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A STUDY OF DEEP PENETRATION TESTS IN SENSITIVE CLAYS

by

Branko Ladanyi

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PREFACE

It is difficult to determine in the laboratory the true undrained shear strength of sensitive Leda clay, a deposit found extensively in the St. Lawrence Lowlands, because of the disturbing influence on such clays of sampling and handling operations. *In situ* testing methods using the field vane, the plate loading device or the static deep penetrometer show much promise as practical means for measuring undrained strength.

This study of the static deep penetration test has furnished experimental information necessary for evaluating the results of such tests performed in typical sensitive clays. The study was made by Dr. B. Ladanyi of Laval University during the summer of 1967, when he was a visiting professor in the Soil Mechanics Section of the Division of Building Research.

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TESTS IN SENSITIVE CLAYS

by

Branko Ladanyi

A number of different methods have been proposed for determining the undrained strength of saturated clays in situ . To date, the vane test has probably been used most often.

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. In clays the vane test is considered to furnish reliable results, provided the mode of failure actually produced corresponds to that assumed in its interpretation[1]. 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, is the fact 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 considered to produce a certain amount of disturbance in sensitive clays, particularly in those of a brittle type[1].

In this study the Deep Penetration Test is understood to be a quasi-static penetration test performed by pushing a cylindrical rod slowly into the soil while its base resistance is continuously recorded. The point of the penetrometer may be conical or flat, but it is assumed to have the same diameter as the rods and to be able to move with respect to the rods only the very small amount necessary for activating the force measuring system. Such a test has the advantage of giving continuous information on the variation of soil strength. Moreover, as the point resistance is measured during penetration, no objection can be raised concerning the effect of clay disturbance prior to the test. The test can, however, furnish only indirect information on the undrained shear strength S_u of the clay. This is related to the measured point resistance q_p by the bearing capacity formula:

$$q_p = p_o + S_u \cdot N_c \qquad (1)$$

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 a proper knowledge of the numerical value of the factor N_c.

On the basis of theory, model studies, and actual field tests, the value $N_c = 9$ has been proposed [2,3] and verified in different locations [4,5,6]. N_c values as low as 5 and as high as 25 have been reported in the literature [7,8,9,10].

An explanation of the observed variation in the N_c values has not yet been offered. It is thought that the low values may be caused by unusual stress-strain behaviour of the clay, either before [11] or after failure[12]. There are indications also that the high values might be attributed to deviations from purely frictionless behaviour of the particular clay [13], and to the influence of a high strain rate during a penetration test [14].

It may be seen that, in general, 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: (i) over-all stress-strain behaviour of the clay in undrained shear; (ii) rate of penetration; (iii) shape of penetrometer. No systematic investigation of N_c value has been made to date, however, that would cover all of the above effects and include different types of natural undisturbed clays. In particular, there is practically no information available on the value of N_c to be used in evaluating deep penetration tests in sensitive clays such as those encountered in Eastern Canada and Scandinavia.

A recent theoretical study [12] shows that in such clays N_c values much smaller than 9 and as low as 5 can be expected. The main purpose of the present investigation is 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;

b) field tests with a commercial type self-recording cone penetrometer of 3.57-cm diameter (10 cm^2 area).

Laboratory penetration tests were performed on undisturbed specimens of sensitive clays from three different locations. Field penetration tests were carried out at two different locations in the Ottawa area. In addition, and in connection with the evaluation of the test results, the problem of undrained compression of sensitive clays at large strains has been investigated and a number of compression tests have been performed. An account of this investigation is given in Appendix A.

LABORATORY PENETRATION TESTS

Purpose

A series of small-scale penetration tests was performed in the laboratory on undisturbed specimens of clay before field penetration tests were made. It was the purpose of these tests to study under controlled conditions the behaviour of a sensitive clay, and to determine the importance of factors that might affect resistance to penetration: rate of penetration, and the proximity of either a free surface or an interface between different clay layers.

Experimental Apparatus

A small cylindrical probe with a flat pressure sensitive base was used. Figure 1 is a schematic diagram of the assembly. When mounted in a triaxial press, the assembly enabled separate measurement and continuous recording of both the pressure at the base of the probe and the total force during penetration.

The pressure at the base of the probe was recorded by a Statham Flush Diaphragm Pressure Transducer (7V, 0-100 psia range) connected to a chart recorder. A detail of the probe tip is shown in Figure 2. During the test the probe was rigidly connected to a transverse guiding beam to keep it vertical but permit the small parallel movement along the vertical rods of the press necessary for activating the force transducer in the upper force measuring system (Figure 1). Force transducer output was recorded on another chart recorder. Figure 3 shows a photograph of the equipment and an exploded view of the probe.

Mounting of the Specimen

Specimens were obtained in a standard 5-in. piston sampler, with the exception of those of varved clay, which were cut from a block specimen. After a minimum of cutting or trimming, the specimens were put into a 26-cm long split steel cylinder, which was tightened slightly around the sample. Liquid wax was poured into the remaining space between the specimen and the cylinder. The uniform lateral support and no lateral displacement condition so obtained was considered essential for approximating the assumption made in the theory and encountered in the field. Under these conditions splitting failure of the specimen was prevented, and only a local plastic failure in the clay was expected.

Rate of Penetration

In all the tests carried out in the experimental arrangement shown in Figures 1 and 3 the rate of penetration was 0.356 cm/min. To study the effect of rate of penetration another series of tests was conducted with the same probe mounted in a Tinius-Olsen testing machine where penetration rates up to 12.7 cm/min could be attained.

Test Results

Clay specimens from three different locations were used. Figures 4 to 9 show the results of penetration tests carried out on six clay specimens taken from a borehole at the DBR/NRC site between depths of 9.75 and 11.20 m. Clay from this site has been described elsewhere [1,15,16]. According to the available data it is thought to have a sensitivity of about 10 to 35, a water content ranging from 72 to 84 per cent, and a field vane undrained shear strength between 0.5 to 0.7 kg/cm^2.

In Figures 4 to 9 the variation with depth of penetration of the following two quantities has been plotted:

1) point resistance, q_p, in kg/cm^2, as recorded by the pressure transducer at the base of the probe;

2) skin friction, L in kg, which is equal to the difference

$$L = Q_{tot} - A_p \cdot q_p \qquad (2)$$

where Q_{tot} denotes the total penetration force recorded by the force transducer, and $A_p = 1.885\ cm^2$ is the base area of the probe. In calculating the L value a correction had to be made for the dead weight of the moving portion of the apparatus below the force transducer. The significance of other lines shown in Figures 4 to 9 will be given in the following paragraph.

Analysis of available experimental evidence indicates that when a saturated clay is penetrated by a cylindrical probe with a flat base at a constant slow rate, and when the penetration starts from the free surface, the following phenomena occur:

First, a surface bearing failure is produced. In plastic clays, the failure occurs as predicted by the Prandtl Theory, i.e. by a formation of distinct failure planes along which the soil is extruded laterally towards the free surface. In more brittle clays such as undisturbed Leda clay, the surface failure is often associated with radial tensile cracking. In the present series of tests the latter type of surface failure was observed most often.

If the probe continues to penetrate the clay following surface failure, an increase in point resistance occurs. This increase, which occurs even in an ideally homogeneous clay, is thought to be the result of a decreasing influence of the free surface as the probe advances deeper into the clay medium[2].

Experimental evidence shows that for a $\varphi = 0$ (rigid plastic or elastic-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. As the tests performed here are intended for studying the resistance of clay to deep penetration, only the portion of the results below the depth marked by 4d in Figures 4 to 9 has been used in the following analysis and comparison. As far as the effect of the bottom surface of the specimen is concerned, it is considered to be negligible. Penetration was always stopped at a distance of more than 3 probe diameters from the bottom of the specimen.

From the point resistance q_p plotted in Figures 4 to 9, and especially the portions below a depth of 4d, where q_p would be expected to remain constant with depth if the material was homogeneous, it can be concluded that the particular clay was not homogeneous, even in such a small scale. Within the considered 10-cm thick interval below a depth of 4d the value of q_p is seen to vary as much as $\pm$ 15 per cent around a mean.

To prove that the observed variation of q_p is due to actual variation of the soil strength and not to any other unknown source, the strength variation in a longitudinal section of two different specimens was checked by a series of fall-cone tests. A 100-gram cone with 30-deg cone angle was used. The undrained shear strength was evaluated using the formula proposed by Hansbo[17]:

$$S_u = K \frac{Q}{h^2} \tag{3}$$

where Q is the weight of the cone, h is the depth of cone penetration, and K is a constant. For the evaluation of the tests, the results of which are shown in Figures 6 and 7, it was assumed for convenience that $K = 2$. As no attempt has been made to verify this K value, the S_u values calculated from these tests can be considered only as proportional to the actual ones. It may be seen, however, that the soil strength variation from the fall-cone tests followed closely that observed in the penetration tests.

This observed variation in the strength of the specimens makes it difficult to compare observations in the small-scale penetration tests with the results of other, larger scale tests such as undrained triaxial or field vane tests. In reality triaxial compression tests, in which failure can occur at the location of least resistance, will probably show a lower limit of the undrained strength within a 10-cm thick interval. On the other hand, the field vane tests are more likely to give an average S_u value for the same interval. The average of results from 5 field vane tests performed near where the present specimens had been taken, were used for comparison. The lines marked by "S_u field vane" in Figures 4 to 9 represent this average result. In Figure 18 the same average S_u line is plotted, together with the extreme limits of the results of the five field vane tests performed at the same location. The variation of S_u around the mean at each level in Figure 18 is fairly large, and gives an idea of the actual reliability of the average S_u line used for comparison. In Figures 4 to 9 the average S_u line has been plotted and compared with a parallel, average, deep penetration line, 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:

$$N_c = q_p/S_u \tag{4}$$

The N_c values so obtained are shown in Figures 4 to 9. They vary from 5.71 to 8.00, with an over-all average from the six tests of $N_c = 7.23$.

The skin friction curves in Figures 4 to 9 show that this force increases regularly with depth, with a slight variation in slope, reflecting the local variation in the strength of the clay encountered at a particular level. Because of different degrees of remoulding along the probe, the lateral adhesion distribution may be expected to be irregular, and it is difficult in this case to find a definite relation between the point resistance and the skin friction curves.

Valuable information can nevertheless be obtained from the L-curves on the average adhesion between the metal and the clay when the probe has penetrated deeply into the clay. As will be seen in Figures 4 to 9, after a penetration of 16 cm when the lateral remoulding can be considered complete, the average value of L is

$$L_{av} = 1/6\,(20.4 + 20 + 20.7 + 20.7 + 20.5 + 19.4)$$

$$= 20.33 \text{ kg}$$

Average adhesion, S_a, is then

$$S_a = \frac{20.3}{16 \times \pi \times 1.55} = 0.26 \text{ kg/cm}^2$$

As the average S_u value by field vane test within the same depth interval is about 0.585 kg/cm^2, it is found that the adhesion of the particular clay on the steel is of the order of 45 per cent of the peak undrained strength of the clay. This result is useful in the evaluation of deep cone penetration tests described later in this report.

Influence of Rate of Penetration on Point Resistance

It is well known that the undrained compressive strength of saturated clays increases with increasing rate of deformation. The rate of increase is about 10 per cent for each tenfold increase in rate of deformation. This general conclusion seems to be valid for a very wide range of strain rates, ranging from very low [18] to very high [19]. The same behaviour has been found for typical sensitive clays [20]. It should be expected, therefore, that the point resistance recorded during a penetration test, being proportional to the undrained strength of the clay, will also increase with increasing rate of penetration. This possibility has already been pointed out by Peck [14].

In order to investigate this effect, a series of laboratory penetration tests was carried out on specimens of Leda clay from a site near Gloucester in the Ottawa area. The specimens were taken at the same level from different borings no more than 10 ft apart. According to the available data, the clay has a sensitivity of about 30 at this particular level, water content of about 80 per cent, and undrained shear strength of about 0.25 kg/cm^2, increasing with depth.

Figure 10 shows the result of a penetration test carried out with Gloucester clay at a constant rate of penetration of 0.356 cm/min. It may be noted that the same analysis as that used on penetration tests on DBR/NRC clay gives, for this particular sample, an average value of N_c = 6.85, and an average adhesion after a penetration of 16 cm of S_a = 0.116 kg/cm^2, which is again about 45 per cent of the average S_u from field vane results.

Figure 11 shows the result of another penetration test carried out on a sample taken at the same location and level from another boring. This test was made in a Tinius-Olsen testing machine in which it was possible to perform practically instantaneous changes in penetration rate. The changes are illustrated by a block diagram in the figure. It may be seen that a sudden increase or decrease in penetration rate resulted in a visible variation in point resistance. The over-all behaviour, however, was similar to that in the constant rate test (Figure 10). From the rapid increases observed in resistance, it may be concluded that for this clay a tenfold increase in penetration rate results in an increase of about 7.5 per cent in point resistance. An attempt to predict theoretically the influence of strain rate in penetration tests is shown later in this report.

Effect of Clay Stratification

If a clay contains distinct layers with different strength properties, the strength variation should be clearly reflected in the variation of the point resistance of the penetrometer. For the strength of any particular layer to influence the penetration resistance fully, the layer must have a certain minimum thickness with respect to the diameter of the probe. According to Meyerhof [21], for saturated clays ($\phi = 0$) this minimum thickness should be about 5 punch diameters, of which 4d are measured from the top and 1d from the bottom of the layer to the base of the punch. For any layer thinner than the above value, the point resistance will not be able to attain the value corresponding to the true strength of the layer, but will be influenced by the strengths of upper and lower layers. To investigate this effect, two penetration tests have been carried out with the same probe on a specimen of a typical varved clay. The specimen was a block specimen taken at Steep Rock Lake, Ontario, from a group of specimens tested and described in a paper by Eden [22].

The two penetration tests were made on the same block sample. As is shown in Figure 12, however, Test A was made from the top towards the bottom of the sample, while Test B was made in the opposite direction.

It will be seen in Figure 12 that the probe shows very clearly the presence of varves in the clay. Because of the insufficient thickness of the varves, the point resistance reflected, in a rather complicated manner, the strength of over- and under-lying layers. Owing to the presence of free surfaces, it should be noted that only the portion between the 4d lines of the two tests can be compared.

Discussion of Laboratory Test Results

From the small-scale laboratory penetration tests it has been found that:

> the bearing capacity factor N_c, which can be deduced from the point resistance q_p using the value of S_u from field vane tests, varies from 5.7 to 8.0, with an over-all average of about 7.2;
>
> the remoulded adhesion S_a between the steel and the clay does not fall lower than about 45 per cent of the peak undrained strength of the clay, even after a penetration of 16 cm;
>
> in a range of penetration rates from 0.3 cm/min to 12.7 cm/min, a tenfold increase in rate of penetration results in an increase of about 7.5 per cent in point resistance;
>
> the laboratory penetrometer appears to be useful in investigating the strength variation in stratified or varved clays;
>
> in any particular layer, however, the true strength can only be felt by a probe with a diameter not greater than one-fifth of the layer thickness.

FIELD PENETRATION TESTS WITH BORROS PENETROMETER

Apparatus

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 is continuously recorded on a constant speed chart. Total resistance at the top of the rods is not recorded by this penetrometer. Figure 13 shows main dimensions of the cone point, with probable approximate location of strain gauges inside. The base of the cone has a diameter of 3.57 cm so that the area of the base equals 10 cm^2. The upper part of the probe and the rods have a diameter of 3.20 cm. A spring dynamometer is provided for calibrating the probe before the test.

Testing Procedure

Although a hand-operated jack is provided for pushing the penetrometer into the soil, the present tests were carried out using a hydraulic drill rig. This was convenient because it enabled the drilling of a borehole through the dried upper crust and pushed the penetrometer into the soil at a reasonably constant rate by means of the hydraulically-operated drillhead.

