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RELATED REPORTS

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ABSTRACT

A piezocone penetrometer has been developed that is capable of simultaneously measuring cone resistance, pore water pressure, and skin friction during cone penetration. The piezocone was evaluated in a marine clay deposit with established engineering properties and where previous extensive cone penetration data are available.

Results indicate that the device provides repeatable and reliable measurements and proved to be extremely useful in the determination of soil stratification and identification. In addition, pore pressure dissipation measurements when penetration stops can be used to estimate the consolidation and/or permeability characteristics of soils.

INTRODUCTION

Evaluation and development of new sophisticated in situ testing devices and techniques as a means of complementing laboratory tests in soil exploration programs have recently become the subject of renewed interest and research. In a recent article, Baligh et al. (2) presented the results of an extensive field testing program in two different soil deposits employing the FUGRO electric cone (4), which measures the cone resistance, q_c, and the skin friction, f_s, and the piezometer probe (1,5), which measures pore pressures, u, generated during steady state penetration. Unlike most in situ tests, cone penetration data are continuous and are thus very useful in detecting major changes in soil strata. Furthermore, when combining q_c and u records, a means for soil identification may also be achieved. For example, Baligh et al. (2) show that in peat, q_c is low and u is high, whereas in relatively clean sands, q_c is high and u is very close to the hydrostatic value.

The potential of q_c and u in soil exploration has led a number of institutions (e.g., the Building Research Station in England, the Norwegian Institute of Technology in Norway, Laval University in Canada, and possibly others) to develop a single cone that can measure q_c and u simultaneously. This paper describes such a device which also measures the skin friction, f_s, in addition to q_c and u. The piezocone penetrometer was evaluated in a marine illitic clay deposit and the data are compared with previous q_c and u records measured separately by means of the FUGRO electric cone and the piezometer probe. The piezocone provides repeatable and reliable measurements and is very useful in the determination of soil stratification and identification.

EQUIPMENT

The piezocone penetrometer is illustrated in Fig. 1. The cone has a 60° apex angle with a $10 cm^2$ base area and

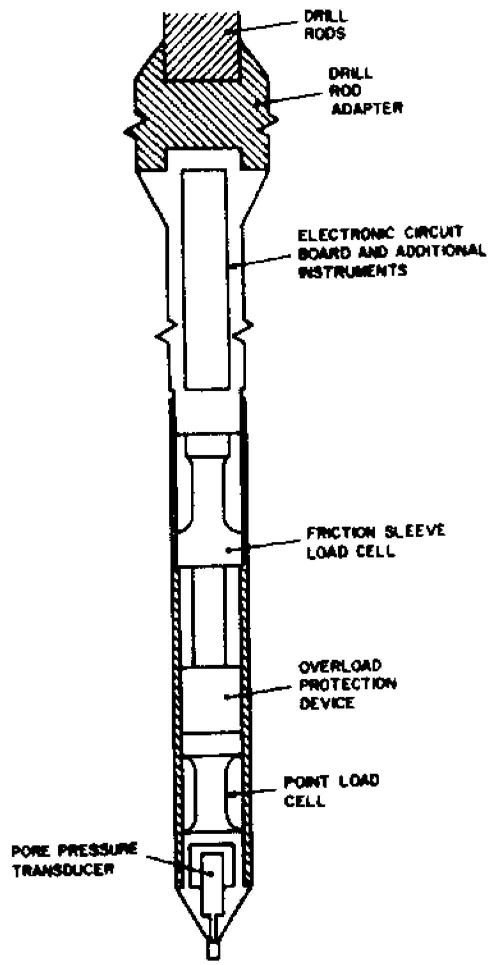


Fig 1: Piezocone Penetrometer.

