

IN-SITU TESTING IN SATURATED SILT, (DRAINED OR UNDRAINED?)

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RESUME

Un pénétromètre statique électrique à canaux multiples a été utilisé pour la conduite de divers essais in-situ sur un dépôt profond de limon argileux normalement consolidé recouvert d'une couche stratifiée de sable et de remblai de densité moyenne à forte d'environ 13 mètres d'épaisseur. Le dépôt de limon argileux s'étend à une profondeur supérieure à 80 mètres.

Les mesures électriques piézométriques, de résistance en pointe et de frottement latéral du pénétromètre ont été obtenues pour le dépôt de limon. Les facteurs affectant la mesure et l'interprétation de l'effort sous la pointe conique, de la contrainte sur le manteau de frottement latéral et des pressions interstitielles sont étudiés et discutés. La détermination des pressions interstitielles était nécessaire à l'évaluation des résultats des essais in-situ. L'effet du taux de pénétration est discuté et le concept d'écrasement effectif est introduit pour tenter d'interpréter l'effort à la pointe dans les sols non-drainés ou partiellement drainés. Les valeurs in-situ des paramètres de consolidation obtenus de l'observation des pressions interstitielles sont comparées aux résultats des essais de laboratoire traditionnels sur des échantillons intacts.

Les avantages de la mesure électrique continue au pénétromètre de la stratigraphie du dépôt de sol étudié sont démontrés par une comparaison directe avec le même profil pédologique sur un site voisin.

ABSTRACT

A multichannel electric cone penetrometer is used to perform a variety of in-situ tests in a thick deposit of uniform normally consolidated clayey silt which is overlain by about 13 meters of medium to dense stratified sands and fill. The clayey silt extends to a depth in excess of 80 meters.

Electric piezometer-friction-cone logging has been carried out in the silt and factors affecting the tip bearing, friction sleeve stress and pore water pressures and their interpretation are studied and discussed. Pore pressure measurements were essential to evaluate the in-situ test results. The effect of rate of penetration is discussed and the concept of effective bearing introduced as an attempt to interpret cone bearing in undrained or partially drained soil. Field values of consolidation characteristics from pore pressure decay are compared with traditional laboratory consolidation test results on undisturbed samples.

The advantages of continuous electric cone logging to evaluate soil stratigraphy are demonstrated by direct comparison with the same silt formation at a neighboring site.

## INTRODUCTION

The continued growth of many large Canadian cities has led to increased construction of larger more complex structures on sites with difficult ground conditions and more stringent performance criteria. In Vancouver large structures such as major highway bridges, cement processing plants, storage tanks and highrise residential and commercial complexes are now being constructed on the deltaic deposits of the Fraser River Delta located immediately to the south of Vancouver. Essentially the delta region is covered by a thin veneer of clays, silts and peats up to about 6m in thickness, which is underlain by tidal-flat deposits of sands and silts to a maximum thickness of 30 m, which in turn is underlain by thick soft marine delta deposits up to 300 m in thickness. In situations where complex structures are founded on soft, stratified soils there is relatively little evaluated experience and the uncertainties implicit in simplified and highly empirical design methods have become extremely significant. The use of more sophisticated and reliable design procedures, and their continued development, has therefore become increasingly important. This, in turn, necessitates improved capabilities for the logging, measurement and selection of soil parameters, usually by in-situ techniques. The requirement for better logging methods and in-situ tests has created increased interest in recent in-situ testing techniques. One such in-situ test is the quasi-static cone (de Ruiter, 1972). The static electric cone offers a fast, economic and repeatable in-situ test especially in loose and soft sediments that is becoming increasingly popular in North America. As a logging tool this technique is unequalled with respect to delineation of stratigraphy and the continuous rapid measurement of parameters like bearing (tip resistance) and friction. However, in mixed soil conditions, as found in deltaic deposits, it is not always clear if the parameters measured relate to drained or undrained behaviour. For clean sands, when penetrating at the standard rate for cone testing of 2 cm/sec, little or no excess pore pressures are normally generated and the measured parameters can be expected to relate to drained behaviour. However, for penetration into silty sands and silts it is less clear if the behaviour is drained or undrained. An understanding of the data in terms of drained or undrained behaviour is important for subsequent design, especially in pile design where the pile is often loaded ultimately under drained conditions.

Most commercially available electric cones measure bearing and friction and more recently bearing and pore pressure. Sometimes a slope sensor is available. However, it is often most desirable to continuously measure bearing, friction and pore pressure. It is also important to monitor the verticality of the sounding.

The 5-channel cone shown in Fig. 1 has been under development at the Department of Civil Engineering at the University of British Columbia for more than a year. The primary functions of measuring bearing, friction and pore pressure are well established, the temperature is a recent addition, and the slope sensor is still under development. The dimensions conform to the European standard and the tentative ASTM standard for electric cones. Full details of the cone and associated equipment are given in a paper by Campanella and Robertson (1981).

## RESEARCH SITE

A research site for in-situ testing is located on an abandoned farm (McDonald's Farm) near the Vancouver International Airport. The site is located on the north side of Sea Island on MOT Canada land near the Municipality of Richmond. Sea Island is located between the North Arm and Middle Arm of the Fraser River on the north side of the main Fraser River Delta. The site is approximately level with the natural ground at elevation +1.6 m. Sea Island is contained by a system of dykes to protect against flooding from the Fraser River.

A summary of the soil profile based on sampling, laboratory testing and cone penetration is shown in Fig. 2. QC represents cone bearing, FC represents friction stress on the cone sleeve, U represents total pore water pressure and RF represents friction ratio.

The upper 2 m of soil consists of soft, compressible clays and silts. The sand from 2 m to 13 m was deposited in a turbulent environment and is therefore relatively non-uniform in density. In general however, the sand increases in density with depth. The sand has a medium to coarse grain size with thin layers of medium to fine sand. A thin transition layer of fine sand with some silt exists from 13 m to 15 m.

The sand is underlain by a thick deposit of soft, normally consolidated clayey silt. The clayey silt is estimated to extend to a depth of more than 300 m. (Blunden, 1973)

Groundwater is approximately 1 m below existing ground surface and groundwater pressures are approximately hydrostatic for the depth shown in Fig. 2.