After balancing the Wheatstone bridge and calibrating the probe readings against the dynamometer for each test, the probe was lowered to the bottom of the borehole and left suspended for about 1 hr for temperature stabilization. Each test was performed by pushing the penetrometer slowly into the soil and recording continuously the penetration resistance. To check the penetration rate each rod was divided into 20-cm intervals by chalk markings. As the recording chart moved at a constant speed of 1 in./min, a mark made on the chart by the operator at each successive 20 cm of penetration enabled the penetration rate to be determined at every moment of the test. At regular intervals the bridge balance zero position was also checked. Average rate of penetration was about 20 cm/min, with a variation of about ± 5 cm/min.

Test Results

The results of deep penetration tests are shown in Figures 14 and 15. In these, Q total, plotted against depth, represents the average load in kilograms registered by the strain gauges at the point within successive 20-cm intervals. The tests shown for each location have been carried out no more than 20 ft apart. It will be seen in Figures 14 and 15 that the results obtained for each location were fairly consistent. In the following evaluation of the results, therefore, only the average of Q total values, measured at a given level in all tests performed at a particular location, were used.

Evaluation of Test Results

Owing to the particular shape of the point of the Borros penetrometer and to the fact that the strain gauges are located at a certain distance above the cone, it is considered that the value of Q total recorded by the strain gauges 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. Thus it is assumed that Q total can be expressed as the following sum:

$$Q_{tot} = A_p \cdot q_p + A_L \cdot \chi \cdot S_u + A'_L \cdot \beta \cdot S_u \qquad (5)$$

in which A_p, A_L and A'_L (Figure 13) are the areas of the base of the cone, the collar, and the surface between the collar and the location of strain gauges, respectively; S_u is undrained shear strength of the clay; χ and β are reduction coefficients for S_u taking into account the remoulding and imperfect contact; and finally, that

$$q_p = p_o + S_u \cdot N_c \qquad (1)$$

is the true point resistance.

Substituting Equation (1) in Equation (5) enables S_u to be obtained by the expression

$$S_u = \frac{Q_{tot} - A_p \cdot p_o}{A_p \cdot N_c + A_L \cdot \chi + A'_L \cdot \beta} \qquad (6)$$

The value of S_u obtained from Equation (6) would, however, correspond only to the particular strain rate associated with a given penetration test. If S_u values obtained from deep penetration tests have to be compared with those obtained in some other types of tests in which the strain rate is different, a strain rate factor should be used with all S_u values in Equation (7).

Denoting the strain rate factor by ρ, Equation (6) becomes

$$S_u = \frac{Q_{tot} - A_p \cdot p_o}{(A_p \cdot N_c + A_L \cdot \chi + A'_L \beta) \cdot \rho} \qquad (7)$$

For the purpose of evaluating the present test results the numerical values of various magnitudes in Equation (7) have been taken as follows:

$A_p = 10\ \text{cm}^2$

$A_L = 5.6\ \text{cm}^2$

$A'_L = 50\ \text{cm}^2$

$\chi = 0.45$

$\beta = 0.10$

The value of $\chi = 0.45$ was chosen in accordance with the results of measurement of lateral adhesion resistance in laboratory penetration tests shown above. The value of $\beta = 0.10$ was taken much lower than χ because of a probable imperfect contact between the clay and the metal in the upper part of the probe, which has a smaller diameter. Substituting the above values in Equation (7), dividing by $A_p = 10\ \text{cm}^2$, and expressing S_u in t/m^2, yields:

$$S_u\ (t/m^2) = \frac{Q_{tot}\ (t/m^2) - p_o\ (t/m^2)}{(N_c + 0.752)\ .\ \rho} \qquad (7a)$$

Here, $Q_{tot} = Q_{tot}/A_p$ and p_o is the total overburden pressure at any level. Finally, in this equation only two magnitudes remain to be determined, viz. the bearing capacity factor N_c and the strain rate factor, ρ. In the following, some theoretical considerations on these two factors are given.

Theoretical Prediction of N_c Value

As a detailed discussion on the determination of N_c factor in saturated clays has been given elsewhere [12], only a summary of the findings pertinent to the present investigation will be described.

There are actually two different theories used for the determination of the factor N_c. The first, which is an extension of the original Prandtl theory to deep punching problems, is strictly valid for a rigid plastic material behaviour. By using this theory, Meyerhof [2] obtained for N_c the value

$$N_c = 9.34$$

According to the assumptions on the material behaviour made in this theory, the above value of N_c should be valid, approximately, for stiff clays of low sensitivity.

Another theory, which takes into account the deformability of the material during shear, is the theory of expansion of a spherical cavity in an infinite medium. It has first been used in connection with a punching problem by Bishop, Hill and Mott [23]. On the basis of the same approach, Meyerhof [2] gave the following expression for N_c:

$$N_c = 1 + \frac{4}{3}\left[1 + \ln \frac{E_s}{3\,S_u}\right] \tag{8}$$

The formula is strictly valid for a linear elastic, perfectly plastic material, and is considered to give reliable N_c values for more deformable clays of low sensitivity. In this formula E_s denotes the secant modulus of deformation obtained from the slope of a secant intersecting the undrained stress-strain curve of the clay at one-half peak compressive strength. In Reference 12 the above theory was extended to materials such as sensitive clays that are characterized by a drop of strength after failure.

A general expression for N_c valid for such materials is given by

$$N_c = \frac{S_a}{S_u} + \frac{4}{3}\,\frac{S_r}{S_u}\left[1 + \ln \frac{E_r}{3S_r}\right] + \frac{4}{3}\left[\frac{\frac{E_s}{S_u} - \frac{E_r}{S_r}\,\frac{S_r}{S_u}}{\frac{E_s}{S_u} - \frac{E_r}{S_r}}\right] \ln \frac{E_s}{S_u} \cdot \frac{S_r}{E_r} \tag{9}$$

The values of S_u, S_r, E_s and E_r in this equation are obtained from a simplified stress-strain plot for the particular clay in undrained compression test (Figure 16). The value of S_a is the remoulded adhesion between the cone surface and the clay.

It has been shown [12] that for a typical Leda clay from the DBR/NRC site with a sensitivity of about 16, the following numerical values could be taken for different ratios in Equation (9):

$$250 \leq \frac{E_s}{S_u} \leq 500, \quad \frac{E_r}{S_r} = 16, \quad \frac{S_r}{S_u} = 0.45$$

The value of $\frac{S_a}{S_u}$, according to the experience described earlier in this report on the adhesion between the metal and the clay, can be taken to equal 0.45. According to Equation (9), for the above range of $\frac{E_s}{S_u}$ ratio the value of N_c should then be situated between

$$5.85 \leq N_c \leq 6.73$$

For comparison, it should be noted that for the same range of $\frac{E_s}{S_u}$ ratio, Equation (8) would give for an insensitive clay

$$8.22 \leq N_c \leq 9.15$$

It is evident, therefore, that the N_c value depends considerably on the post-peak behaviour of the clay.

A recent investigation [24] shows that the drop in strength after the peak is much more pronounced in sensitive clays than in ordinary clays, and can in fact be expected to be proportional to the clay sensitivity. It follows, therefore, that N_c value should generally be expected to decrease with increasing sensitivity of clay.

Theoretical Prediction of the Strain Rate Effect

One method of assessing this effect has been proposed by Peck [14]. The following approach presents a different point of view.

If the cavity expansion model is assumed to be valid for a deep penetration of a penetrometer into clay, it is found that the amount of strain the clay undergoes around the penetrometer point during penetration varies with the cube of distance from the point. Even if the rate of penetration is constant, therefore, the strain rate produced in the surrounding clay will vary with the distance from the penetrometer. Thus, if the effect of strain rate has to be determined, one has to define first some corresponding average strain rate undergone by the clay during penetration.

If it is assumed that the cone penetrates clay at a constant rate, it may be taken that each time the cone penetrates a length equal to its diameter $d = 2a$ ($\approx$ its height) the lower part of the plastic zone advances the same distance. The volume of the slice of clay just brought to failure is therefore approximately equal to (see Fig. 17)

$$V = \pi r_f^2 \cdot 2a \qquad (10)$$

where r_f is the radius of the plastic region (Ref. 23, see p. 151)

$$r_f = a\left(\frac{E_s}{3S_u}\right)^{1/3} \qquad (11)$$

Inside this slice the shear strain γ varies according to the equation (Ref. 12)

$$\gamma = \left(\frac{a}{r}\right)^3 \qquad (12)$$

An average value of γ in the slice can be calculated as follows

$$\gamma_{av} = \frac{1}{V} \cdot \int_{r_f}^{r_f + 2a} \gamma \cdot dV \qquad (13)$$

Substituting Equations (10) and (12) in Equation (13) and taking $dV = \pi r_f^2 \cdot dr$, it becomes

$$\gamma_{av} = \frac{1}{\pi r_f^2 \cdot dr} \int_{r = r_f}^{r = (r_f + 2a)} \left(\frac{a}{r}\right)^3 r_f^2 \pi \cdot dr \qquad (14)$$

Equation (14) yields

$$\gamma_{av} = \frac{1}{4} \left[\left(\frac{a}{r_f}\right)^2 - \left(\frac{a}{r_f + 2a}\right)^2 \right] \qquad (15)$$

Finally, substituting Equation (11)

$$\gamma_{av} = \frac{1}{4} \left(\frac{3S_u}{E_s}\right)^{2/3} \left[1 - \frac{1}{\left[1 + 2\left(\frac{3S_u}{E_s}\right)^{1/3}\right]^2} \right] \qquad (16)$$

As for the clays investigated

$$250 < \frac{E_s}{S_u} < 500$$

the corresponding γ_{av} from Equation (16) is

$$0.0069 > \gamma_{av} > 0.0038$$

or, since the axial strain ϵ_1 in a volume constant case is equal to $\frac{2}{3} \gamma$,

$$0.0046 > \epsilon_{1av} > 0.0025$$

In other words, if the rate of penetration is one diameter per minute, the corresponding average strain rate will be between 0.25 and 0.46 per cent/min. For the actual penetration rate of 20 cm/min, or 5.6 diam/min, the significant strain rate produced in the clay will be 5.6 times higher than the above values, viz.

$$2.6\% > \varepsilon_{1\,av} > 1.4\%/\text{min}$$

As in actual undrained tests and field vane tests the rate of strain is equal to about 1 per cent/min, the value of ρ can be calculated approximately by the equation (Ref. 14)

$$\rho = \frac{S_{up}}{S_u} = 1 + 0.1 \log_{10} \left(\frac{\dot{\varepsilon}_{1\,av}}{\dot{\varepsilon}_{1\,st}} \right) \tag{17}$$

in which S_{up} and $\dot{\varepsilon}_1$ correspond to the penetration test, and S_u and $\dot{\varepsilon}_{1\,st}$ to a standard undrained compression test. If $\dot{\varepsilon}_{1\,av} = 2.6$ per cent/min and $\dot{\varepsilon}_{1\,st} = 1$ per cent/min, Equation (17) gives

$$\rho = \frac{S_{up}}{S_u} = 1 + 0.1 \log 2.6 = 1.0415$$

The value of the strain rate factor in Equation (9) can, therefore, be taken $1.04 > \rho > 1.015$ for the assumed variation of $\frac{E_s}{S_u}$ ratio.

It is noted that the strain rate effect will be much higher when the cone is brought to movement from a state of rest. The limits of integral Equation (14) should then be extended to the whole plastic zone, and γ_{av} obtained is much higher. In fact, a rapid temporary increase in resistance after every stop in penetrometer movement has been observed in the present tests. It is, therefore, preferable that a constant rate of penetration is retained for the longest possible intervals with a minimum number of stops in penetration.

Results of Evaluation

The above theoretical values of the factors N_c and ρ allow Equation (1a) to be used for the evaluation of the performed field penetration tests. Taking $5.85 \leq N_c \geq 6.73$ and $1.040 \geq \rho \geq 1.015$, Equation (7a) yields

$$\text{for } \frac{E_s}{S_u} = 250: \quad S_u = \frac{Q_{tot} - p_o}{6.86} \tag{18a}$$

$$\text{and for } \frac{E_s}{S_u} = 500: \quad S_u = \frac{Q_{tot} - p_o}{7.60} \tag{18b}$$

It is noted, however that Equations (18a) and (18b) correspond to a clay of $S_t \approx 16$. For higher sensitivities, the values in the denominator are expected to be correspondingly lower owing to lower N_c values.

Because for the clay in situ the ratio $\frac{E_s}{S_u}$ will probably be higher than lower, Equation (18b) has been chosen for the calculation of S_u values shown in Figures 18 and 19. In both figures the S_u values so calculated have been compared with S_u values obtained in field vane tests performed with a 110- by 55-mm vane. In the figures the range of sensitivity at different depths is also indicated.

The S_u values shown have been obtained by using average Q_{tot} values from the penetration tests shown in Figures 14 and 15, respectively. The overburden pressure p_o was calculated at each level from actual saturated unit weights of the clay determined on undisturbed samples. It will be seen in Figure 18 that at the DBR/NRC site S_u values from penetration tests follow approximately the same trend as those from field vane tests, with more variation owing to the smaller scale of the test. In absolute value, the S_u from penetrometer tests is in this case generally lower than the average from field vane tests. 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 is found that with $N_c = 5.50$ the agreement would be more satisfactory, especially below the 12m level where a highly sensitive clay is found.

Comparison of S_u values at the Gloucester site (Figure 19) shows again that very similar aspects of S_u variation with depth are obtained from the two types of tests. Here, however, S_u values calculated with $N_c = 6.73$ 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.

It is interesting to note that about the same variation of N_c values has been found in the laboratory penetration tests performed in this study.

CONCLUSIONS

On the basis of the present investigations the following conclusions can be stated:

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

2. The values of bearing capacity factor N_c 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 data 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 undrained compression tests. It is concluded that the effect of penetration rate 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 determination.

ACKNOWLEDGEMENTS

The tests described in this report were carried out during the author's summer term as a visiting scientist at the Division of Building Research, National Research Council, Ottawa. The field and laboratory tests were made with the assistance of Mr. D. C. MacMillan and Mr. K. Timmins. Mr. W. J. Eden, Research Officer, has taken part in all phases of this study and in the preparation of this report. The author wishes to express his gratitude to these and other colleagues at the Soil Mechanics Section who have facilitated the field and laboratory investigations described.

