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USE OF THE DEEP PENETRATION TEST IN SENSITIVE CLAYS

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EMPLOI DE L'ESSAI DE PENETRATION PROFONDE
DANS LES ARGILES SENSIBLES

SOMMAIRE

Les auteurs ont mis en oeuvre l'essai de pénétration profonde, tant en place qu'au laboratoire, comme nouvelle méthode de détermination de la résistance au cisaillement des sols non égouttés. Ils montrent que pour les argiles sensibles la force portante N_c est considérablement inférieure à 9. Les travaux ont montré que l'essai de pénétration profonde constitue une méthode fructueuse de mesure des résistances des sols non égouttés, qu'il n'est pas influencé par les bouleversements et qu'il donne une courbe continue des résistances en sol non égoutté.

USE OF THE DEEP PENETRATION TEST IN SENSITIVE CLAYS

UTILISATION DE L'ESSAI DE PENETRATION EN PROFONDEUR DANS LES ARGILES SENSIBLES

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SYNOPSIS The deep penetration test was subjected to trials in both the field and laboratory as a possible method of determining the undrained shear strength. It is shown that in sensitive clays the bearing capacity factor N_c is considerably less than 9. The trials showed that the deep penetration test is a promising method of measuring undrained strength as it is not affected by disturbance and yields a continuous record of undrained strengths.

INTRODUCTION

Of the several different methods proposed for determining the undrained strength of saturated clays in situ, the vane test has probably been the one most commonly used. The vane test measures directly the ultimate undrained shear strength of clay on predetermined failure planes under conditions similar to those in a direct shear test. Its main advantage is its simplicity in both performance and interpretation. The vane test is considered to furnish reliable results in soft clays, provided the actual mode of failure corresponds to that assumed in its interpretation.

A disadvantage of the vane test is that it can give only a discontinuous picture of undrained shear strength variation in a vertical soil profile. Another disadvantage is that the test requires introduction of the vane apparatus into the soil before the shear test is performed. Although this may be of little consequence in most types of clays, it is thought to produce a certain amount of disturbance in sensitive clays, particularly in those of a brittle type (Crawford and Eden, 1965; Eden, 1966).

Another type of test that can be used for the same purpose is the quasi-static deep penetration test. If the test is performed by a self-recording, fixed-point type of penetrometer, as was done in this study, continuous information on undrained strength of clay is obtained, and no objection can be raised concerning the effect of clay disturbance prior to the test. The test cannot furnish directly, however, the value of the undrained shear strength (s_u) of the clay, but the latter has to be calculated from the measured tip resistance (q_p) using the bearing capacity formula

$$q_p = p_o + s_u N_c \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where p_o is the total overburden pressure at the level of the point and N_c is the bearing capacity factor. It is obvious, therefore, that a correct evaluation of penetrometer test results in saturated clays will depend on knowing the numerical value of the factor N_c.

On the basis of theory and model studies, the value $N_c = 9$ has been proposed (Meyerhof, 1951; Skempton, 1951) and verified in the field (Meyerhof and Murdock, 1953). N_c values as low as 5 and as high as 25 have also been reported in the literature (Sowers, 1961; Ward, Marsland and Samuels, 1965).

It can be seen that the value of the bearing capacity factor N_c for deep penetration of saturated clays is far from being a constant. It appears to be influenced by a number of factors such as: (1) Over-all stress-strain behaviour of the clay in undrained shear; (2) rate of penetration; and (3) shape of penetrometer point. No systematic investigation of the N_c value has been made to date, however, that would cover all these effects and include different types of natural undisturbed clays. In particular, there is very little information available on the value of N_c to be used in evaluating deep penetration tests in sensitive clays such as those encoutered in Eastern Canada and Scandinavia.

A recent theoretical study (Ladanyi, 1967) shows that in such clays N_c values as low as 5 can be expected. The main purpose of the present investigation was to determine experimentally the values of the factor N_c in typical sensitive clays, as found in the Ottawa area, and to compare these values with theoretical predictions.

