found to be consistent with other studies in the literature.

1) Installation of the probe causes a stress change in the soil irrespective of the cutting shoe. The slightly undersized shoe appears to produce a better estimate for horizontal stress than other sizes.

2) The initial modulus is increased by about 30 per cent with an oversized hole and decreased by about four times with the presence of an annulus zone of softened soil. A slightly undersized borehold yields a slightly lower estimate of modulus.

3) Stress release and softening cause an unrealistically high estimate of undrained strength. The slightly undersized borehole yields the lowest strength which is already higher than those from other tests.

Based on this study it is desirable, therefore, to select a slightly undersized cutting shoe as it is not always possible to have a matched one. The test should be conducted carefully and the results treated with caution. It is likely that the measured horizontal stress and initial modulus will be in the right range while the undrained strength may still be overestimated.

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