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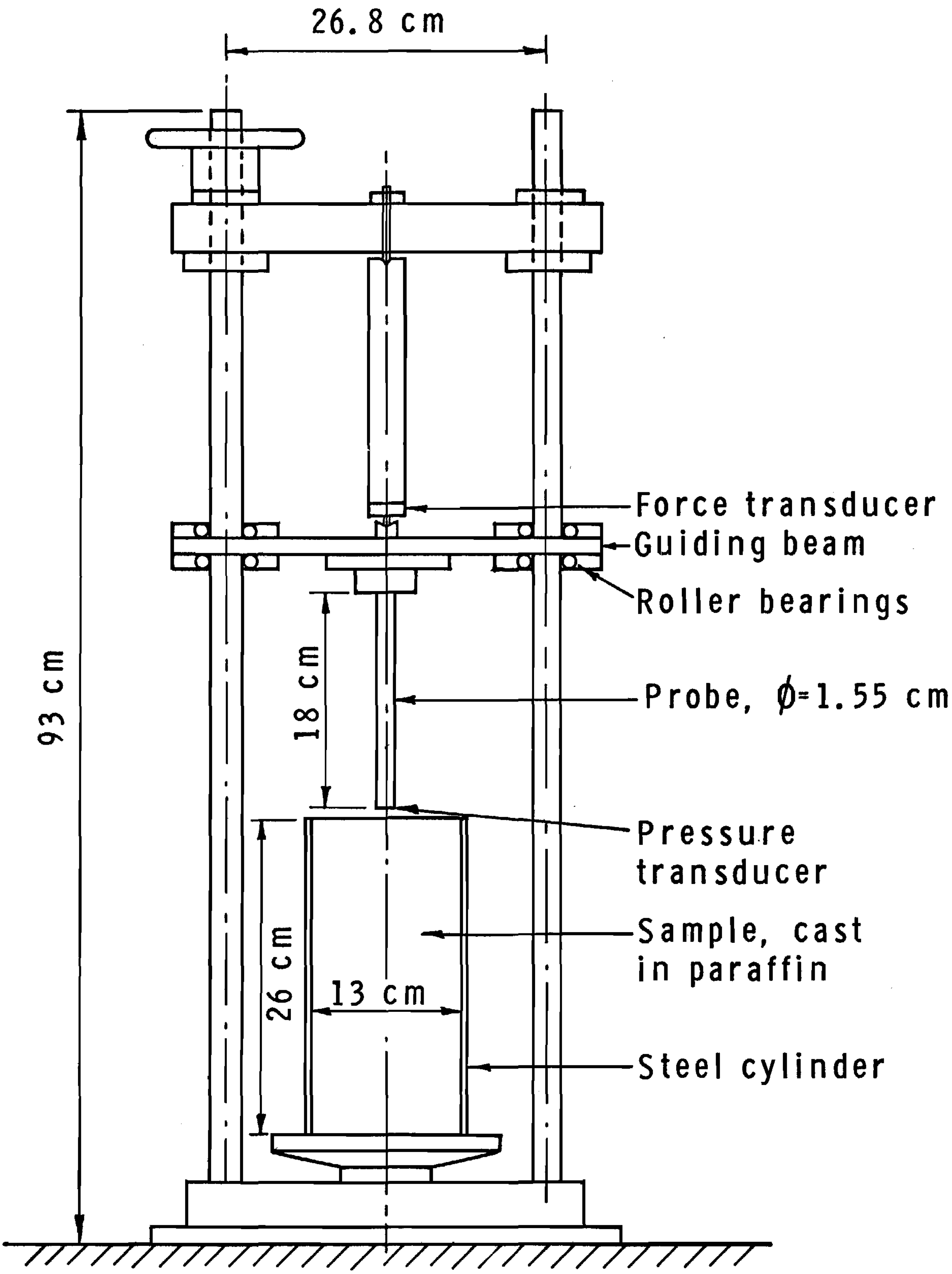

FIGURE 1

EXPERIMENTAL ARRANGEMENT FOR LABORATORY PENETRATION TESTS

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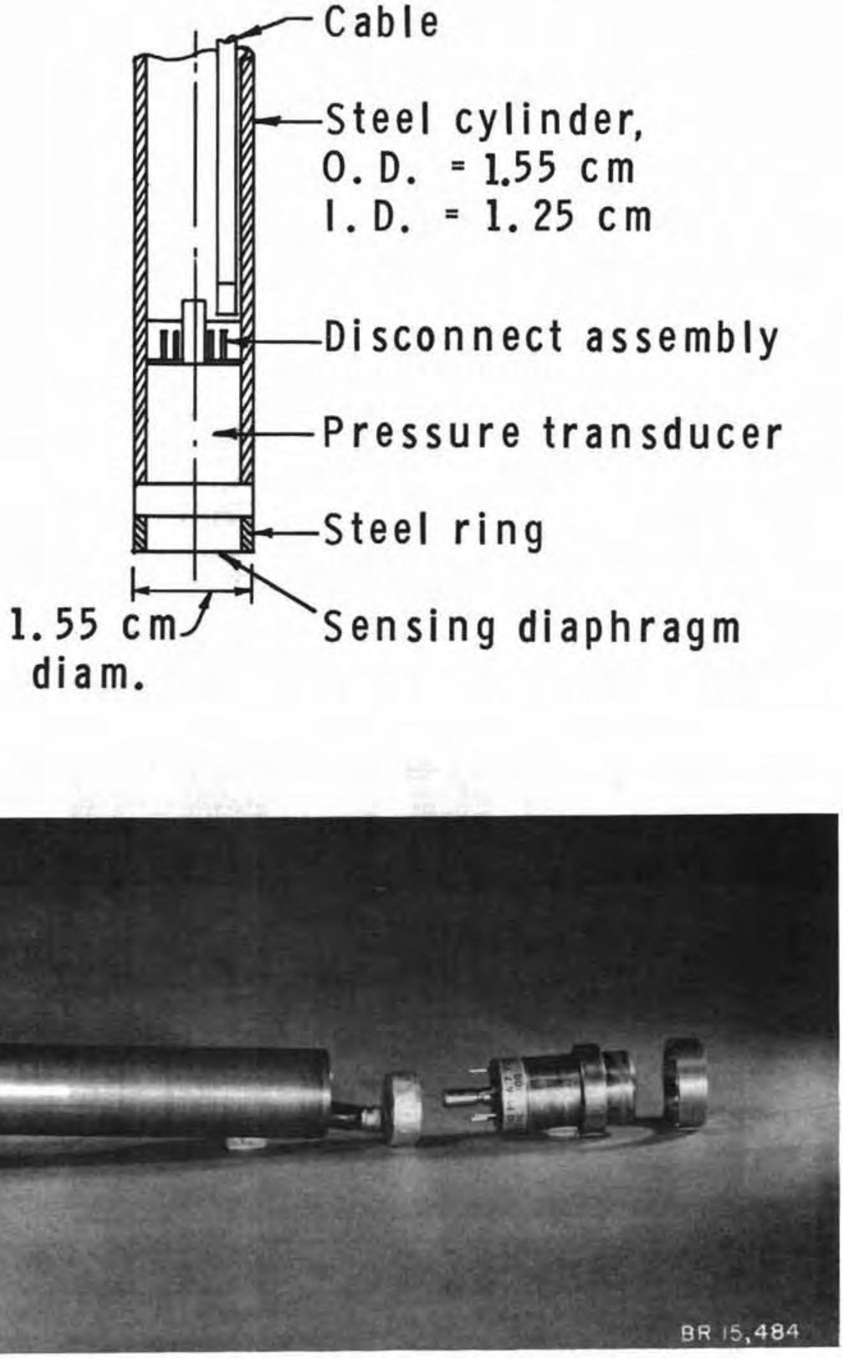

FIGURE 2

DETAIL OF THE PROBE TIP

BR 4123-2

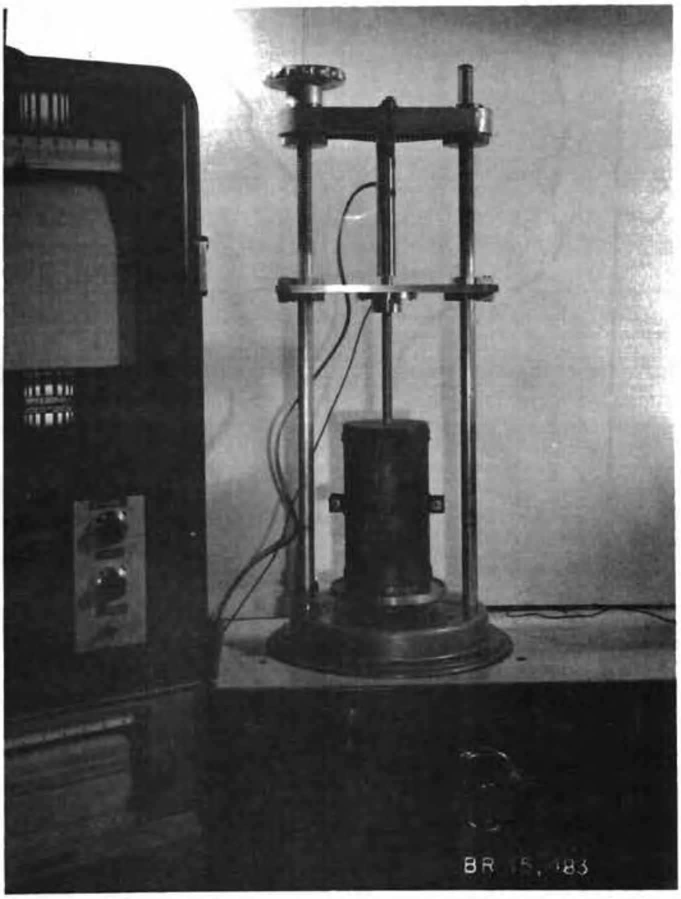

Figure 3: General view of the laboratory penetration test equipment.

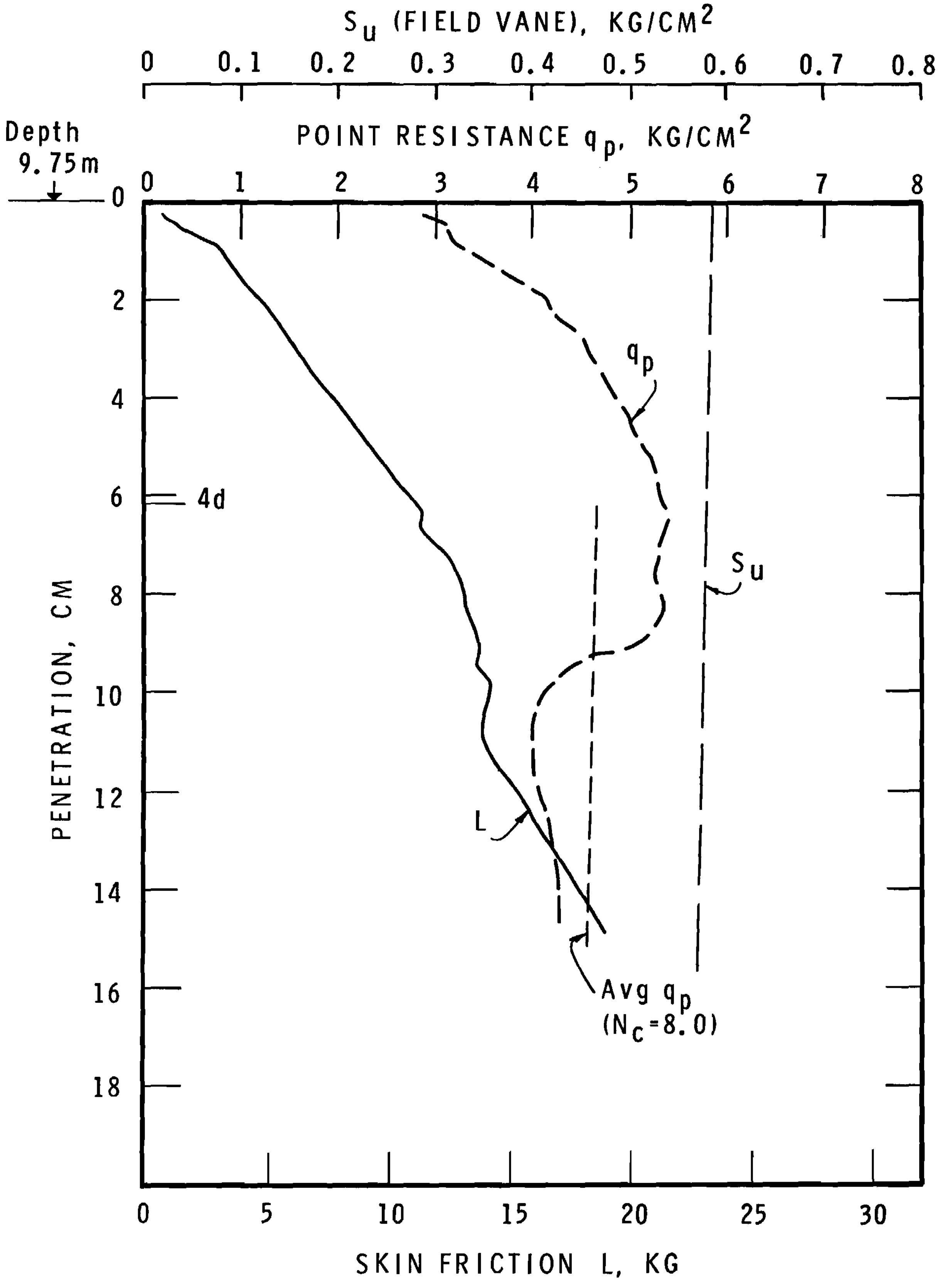

FIGURE 4

LABORATORY PENETRATION TESTS: NRC-MRL CLAY

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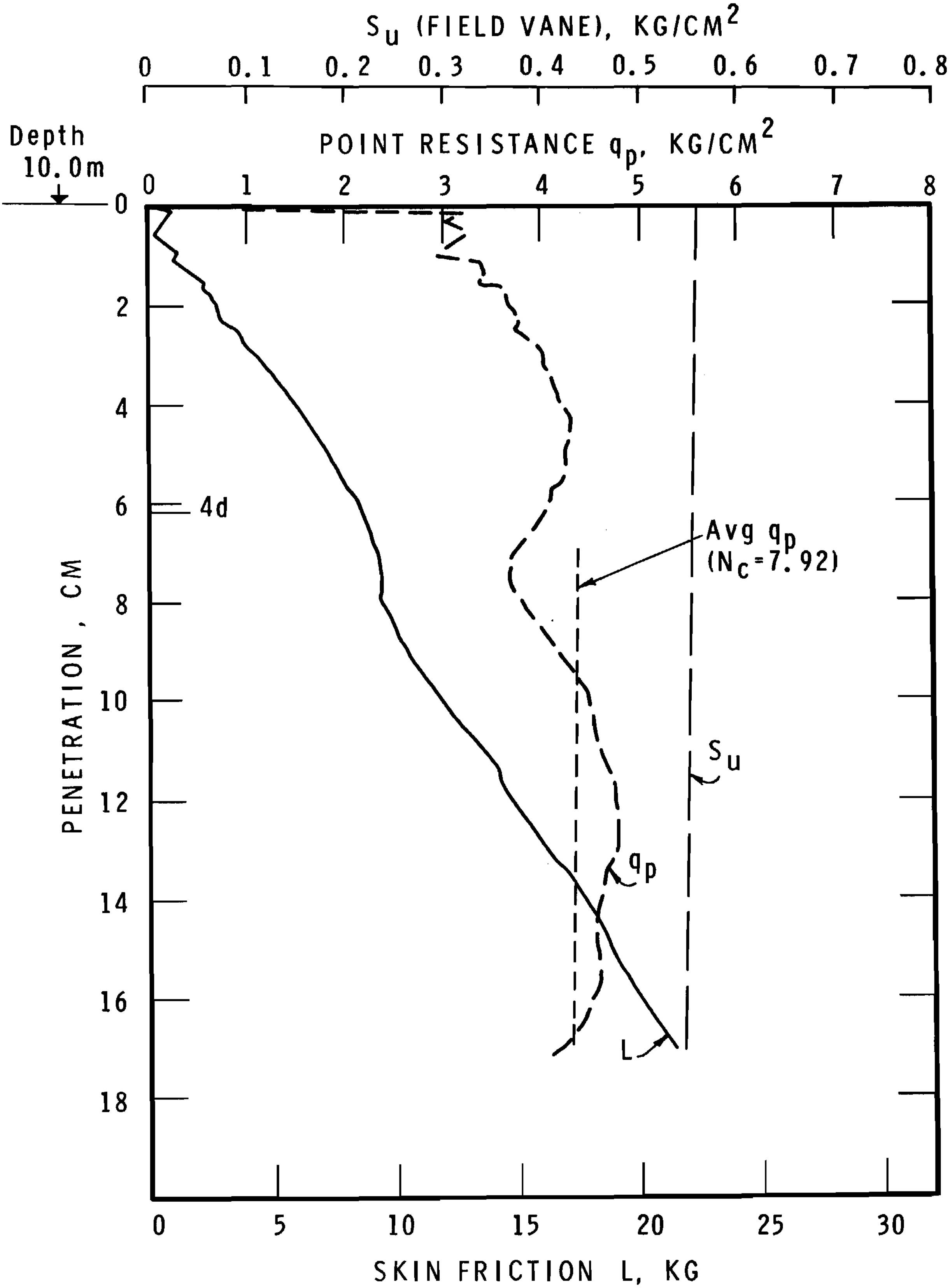