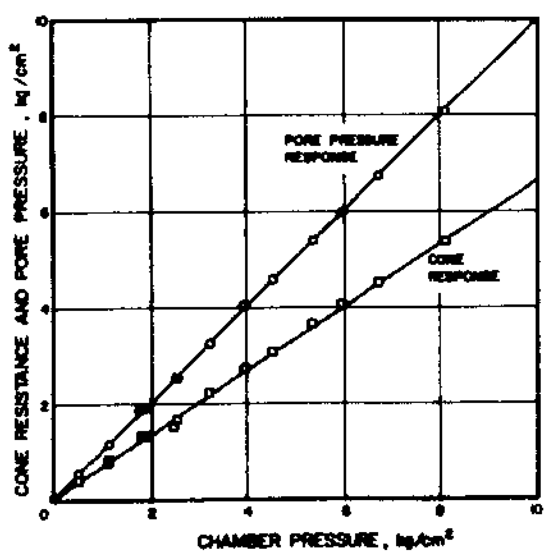


Fig 2: Results of piezocone calibration.

contains a porous stainless steel tip which is hydraulically connected to a pressure transducer for measuring the pore water pressure. The force required to push the cone is measured by a load cell located behind the porous stone (see Fig. 1). The friction sleeve consists of a freely rotating hollow cylinder of area 225cm^2 and is equipped with a load cell for measuring the friction force. Depth is recorded as an electrical signal. All data are displayed on strip chart recorders for observation during field operations and are also recorded on magnetic tapes for subsequent computer processing.

The penetrometer is equipped with a protection device to avoid overloading the load cell measuring the cone resistance. Overloading penetrometers is a major concern, especially in offshore exploration programs where time is very expensive. As a result, a large capacity load cell is usually used to allow the cone to penetrate through hard strata at the price of very poor resolution in soft clay layers. The features incorporated in this piezocone allow adoption of a sensitive cell (say 1 ton capacity) and, should a hard layer be encountered, protection pins shear thereby protecting the cell. Such an event is readily detected from the output signal and a higher capacity load cell can be easily installed.

An essential requirement for the successful use of the piezocone is careful deairing of the porous elements aimed at the removal of all gases from the pore pressure measuring system. Methods of proper deairing are described in detail in Baligh et al. (2).

Practical details of the device require an 0 ring seal to be located between the cone base and the housing mounted behind it. The positioning of this seal allows free access of water to an area at the base of the cone tip resulting in a decrease in the measured cone resistance. To evaluate this effect, the piezocone was inserted in a water-filled chamber in which known increments of pressure were applied. The resulting measurements of the pore pressure u and cone resistance q_c are plotted in Fig. 2 against the applied pressure. The results show that the pore pressure response is 100% (achieved within 0.1 second) whereas the cone resistance response is 67%.

Having established the cone resistance response, and knowing the pore pressures at the cone base(which can be estimated from those measured at the tip), the true cone resistance can be calculated. Clearly, this effect can be significant in soils in which large penetration pore pressures are generated (e.g., soft clays).

Although the actual response will vary with the particular device, this effect is common to all cones known to the authors.

SITE DESCRIPTION

The piezocone was used at a site in Saugus, Massachusetts, 160 to 200 ft to the east of the unfinished Interstate 95 embankment centerline at a location designated Station 246. This site has been comprehensively studied by M.I.T. in the last two decades. Available data include extensive cone penetration measurements taken in 1977 and presented by Baligh et al. (1) using the FUGRO electric cone and the piezometer probe.

Figure 3 shows the soil profile at the test site as determined by conventional sampling and laboratory testing methods. The upper 25 ft consist of peat, sand and stiff clay layers which overlie about 120 ft of Boston Blue Clay (BBC). Estimates of the maximum past pressures, $\bar{\sigma}_{vm}$, from conventional oedometer and constant rate of strain consolidation tests indicate that the clay above a depth of approximately 75 ft is significantly overconsolidated.

Figure 4 shows the cone penetration resistance, q_c, obtained during the 1977 program by a 60° FUGRO cone at two holes located about 25 ft apart. The figure also shows the steady state penetration pore pressure, u, at the tip