**FACTORS AFFECTING MEASURED PARAMETERS FROM ELECTRIC CONE**

Before analyzing any electric friction cone data it is important to realize and account for the potential errors that each element of data may contain. During development of our equipment several significant aspects concerning the data collection and interpretation have come to our attention. Some of these points are summarized here.

Bearing and Friction

The tolerance in machining the standard Fugro type friction cone is such that the difference in diameter between the tip and the sleeve can be up to 0.010 inches (0.25mm). This combined with wear during usage often results in significant differences in diameter between the tip and sleeve. It has been found that differences in diameters, especially when the tip is larger than the sleeve, can result in significant variations in measured friction values. This variation can be reduced by careful machining during construction and regular tolerance checks during the life of the cone. The O.D. of the cone should be identical or less than O.D. of friction sleeve (+ 0.00 mm to + 0.25 mm).

The load cells within the cone are often temperature dependent and are almost always calibrated at room or air temperature. However, soil and groundwater are often considerably cooler than the calibration temperature and a shift in the zero can occur for both load cells during penetration. This usually has little consequence to the tip measurement which is usually a large value. However, the zero shift can have a significant effect on the friction measurement, particularly for soft soils. Temperature affects should therefore be accounted for when penetrating in soft soils. A temperature sensing element in the cone such as the thermister shown in Fig. 1 can provide the basis for calibrated zero shift corrections due to temperature and it is useful in northern environments.

It has been observed by us and others that when the cone is exposed to an all round water pressure there is also a shift in the zeros for both the friction and tip measurements. The shift in zeros is due to the unequal end areas of the standard cone design. A cone is presently under

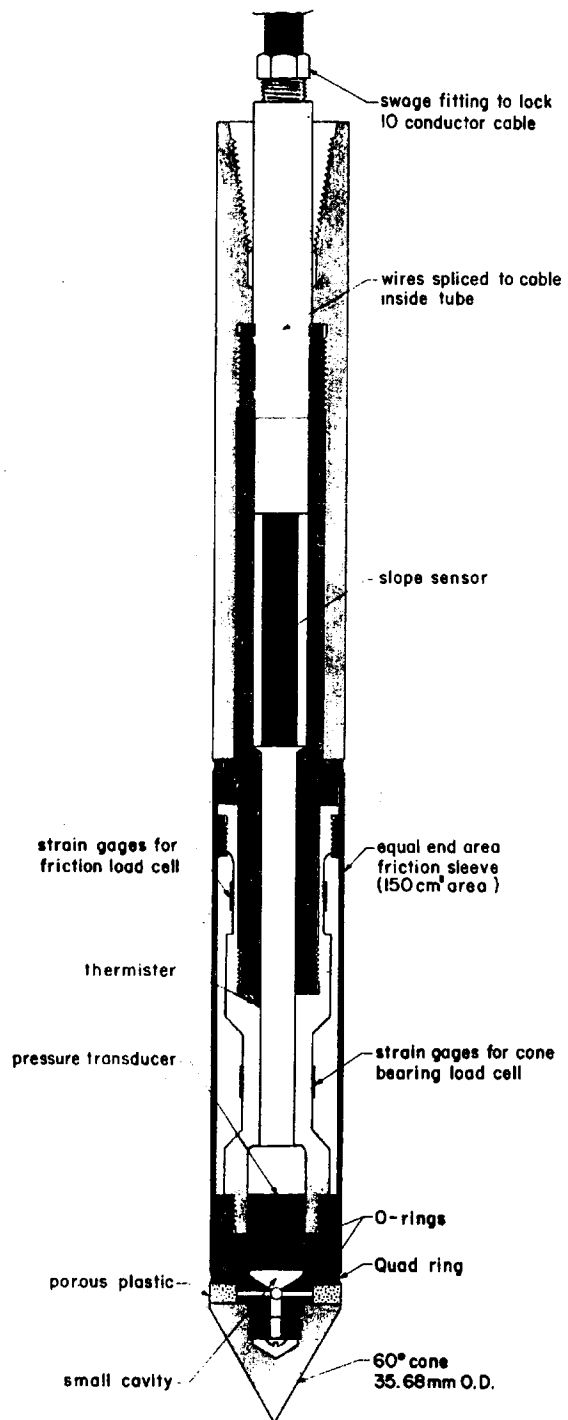


Fig. 1. 5-Channel Cone Penetrometer.