FIGURE 5

LABORATORY PENETRATION TESTS: NRC-MRL CLAY

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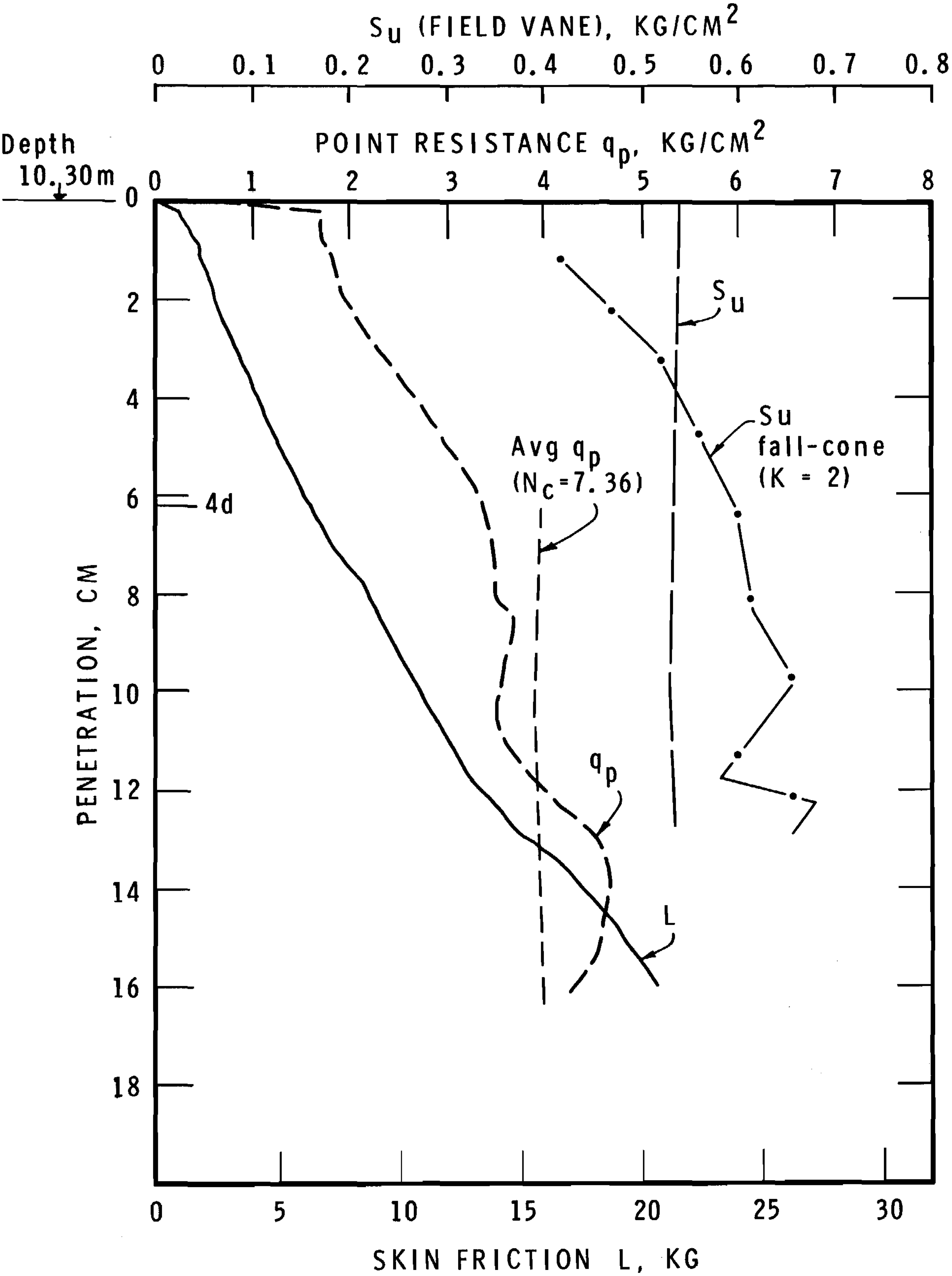