For this purpose, two series of penetration tests were carried out:

a) small-scale laboratory tests carried out with a specially designed self-recording penetrometer of 1.55 cm diameter;

b) field tests with a commercial self-recording cone penetrometer of 3.57 cm diameter.

Laboratory penetration tests were performed on undisturbed specimens of sensitive clays from two different locations. Field penetration tests were carried out at the same two locations in the Ottawa area.

LABORATORY PENETRATION TESTS

Apparatus and Procedure

A small cylindrical probe with a flat pressure-sensitive transducer installed in the base was used (Figure 1).

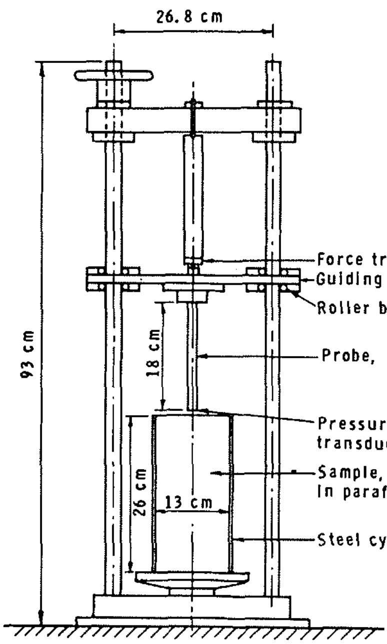

Fig. 1 Experimental Arrangement For Laboratory Penetration Tests.

When mounted in a triaxial press, the assembly permitted separate measurement and continuous recording of both the pressure at the base of the probe and the total force during penetration.

Undisturbed specimens of clay, obtained in a 5-in. Osterberg piston sampler, were placed in a 26-cm-long split steel cylinder. Liquid wax was poured into the remaining space between the specimen and cylinder to provide uniform lateral support.

The rate of penetration was 0.356 cm/min in all the tests. Another series of tests was conducted to study the effect of rate of penetration with the same probe mounted in a universal testing machine where penetration rates up to 12.7 cm/min could be attained.

Test Results

Clay specimens from two different locations, at the National Research Laboratories and Gloucester Naval Station (Crawford and Eden, 1965), were used. Figures 2 and 3 show typical results of penetration tests from each site. The clay at the NRC site had a sensitivity ranging from 10 to 35, water contents from 72 to 84 per cent and a field vane strength from 0.5 to 0.7 kg/sq cm, increasing with depth. The Gloucester clay had a sensitivity of about 30 to a 5 m depth, a water content from 50 to 70 and a field vane strength of 0.25 kg/sq cm.

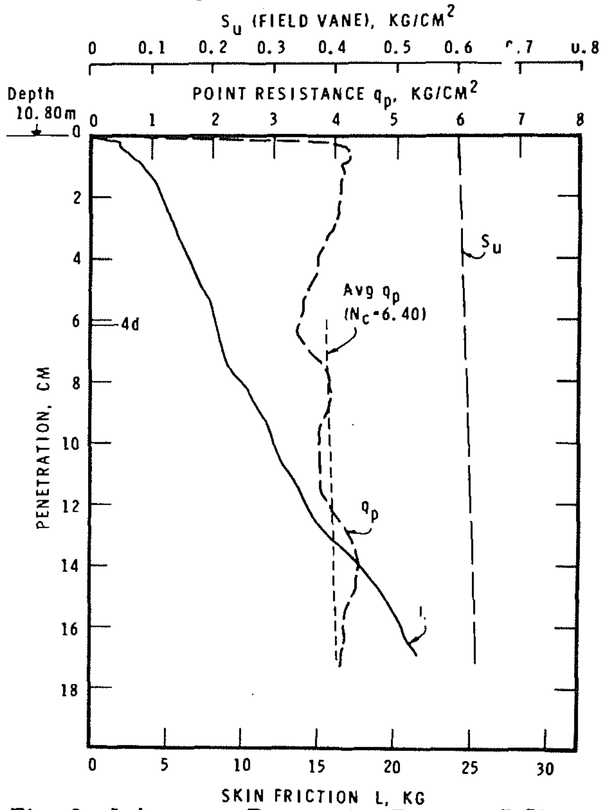

Fig. 2 Laboratory Penetration Test: NRC Clay.

