

A New Approach to Measuring Dilatancy in Saturated Sands

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ABSTRACT

The determination of *In-Situ* properties of sand has proven to be a difficult objective, especially when it includes assessing volume change characteristics like dilatancy. Difficulty in obtaining representative undisturbed samples as well as problems with extrapolating laboratory test results to the field, has caused many to place increased reliance on in-situ testing. One such test that is continuing to gain acceptance is the piezocone penetration test (CPTU). While the CPTU is particularly good for stratigraphic detailing and evaluating many geotechnical parameters, the assessment of volume change characteristics is, as yet, not well defined.

A new approach has been developed which uses the measurement of bulk soil resistivity, a geophysical technique, to evaluate the in-situ dilatancy characteristics of sand. The method makes use of a module mounted behind a standard piezocone to measure resistivity. The interpretation is based on the resistivity contrast between remolded sand at constant volume conditions and relatively undisturbed sand. These measurements are recorded continually along with the usual CPTU data and are therefore logging the dilatancy characteristics at high depth resolution. A discussion of the method of analysis, assumptions and limitations are given, and typical results presented and compared. To date the results suggest that the method does not require groundwater sampling or laboratory testing and therefore has obvious advantages over other approaches being developed. The method is performed in combination with the CPTU in order to identify soil stratigraphy and geotechnical properties and at the same speed and reliability.

Key Words: Cone Penetrometer, Resistivity, Dilatancy, Volume Change, Density, Sand, Geophysical, Geotechnical, Properties, In-situ Testing,

INTRODUCTION

The electronic cone is rapidly becoming the tool of choice for geotechnical engineers who have gained a wide experience in in-situ testing. Since its inception, electronic cone testing technology has been constantly evolving, with the development of new cone designs, as well as new tests to measure an increasing number of in-situ properties. Recently a resistivity module was developed at U.B.C. (Campanella and Weemees, 1990) which permits bulk soil resistivity to be measured in-situ along with the standard piezocone penetration test (CPTU) parameters. These measurements have been used to study groundwater contamination, but can also evaluate the soil porosity (Archie, 1942).

PROCEDURES AND EQUIPMENT

The resistivity cone penetration test (RCPTU) is a modification of the standard piezocone test (CPTU). All of the downhole electronic equipment used was designed and built at U.B.C. The cone used has an end area of 10 sq. cm. and a friction sleeve area of 150 sq. cm. The cone is capable of measuring cone bearing stress (Q_c), local sleeve friction stress (F_s), pore pressure (U) at two locations, temperature (T) and inclination (I) simultaneously. In addition the cone is equipped with an accelerometer to record seismic signals for determination of dynamic soil properties.

The ability to measure the resistance to current flow in soils, has been one of the more recent developments in penetration technology at U.B.C. The five electrode array resistivity module is located behind the piezocone, as shown in Fig. 1. The electrode separation varies from 9.5 to 77.5 mm providing different depths of lateral penetration. The outer electrodes are the current supply electrodes, but are also used as measurement electrodes. A constant peak current AC source set at 1000 Hz, can be adjusted in amplitude according to the resistivity of the soil to allow voltage measurements across the electrodes during penetration. For more information on the design and specific electronics of the module, the reader should refer to Weemees (1990) and Kokan (1992). Data was logged using the U.B.C. in-situ testing digital data acquisition system.

MEASUREMENT OF SOIL RESISTIVITY

Geophysical techniques are being used increasingly in penetration testing technology to obtain high quality geotechnical data. These methods are often superior to other methods in that they are fast, relatively non-invasive and do not require extensive lab testing of soils. Resistivity of the soil is not directly measured, but it is inferred from the measured voltage across an electrode pair at a constant supplied current (I). The resistance of the soil, from Ohm's Law, is then:

$$(1) \quad R = \frac{V}{I}$$

The resistance is not a fundamental soil property, but rather depends on the current path length (L) and the cross-sectional area (A) of the effective resistive unit. In the case of the resistivity cone, with the assumptions that the soil acts as a homogeneous isotropic media, the electrodes act as perfect conductors and the resistivity module circuitry acts as a perfect current supply source, then the ratio A/L is constant and equal to K. Electrical resistivity (ρ) is a fundamental soil property which is related by the following relationships:

$$(2) \quad \rho = \frac{A}{L} R = K R = K \frac{V}{I}$$

The calibration factor (K) is affected by the geometry of the electrode dimensions. K can be determined by the direct calibration of the module totally submerged in a constant temperature buffer solutions of known resistivity. For more information on the calibration procedure, the reader is directed to Kokan (1992).

FACTORS AFFECTING RESISTIVITY MEASUREMENTS IN SOILS

The electrical resistivity measured across the electrodes is the bulk resistivity of the soil and is referred to as the apparent resistivity. It is a combination of the resistivity due to the soil skeleton itself as well as the resistivity of the pore fluid. In saturated soils the latter effect dominates.

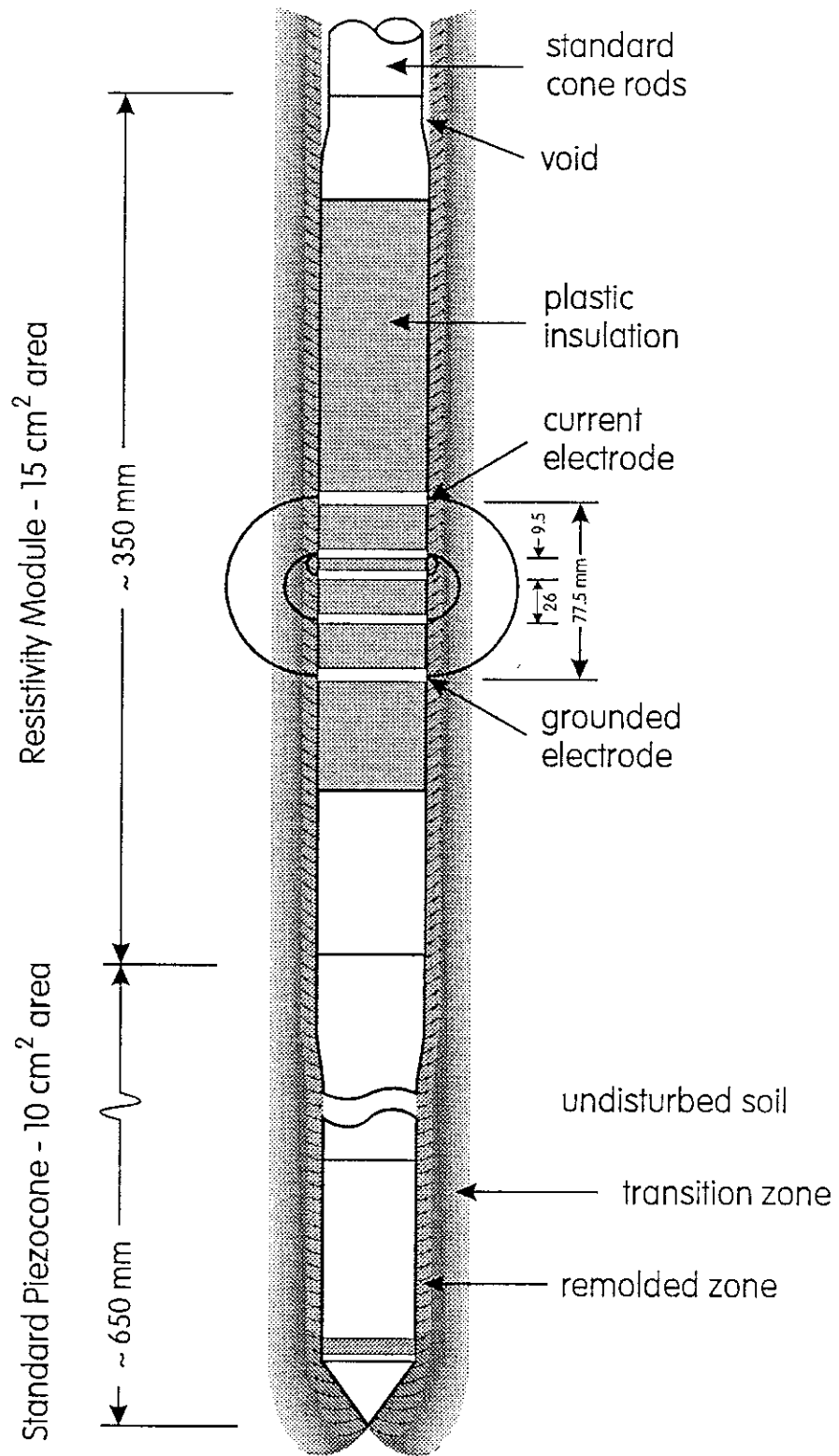


Fig. 1 Piezocone Penetrometer with Resistivity Module, (RCPTU)

The bulk resistivity of the soil is related to the resistivity of the pore fluid by the formation factor (F), which was originally defined by Archie (1942) as follows:

$$(3) \quad F = \rho_b / \rho_f$$

where ρ_b = bulk soil resistivity and ρ_f = pore fluid resistivity. The formation factor (F) is in turn related to soil porosity (n) by Archie's equation:

$$(4) \quad F = A n^{-m}$$

This particular relationship holds for saturated porous media where A and m are constants and the constituent particles are non-conductive relative to the pore fluid. For unconsolidated soils $A \approx 1$ and for sands $m \approx 1.5$. As fines and clay content increases, m increases and can be as large as 1.8 to 3.0 (Urish, 1981)