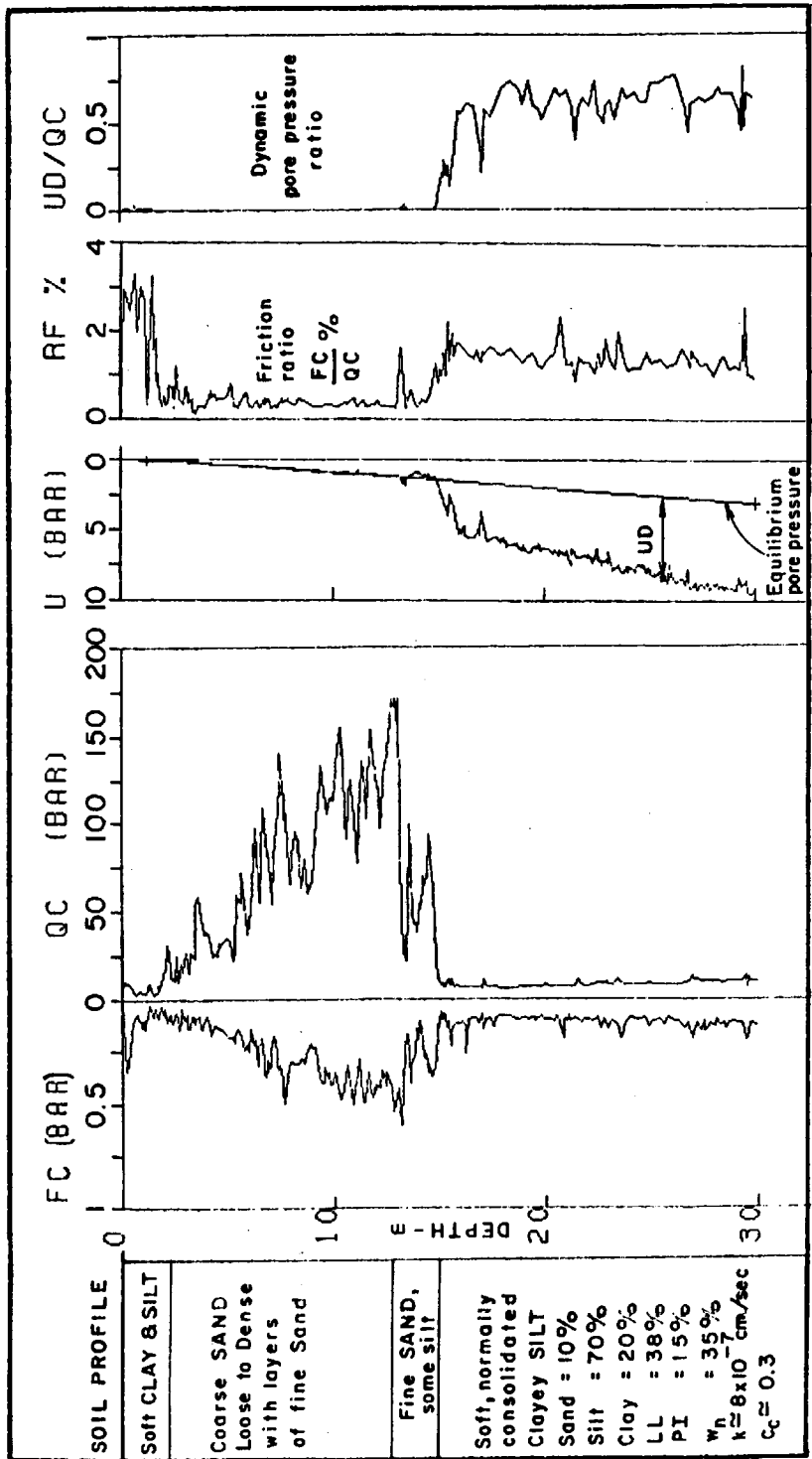


Fig. 2. Soil Profile for Research Site at McDonald's Farm, Sea Island, B.C.

development that should overcome this problem and this design is shown in Fig. 1. High water pressures exist in both deep profiles below the water table and in low permeability saturated soils where very large positive dynamic pore pressures are generated. Again this shift in the zeros is less critical for the tip measurement but can be significant for the sleeve friction. Fig. 3 illustrates a friction cone profile through a clayey silt where the initial evaluation indicated a zero, or in places, even negative friction values. However, with careful attention applied to the zero shifts, due to both temperature and water pressure affects, a small positive friction value was obtained. These factors affecting the measured friction value can become important when using the friction for detailed soil classification or evaluation of the undrained shear strength for design of piles (Nottingham 1975).

It is usually accepted that when measuring friction with the Begemann mechanical cone, these values are always higher than those measured with the electric cone, especially in soft soils. Our experience has shown that when the friction force on the mechanical cone is corrected for weight of inner rods and for end bearing on the sleeve (assume full closure of hole with bearing same as tip), and the electric cone friction is corrected for temperature and measured total pore pressure during penetration then the friction ratio by each device is comparable in soft and loose saturated soil.

#### Pore Pressures

The inclusion of the pore pressure element has greatly improved our understanding of the cone data. However, it is important to ensure that the pore pressure element is measuring the correct dynamic or static pressure. It is therefore essential that the element is completely saturated and maintains its saturation throughout the profile. We have found that saturation can best be achieved and maintained by using glycerin and designing the sensing cavity to be as small as practical and to avoid unnecessary corners that may entrap air. The porous element, in our case we use porous plastic, must be continually cleaned in an ultrasonic bath and kept saturated in glycerin. The glycerin has been found to work admirably even during deep profiles with a low water table. The effectiveness of this method was illustrated during a recent study at a large tailings dam in B.C. where the piezometer friction cone was pushed for over 40m through unsaturated fine sands before encountering the water table and measured

by the piezometer. Confirmation of the reading was obtained from a nearby standpipe piezometer installed during the previous drilling program.

Response to the dynamic pore pressure appears to be significantly affected by entrapped air within the sensing element. This is particularly true for soft low permeability soils such as normally consolidated clays. An illustration of the effect of an unsaturated piezometer cone is shown on Fig. 4. An earlier model piezometer cone that had a large sensing element cavity that could not satisfactorily be saturated showed that when pushing was stopped during penetration through a soft clay the measured pore pressure continued to rise for a short period followed by the expected decrease due to pore pressure dissipation. However, when using the more recently designed piezometer cone in the same deposit the continued increase in measured pore pressure was not observed following a stop in penetration. It was concluded that the continued increase in measured pore pressure observed in the earlier model was due to time effects due to water flow caused by some entrapped air within the element. It should also be noted that the dynamic pore pressure measured with the unsaturated piezometer is significantly less than the pore pressure measured by the saturated piezometer.

The importance of pore pressures in the interpretation of cone data has been discussed by others (Wissa et.al. 1975, Schmertmann 1974 and Senneset 1974) and shall not be repeated here except to caution that care is required to ensure correct pore pressure measurement.

#### EXAMPLES OF CONE INTERPRETATION

##### Pore pressures

The inclusion of pore pressure measurements during cone penetration considerably improves our understanding of the cone data. The pore pressure measurements may, one day, enable an effective stress appraisal to be made of the cone data. However, further research is required in this direction, and the potential for future improvements in interpretation look promising.

It has been recently suggested that the measured pore pressures during cone penetration could be used to indicate consolidation history of clays (Baligh et. al. 1980). The proposed method involves the use of the pore pressure ratio ( $u/q_c$ ). It appears the proposed pore pressure ratio uses total pore pressures measured