In Figures 2 and 3 the variations with depth of penetration of the following two quantities have been plotted: (1) point resistance as recorded by the pressure transducer at the base of the probe, and (2) skin friction which is equal to the difference

$$L = Q_{tot} - A_p q_p \quad \ldots\ldots\ldots\ldots\ (2)$$

where L is the skin friction in kg, Q_{tot} denotes the total penetration force recorded by the force transducer, and A_p = 1.885 sq cm is the base area of the probe.

Analysis of Test Results

Experimental evidence shows that for a frictionless plastic material the punch has to penetrate to a depth of at least 4 diameters before the effect of the free surface disappears and a true deep failure phenomenon is attained (Meyerhof, 1951). For this reason, only the portion of the results below the depth marked by 4d in Figures 2 and 3 has been used in the following analysis and comparison. The effect of the bottom surface of the specimen was made negligible by stopping penetration at a distance of more than 3 probe diameters from the bottom surface.

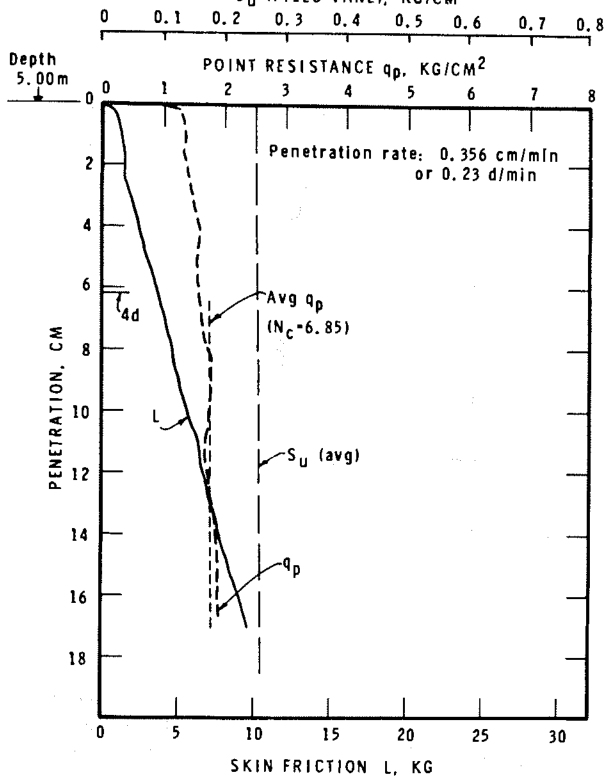

Fig. 3 Laboratory Penetration Test, Gloucester Clay.

The average result from a number of field vane tests performed close to the same location was used for comparison. In Figures 2 and 3 the average s_u line has been plotted and compared with the parallel average q_p-line from laboratory penetration tests, which is shown as a dashed line. As the overburden pressure was practically zero in the laboratory tests, the experimental average N_c values could be determined from the formula:

$$N_c = q_p/s_u \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The N_c values so obtained in all the tests performed on the NRC clay were found to vary from 5.71 to 8.00, with an over-all average from the six tests of N_c = 7.23. On the other hand, N_c values obtained from three tests on the Gloucester clay, all from the same level, did not differ much from the value N_c = 6.85 shown in Figure 3.

Some additional specimens from the same level were used for investigating the effect of the rate of penetration on the measured point resistance. The tests were performed in a universal testing machine permitting controlled penetration rates of up to 12.7 cm/min to be attained. It was found that for this clay a tenfold increase in penetration rate resulted in an increase of about 7.5 per cent in tip resistance.