RESISTIVITY MEASUREMENT IN SANDS

Since sand particles themselves are relatively non-conductive, the flow of current through saturated sand must occur mainly by electrolytic conduction. Hence the bulk resistivity measured in saturated sands is largely a function of the pore water conductivity and the amount of conductive pore fluid. The amount of conductive pore space is influenced by a number of soil related factors such as porosity, tortuosity of pore space as well as grain size and shape factors (Urish 1981). It was recognized by Campanella & Weemees (1990) that there was a relationship between cone bearing, normalized for the effect of changes in effective overburden stress, and formation factor which suggested that the measured bulk resistivity must be related in some way to density and therefore to porosity. Figure 2 shows the sand portion of the resistivity profile from the Laing Bridge site presented over top of the cone bearing results. Also presented are the pore fluid resistivities measured from groundwater samples that were taken with a BAT groundwater system (Torstenson, 1984). The fact that the groundwater is controlling the bulk

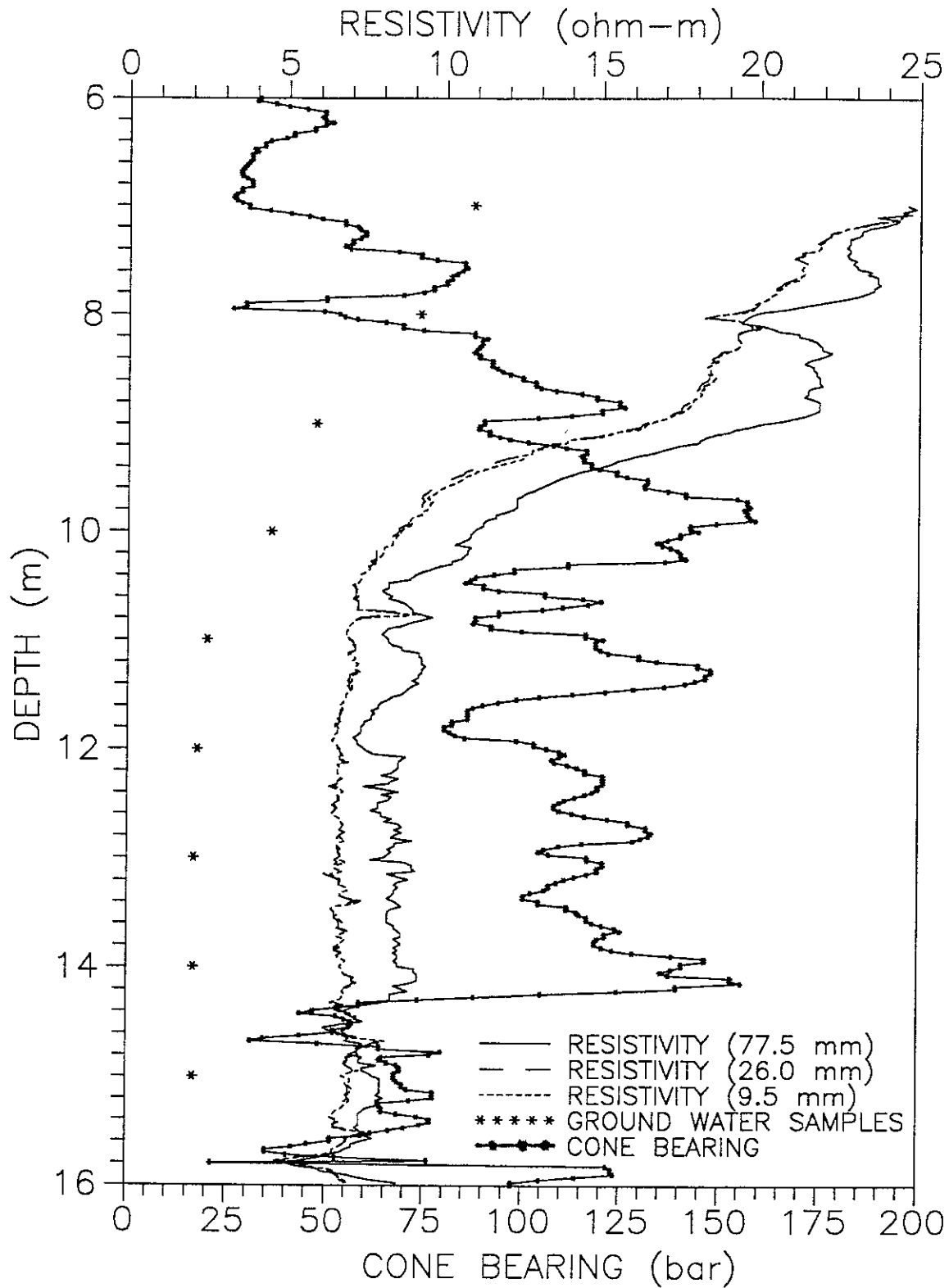


Fig. 2 A Comparison of Resistivity at 9.5, 26.0, 77.5mm spacing, Groundwater Resistivity and Cone Bearing at Laing Bridge site.

resistivity response is evidenced by the parallels between groundwater and bulk resistivities seen in Fig. 2. At the scale provided it is apparent that the resistivity values for the 9.5 mm and 77.5 mm spacings plot near one another and exhibit the same basic trend. However, it is not apparent, yet the resistivity values at 9.5 and 26mm spacings are almost identical and suggest that at these two close spacings there is little or no change in the soil porosity being sampled (see Fig.1). The difference in resistivity between the 9.5 and 77.5mm spacings is due to differences in porosity being sampled and is the basis for the proposed method for dilatancy characterization. Also, from 11 to 14m depth the changes in cone bearing parallel the changes in bulk resistivity profile measured with the large electrode spacing. Since the pore fluid resistivity is constant in this region, it is possible to conclude that the bulk resistivity changes are related to the changes in cone bearing.

USE OF THE RCPTU TO DETERMINE SAND BEHAVIOR

It was previously shown that cone bearing can be related to formation factor, which can be mathematically related to porosity in clean well rounded sands (Campanella and Weemees, 1990). Therefore formation factor could be used as a quantitative means of determining sand density (Delft,1982, Van de Graff and Zuidberg, 1985). Dense sands show higher bulk resistivity values than loose sands in a pore fluid of a fixed resistivity due to their smaller pore fluid volume. Because the resistivity module is a displacement device, soil around the probe is sheared during penetration of the probe as shown in Fig. 1. The degree of disturbance decreases with increasing radial distance away from the probe. For the RCPTU, one would expect that an electrode spacing capable of allowing the current path to pass into the less disturbed formation would be necessary to obtain a measure of relatively undisturbed or "far field" bulk resistivity. This requires as large a spacing as practically feasible. Small electrode spacings would in general measure resistivities near the instrument, in the "near field", where the soil has been sheared considerably by penetration. In sand one would expect that the density in this near field zone of severe remolding and shearing would be relatively constant, and close if not equal to critical density at the in-situ mean effective stress. Hence only the formation factor calculated using the large electrode spacing should be related to density and cone bearing. This was demonstrated quite clearly by Campanella and Weemees (1990). Defining porosity quantitatively from formation factor, while possible in theory, has proven difficult in practice. Extensive site specific correlations are required for this to be achieved. In the Netherlands this

approach has been used by Delft (1982) with very limited success.

Another approach to the understanding of in-situ density in sand has been developed. Rather than trying to look at the problem of measuring absolute density and comparing it to reference densities of sands, the writers have undertaken to consider only the density or volume change that occurs during shear. By comparing near field resistivity to far field resistivity, it is possible to observe the relative differences in sand porosity or density between the near field (remolded) and the far field (undisturbed). If the assumption is made that the remolded sand near the probe is at or near critical state, then one has an in situ reference density and corresponding bulk resistivity. Because denser sands will have higher bulk resistivities than looser sands, comparison of near and far field bulk resistivity should indicate whether the soil has become looser or denser near the probe. Therefore, sands can be identified as contractive or dilative based on their volume change behavior during penetration induced shear.

THEORETICAL BASIS

Dilatancy refers to the volume change that sand undergoes when it is sheared. Naturally occurring sands can have substantial differences in their dilatancy characteristics. Variations in mean grain size, grading, mineralogy and in situ stress can all influence the dilatancy behavior. These observations have been repeatedly demonstrated during laboratory testing. Steady state concepts are the most recent framework in which dilatancy behavior has been discussed. The basis for this type of analysis is that sand has a steady state line which exists in void ratio - effective confining stress space (Vaid et al, 1990). The steady state line can be determined from triaxial tests in the laboratory. The position of a sand element with respect to the steady state line determines its behavior when sheared. It is well understood that increasing void ratio or decreasing density promotes volume decrease or contraction during shear. Similarly decreasing void ratio or increasing density promotes volume increase or dilation during shear. Furthermore increasing confining stress promotes volume decrease or contractive behavior. The position and slope of the steady state line is different for sands of different composition. Moreover even for a given sand, such as Ottawa Sand (ASTM C-109), the position of the steady state line is also stress path dependent (Vaid et al, 1990). Therefore it appears that steady state concepts must be applied in the context of the specific soil tested and the direction of loading.