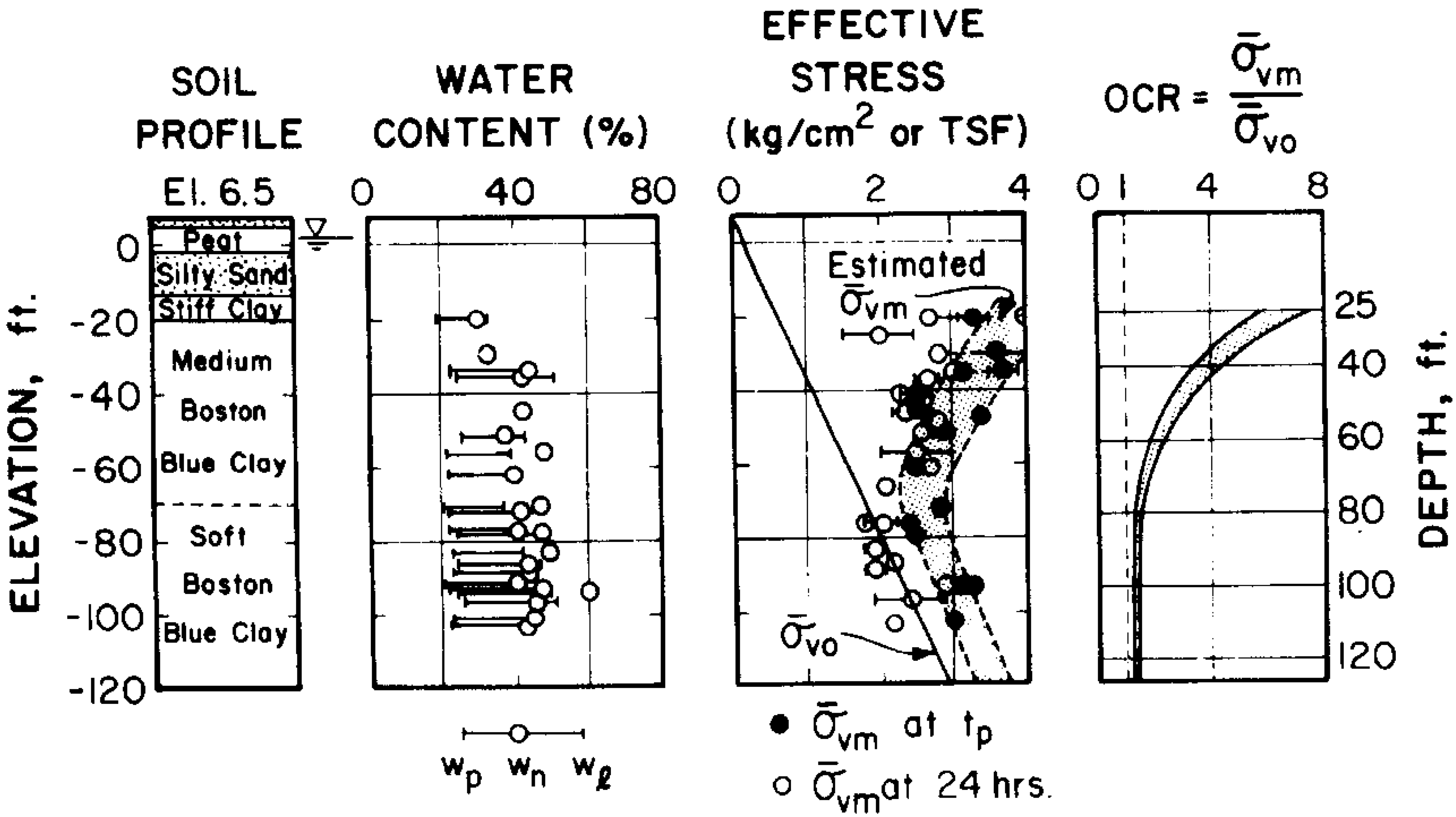


Fig 3: Soil profile in Boston Blue Clay at Station 246.