FIELD PENETRATION TESTS

Apparatus and Procedure

The Borros penetrometer used in the field tests is a self-recording cone penetrometer with a loading potential up to 4 tons at the point. The varying load during penetration is sensed by electrical resistance strain gauges mounted in a sealed piece behind the point, and this is continuously recorded on a constant speed chart. Total resistance at the top of the rods is not recorded by this penetrometer. Figure 4a shows main dimensions of the cone point.

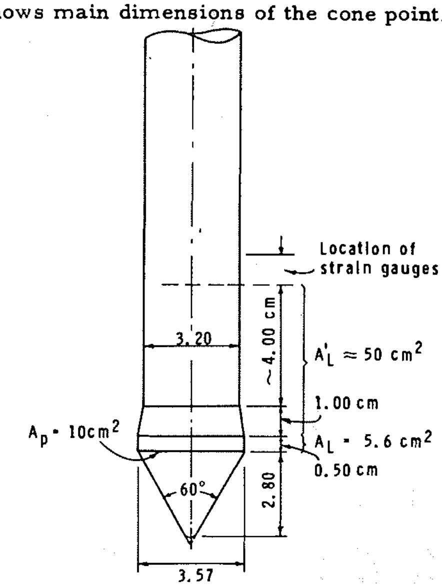

Fig. 4a The Point of "Borros" Penetrometer.

Although a hand-operated jack is provided for pushing the penetrometer into the soil, the tests were carried out using a hydraulic drill rig. This allowed the drilling of a borehole through the dried upper crust and the pushing of the penetrometer into the soil at a reasonably constant rate by means of the hydraulically-operated drillhead. Average rate of penetration was about 20 cm/min, with a variation of about ±5 cm/min. During the tests, a constant rate of penetration was maintained for the full stroke of the drill head (nearly 2 cm).

Test Results

The results of field penetration tests are shown in Figures 4b and 4c. In these, Q_{tot}, plotted against depth, represents the average load in kilograms registered by the strain gauges at the point within successive 20-cm intervals. As the results obtained for each location were fairly consistent, only the average of Q_{tot} values measured at a given level in all tests performed at a particular location were used in the following evaluation of the results.

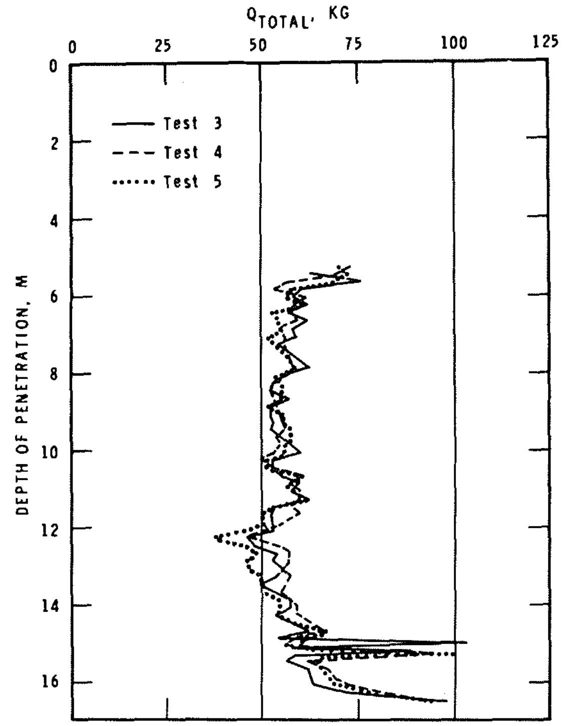

Fig. 4b Total Point Resistance, Q_{tot}, Recorded in Three Field Penetration Tests at NRC Site.