While steady state concepts have been discussed mainly in the context of laboratory tests, recently they have been extended to in situ tests (Been et al, 1987, Sladen and Hewitt, 1989). In the state parameter approach, Been et al, 1987, relate CPT cone bearing to the state parameter which is used to define the contractive-dilative boundary or steady state line. The method requires the independent assessment of the steady state line and in situ horizontal stress. While the estimation of in-situ horizontal stress can usually be estimated, determination of the steady state line requires extensive laboratory testing to be conducted on representative samples. Sladen and Hewitt (1989) proposed a contractive-dilative boundary for sand, based on cone bearing stress from back analyses on hydraulic fill structures in the Beaufort Sea. Because these methods rely on empirical relationships that were extracted from very specific data bases, they are usually site specific and the potential exists for misinterpretation of data from other sites.

The methodology proposed herein by the writers differs from the above in a fundamental manner. The volume change associated with shearing is observed directly. Therefore there is no need for laboratory or field correlations to predict dilatancy in situ. Dilatancy can be estimated by looking at the volume change that has occurred during shear at various distances away from the penetration probe. The level of shear induced by the penetration of a probe, such as the cone used in the CPTU, decreases as the radial distance away from the probe is increased. Chong (1988) describes the volumetric strain as a function of radial distance to be a critically damped compression wave. Since the penetration of the electric field from the resistivity module is proportional to the spacing, by varying the spacing one can expect to vary the level of volumetric strain that is measured. Resistivity methods have been used before to measure volume changes in granular soils. Windle and Wroth (1975) used resistivity to determine the volume changes that occur during a pressuremeter test.

DILATION PARAMETER

In order to have some way of quantifying the dilatancy behavior it is necessary to establish a parameter that is related to the amount of dilation or contraction that is observed during penetration induced shearing. For this reason the parameter (D), the dilation parameter, was chosen. The value of D is defined by the writers to be a ratio of measured near field to far field bulk resistivities as follows:

$$(5) \quad D = \frac{\rho_{b095}}{\rho_{b775}}$$

The significance of the dilation parameter and its relationship to the formation porosity can be seen by combining Eqns. (3) and (4), which gives:

$$(6) \quad \rho_b = \rho_f (A n^{-m})$$

now substituting Eqn. (6) into Eqn. (5) and noting that the formation characteristics and pore fluid resistivity can be considered constant at a given depth gives:

$$(7) \quad D = \frac{\rho_f A (n_{095})^{-m}}{\rho_f A (n_{775})^{-m}}$$

canceling gives:

$$(8) \quad D = \left[\frac{n_{775}}{n_{095}} \right]^m = f \left[\frac{(\text{Porosity})_{\text{und}}}{(\text{Porosity})_{\text{rem}}} \right]$$

where:

(Porosity)_{und} = Porosity of undisturbed sand in the far field as measured by the widely spaced electrodes, and

(Porosity)_{rem} = Porosity of remolded sand near shaft as measured by closely spaced electrodes.

Therefore, if $D < 1$, then the porosity of the undisturbed sand is less than the remolded or steady state porosity and the sand would be *dilatative* (or increase in volume due to shearing). If $D > 1$ then the porosity of the undisturbed sand is larger than the remolded or steady state porosity and the sand would be *contractive* (or decrease in volume due to shearing).

The dilation parameter was defined in this manner since of the four electrode spacings, the 9.5mm and the 77.5mm spacings represented the smallest and the largest available on the module at the time. The use of a quotient term as the dilation parameter was chosen since it implicitly normalizes with respect to the bulk resistivity value. In this way variation in the pore water resistivity with depth does not have an effect on the value of D. Hence there is no need for pore fluid sampling.

Upon examination of the in-situ methods available it is clear that a need exists for developing some type of analytical technique for characterizing the dilatancy behavior of sands for application in stress-deformation modeling and, more specifically, liquefaction modeling. While the pressuremeter shows great promise as the definitive analytical tool for in situ testing, it cannot match the RCPTU test in terms of speed and effectiveness. Furthermore, the pressuremeter requires interpretation of a stress strain relationship to extract comparable dilatancy information. In order to demonstrate the usefulness of the RCPTU test, a field program was carried out at several U.B.C. research sites.

FIELD INVESTIGATION PROGRAM AND RESULTS

Data is presented here from three sites in the lower Fraser River Delta, British Columbia, Canada. These sites have significant sequences of clean fluvial sands, deposited by a prograding Fraser River. Of most concern to designing geotechnical engineers are the loose possibly liquefiable sands and non plastic silts that tend to be found between five and fifteen meters of depth. The present Fraser Delta is a consequence of the latest phase of deposition from post glacial ice ablation and Fraser River scour. The Fraser Delta consists of a complex sequence of glacial, glaciofluvial, glaciomarine and fluvial sediments that extend up to several hundred meters in depth. The most recent sediments are the fluvial sediments, resulting from continuous cycles of scour and deposition caused by flooding and channel relocation.

SITE DESCRIPTIONS

Arthur Laing Bridge Site

This site is adjacent to the southern off ramp of the Arthur Laing Bridge at the Vancouver International airport. It is at the north eastern limit of Sea Island next to the north arm of the Fraser River and in relatively close proximity to the present delta front of the Fraser River. The RCPTU profile from one of the soundings is presented in Fig. 3. The top 4 meters of soil consist of organic rich silts and loose silty sands as indicated by the high friction ratio and low cone bearing. Below this is a sequence of clean sand extending to about 14 meters. This sand shows a general trend of increasing density with depth. Both the friction ratio and the penetration pore pressure response confirm the fact that the sand between 4 and 14 meters is very clean. Below 14 meters the sand becomes stratified with silty layers. The resistivity profile indicates a moderate level of total dissolved solids in the groundwater in the upper 10 meters of the deposit. The approximate limit of potable water corresponds to a bulk resistivity of 25 to 50 ohm-m (approximately 500 mg/l total dissolved solids). A sharp decrease in the bulk resistivity is noted at 10 meters, at which point the resistivity halves. Below the lower silty sand at about 19 meters, there is a plastic clayey silt unit containing some thin silty sand lenses.

Miller Road Site

This site is approximately 400 meters south of Laing Bridge site, also on the eastern limit of Sea Island. Figure 4 shows one of the RCPTU profiles from this site. The upper 6.5 m of the profile consists of sand fill which is characterized by variable cone bearing arising from the placement technique. Directly under the sand fill are the overbank silts and silty sands characteristic of this part of Sea Island. These deposits are underlain by a sequence of sands with silt layers. The resistivity profile demonstrates the present water table level to be at about 6 meters below the top of the fill, at about the same level as the first native soils. These soils are silty with plastic fines, causing the resistivity profile to approach the 10 ohm-m level. Once into the cleaner sands the bulk resistivity appears to be on average 40 ohm-m through until about 18 meters where the resistivity drops. This drop as in the Laing Bridge site, is controlled by the changing pore fluid conductivity. The bulk resistivities are in the same range as the Laing Bridge site as expected since the distance between the sites is less than 400 m.

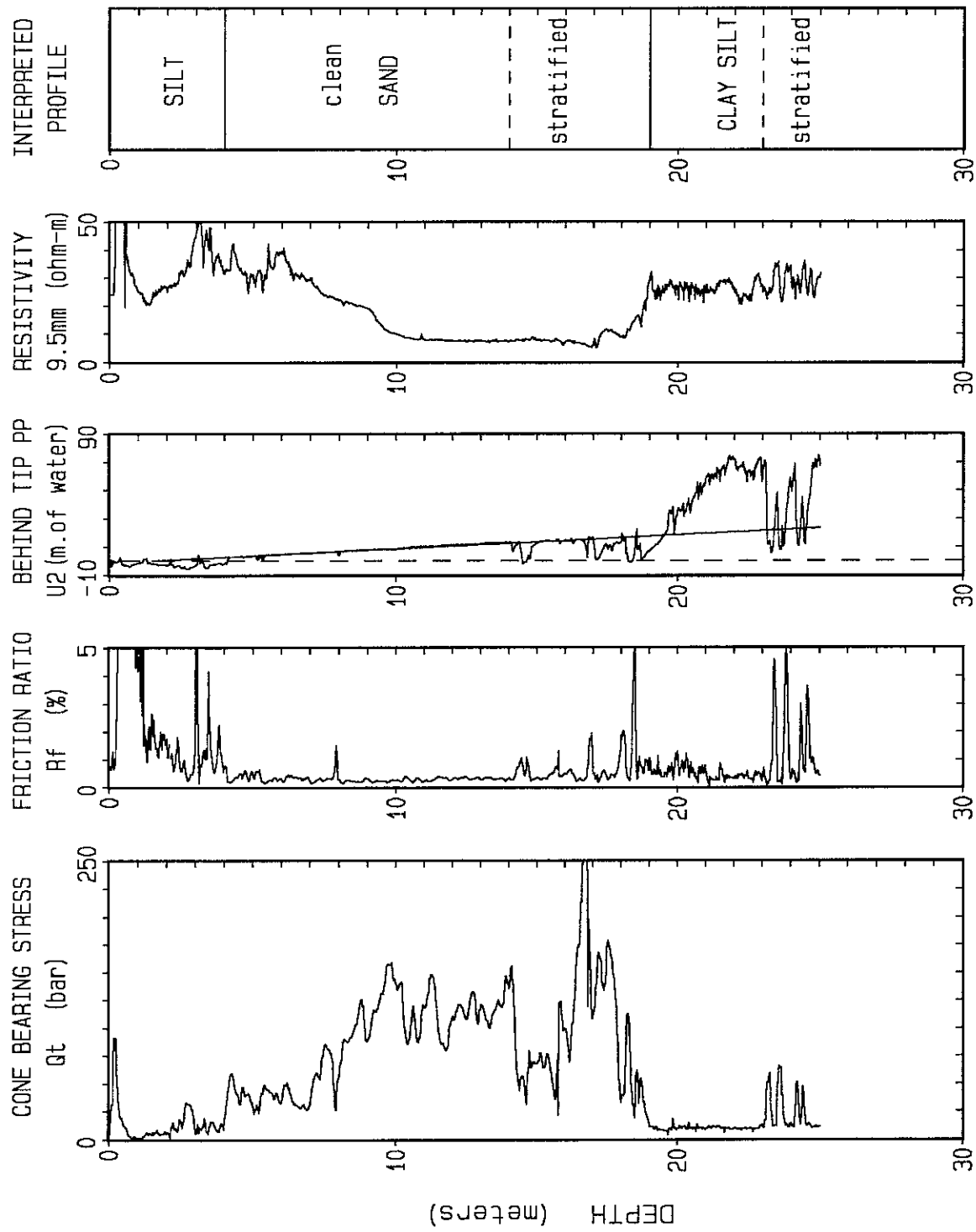


Fig. 3 RCPTU Sounding from Arthur Laing Bridge Site (LAING11.EDT)