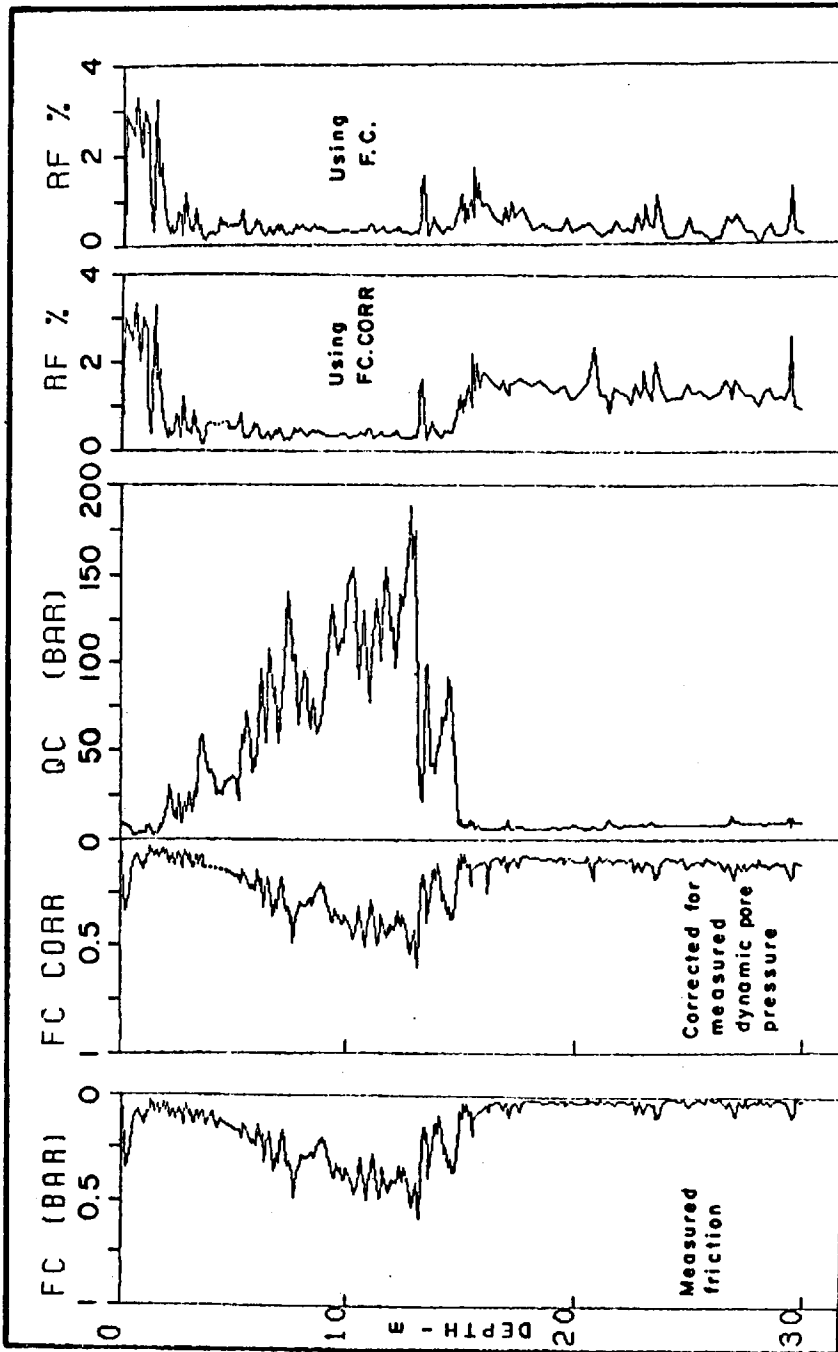


Fig. 3. Example of Friction Correction on Cone Interpretation (McDonald's Farm, Sea Island, B.C.).

BURNABY SITE - VERY SOFT SILTY CLAY

$q_c = 4 \text{ kPa}$ ,  $k = 10^{-7} \text{ cm/sec}$

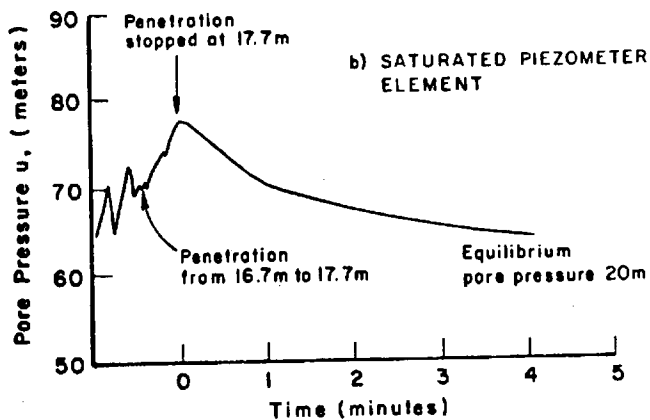
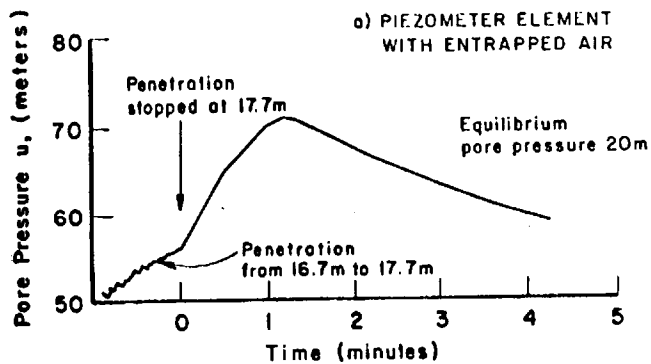


Fig. 4. Influence of Saturation on Pore Pressure Response of Piezometer Cone.

during penetration. However, it may be more appropriate to use dynamic pore pressures for the pore pressure ratio. The dynamic pore pressures are defined as the pore pressures above or below the static equilibrium pore pressures generated during penetration. Fig. 2 includes the measured pore pressures and the dynamic pore pressure ratio. It is interesting to note how well the pore pressure and pore pressure ratio define the boundary between the sand and the underlying clayey silt. This is one case where the inclusion of a pore pressure element in the cone can be of extreme value.

It appears that for normally consolidated soils the dynamic pore pressure generated is linear with depth similar to the cone resistance. The dynamic pore pressure ratio,  $(\Delta u/q_c)$  or  $UD/QC$  as shown in the computer graphics printout, also appears to be constant at approximately 0.7. This value agrees quite well with that predicted from the theory of the expansion of a spherical cavity (Vesic 1972). The total pore pressure ratio proposed by Baligh et al., 1980, will only be constant with depth for normally consolidated soils if the equilibrium water pressure is hydrostatic, i.e. linear with depth.

The use of dynamic pore pressures highlight the importance of evaluation of equilibrium static pore pressures. This can easily be achieved by one or more pore pressure dissipations during a stop in penetration. The pore pressure dissipation data can also be used to infer consolidation characteristics of the soil (Gillespie and Campanella, 1981).