FIGURE 6

LABORATORY PENETRATION TESTS: NRC-MRL CLAY

BQ 4123-5

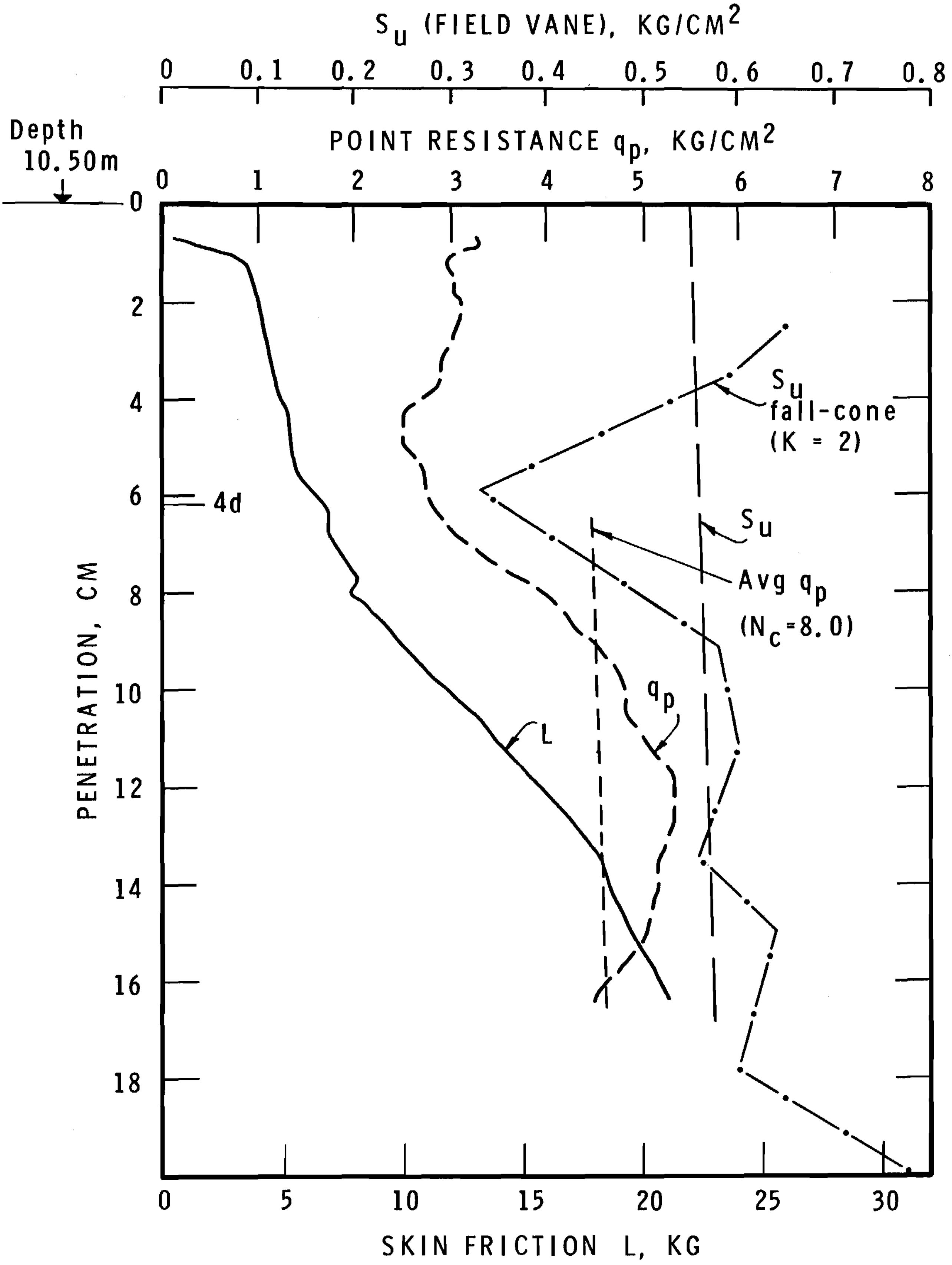

FIGURE 7

LABORATORY PENETRATION TESTS: NRC-MRL CLAY

BR 4125-6

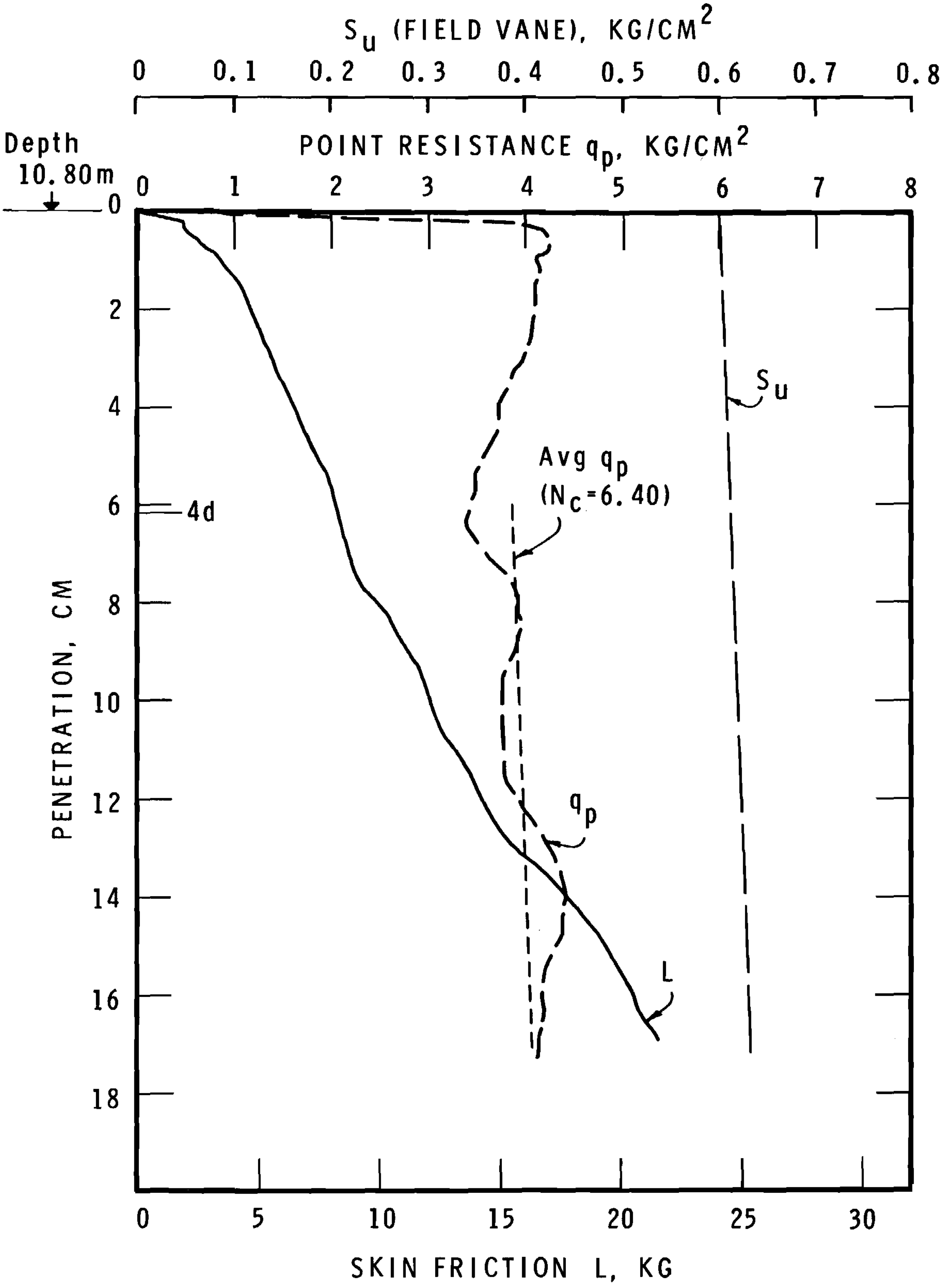

FIGURE 8

LABORATORY PENETRATION TESTS: NRC-MRL CLAY

BR 4123-7

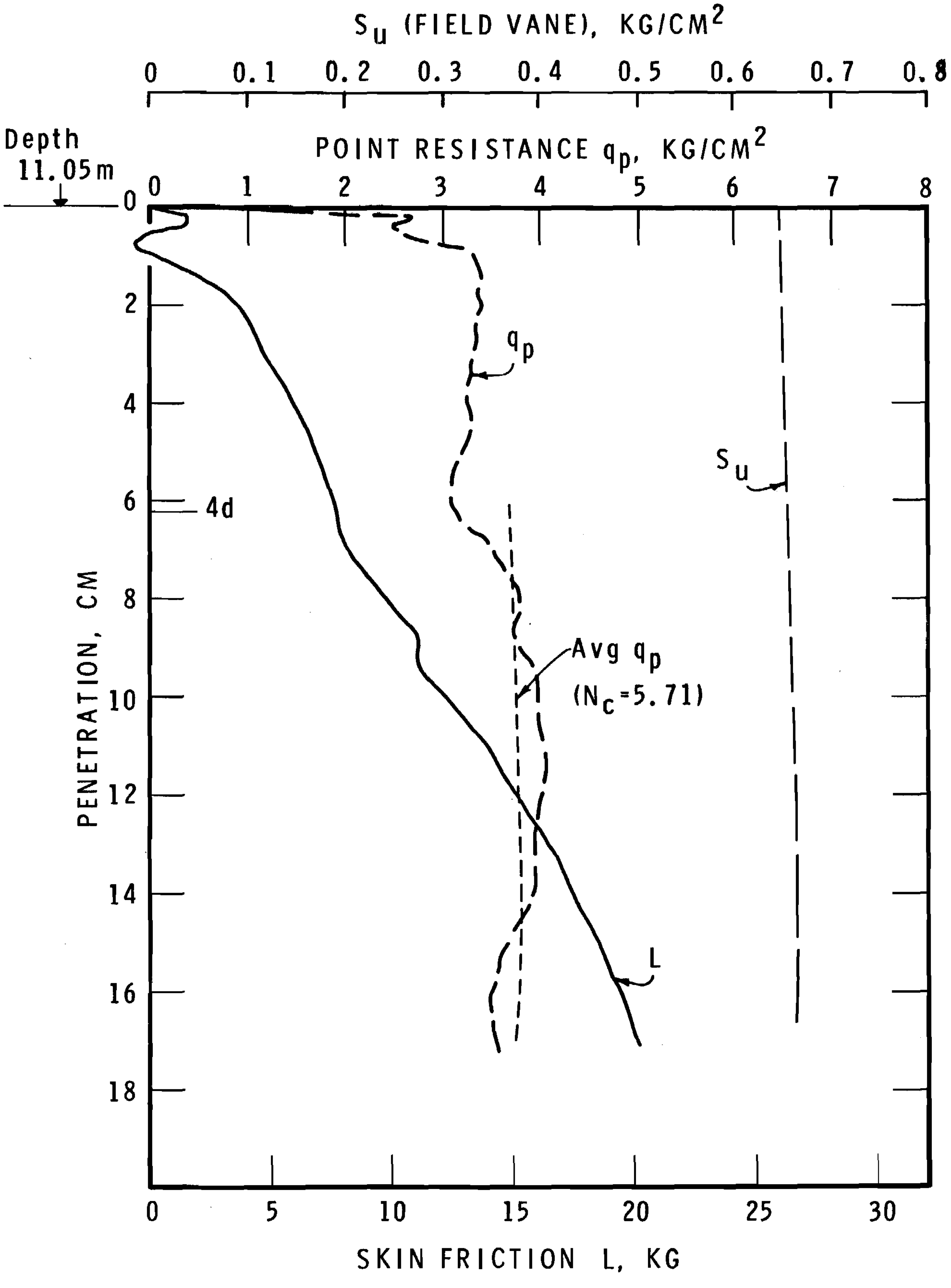

FIGURE 9

LABORATORY PENETRATION TESTS: NRC-MRL CLAY

BQ 4123-8

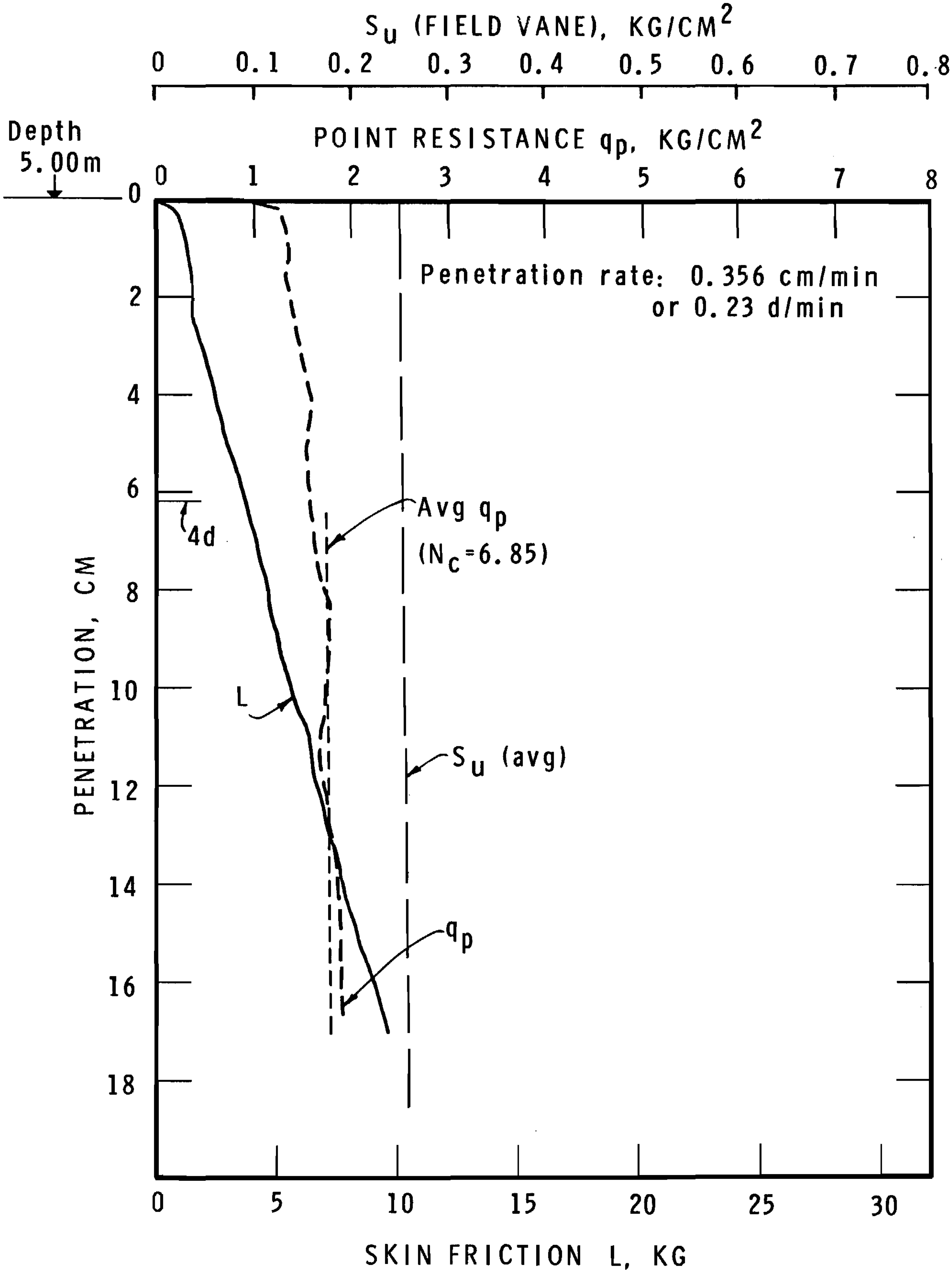

FIGURE 10

LABORATORY PENETRATION TEST, GLOUCESTER CLAY

8R 4123-9

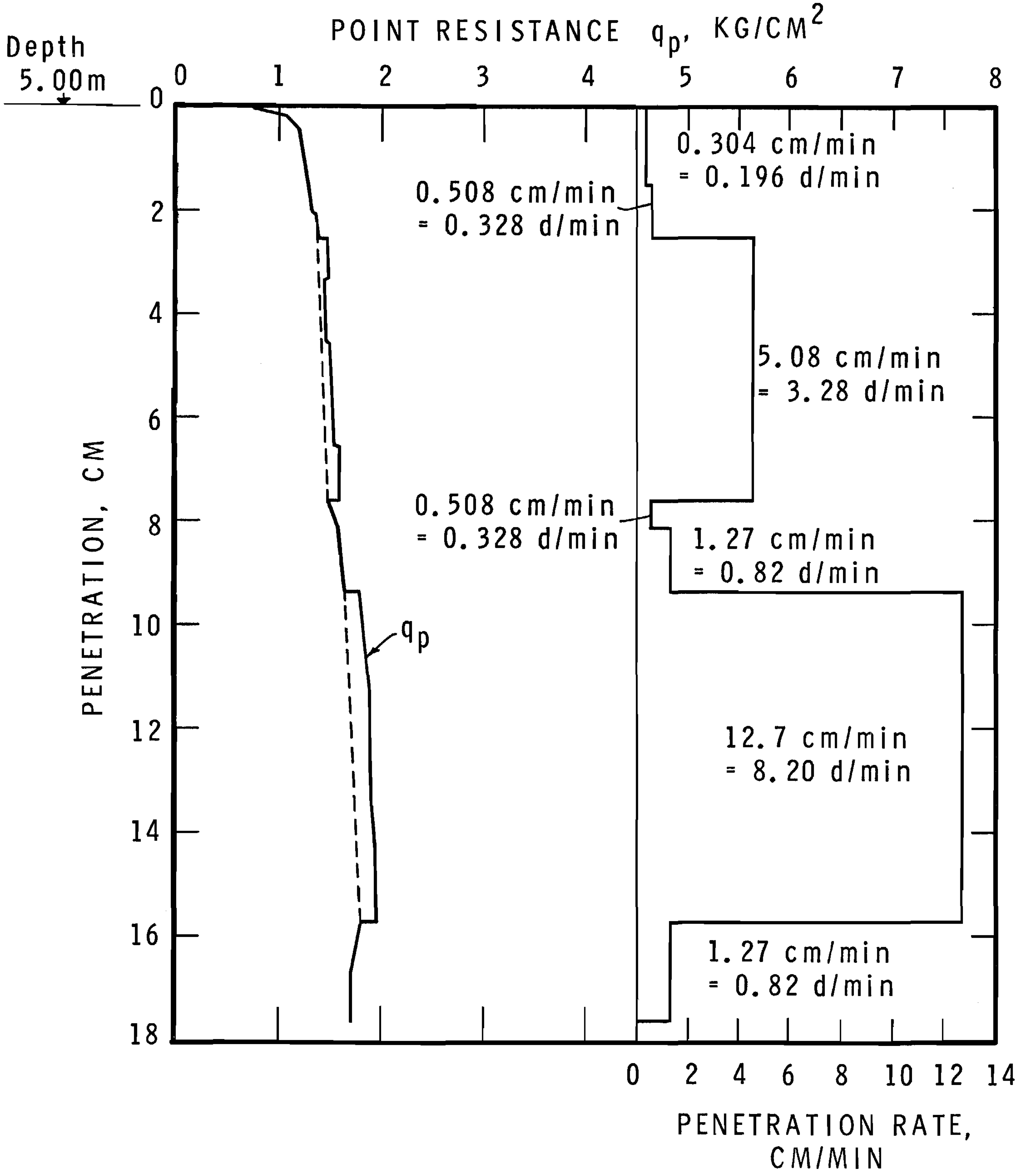

FIGURE 11

VARIABLE RATE PENETRATION TEST ON GLOUCESTER CLAY

BR 4123-10

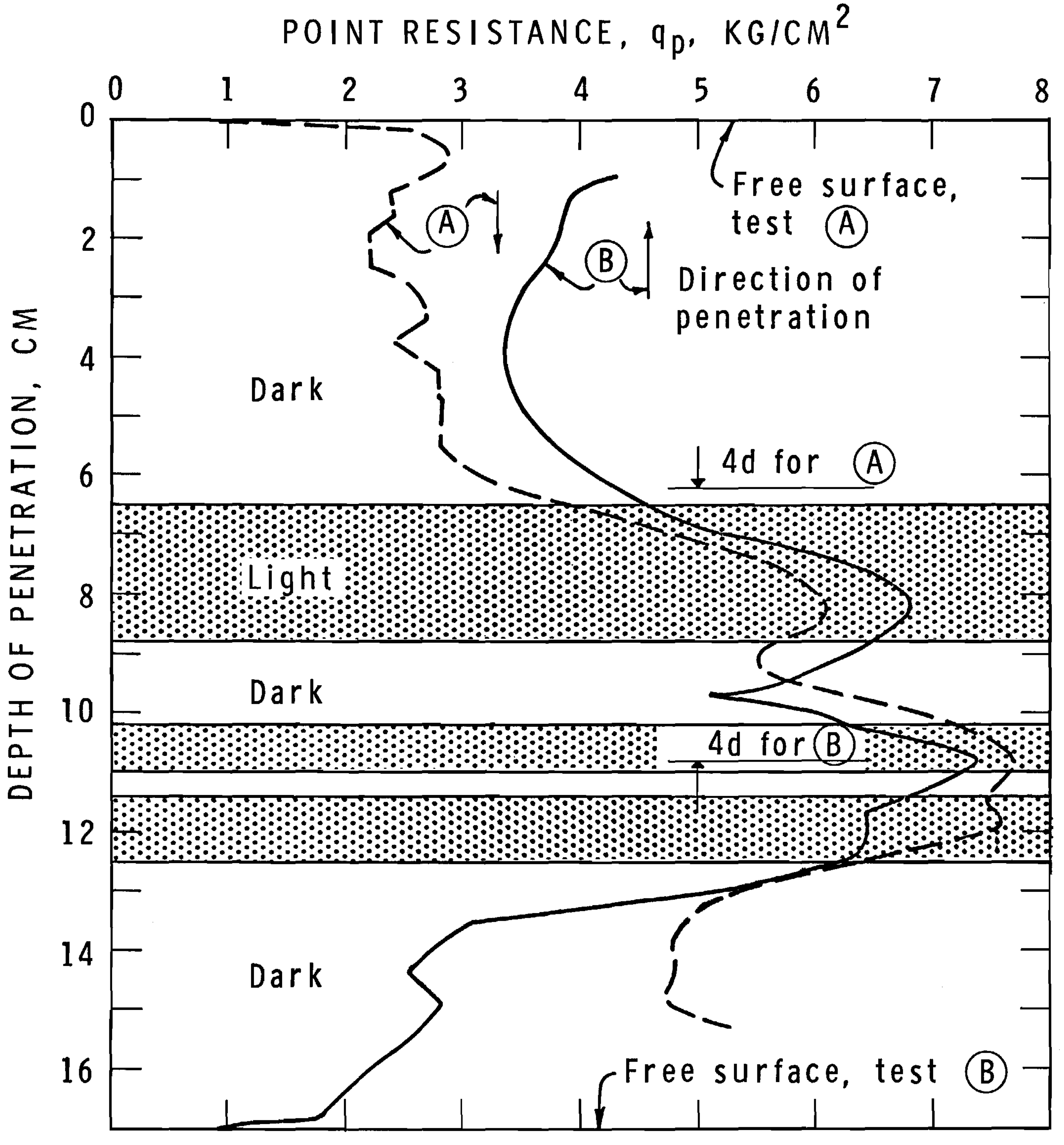