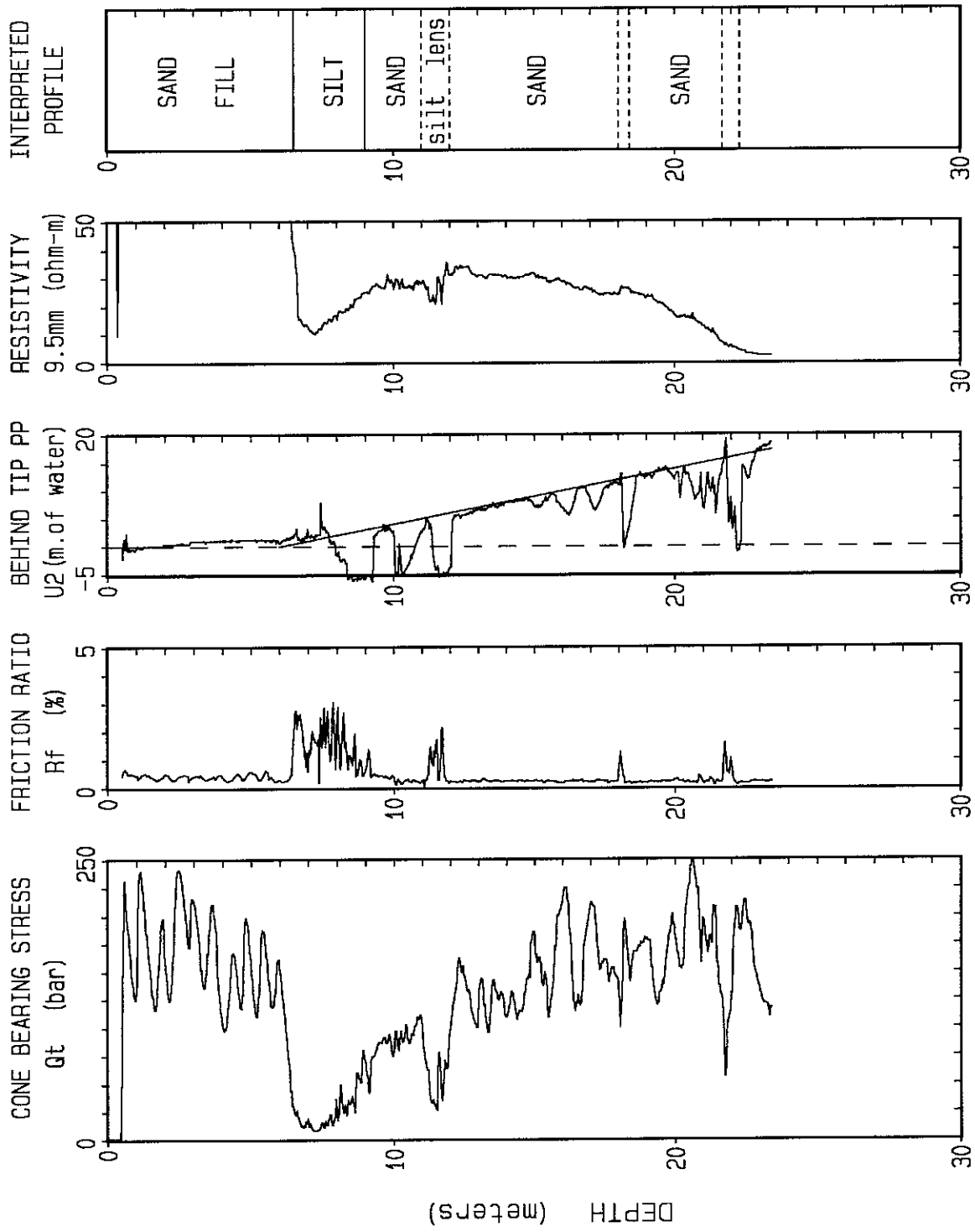


Fig. 4 RCPTU Sounding from Miller Rd. Research Site (MILRES1.EDT)

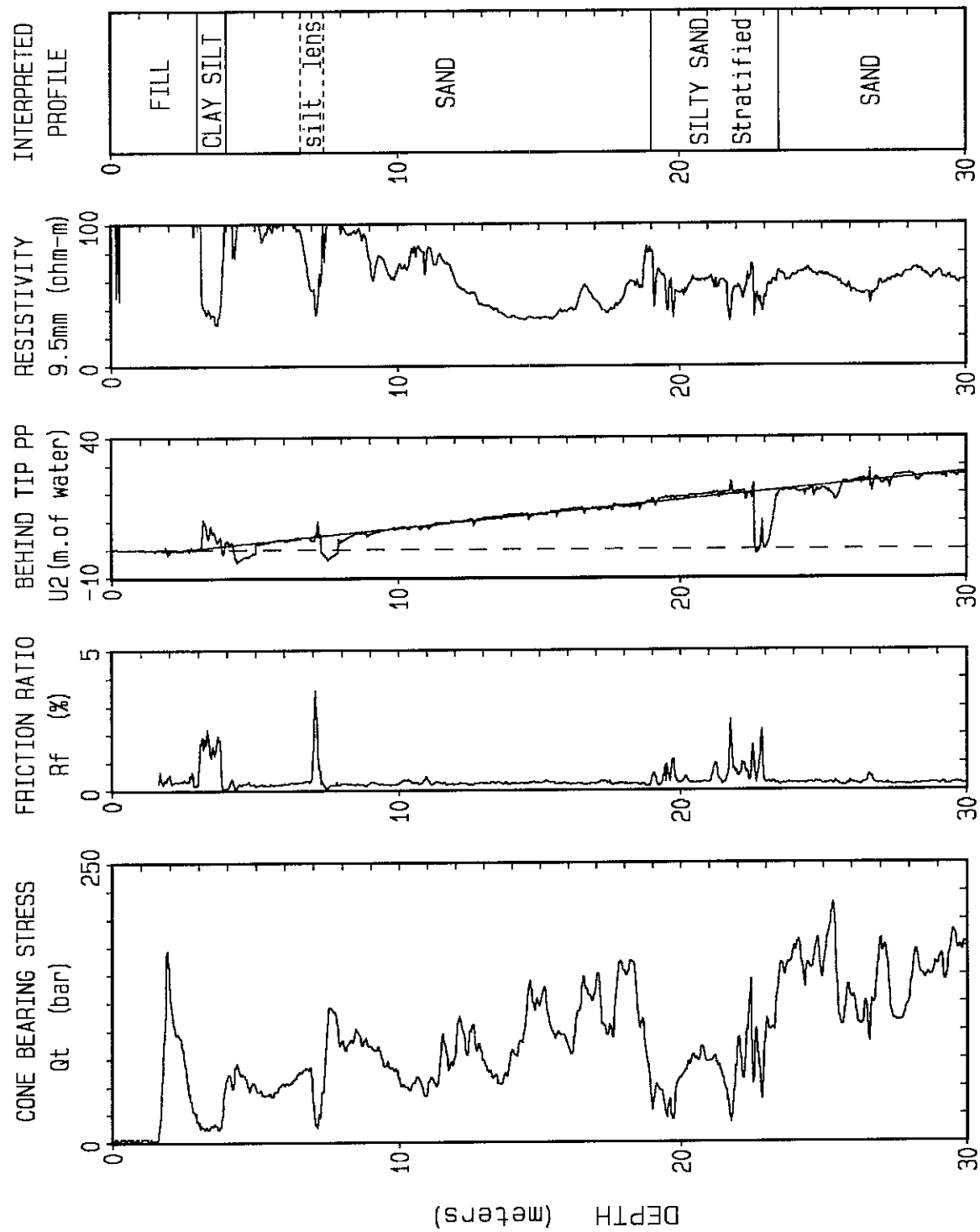


Fig. 5 RCPTU Sounding from Fraser Bridge Research site (FRAS2.EDT)

Alex Fraser Bridge Site

This U.B.C. research site is located on Annacis Island in New Westminster B.C. The site includes the north pier of the Alex Fraser Bridge as well as the northern approach span support piers. There has been extensive vibro-replacement densification done around the main pier as well as the approach span piers. Annacis Island is located upstream from the previous sites. It is a smaller channel island, similar to other islands upstream from the mouth of the delta. Fig. 5 shows that the site is presently covered with sand fill to a depth of 3 meters near the water table depth. Beneath the sand fill there is approximately 1 meter of clayey silt overbank deposits which are underlain by sand to a depth of 7 meters where there is a 1 meter silt layer. Beneath 8 meters the sand is fairly clean to a depth of about 19 meters. From 19 to about 21.5 meters weaker silt lenses exist. The silty lenses are marked by sharp decreases in penetration pore pressure and increases in friction ratio in combination with very reduced cone bearing. The sands are characteristically loose near the surface throughout the site; hence, vibro-densification was recommended by the geotechnical consultants for this portion of the project (Bazett and McCammon, 1986). This sounding (FRAS2.EDT) is in the untreated area. The bulk resistivity at the site indicates a relatively low level of total dissolved solids in the pore fluid. The stratigraphic variability is also reflected in the measured resistivity.