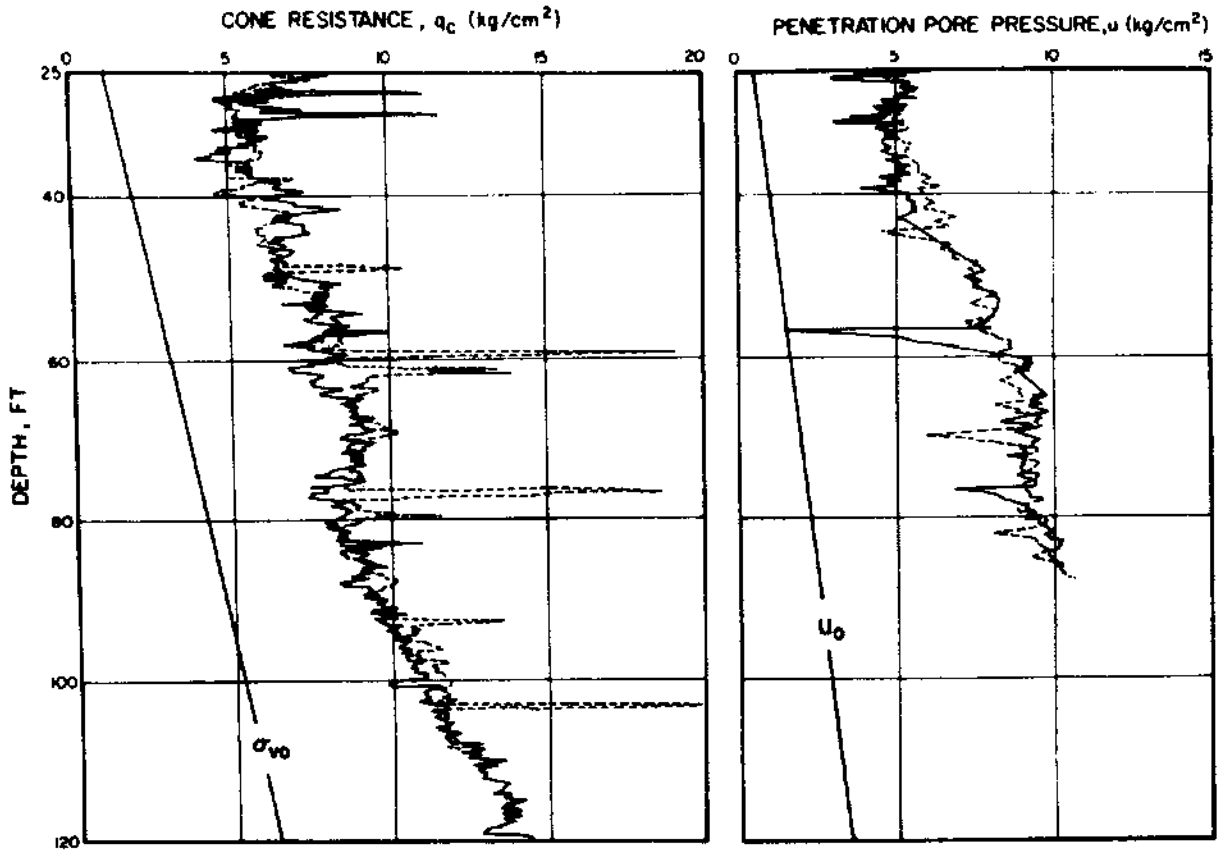


Fig 4: Previous cone penetration data at Station 246 (from Baligh et al., 1).

of a 60° piezometer probe measured in two separate holes located within a 50 ft radius from the cone tests.

TESTING PROGRAM

Cone penetration measurements were taken in two holes spaced 10 ft apart and within a radius of 50 ft of the 1977 testing holes referred to earlier. In the first hole, continuous measurements of the cone resistance, q_c, pore pressure, u, and skin friction, f_s, were taken from a depth of 20 ft down to the interface with the underlying glacial till which was encountered at a depth of approximately 140 ft.

To assess whether the presence of the porous stone at the tip affects the measured cone resistance, the porous tip was replaced by a solid dummy for the second hole. Measurements of q_c and f_s were started at a depth of 4 ft and continued through to the glacial till.