The pore pressure element for our piezometer friction cone is located immediately behind the tip. This position has been found by us and others (Roy et. al. 1980) to record dynamic pore pressures that are very close to the maximum in soft soils.

It is well recognized that the maximum pore pressure developed during penetration in soft soils is near the cone tip. However, at standard penetration rates of 2 cm/sec the area behind the tip is in the previous location of the tip within several seconds. During this very short time period there has usually been very little time for dissipation of the maximum pore pressures.

The area behind the tip is also better protected for penetration through denser soil where damage can occur to porous elements located on the tip. The piezometer element located behind the tip appears to be a reasonable compromise for evaluation of both dynamic and dissipation pore pressures. However, it does appear that in stiffer soils this location may produce a more dilatant dynamic pore pressure response. Further research is required into these affects. The optimum position of the pore pressure element may depend on the results desired and the type of soil to be investigated.

Rate of penetration

The standard rate of penetration for a cone test is 2 cm/sec. Traditionally cone penetration in sands have been considered to be drained and penetration in clays undrained. However, for mixed soils such as silts and clayey silts it is less well

defined if the penetration is in a drained or undrained condition. Fig. 5 shows the results of piezometer cone data at the research site, (profile shown in Fig. 2) but for different penetration rates. The data is summarized for the results obtained as the cone passes the 20 m depth. The soil is a clayey silt with a permeability in the order of  $8 \times 10^{-7}$  cm/sec. The results show that the penetration is essentially undrained down to a penetration speed of about 0.2 cm/sec. As the penetration speed is progressively decreased below this speed the total pore pressure during penetration decreases and a corresponding increase is observed for the cone bearing and friction, corrected for zero shift. The increase is particularly noticeable for the friction. The increase is less noticeable for the bearing in part because the bearing also records the water pressure. Thus, as the water pressure decreases the bearing tends to decrease, but this is offset by the increase in effective stress in the soil which increases the bearing. To illustrate this behaviour the effective bearing is also shown on Fig. 5. The effective bearing is defined as the bearing (corrected for temperature and all round pressure effects) minus the total water pressure.

It is interesting to note that this effective bearing data shows how small an effective pressure (bearing) was required to penetrate the soft clayey silt under undrained conditions; the effective bearing was about 1/4 of the total bearing. These values are still extremely small when compared to the almost two orders of magnitude larger bearing values for the overlying dense sand which is being sheared under drained conditions. The data also illustrates the marked increase in the effective stresses around the tip as the rate of penetration decreases and the pore pressures drop by over 15 m of water pressure or about 1-1/2 bar (150 Kpa). The resulting change in effective stresses due to partially drained conditions around the tip produce an almost twofold increase in the effective bearing required to penetrate the silt. This behaviour is analogous to the observed triaxial test behaviour of normally consolidated clays when comparing undrained with drained results as illustrated in Fig. 6.

The proposed concept of effective bearing defined as the total bearing stress minus the total water pressure represents a first order attempt at interpreting cone results as an effective strength characteristic. This would allow comparison of measured bearing stresses in undrained and

partially drained soils with those in drained soils. Of course, the in-situ effective normal stress at the cone tip is still a missing essential parameter and must be estimated if one is to attempt a complete effective stress analysis. It is believed that the friction sleeve measurement may correlate well with the lateral effective normal stress and may provide the missing parameter. The concept of effective bearing and effective stress interpretation of cone sounding are currently topics of intense research. It has become apparent, however, that it is essential to continuously monitor both pore pressure and bearing during penetration.