DILATANCY ANALYSIS

The dilatancy behavior of sands is affected by mineralogical and grain size factors in addition to placement density and confining pressure. Significant variations in mean grain size, grading and mineralogy have been observed in the Fraser Delta (Armstrong, 1984). It is expected that the factors affecting dilatancy behavior also affect measured cone bearing, however it is not clear whether they are affected in the same manner. This topic will be addressed as the data is presented.

The dilation parameter (D) is presented together with normalized cone bearing. The normalization applied here is that proposed by Sladen and Hewitt (1989). The Sladen and Hewitt normalization is as follows:

$$(9) \quad Q_{tn} = \frac{Q_t}{(\sigma'_v)^{0.65}}$$

where:

Q_{tn} = normalized total cone bearing stress

Q_t = total cone bearing stress after pore pressure correction

σ'_v = vertical effective stress.

This normalization format was adopted since it appears to be superior in terms of correcting for overburden effects on measured cone bearing. Vertical effective stresses were estimated using an assumed soil density. Normalized cone bearing has also been shown to be correlated to in situ relative density (Baldi et al, 1982; Robertson and Campanella, 1989), which makes it convenient for comparison of the resistivity method of dilatancy characterization of sands. Sladen and Hewitts' criterion for the dilative-contractive boundary was $Q_{tn} = 70$ bar. Sands that are less than 70 bar are considered loose or contractive, while sands that are greater than 70 bar are considered dense or dilative. Clearly this criterion cannot be rigorously applied to any type of sand as dilatancy is effected by factors such as mineralogy, age and OCR. The Sladen and Hewitt criterion will be checked to see if it is valid for Fraser Delta sands.

Arthur Laing Bridge Site

The RCPTU's conducted at this site were located about 2 meters from a mud rotary drill hole where SPT's were done at five foot intervals. Hence grain size data in the sands was available. Fig. 6 shows the dilation parameter and normalized cone bearing computed to 20 meters for the RCPTU shown in Fig. 3. The sequence of sand between 4 and 14 meters is a good one for the analysis since it is clean, has a uniform grain size ($D_{50} = 0.30$ mm, ± 0.02 mm) and shows considerable variability in density. There is a noticeable relationship between normalized cone bearing and dilation parameter. The increases in cone bearing are in sequence with decreases in dilation parameter and hence increase in inferred dilation. In the upper part of the sand zone from 4 to 8 meters, the sands are loose to medium loose as indicated by normalized cone bearing being in the range of 40 to 60 bar. The dilation parameter recorded in this region was greater than unity on average, indicating that contraction was taking place. In the lower sands from 8 to 14 meters, which appear to be quite dense as indicated by normalized cone bearings greater than 70 bar, D is less than unity indicating dilative behavior.

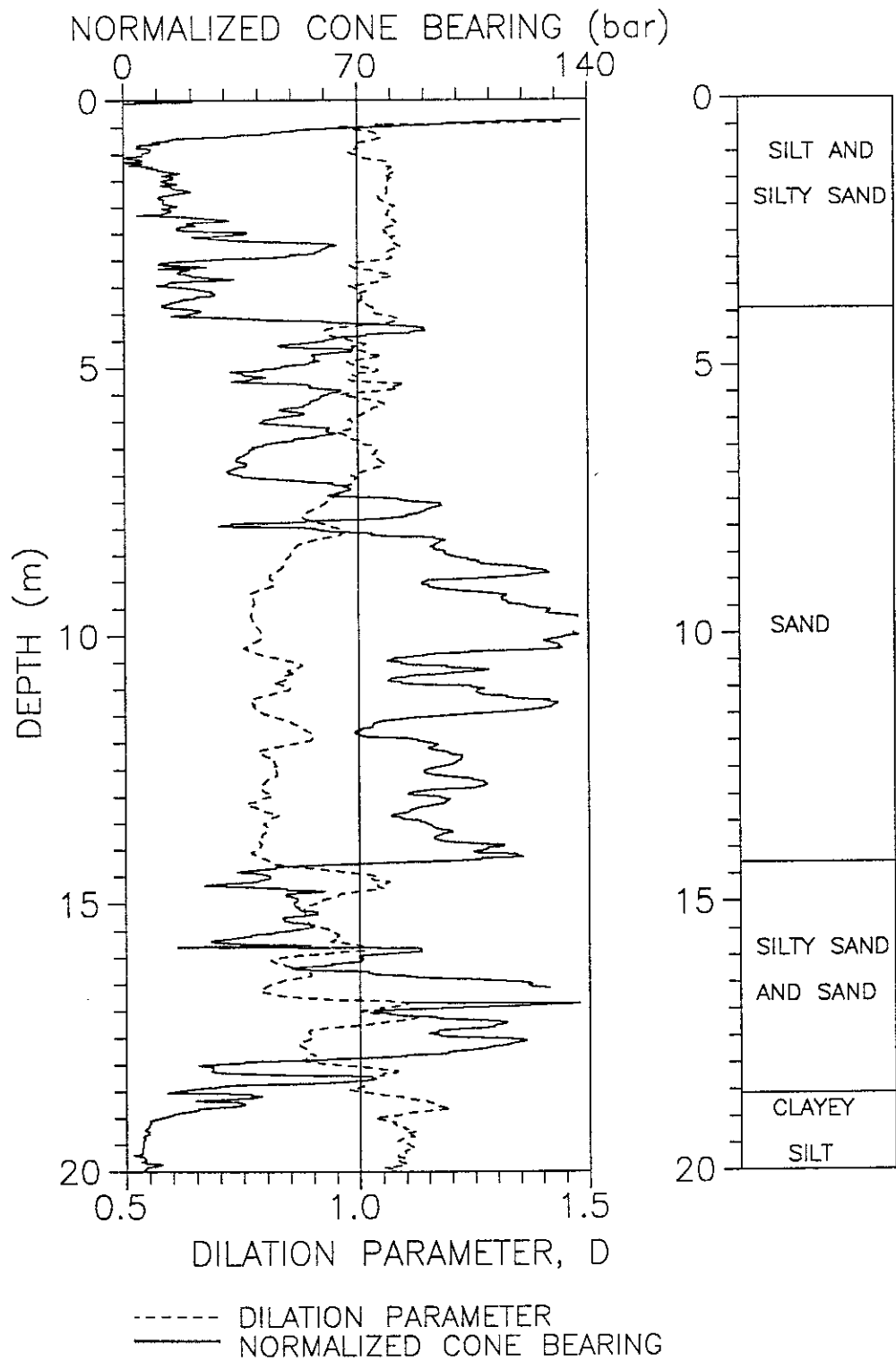


Fig. 6 Dilation parameter and normalized cone bearing stress with depth for Laing Bridge site. ($D < 1$ dilative; $D > 1$ contractive)

Miller Road Site

Fig. 7 shows the dilation parameter plotted along side normalized cone bearing from 8 to 22 meters for the RCPTU shown in Fig. 4 for the Miller Rd. site. This sounding was chosen since it includes mostly clean sands below the water table at resistivities of about 35 ohm-m compared to the Laing Bridge site (Figs. 3 and 6) where more stratified soils below 10m depth had resistivities around 10 ohm-m. The previous trends are again evident in the clean sands at Miller Rd. Most of the sands appear to have D less than unity, indicating that they are dilative. One observation that can be made is that the response of D to changes in cone bearing appears to be attenuated somewhat where the sands are more highly stratified.

Alex Fraser Bridge Site

The results shown in Fig. 8 are from the RCPTU results shown in Fig. 5. In the upper looser sands there is some contraction, indicated by a greater than unity value of dilation parameter. Below there is mainly minor dilation, though contraction is quite noticeable at several depths. The relationship between normalized tip resistance and dilation parameter while evident, is not nearly as good as for the previous two sites. It appears that most of the sand lies just on the less than unity or dilative side of the figure. This site is quite different stratigraphically from the previous sites. The amount of layering observed in the sands is much greater and the range of densities is smaller.