FIGURE 12

PENETRATION TESTS ON VARVED CLAY FROM STEEP ROCK LAKE

8Q 4123-11

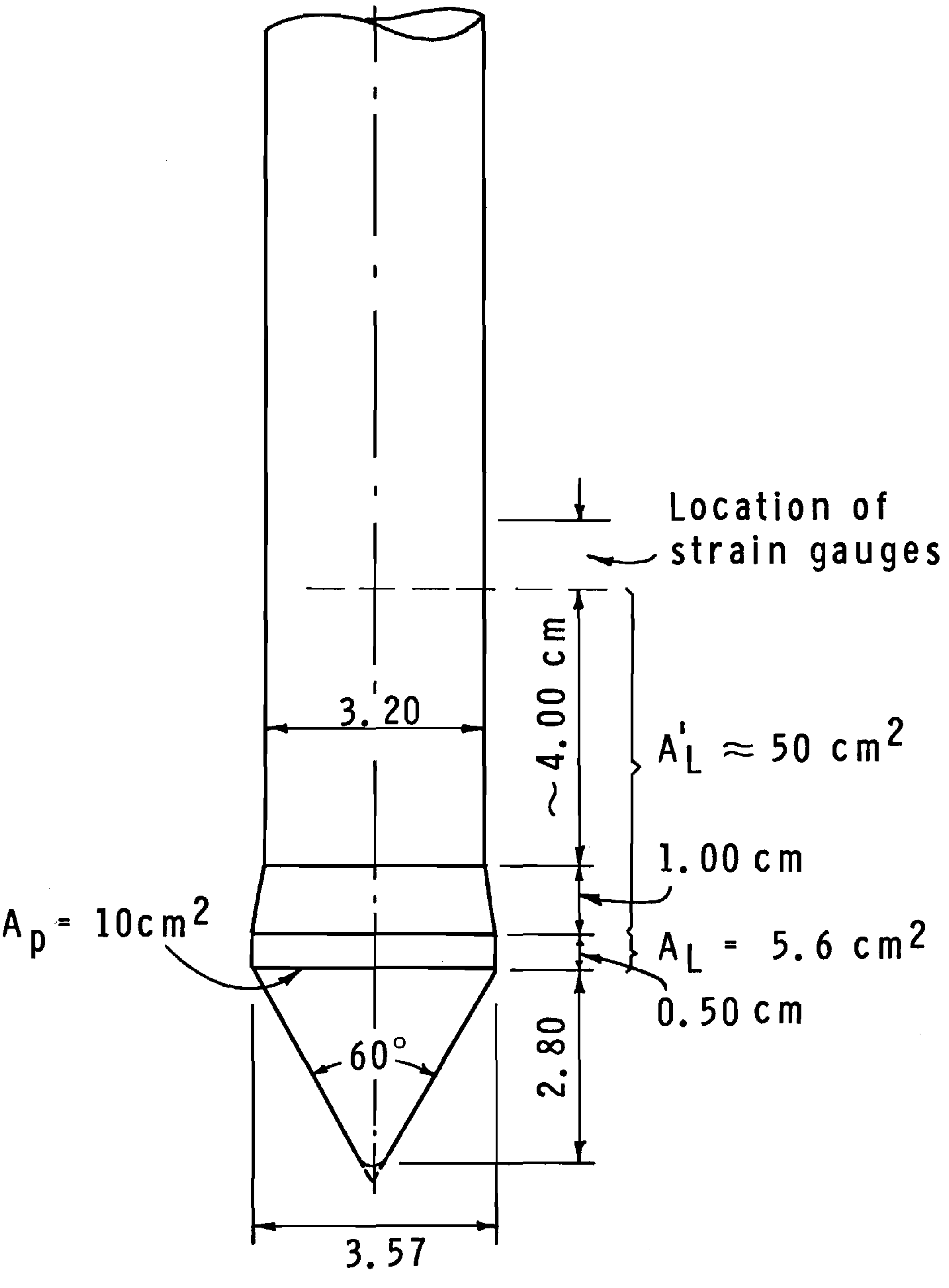

FIGURE 13

THE POINT OF "BORRO" PENETROMETER

BR 4123-12

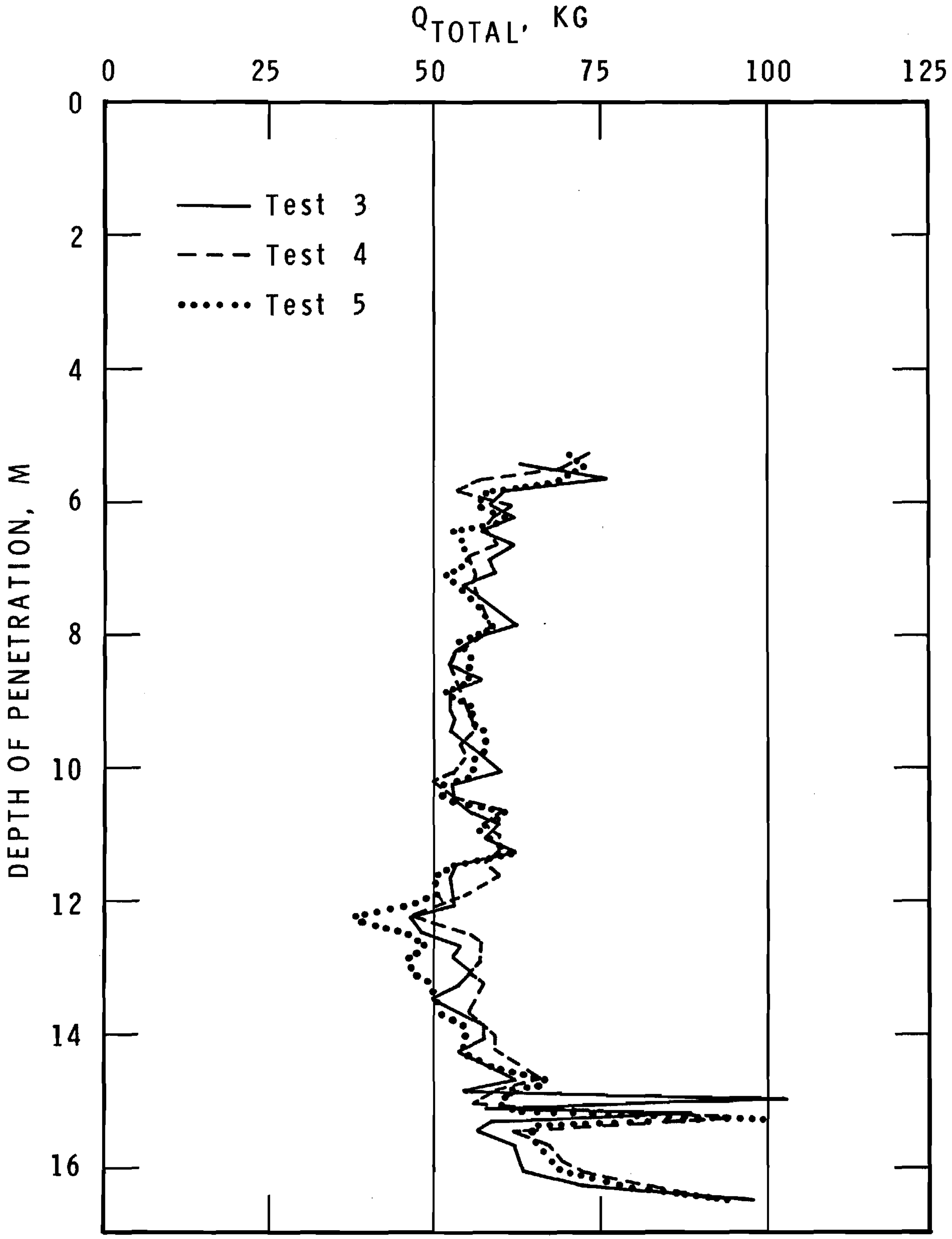

FIGURE 14

TOTAL POINT RESISTANCE, Q_{TOT}, RECORDED IN THREE FIELD PENETRATION TESTS AT NRC-MRL SITE

BQ 4123-13

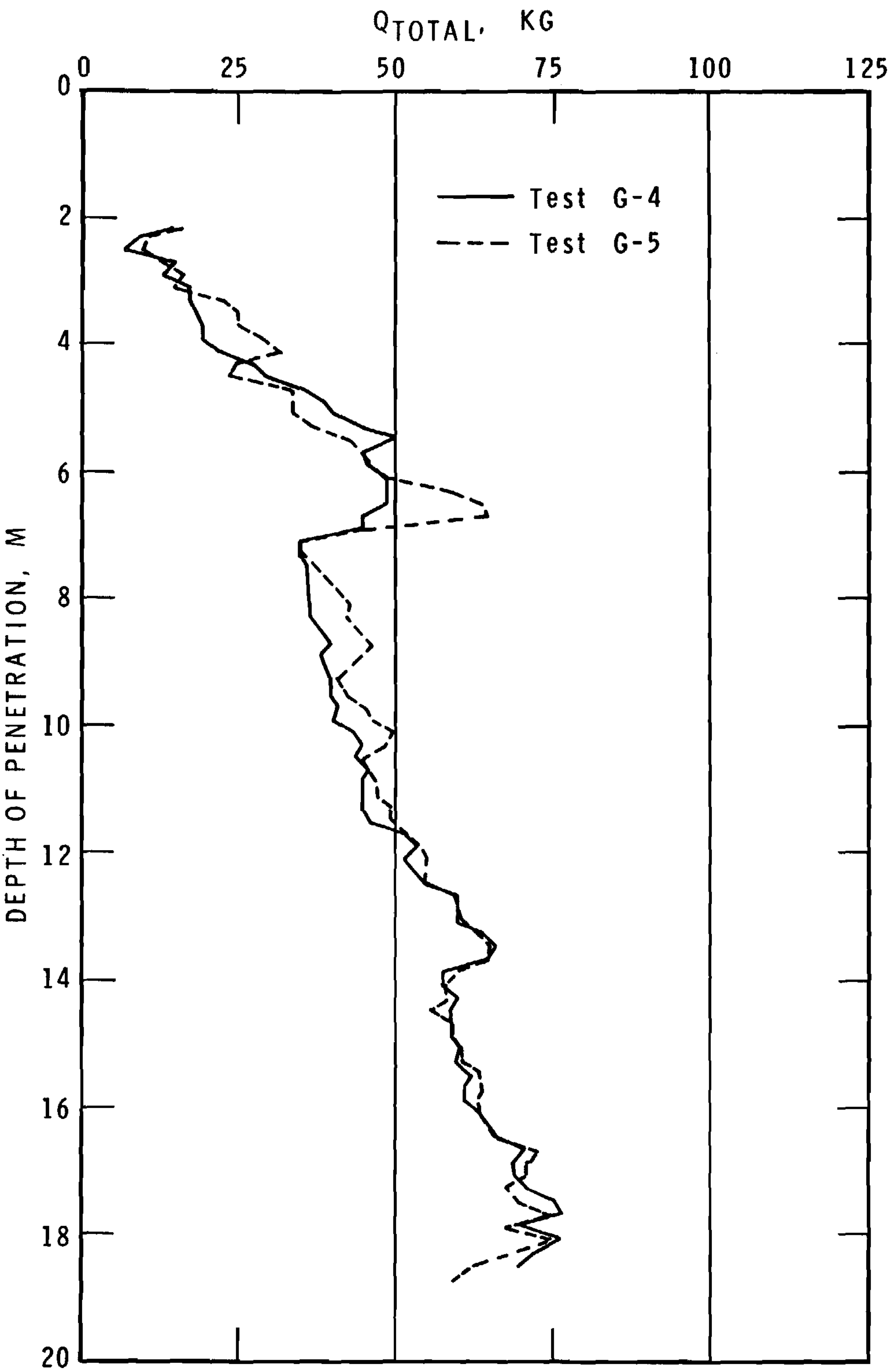

FIGURE 15

TOTAL POINT RESISTANCE, Q_{TOT}, RECORDED IN TWO FIELD PENETRATION TESTS AT GLOUCESTER SITE

8R1123-14

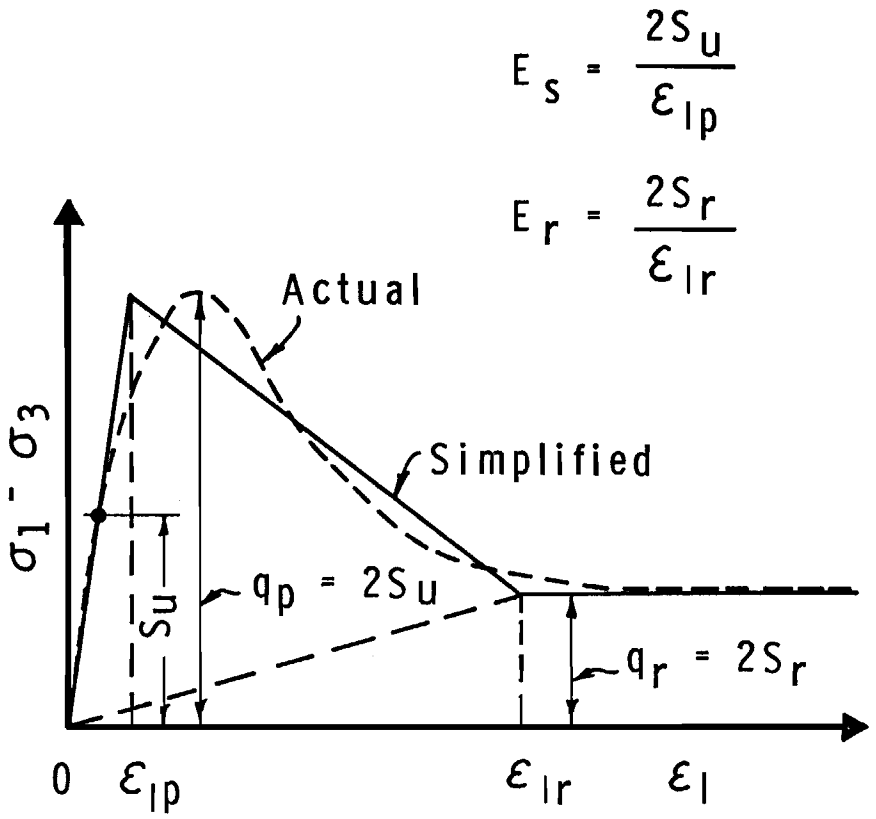

FIGURE 16

SIMPLIFIED STRESS-STRAIN BEHAVIOUR OF A SENSITIVE CLAY IN UNDRAINED COMPRESSION TEST ASSUMED IN N_c CALCULATION.