Evaluation of Test Results

Owing to the particular shape of the point of the Borros penetrometer and because the strain gauges are located at a certain distance above the cone, it is considered that the recorded value of Q_{tot} contains not only the point resistance but also some resistance due to lateral shear along the part of the point between the cone and the strain gauges. The corresponding value of undrained shear strength was, therefore, calculated from the expression:

$$s_u = \frac{Q_{tot} - A_p p_o}{(A_p N_c + A_L \alpha + A'_L \beta)\rho} \quad \ldots\ldots\ldots (4)$$

in which A_p, A_L and A'_L (Figure 4(a)) are the areas of the base of the cone, the collar, and the surface between the collar and the location of strain gauges, respectively; α and β are reduction coefficients for s_u taking into account the remoulding and imperfect contact, and ρ is a strain rate factor to enable comparison of s_u values obtained in the penetration tests with those measured in some other types of tests performed at a different strain rate.

For the purpose of evaluating the present test results, the numerical values of various magnitudes in Eq. 4 have been taken as follows: A_p = 10 sq cm; A_L = 5.6 sq cm; A'_L = 50 sq cm; α = 0.45; β = 0.10; and $1.015 \leq \rho \leq 1.040$. From these, α and β values correspond to the data from laboratory penetration tests and ρ has been evaluated by an approximate analysis taking into account average shear strains produced in the plastic region surrounding the point during penetration.

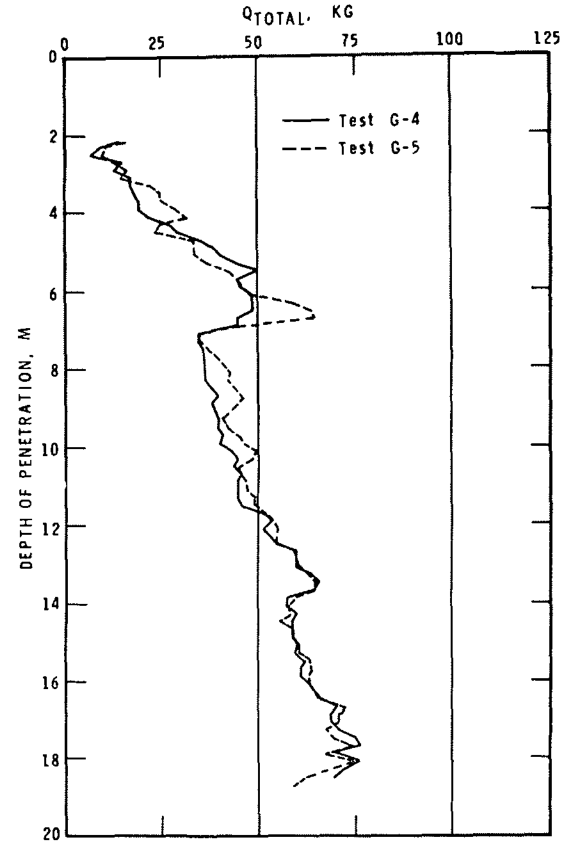

Fig. 4c Total Point Resistance, Q_{tot}, Recorded in Two Field Penetration Tests At Gloucester Site.

Substituting the above values in Eq. 4, dividing by A_p = 10 sq cm, and expressing s_u, Q_{tot} and p_o in t sq m yields:

$$s_u = \frac{Q_{tot} - p_o}{(N_c + 0.752)\rho} \quad \ldots\ldots\ldots\ldots (5)$$

Theoretical Prediction of N_c value

By extending the theory of expansion of a spherical cavity in an infinite medium to an elastic-plastic-frictionless material characterized by a drop of strength after failure, Ladanyi (1967) has shown that, for a typical sensitive clay, an approximate N_c value can be calculated from the expression following Eq. (6). The values of s_u, s_r, E_s and E_r in this equation correspond to a simplified stress-strain plot for the particular clay obtained in

undrained compression test (Figure 5). The value of s_a is the remoulded adhesion between the cone surface and the clay.