Summary

With the data from three sites presented in Figs. 6, 7 and 8, it is of interest to compare the measured range of the D Parameter with the theoretical range as calculated from Eqn. 8. On the average it can be assumed (from local experience) that a typical saturated, naturally occurring, deltaic sand can have a maximum density void ratio of 0.55 or a porosity of 0.355 and a minimum density void ratio of 1.00 or a porosity of 0.500. Now if the critical state or constant volume, fully remolded void ratio is taken as 0.80 or a remolded porosity of 0.444, the following theoretical values of dilation parameter, D , can be calculated from Eqn. 8 taking $m=1.5$: $D=1.19$ (loose) and $D=0.71$ (dense). The actual range of D measurements in the sand was from a low of 0.75 to a high of 1.13. Thus, the measurements are reasonable and within the bounds of practical limits. It is anticipated that with the wider spaced electrode array that is planned the resistivity measurements will sample a little more of the undisturbed zone; thus, providing a slightly wider range of measured D values.

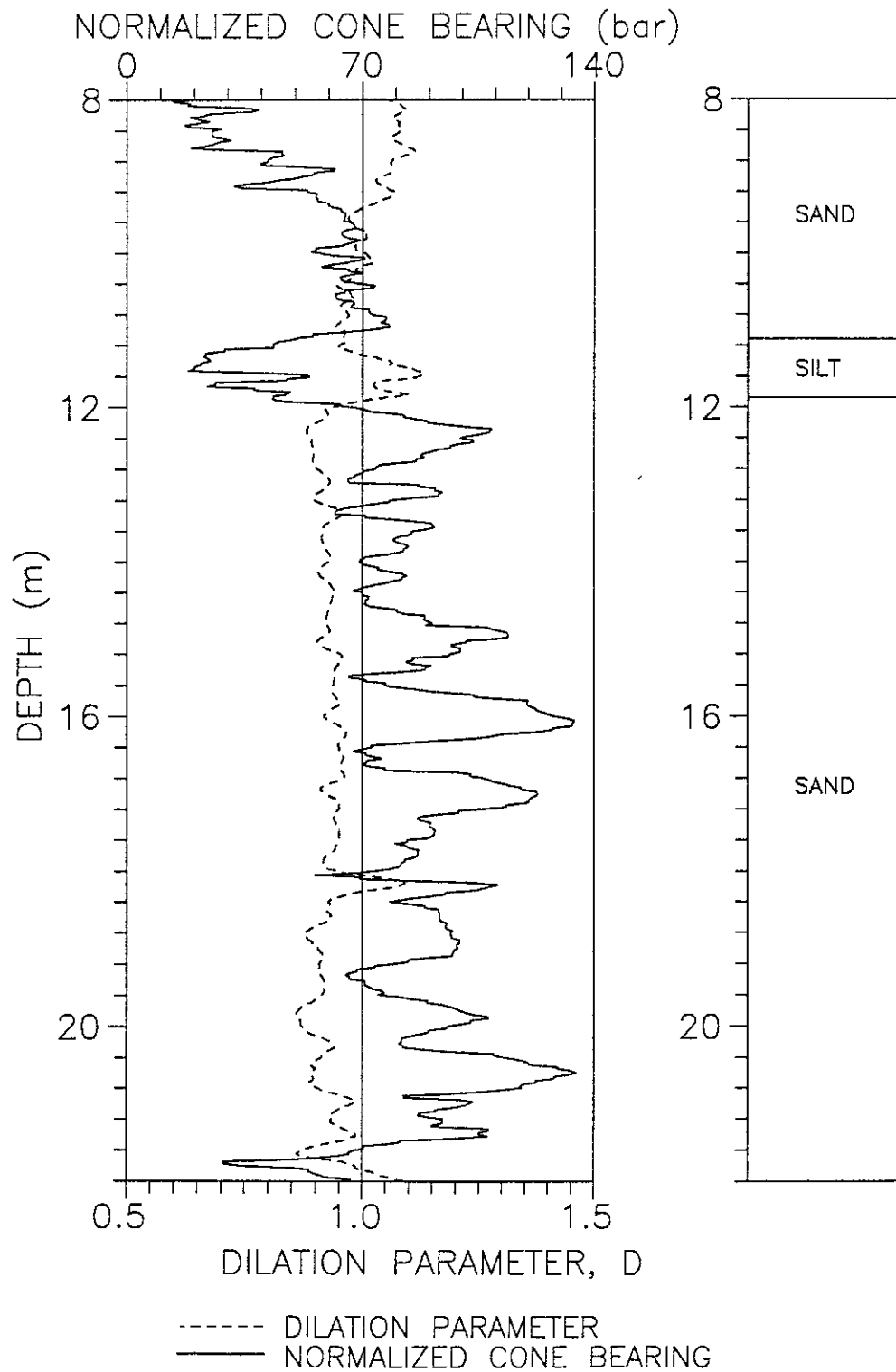


Fig. 7 Dilation parameter and normalized cone bearing stress with depth for Miller Road site. ($D < 1$ dilative; $D > 1$ contractive)

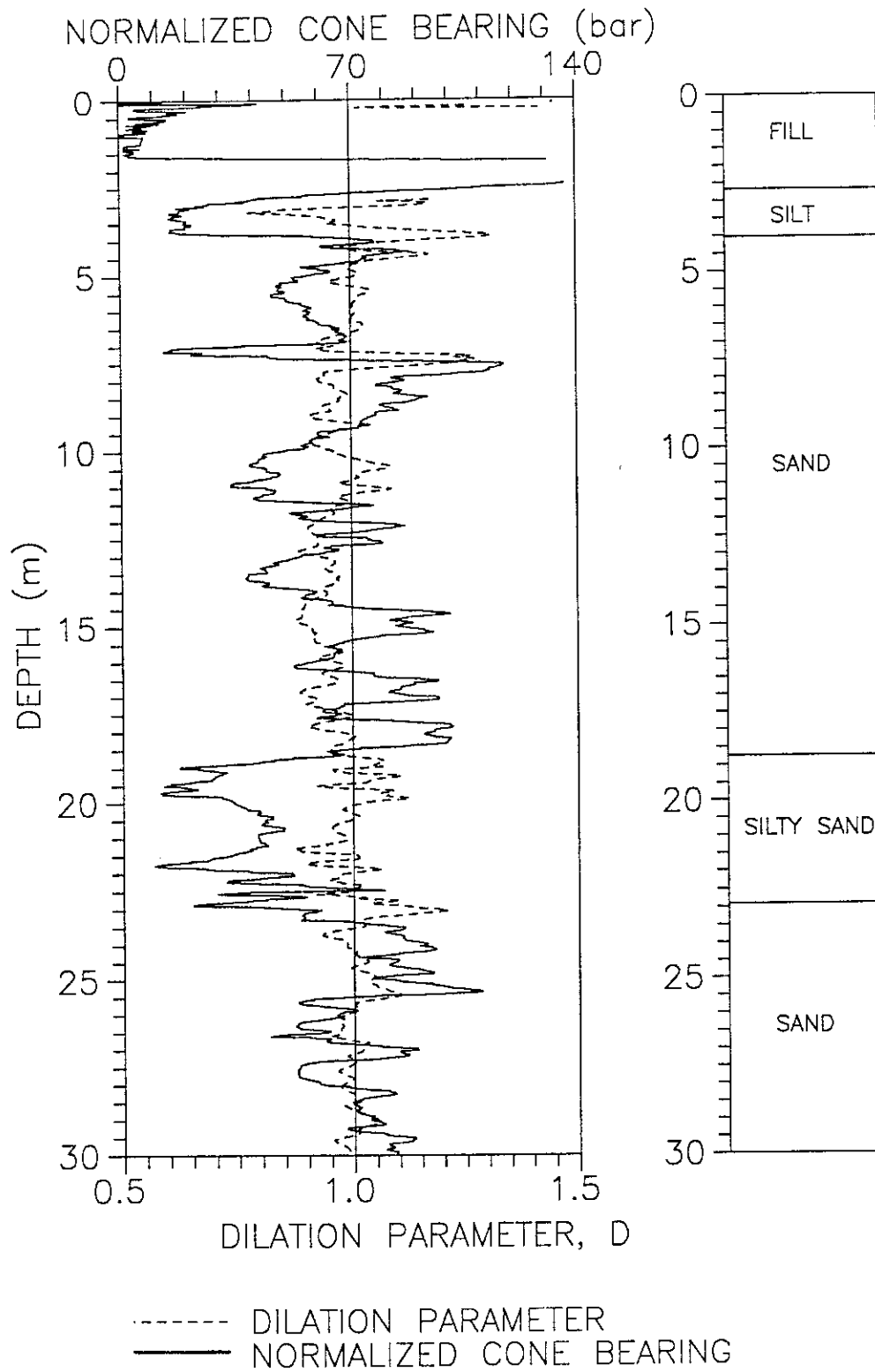


Fig. 8 Dilation parameter and normalized cone bearing with depth for Fraser Br. site, North Pier on Annacis Is. ($D < 1$, dilative; $D > 1$, contractive)

From the data presented, it appears that a trend of decreasing dilation parameter with increasing normalized cone bearing can be demonstrated in clean sands. The relationship is most pronounced when the sands are relatively uniform, such as at Arthur Laing Bridge site and Miller Road site. In highly layered and/or stratified sands, such as shown in Fig. 8 for the Alex Fraser Bridge site, observed changes in dilation parameter do not seem to be as large, in magnitude, as the observed changes in normalized cone bearing. This is expected since the resistivity measurement from the 77.5 mm electrode spacing averages over a relatively large distance. In contrast the value of cone bearing is an instantaneous "snapshot" of the resistance to penetration at a specific depth point. Thus, resistivity is less effective at responding to thin soil layers than cone bearing.