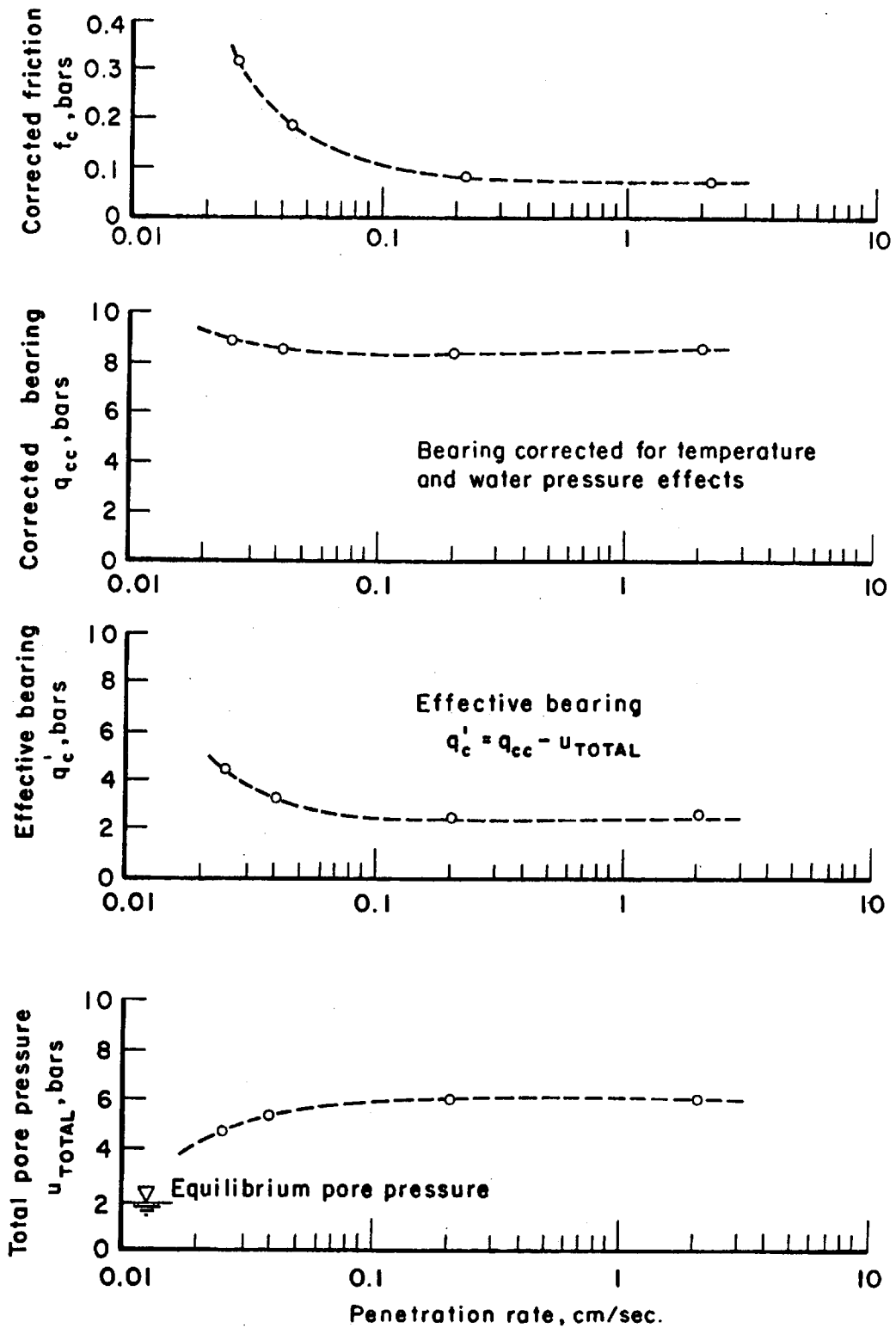
### Friction

The measured shaft friction is directly related to the radial effective stress around the sleeve and as such responds directly to changes in effective stress. To study this effect, the friction sleeve and pore pressure element were progressively moved away from the tip with the use of extension tips. The friction, corrected for temperature and average all round water pressure, and pore pressure versus distance from the tip is shown in Fig. 7 for penetration at 2 cm/sec past the 20 m depth in the undrained soft clayey silt at McDonald's Farm. The results show that the total pore pressures decrease along the shaft from their maximum at the tip. Decreasing pore pressures result in an increase in radial effective stresses which cause a direct increase in friction.

The pore pressure decrease is caused by a decrease in the total radial stresses. This behaviour is very similar to that observed around piles pushed into clay (Roy et al. 1981 and Blanchet et al. 1980), where the pore pressures recorded at the tip or base of the pile are a maximum. The maximum pore pressure at the tip as well as the smaller constant value along the shaft can be estimated from cavity expansion theory for undrained conditions (Vesic, 1972) assuming spherical expansion at the tip and cylindrical expansion along the shaft.

### DISSIPATION OF EXCESS PORE PRESSURE

Upon the arrest of penetration, high positive excess pore pressures generated during cone penetration in cohesive soils such as the clayey silt at the McDonald site, immediately start to dissipate. The rate of dissipation of the positive excess pore pressures is well known to depend upon the coefficient of consolidation of the soil. By monitoring the rate of dissipation of the excess pore pressures,



All measurements at 20m depth

Fig. 5. Penetration Rate Affects in Clayey Silt Deposit (McDonald's Farm, Sea Island, B.C.).

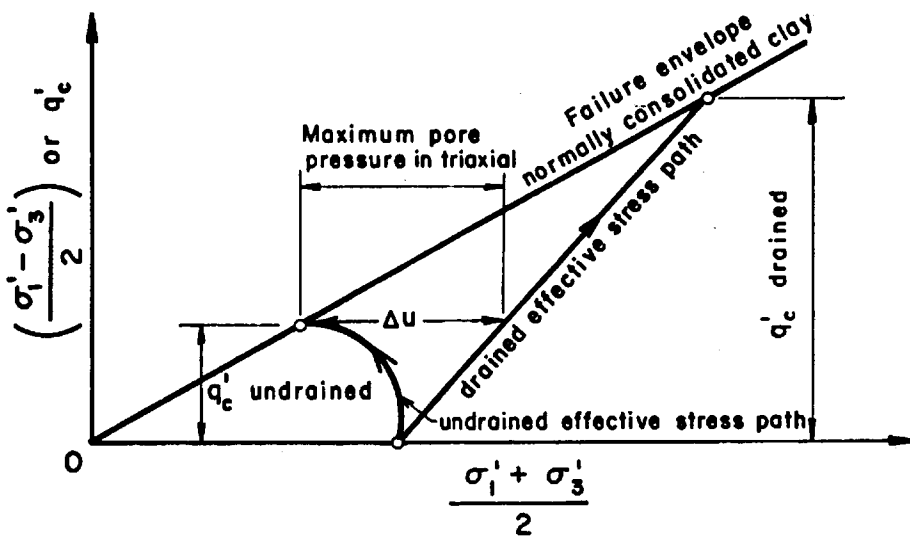


Fig. 6. Analogous Behaviour of Cone Penetration and Triaxial Testing (Drained and Undrained).

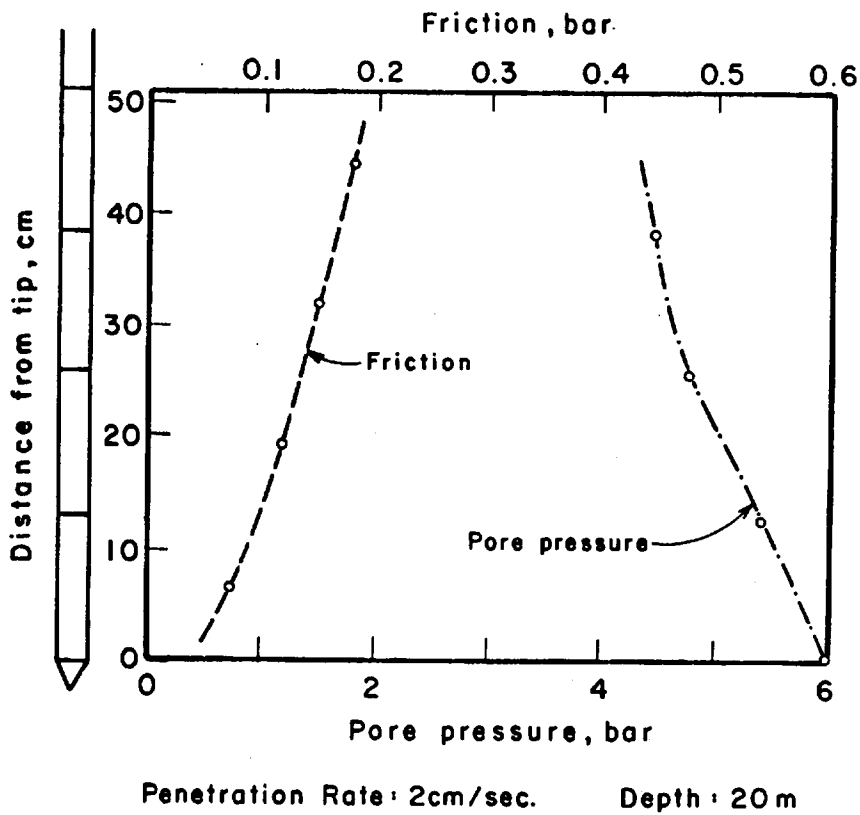


Fig. 7. Friction and Pore Pressure Along Shaft during Cone Penetration in Clayey Silt (McDonald's Farm, Sea Island, B.C.).