BQ4123-15

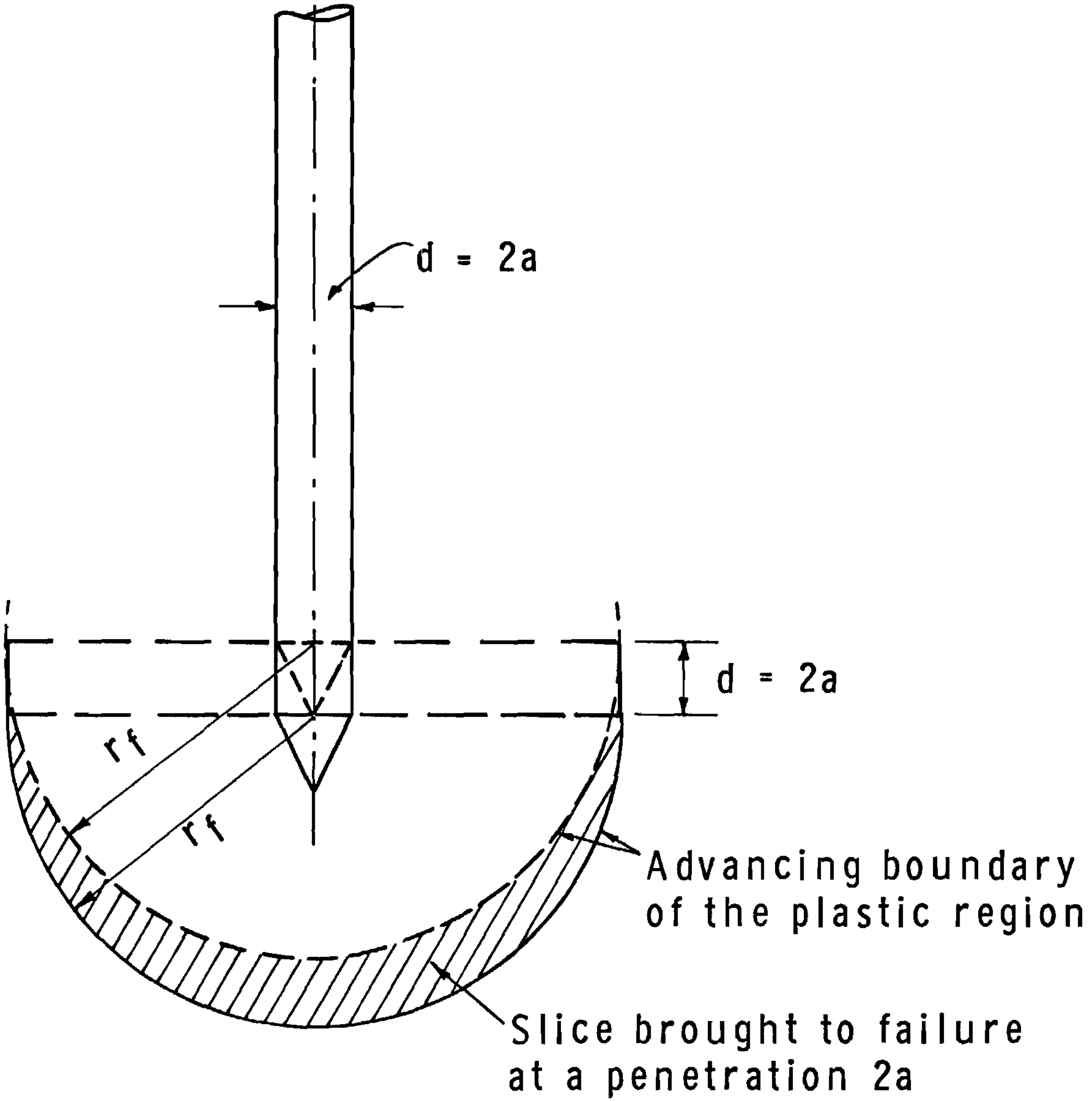

FIGURE 17

SCHEME FOR THE EVALUATION OF STRAIN RATE EFFECT

BR 1123 -16

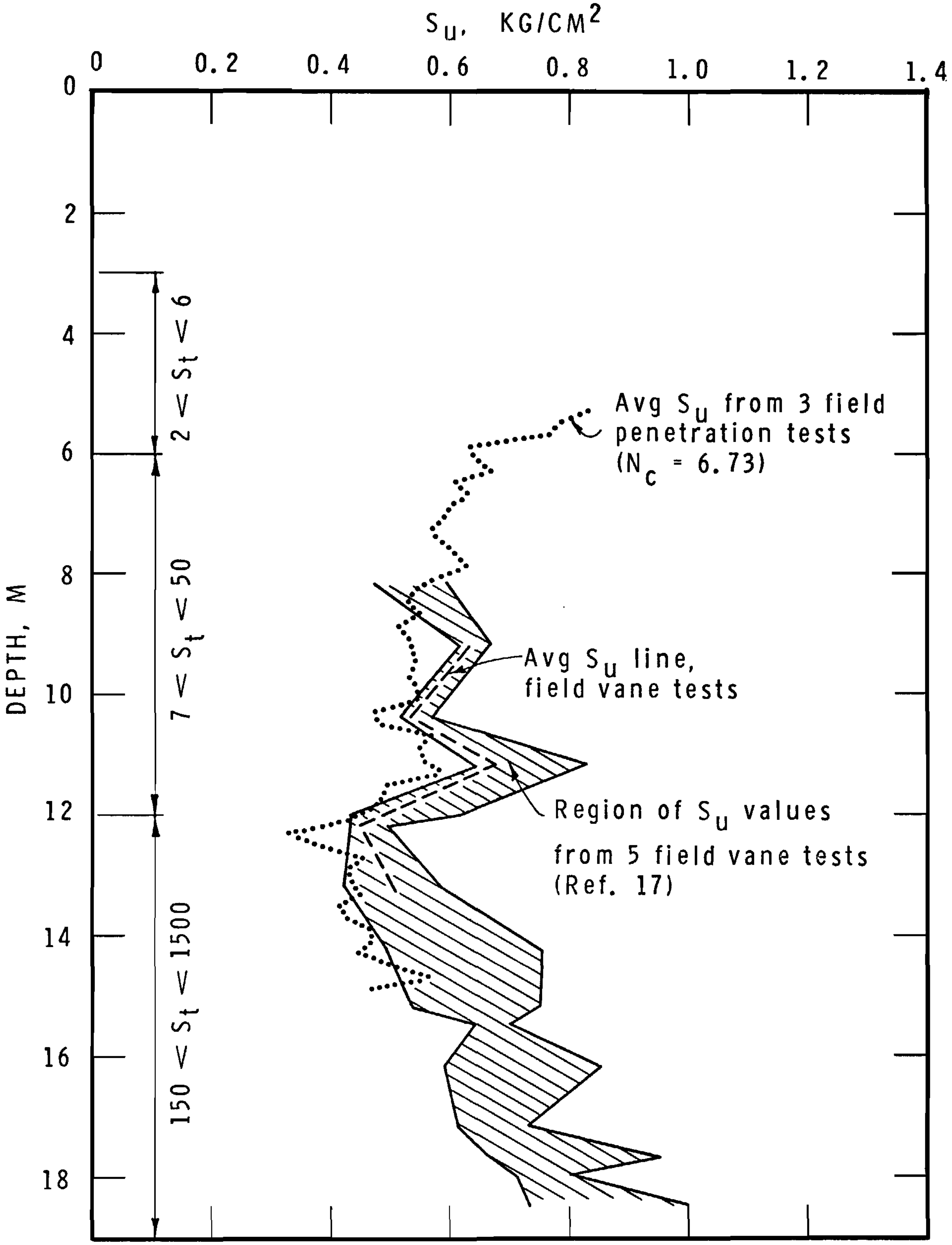

FIGURE 18

COMPARISON OF S_u VALUES FROM FIELD VANE AND PENETROMETER TESTS AT NRC-MRL SITE

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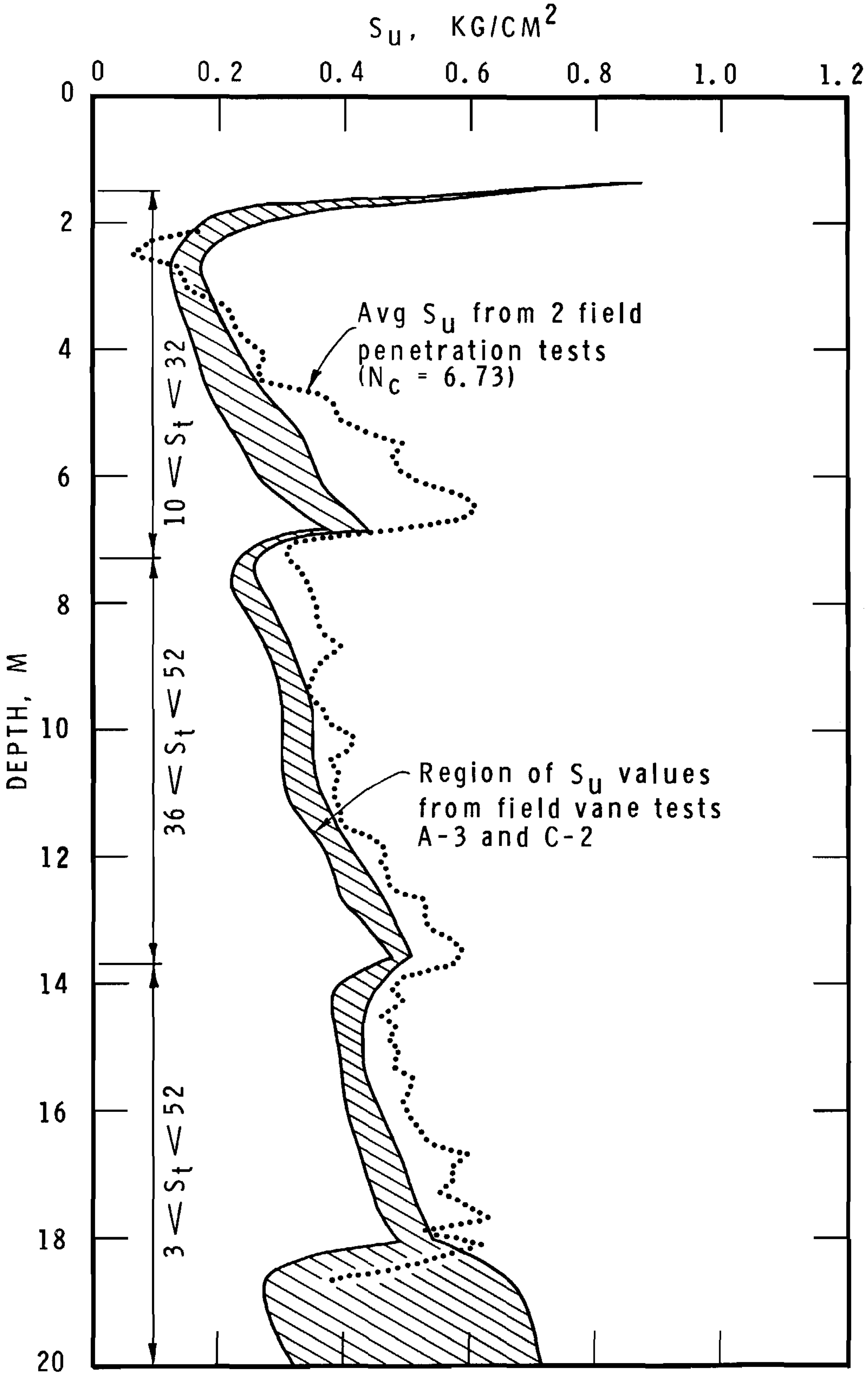

FIGURE 19

COMPARISON OF S_u VALUES FROM FIELD VANE AND PENETROMETER TESTS AT GLOUCESTER SITE

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APPENDIX A

LARGE STRAIN COMPRESSION TESTS

As described earlier in this report and in Reference 12, it is necessary to know the complete behaviour of clay in undrained compression up to large shear strains of the order of 100 per cent in order to determine a theoretical value of the bearing capacity factor N_c.

As such large strains are difficult to achieve in conventional triaxial equipment, several attempts have been made by the author to obtain this necessary information by specially devised tests. One such attempt, involving a compression test combined with a laboratory vane test, is described in Reference 24. Tests described in this present study represent another attempt to obtain the same information.

The main purpose of these tests was to find a method of compressing a clay sample under large strains, with simultaneous measurement of compression resistance not possible in the method described in Reference 24. The tests had to satisfy the following two requirements:

1. the attainment of large compression strains without formation of distinct failure planes, and

2. determination of the yield stress at any moment of the test.

The first requirement can normally be satisfied if a smaller than ordinary aspect ratio $\frac{h}{d}$ is used $^{A-1}$. There is no guarantee, however, that this is sufficient for brittle clays.

In order to satisfy the second requirement the test should be made in such a way that practically no end restraint is present at any time during the test. Attempts to minimize the end restraint by using a combination of membranes and grease between the sample and the platens have been successful in the conventional range of strains $^{A-1,\ A-2}$. It is, however, doubtful whether the same method would be satisfactory for axial strains over 20 per cent.

As it was intended that axial strains of much more than 20 per cent should be allowed, it could not be certain that the end restraint would be negligible throughout the test. It was decided, therefore, to measure the contact pressure distribution at one end of the sample, and to determine by calculation the value of the true yield stress that would act if no end restraint were present.

This was achieved by compressing the specimen between two parallel overlapping platens coated with teflon sheets and greased with silicone grease, and by measuring independently the pressure at the centre of the upper platen by a pressure transducer and the total compression force by a force transducer. The experimental arrangement used in these tests is shown in Figures A-1 and A-2.

From the two independent measurements, which were recorded on a chart, the value of the yield stress at any moment of the test was determined theoretically, based on the following assumptions:

1. the compressed sample has a cylindrical shape and retains this shape at any strain,
2. the only lateral restraint is given by the friction and adhesion between the sample and the end platens,
3. the stress due to the end restraint is distributed uniformly throughout total thickness of the sample,
4. the sample is in a state of plastic yielding.

The differential equation of equilibrium for an axially symmetric state of stress with a radially acting body force, R,is

$$\frac{\partial \sigma r}{\partial_{r}} + \frac{\sigma r - \sigma_{o}}{r} + R, = 0 \qquad (A\text{-}1)$$

where σr and $\sigma\theta$ are radial and circumferential principal stresses, respectively, and r is any radius.

In determining the value of the radial restraint force R, it can be assumed that either there is a constant coefficient of friction between the sample and the platens, or there is an adhesion of constant value. As is shown in metals $^{A-3}$, neither of the two assumptions is found to be fully satisfied in actual tests. In clays, however, the second assumption appears more feasible.

If, then, it is assumed that there is a constant unit adhesion, S_a, acting radially at the sample at both end platens, it can be shown that in Equation (A-1)

$$R = \frac{2\,S_a}{h} \tag{A-2}$$

where h is the height of the sample.

As the equilibrium at r = 0 requires that $\sigma r = \sigma_o$, Equation (A-1) reduces to

$$\frac{d\sigma r}{dr} = -\frac{2\,S_a}{h} \tag{A-3}$$

Integrating yields

$$\sigma r = -\frac{2\,S_a}{h}\,r + c \tag{A-4}$$

On the other hand, if the clay is yielding, the difference between the major principal stress, σ_1, which is longitudinal in this case, and the minor principal stress, $\sigma_3 = \sigma r$, should be constant and equal to a yield stress σ_o

$$\begin{aligned} \sigma_1 - \sigma r &= \sigma_o \\ \sigma r &= \sigma_1 - \sigma_o \end{aligned} \tag{A-5}$$

Equation (A-4) becomes then

$$\sigma_1 - \sigma_o = \frac{2\,S_a}{h} \cdot r + c \tag{A-6}$$

Taking into account the boundary condition that at $r = r_o$, $\sigma_1 = \sigma_o$ (no end restraint at the rim), then

$$\sigma_1 = \sigma_o + 2\,S_a\,\frac{r_o - r}{h} \tag{A-7}$$

Figure A-3 shows the distribution of the contact stress σ_1, according to Equation (A-7).

In actual tests, two average stresses have been determined: one, σ_p, acting on the surface of the pressure transducer with the radius a, and another, σ_f, acting on the total surface of the sample of radius, r_o, as obtained from the force transducer recording (Figure A-3).

Calculating the average pressures on the two surfaces by using Equation (A-7), the following is obtained:

$$\sigma_p = \sigma_o + 2 S_a \left(\frac{r_o}{h} - \frac{2}{3} \frac{a}{h} \right) \qquad \text{(A-8)}$$

$$\sigma_f = \sigma_o + \frac{2}{3} S_a \frac{r_o}{h} \qquad \text{(A-9)}$$

From the two equations, the value of S_a can be eliminated, and σ_o is obtained as follows:

$$\sigma_o = \sigma_f \left[1 - \frac{\frac{\sigma_p}{\sigma_f} - 1}{2 \left(1 - \frac{a}{r_o} \right)} \right] \qquad \text{(A-10)}$$

It should be noted that σ_f and r_o represent current values that are obtained following the usual correction for the variation in the size of the sample under the assumption of a constant volume throughout the test.

Owing to the lack of time, only a very limited number of tests have been carried out with this method. All tests were made with samples of DBR/NRC clay taken by a 5-in. piston sampler at a depth of about 30 ft. Figure A-4 shows the result of such a test made on a sample with an aspect ratio $\frac{h_o}{d_o}$ of about 0.50 ($2 r_o = 7.11$ cm, $h_o = 3.58$ cm) in which the sample was compressed between dry teflon platens. It will be seen that, despite a buildup of lateral end restraint, the calculated yield stress σ_o showed the expected drop of strength after the peak.

Figure A-5 shows the results obtained by the same apparatus when compressing samples of clay with the usual aspect ratio of about 1.5. It is interesting that a more consistent stress-strain behaviour is obtained if σ_o is calculated as described above. Both tests, made on samples taken from the same level of a large 5-in. sample, have shown different stress-strain behaviours in terms of σ_f but very similar ones in terms of σ_o. It is concluded, therefore, that the described apparatus shows much promise as a tool for performing unconfined compression tests on clay samples. Further study will be needed, however, especially with various types of clays and methods of eliminating the end restraint, to obtain with this apparatus reliable results concerning the post-peak strength of undisturbed clays up to shear strains of the order of 100 per cent.

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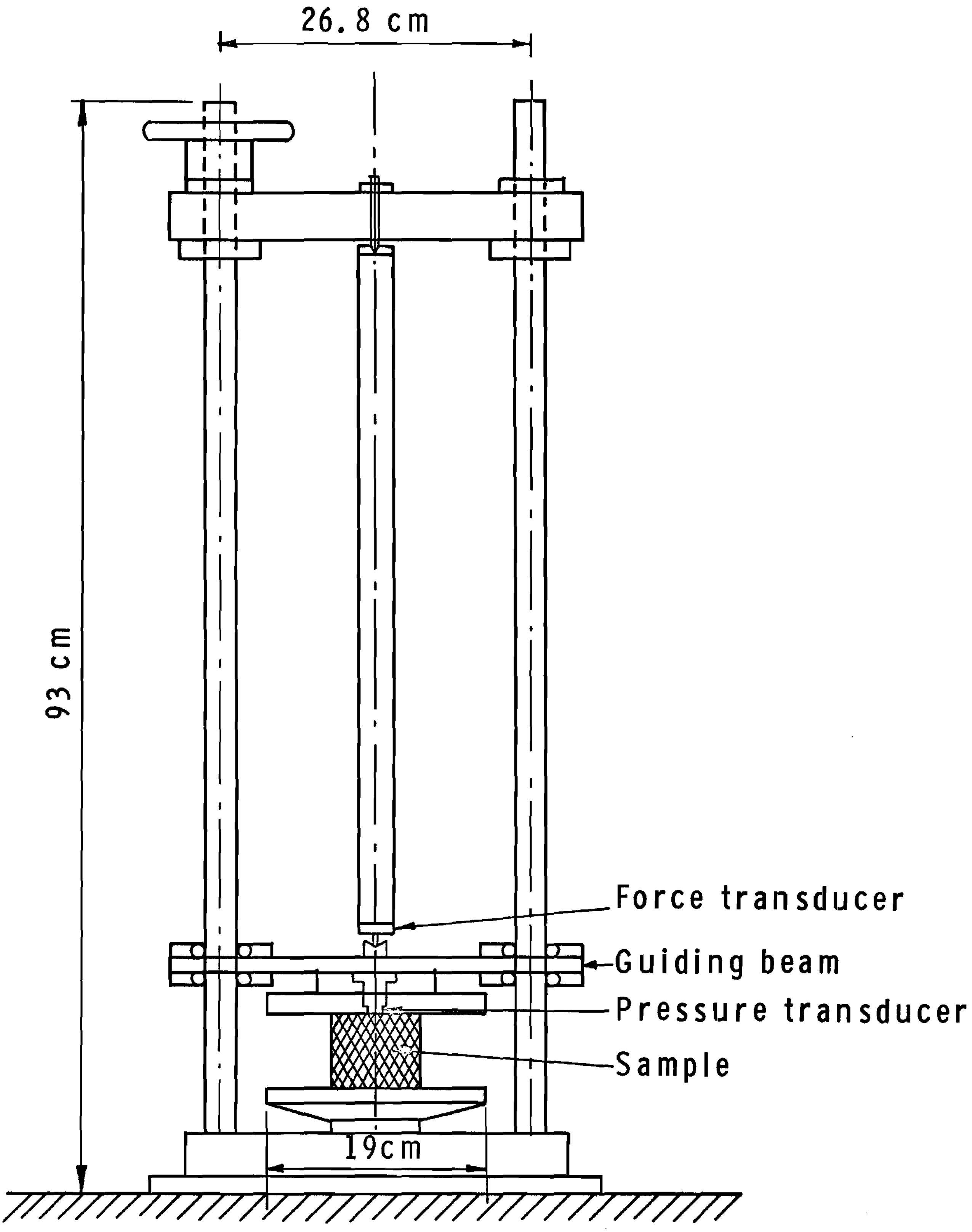