Q_{tn} - DILATANCY RELATIONSHIPS

Because the test used to measure D is a modified CPTU, it is natural to use cone bearing stress as a first basis of comparison. The data presented so far have shown that there is some basis for developing a functional relationship between Q_t or Q_{tn} (normalized) and D . Fig. 9 shows normalized cone bearing (according to Eqn. 9) vs. dilation parameter, averaged at 0.25 meter intervals in the clean sands. The results from the Laing Bridge site show an extremely good linear correlation between normalized cone bearing and dilation parameter. The Miller Road site also shows a good trend, but the slope appears somewhat steeper than the previous site. For the Miller Road site, it seems clear that on balance there is less dilation for a given value of normalized cone resistance than for the Laing Bridge site. Approximately 6.5 meters of sand fill above the water table is present at the Miller Road site. This corresponds to an increase in vertical effective stress between 100 and 125 kPa, causing increased confining stress which has been demonstrated to decrease observed dilative behavior in laboratory tests on sands.

Sladen and Hewitt (1989) suggest a value of $Q_{tn}=70$ bar for the boundary between contractive and dilative behavior. Given the data presented in Fig. 9, which shows a mean value of $Q_{tn}=55$ bar (normalized Q_t) at $D=1$, Sladen and Hewitt's value may be overly conservative when applied to Fraser Delta sands.

RELATIVE DENSITY - DILATANCY RELATIONSHIPS

Although relative density (D_r) is a difficult parameter to evaluate, it continues to be used as a guide in design. Recent calibration chamber testing, has provided useful correlations between cone resistance (Q_t) and relative density for several reference sands (Baldi et al, 1982). One of the reference sands, Ticino Sand, is moderately compressibility and is similar in characteristics to the sands found in the Fraser River Delta. Using the cone interpretation computer program CPTINT ver 4.2, developed at U.B.C., it was possible to estimate D_r for the Fraser Delta sands using the correlations for Ticino sand.

Figure 10 shows a typical relationship for relative density vs. the Dilation Parameter, D , for the two soundings at the Laing Bridge site. The results suggest a good linear relationship between D and relative density, D_r , with a mean value of $D_r=45\%$ at $D=1$ as the boundary between dilative-contractive behavior. The linear relationship is not surprising since D_r is also a function of Q_t normalized to a power function of vertical effective stress (Bellotti et al, 1985), similar to Sladen and Hewitt, 1989.

DENSIFICATION CONTROL

One of the areas in which the CPTU is becoming the preeminent test is for compaction or densification control. It is believed that the dilation parameter could be used as an independent method of assessing ground improvement for any method of densification. Fig. 11 shows normalized cone bearing and dilation parameter for two RCPTU's at the Alex Fraser Bridge site where one was just in the densified footprint and the other was some 15 m east in the untreated area. The change in normalized cone bearing is noticeable, with, in most cases, an increase in normalized cone bearing observed in the improved area. The dilation parameter decreases concurrently with increases in normalized cone bearing. This suggests that the densification has improved the site characteristics by causing the sand to undergo increases in density causing increased dilation or a decreases in the dilation parameter D .

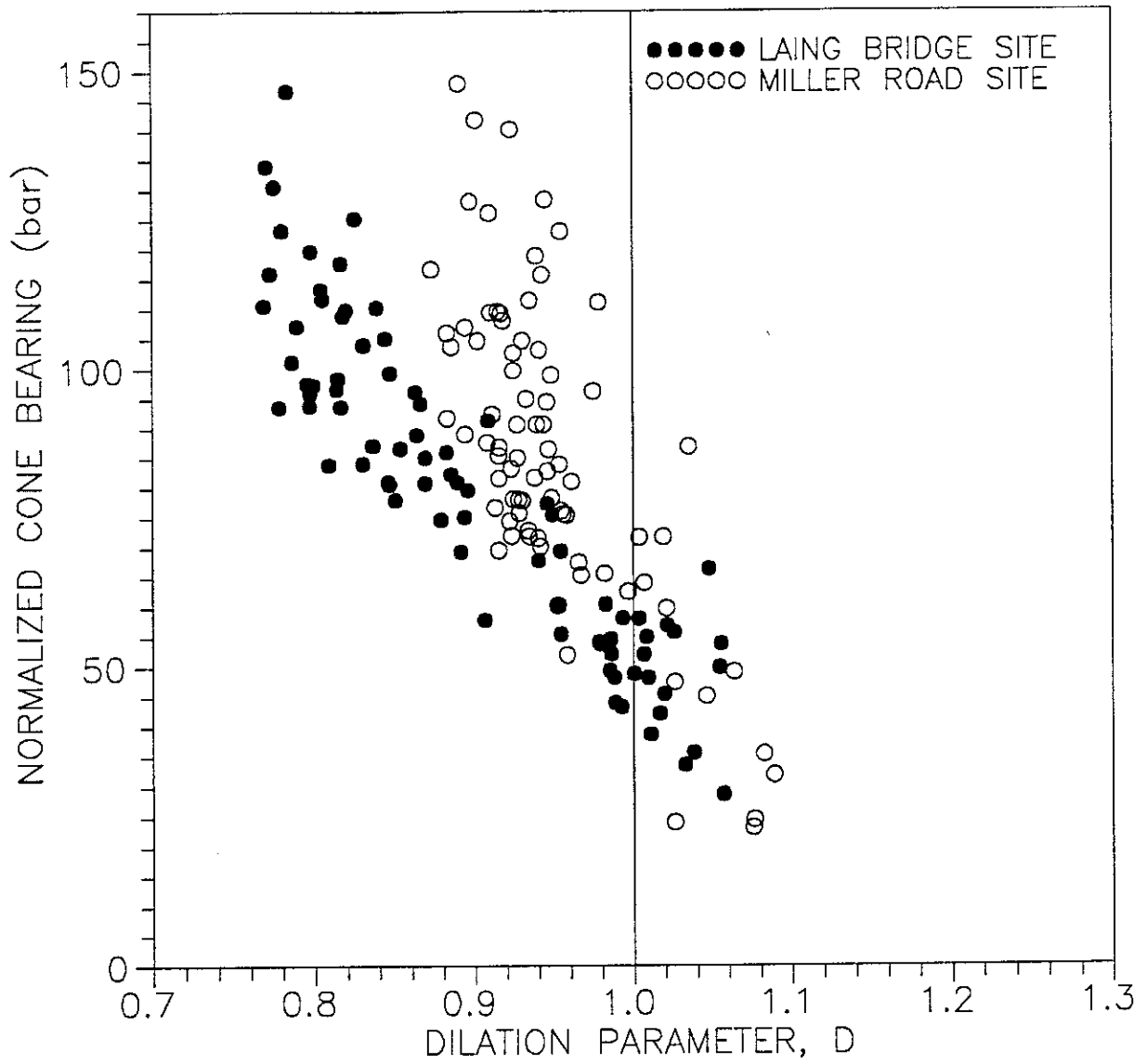


Fig. 9 Normalized Cone Bearing vs. Dilation Parameter for Laing Bridge site (sand from 4 to 14 m) and Miller Rd. site (sand from 8 to 18 m)