an estimate of the coefficient of consolidation of the soil may be obtained. Several theoretical solutions are available to obtain the coefficient of consolidation from the dissipation of excess pore pressures generated by cavity expansion (Torstensson 1977, Randolph and Wroth 1979 and Baligh and Levadoux 1980). The applicability and meaning of the solutions is complicated by several phenomena. These phenomena include:

- the importance of vertical as well as cylindrical diffusion;
- the effect of soil disturbance; and
- uncertainty over the distribution and level of total radial stresses.

In spite of these limitations, the usefulness of the theoretical solutions is encouraged by the repeatability of the test and the vast range in the dissipation rates measured for various soils encountered.

The influence of vertical dissipation, as well as radial dissipation, was shown by Gillespie and Campanella (1981) to be small. This result was obtained by comparing dissipations recorded at various distances up the shaft from the tip. Since radial dissipation appears to dominate the consolidation process, a cylindrical dissipation solution such as that by Torstensson (1977) was chosen in order to compare field dissipation results to laboratory test results.

Constant rate of strain consolidation tests were performed on 3 inch diameter samples trimmed in horizontal and vertical directions from a 3 1/2 inch diameter undisturbed sample obtained adjacent to the location of the pore pressure dissipations. In this manner, the predicted value could be compared directly to the laboratory measured values for the coefficient of consolidation.

A typical pore pressure dissipation, results of the laboratory testing, as well as the predicted coefficient of consolidation from the pore pressure dissipation, are shown in Fig. 8. The coefficient of consolidation was predicted using the cylindrical solution of Torstensson (1977) at the 50% level of dissipation. Comparison between the predicted coefficient of consolidation and the laboratory measured value reveals that the predicted value compares favourably with the horizontal coefficient of consolidation,  $c_h$ , in the over consolidated state. This result supports the view that consolida-

tion takes place in the recompression mode during pore pressure decay after cone penetration testing in cohesive soils has created excess pore pressures. Use of existing theoretical solutions such as those by Torstensson (1977) would seem, at least from the experimental results obtained during this study, to be applicable for calculating the coefficient of consolidation in the horizontal direction for soil in the overconsolidated state. Furthermore, a knowledge of the compressibility of the soil would allow direct calculation of the coefficient of permeability.

#### STRATIGRAPHY

In deltaic deposits such as the Fraser River Delta, the stratigraphy of the soft sediments can be extremely variable. The stratification, however, can be extremely important for assessment of such things as consolidation rate. An example of the advantage of the electric cone as a logging tool with respect to delineation of stratigraphy is shown in Fig. 9. This figure shows two cone logs taken from different areas on Sea Island in the Fraser River Delta area. The research site at McDonald's Farm consists of approximately 15 m of sand overlying a soft uniform normally consolidated clayey silt. The PWA site, which is located approximately 4 kilometers south of the McDonald's Farm site, consists of approximately 20 m of sand overlying the same normally consolidated clayey silt. The PWA site is, however, interbedded with sand lenses at approximately 750 mm intervals.

Conformation that the higher bearing layers within the clayey silt formation are actually sand and not a more compact silt was obtained when the excess pore pressure dissipated within seconds of the piezometer element entering the higher bearing layers. The thickness of the sand layers are such that the bearing is probably unable to reach its true value within the layer since the bearing becomes influenced by the soft layer beneath. The friction value, however, is only influenced by the soil in immediate contact with the sleeve. Thus, the friction value appears to be able to attain its full value. As illustrated by Fig. 9, sand lenses are found in restricted areas throughout the Fraser River Delta, which are thought to be the result of an extreme flooding condition. The presence of the sand lenses at some sites has the effect of reducing the possible drainage path and significantly hastening the consolidation process.

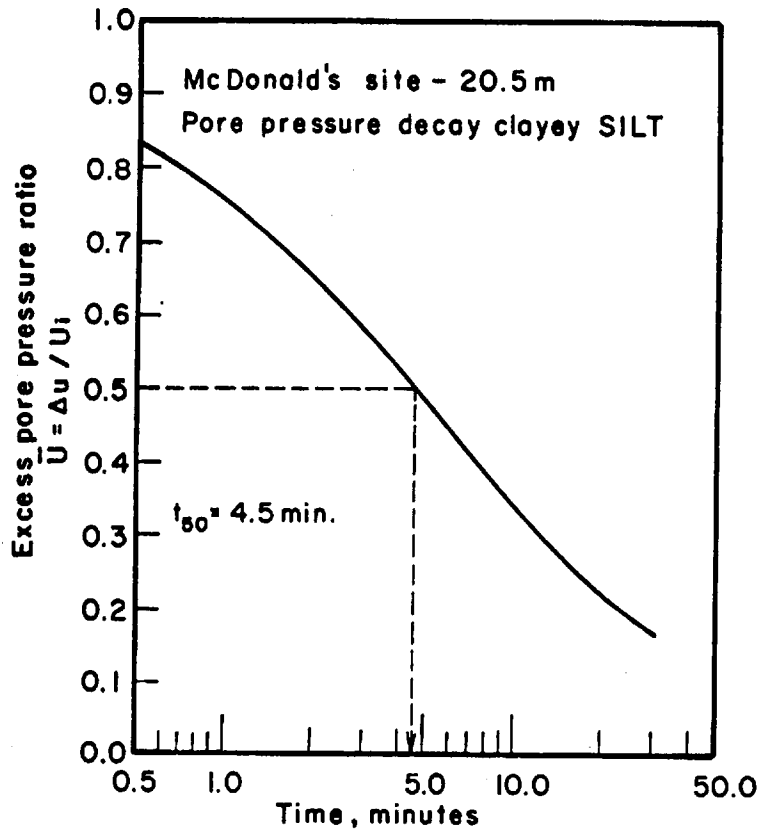


Fig. 8. Measured and Predicted Coefficient of Consolidation from Excess Pore Pressure Decay and Laboratory Test Results.