FIGURE A-1

EXPERIMENTAL ARRANGEMENT FOR LARGE STRAIN COMPRESSION TESTS

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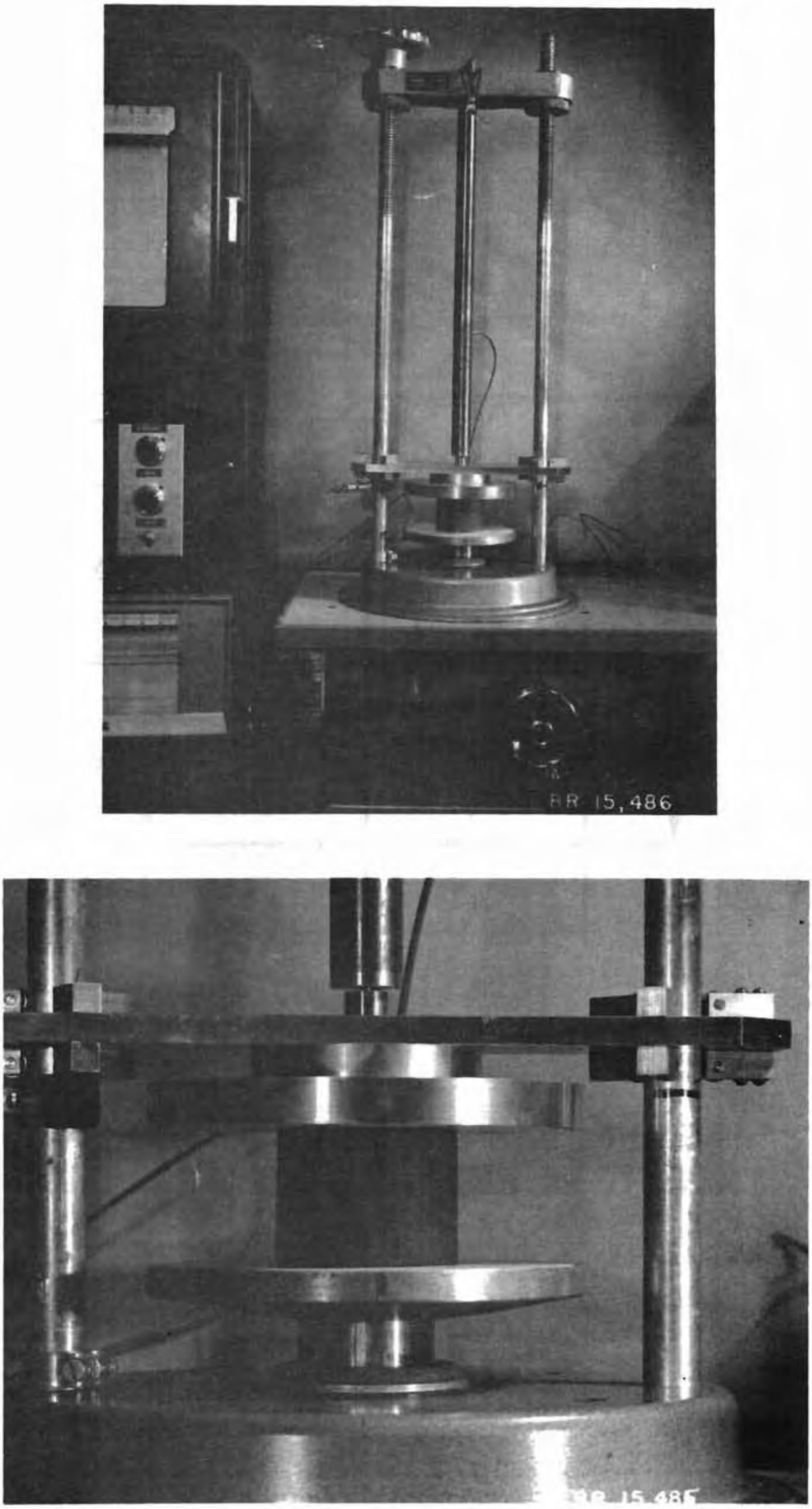

Figure A-2: Two views on the large strain compression apparatus.

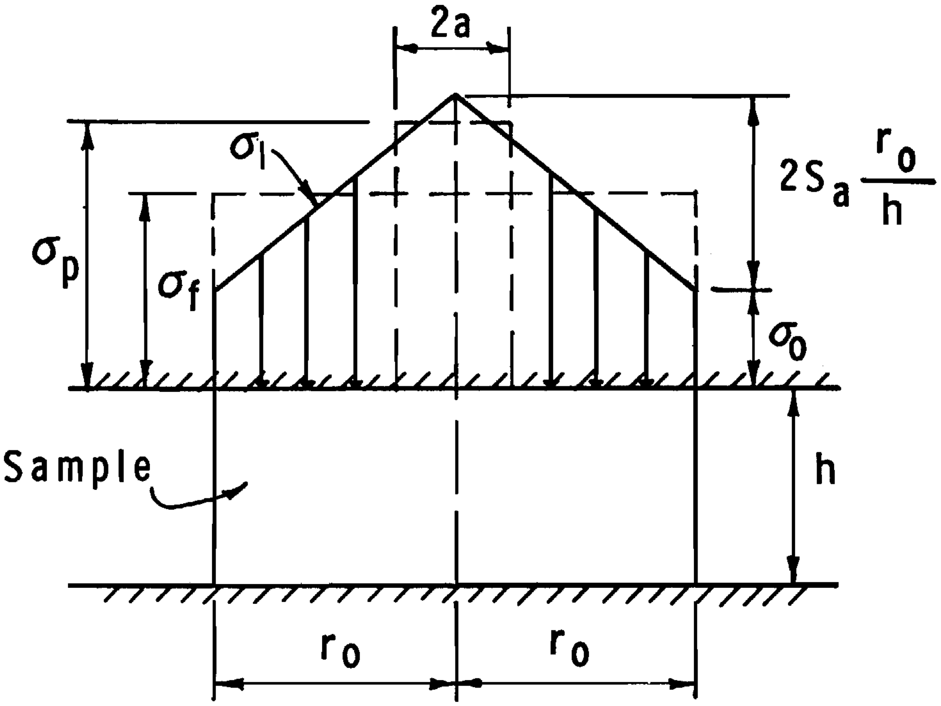

FIGURE A-3

DIAGRAM OF CONTACT PRESSURE IN COMPRESSION WITH END RESTRAINT

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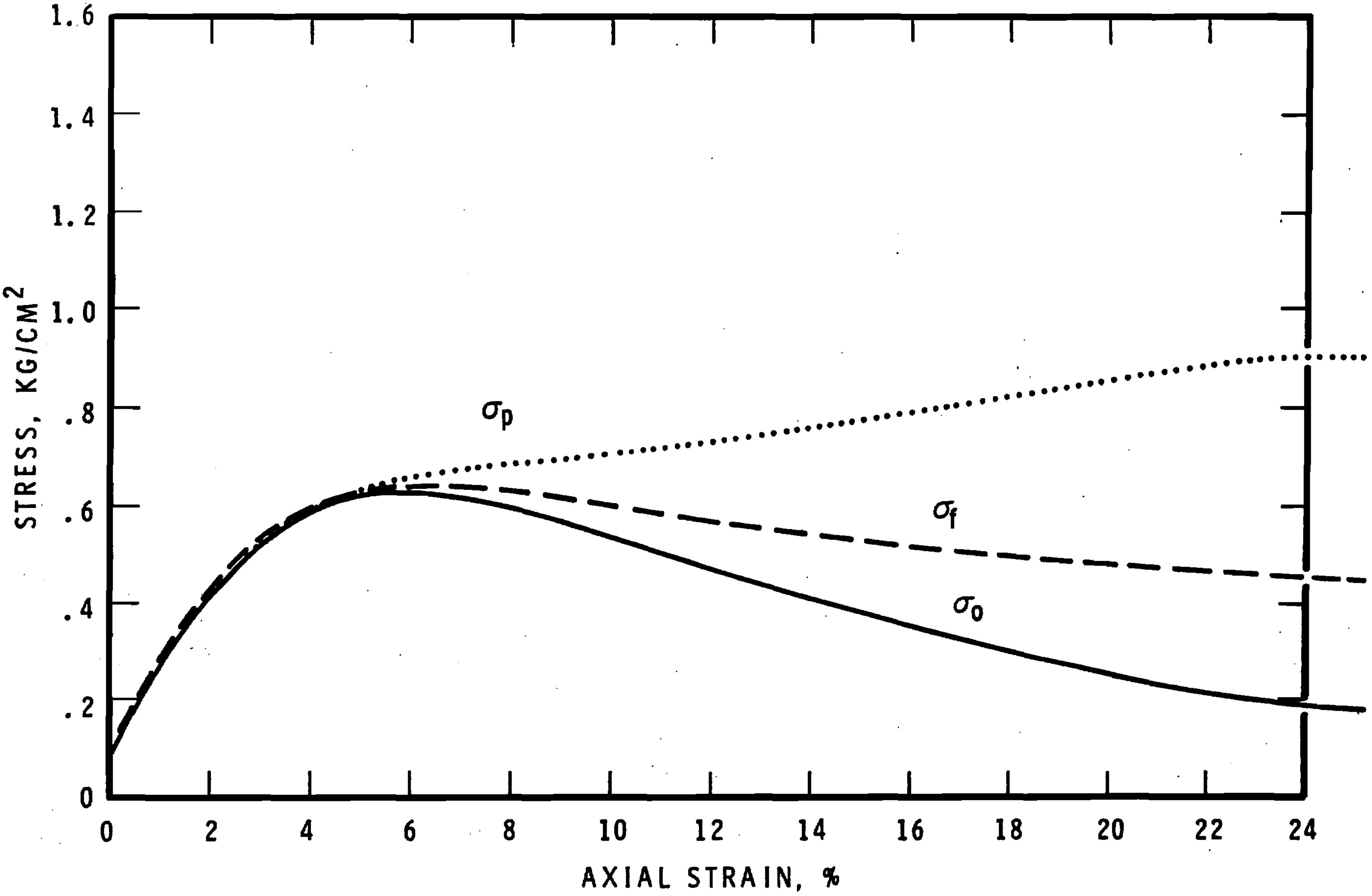

FIGURE A-4

LARGE STRAIN COMPRESSION TEST ON A SAMPLE OF NRC-MRL CLAY (DEPTH $\approx$ 30') WITH $\frac{h_o}{d_o} \approx 0.5$ AND DRY TEFLON PLATENS

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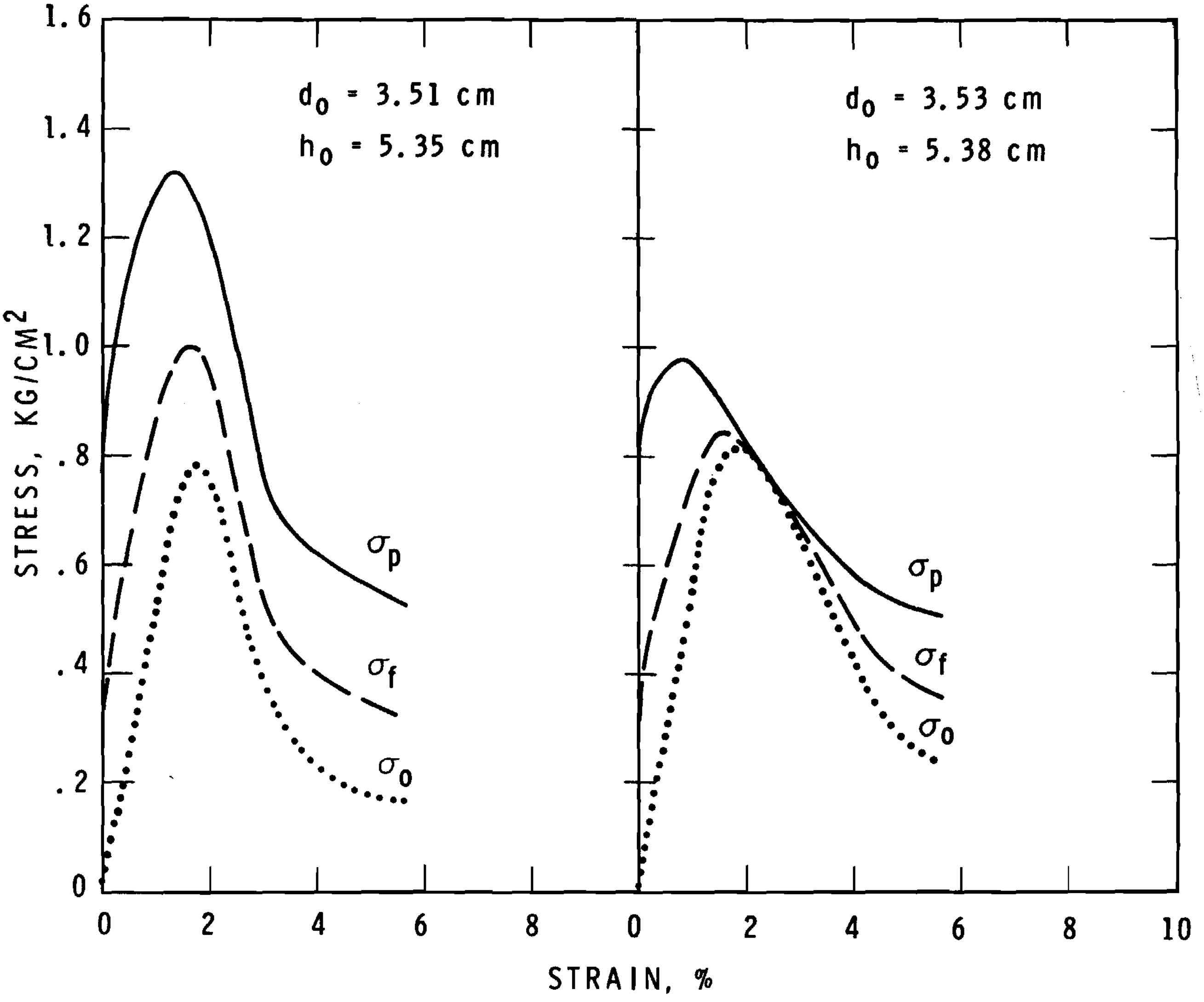

FIGURE A-5

COMPRESSION TESTS ON TWO IDENTICAL SAMPLES OF NRC-MRL CLAY (DEPTH $\approx$ 30') WITH $h_0/d_0 \approx 1.50$ AND WITH TEFLON PLATENS AND SILICONE GREASE

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