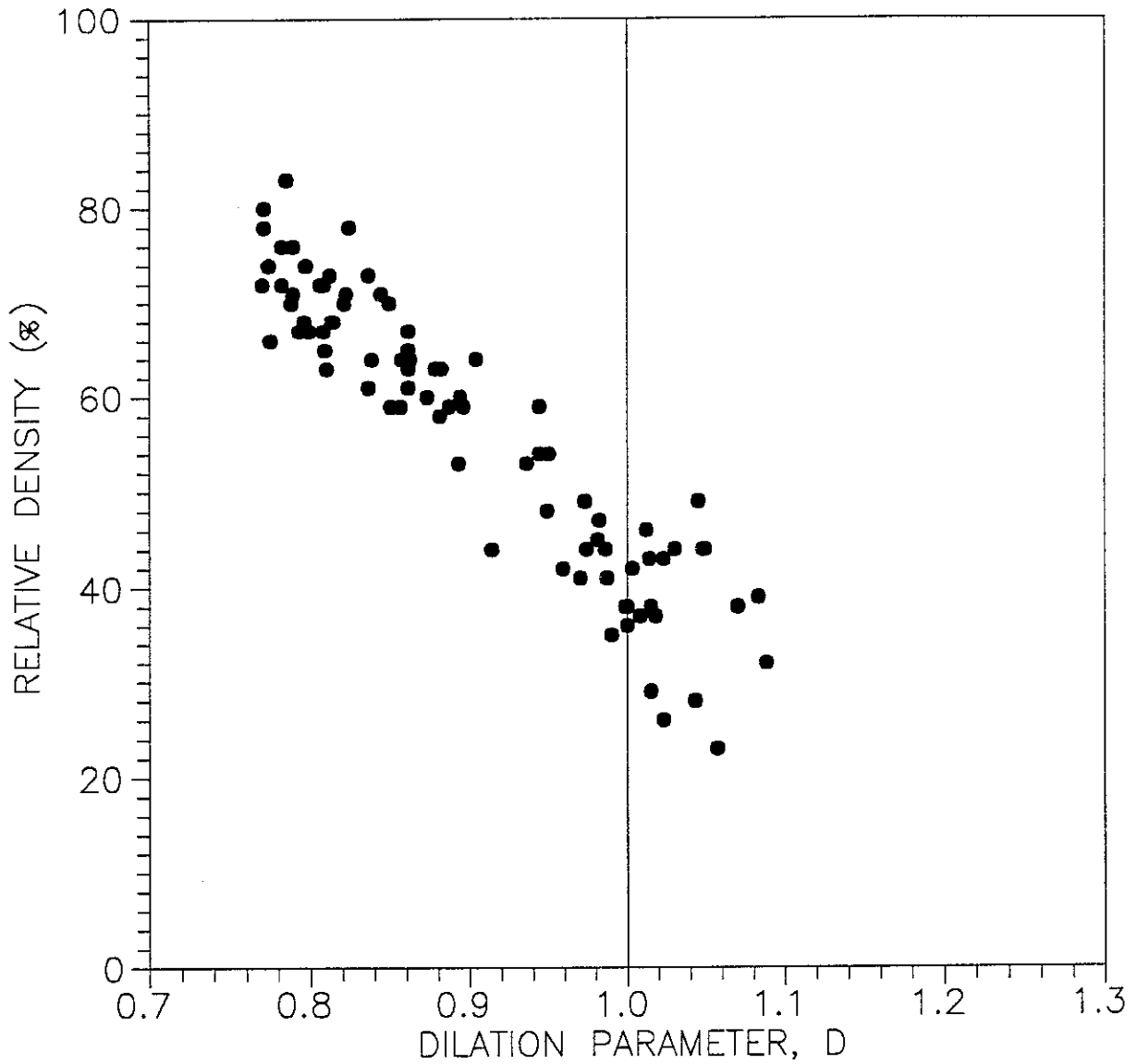


Fig. 10 Interpreted Relative Density vs. Dilation Parameter for Sand at Laing Bridge site from 4 to 14m depth

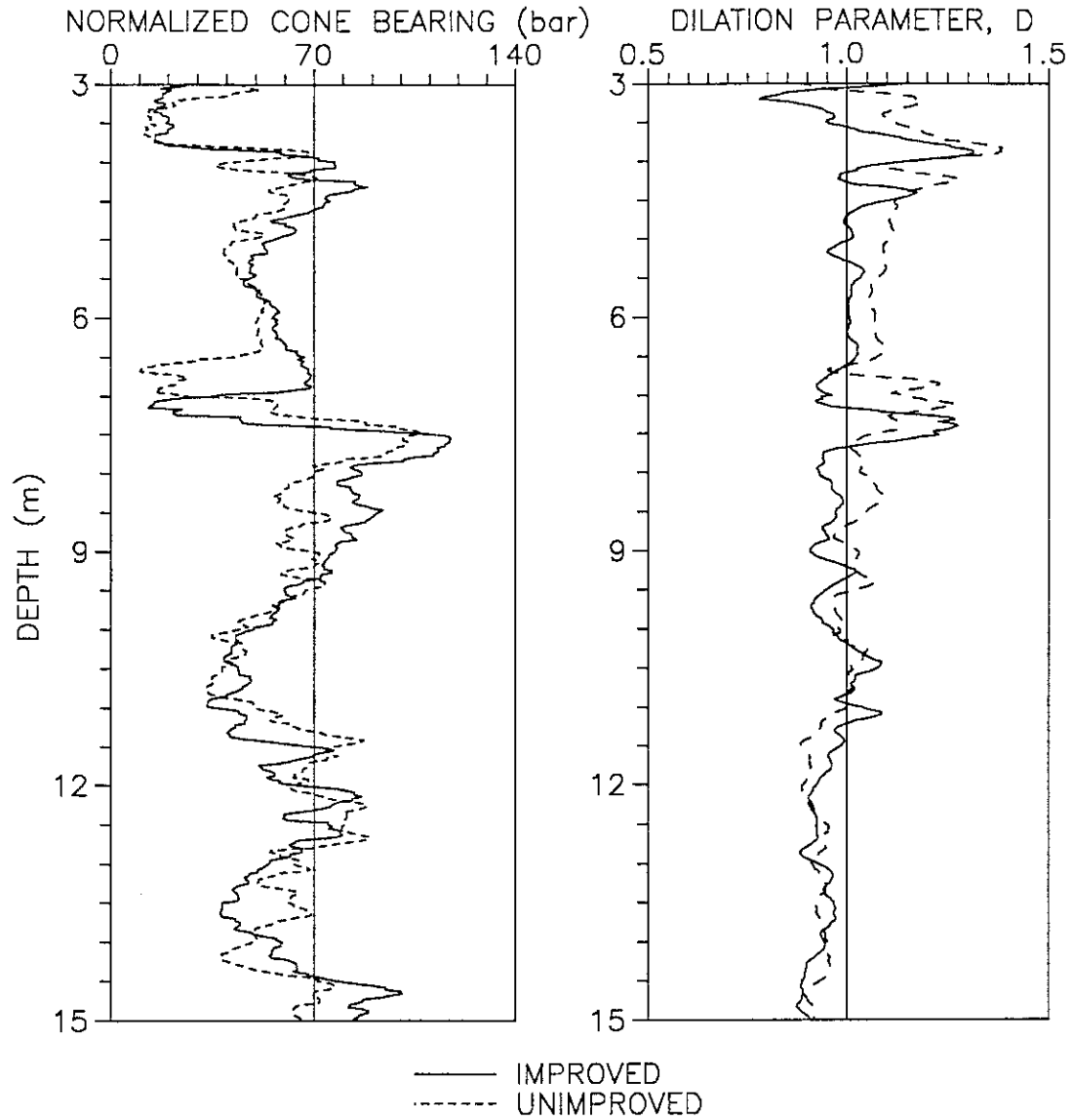


Fig. 11 Comparison of Improved and Unimproved Soil at Fraser Br. Site using Normalized Cone Bearing and Dilation Parameter.

APPLICATIONS

There are several practical applications where the RCPTU can be successfully employed to increase the level of confidence for design specifications. All of these applications would likely require the condition of saturated soil, since it has been shown that bulk soil resistivity measurements are dominated by the pore fluid resistivity. Ordinarily, high groundwater tables are associated with coastal, river delta and low land developments where most of the problems exist. The pore volume of a dry soil acts as an insulator rather than a conductor and it is unlikely that a measurable change in bulk resistivity would result from a change in density. However that aspect has yet to be fully evaluated.

Dilation parameter measurements would be particularly useful in providing a better understanding of the fundamental behavior of sands with respect to liquefaction susceptibility and volume change behavior during shearing. As an index value related to volume change behavior, the D parameter in combination with classification, strength, seismic and seepage parameters adds an enormous dimension to the interpretive power of the piezocone for site characterization.

Densification control is a particularly good application for the multiple electrode resistivity piezocone as has been demonstrated in the preceding discussion. Measurement of the Dilation parameter can be used as an additional specification for densification. Soil improvement specifications can be modified to include a required D value for densification. RCPTU could be useful in setting design specifications for man made sand islands such as those constructed in the Beaufort Sea for drilling platforms because of the relative uniformity of dredged sands used in construction and the resistivity range of the pore fluid.

In addition the resistivity measurements on their own are of particular use to study groundwater contamination and contaminant transport.(Campanella and Weemee, 1990). Because of the current environmental concerns many projects require the assessment of both physical and chemical stability. One such obvious project is the stability of mine tailings dams and waste ponds where earthquake stability and liquefaction are as important as groundwater contamination from acid drainage and toxic wastes. The advantages of a single resistivity piezocone (RCPTU) for detailed stratigraphic logging, determining seepage characteristics, liquefaction and dilatancy parameters as well as contaminant transport assessment and monitoring are obvious for such a project.

CONCLUSIONS AND RECOMMENDATIONS

The data presented from three sites illustrate the useful application of geophysical measurements, namely, soil resistivity in combination with the piezocone penetration test to the study of practical problems in geotechnics. The measurement of relative porosity changes between undisturbed and remolded sand during penetration induced shearing is a concept that is both novel and important for understanding dilatancy behavior of sands in-situ.

A dilation parameter, D , is proposed which is directly calculated from the ratio of bulk soil resistivity for closely spaced electrodes to widely spaced electrodes. As D increases, and is larger than 1, the sand is becoming more contractive during shear and as D decreases, and is less than 1, the sand is becoming more dilative. $D=1$ is the dilative-contractive boundary. The dilation parameter measurements have been shown to lie within the range of possible theoretical values. The usefulness of the D parameter measurement and the subsequent conclusions are highlighted by the fact that no pore water samples are required and no lab tests are needed to establish the critical state density.

By comparing the resistivity measurements at different electrode spacings, it may be possible to consider the effect of different levels of shearing on porosity. It is the writers belief that when accepted, the proposed dilation parameter will provide additional independent information which can be used as a practical addition to any field investigation currently using the CPTU or seismic CPTU as its principal investigative tool. It should also encourage those who are currently using other in-situ tests to gain similar information to consider the use of the RCPTU.

Further research will concentrate on changing the electrode spacings used for measuring resistivity as well as increasing the scope of test sites, especially to include ground improvement sites in loose sands. Currently a new resistivity module is being built at U.B.C. that has a maximum electrode spacing which is double the current largest spacing. This new probe will assist in determining the optimum spacing. It would also be of interest to evaluate the sensitivity of the D parameter over a wide range in pore fluid resistivity, which we feel will naturally occur with increased experience at different locations.

Probably the best technique for correlation testing is the use of a large scale calibration chamber where a sand at known uniform density and dilation characteristics would be penetrated by a multiple electrode resistivity cone.

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