$$N_c = \frac{s_a}{s_u} + \frac{4}{3}\,\frac{s_r}{s_u}\left[1 + \ln\frac{E_r}{3s_r}\right] + \frac{4}{3}\left[\frac{(E_s/s_u)-(E_r/s_r)(s_r/s_u)}{(E_s/s_u)-(E_r/s_r)}\right].\ \ln\frac{E_s}{s_u}\cdot\frac{s_r}{E_r} \qquad (6)$$

$$E_s = \frac{2S_u}{\mathcal{E}_{1p}}$$

$$E_r = \frac{2S_r}{\mathcal{E}_{1r}}$$

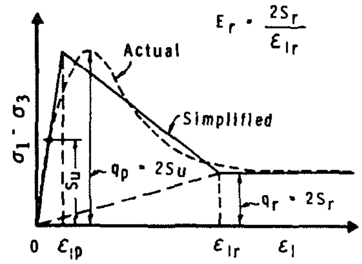

Fig. 5 Simplified Stress-Strain Behaviour of A Sensitive Clay in Undrained Compression Test Assumed in N_c Calculation.

It has been shown (Ladanyi, 1967) that for a typical Leda clay from the NRC site with a sensitivity of about 16 the following numerical values could be taken for different ratios in Equation 6: $250 \le (E_s/s_u) \le 500$; $(E_r/s_r) = 16$; $(s_r/s_u) = 0.45$, $(s_a/s_u) = 0.45$. According to Equation 6, for the above range of E_s/s_u ratio the value of N_c should then be situated between $5.85 \le N_c \le 6.73$.

For comparison, it should be noted that for the same range of E_s/s_u ratio, the same analysis would give, for an insensitive clay,

$$8.22 \le N_c \le 9.15.$$

It is evident, therefore, that N_c value depends considerably on the post-peak behaviour of the clay. A recent investigation (Ladanyi et al, 1968) shows that the drop in strength immediately after the peak is much more pronounced in sensitive clays than in ordinary clays. It follows, therefore, that N_c value should generally be expected to decrease with increasing sensitivity of clay.

Results of Evaluation

Taking $5.85 \le N_c \le 6.73$, and $1.015 \le \rho \le 1.040$, Eq. 5 yields:

for $E_s/s_u = 250$: $s_u = (Q_{tot} - p_o)/6.86$ .... (7)

for $E_s/s_u = 500$: $s_u = (Q_{tot} - p_o)/7.60$ .... (8)

Because it was thought that for the clay in situ the ratio E_s/s_u would probably be nearer to the higher value shown above, Eq. 8 has been chosen for the calculation of s_u values shown in Figures 6a and 6b. In both figures the s_u values were obtained by a 110 by 55 mm field vane. The range of sensitivity at different depths is also indicated in the figures. The s_u values shown have been obtained by using average Q_{tot} values from the penetration tests shown in Figures 4b and 4c, respectively.

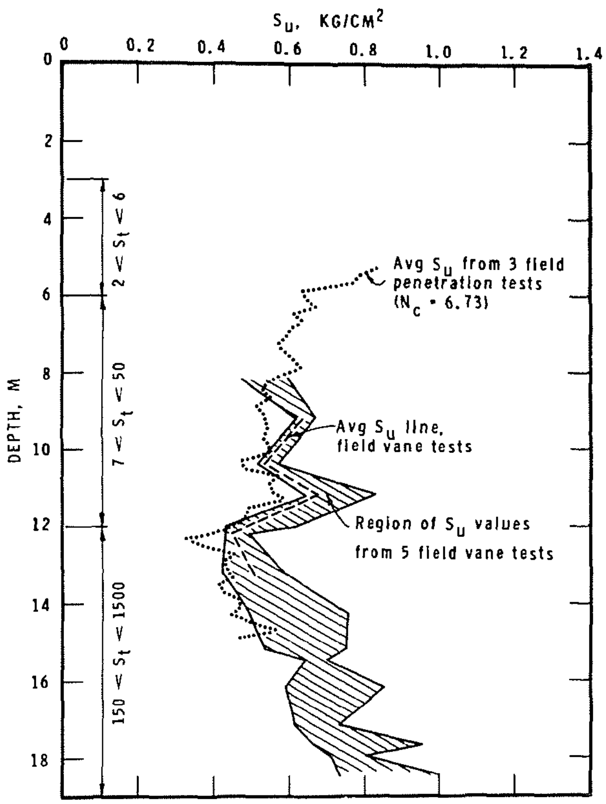

Fig. 6a Comparison of s_u Values From Field Vane And Penetrometer Tests At NRC Site.