#### SUMMARY

In-situ tests using an electric piezometer friction cone have been conducted in a thick deposit of uniform normally consolidated clayey silt. The inclusion of the pore pressure measurement has greatly improved our understanding of the cone data. It is essential, however, that the pore pressure element be completely saturated. Results show that continued increases in pore pressure after penetration is stopped was due to a lack of saturation of the pore pressure sensing system. The measured friction and bearing values should be corrected for zero shifts due to both temperature and all round water pressure affects, especially for penetration in soft saturated soils.

For the soft clayey silt tested at the McDonald's Farm site, the standard penetration rate of 2 cm/sec is sufficient to ensure undrained behaviour. At rates less than 0.2 cm/sec partial drainage occurs.

#### IN-SITU DISSIPATION TEST RESULTS :

$$c_h = r^2 T / t_{50} \quad *$$

$$c_h = 3.0 \text{ cm}^2/\text{min.}$$

\* Torstensson, 1977  
Cylindrical solution

$$E/S_u = 500$$

#### LABORATORY TEST RESULTS:

Constant rate of strain

Consolidation tests

Normally consolidated:

$$c_h = 0.75 \text{ cm}^2/\text{min.}$$

$$c_v = 1.10 \text{ cm}^2/\text{min.}$$

Overconsolidated, OCR = 2 :

$$c_h = 3.5 \text{ cm}^2/\text{min.}$$

$$c_v = 3.3 \text{ cm}^2/\text{min.}$$

The concept of effective bearing has been introduced as a first order attempt at interpretation of cone results as an effective strength characteristic. Test results show the potential use of friction sleeve measurements as a direct indicator of radial effective normal stress. These concepts, together with that of cavity expansion, are active research topics, and the potential for future improvements in interpretation looks promising.

The pore pressure dissipation data obtained during a pause in cone penetration can be analysed to provide information on the consolidation characteristics of the soil. Comparison with laboratory measured consolidation data shows that the predicted value of the coefficient of consolidation based on pore pressure decay compares favourably with the horizontal coefficient of consolidation in the overconsolidated state. This supports the view that consolidation takes place in the recompression mode during pore pressure decay after cone penetration in cohesive soils has created excess pore pressures.

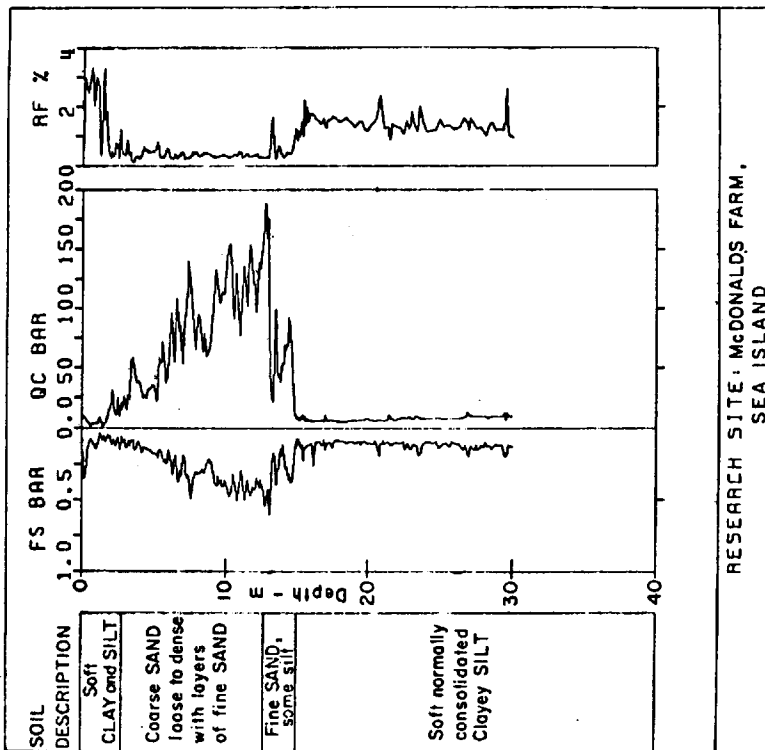
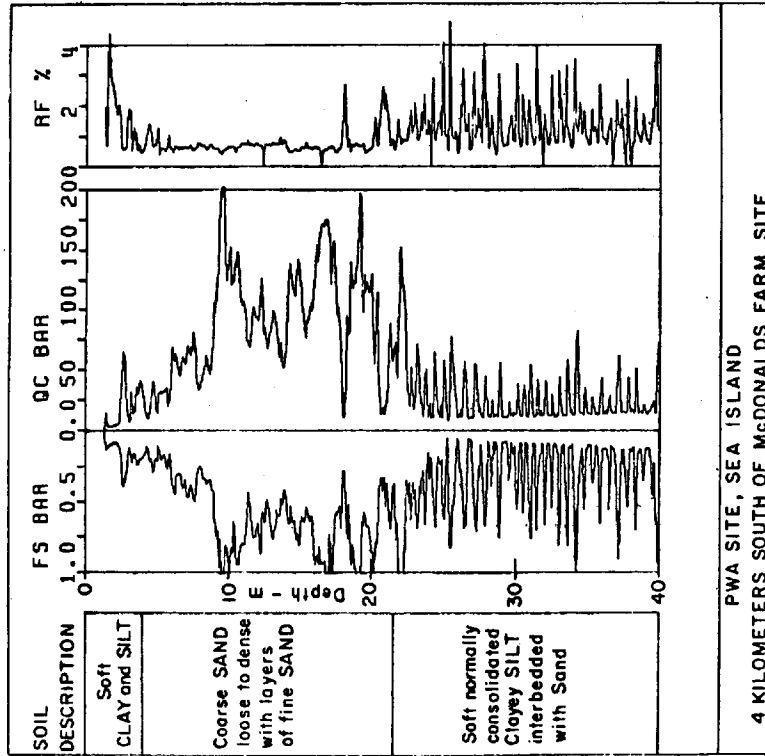


Fig. 9. Example of Stratification Logging by Electric Friction Cone.

Details of stratification are shown to be immediately evident when performing continuous electric cone logging in deltaic deposits.

#### ACKNOWLEDGEMENTS

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