Figure 6a shows that at the NRC site s_u values from penetration tests follow approximately the same trend as those from field vane tests. They are generally lower than the average from field vane tests in absolute value. It is probable that, owing to the brittle and jointed character of the particular clay, the actual N_c value is lower than that used in the evaluation. It was found that with $N_c = 5.50$ the agreement would be more satisfactory, especially below the 12 m level where a highly sensitive clay is found.

Comparison of s_u values obtained at the Gloucester site, (Figure 6b), shows a similar increase in s_u with depth for the two types of test. Here, however, s_u values calculated from $N_c = 6.73$ seem to be a little too high. A better agreement could have been obtained if N_c had been taken to equal about 7.50.

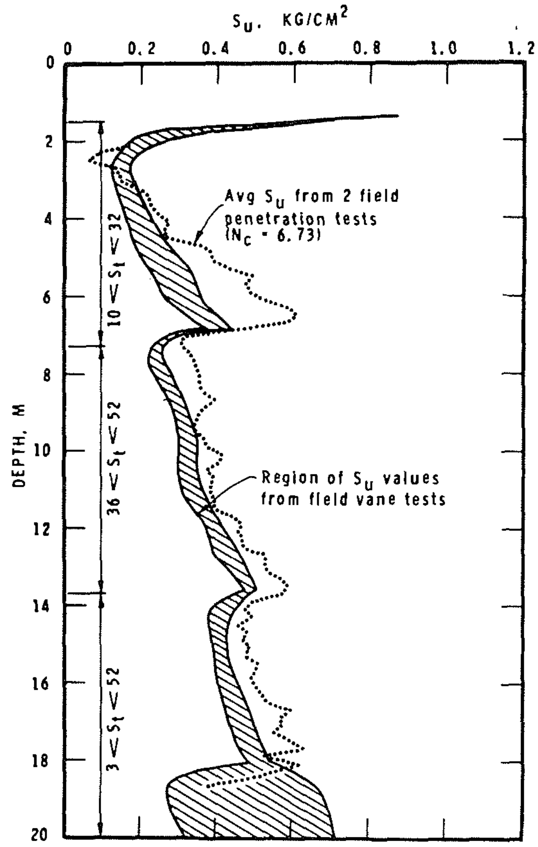

Fig. 6b Comparison of s_u Values From Field Vane And Penetrometer Tests at Gloucester Site.

CONCLUSIONS

On the basis of this investigation, the following conclusions are suggested:

1. For the penetration rates used in the tests, sensitive clays behave during deep punching as ordinary clays: failure occurs without any sign of eventual liquefaction owing to high local remoulding.

2. Bearing capacity values that are valid for deep penetration in undrained shear are lower in sensitive clays than in ordinary clays. Instead of a value $N_c \approx 9$ commonly found in ordinary clays, the N_c for sensitive clays varies from about 5.50 to 8.00, with the lower values occurring at high sensitivities. Actual N_c values found in this study by using, for comparison, the best field vane results are $5.70 < N_c < 8.00$ in laboratory penetration tests and $5.50 < N_c < 7.50$ in field penetration tests. The theory gives $N_c = 6.73$ for $S_t \approx 16$. As N_c is found to vary with clay sensitivity, more records from field and laboratory penetration tests will be needed to relate its value more closely with sensitivity.

3. Resistance to penetration increases with increasing rate of penetration. The increase in point resistance found in laboratory small-scale tests was 7.5 per cent for a tenfold increase in penetration rate; this follows the trend normally found in the undrained compression test. It is concluded that the effect of the rate of penetration should be taken into account when comparing results of deep penetration tests with results of other types of field and laboratory tests for undrained strength determinations.

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