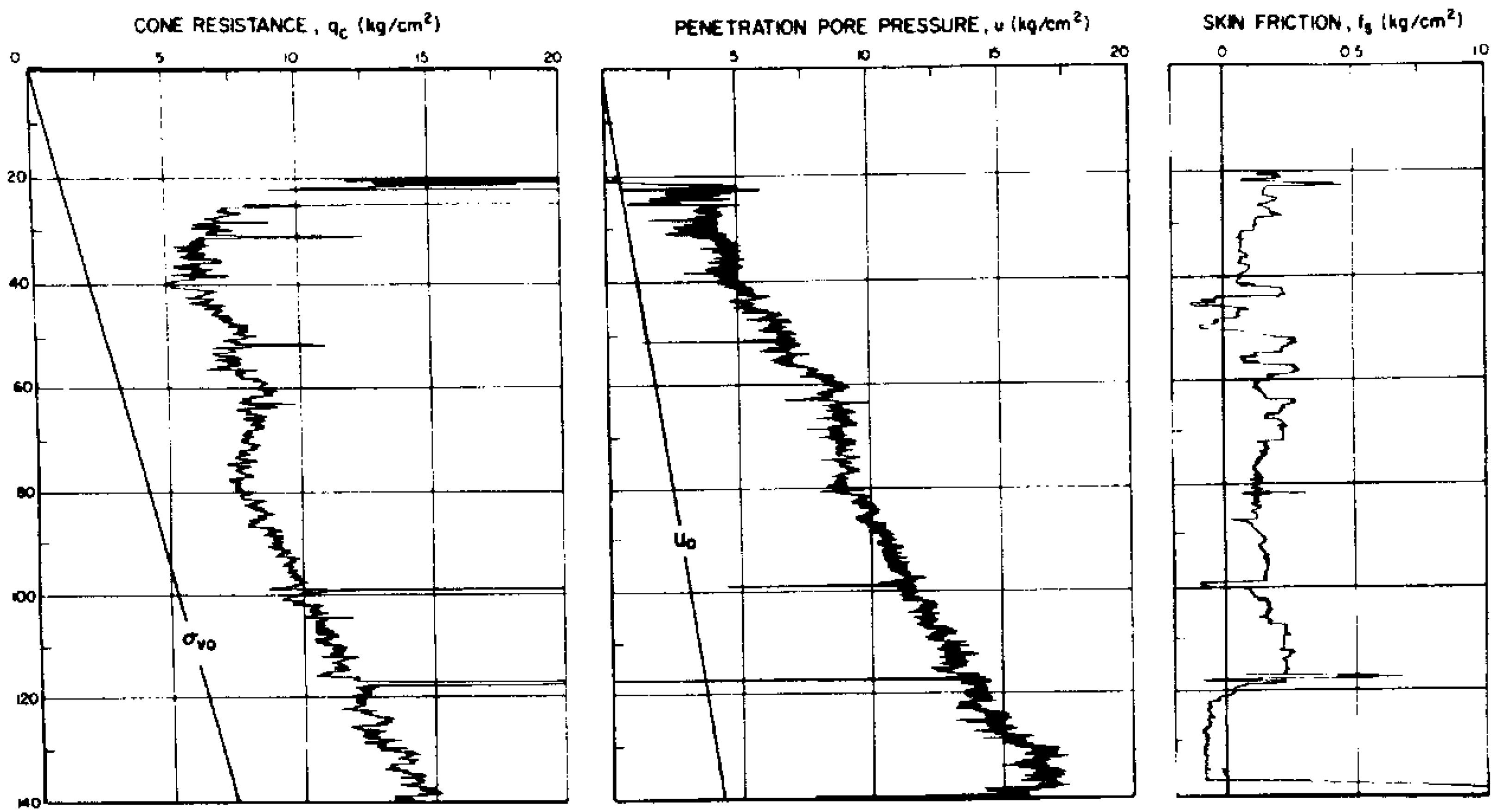
The piezocone was pushed at the rate of 2cm/sec and the measurements were recorded on magnetic tapes using a data logger and also on multi-channel high speed strip chart recorders for immediate visual display and monitoring of the load cell protection device.

RESULTS

(A) Comparison with Previous Measurements

The cone penetration data measured from the two holes using the piezocone are shown in Figs. 5 through 7. The q_c data shown in Figs. 6 and 7 are the same apart from the scales adopted. It is interesting to note that each individual record contains approximately 6,000 data points, which corresponds to a reading about every 0.25 inch.

Comparison of the q_c and u records illustrated in Fig. 5 with those measured separately by means of the FUGRO electric cone and the piezometer probe and presented in Fig. 4 shows that:



<u>Fig 5</u>: Simultaneous cone resistance, pore pressure and skin friction measurements obtained by the Piezocone.

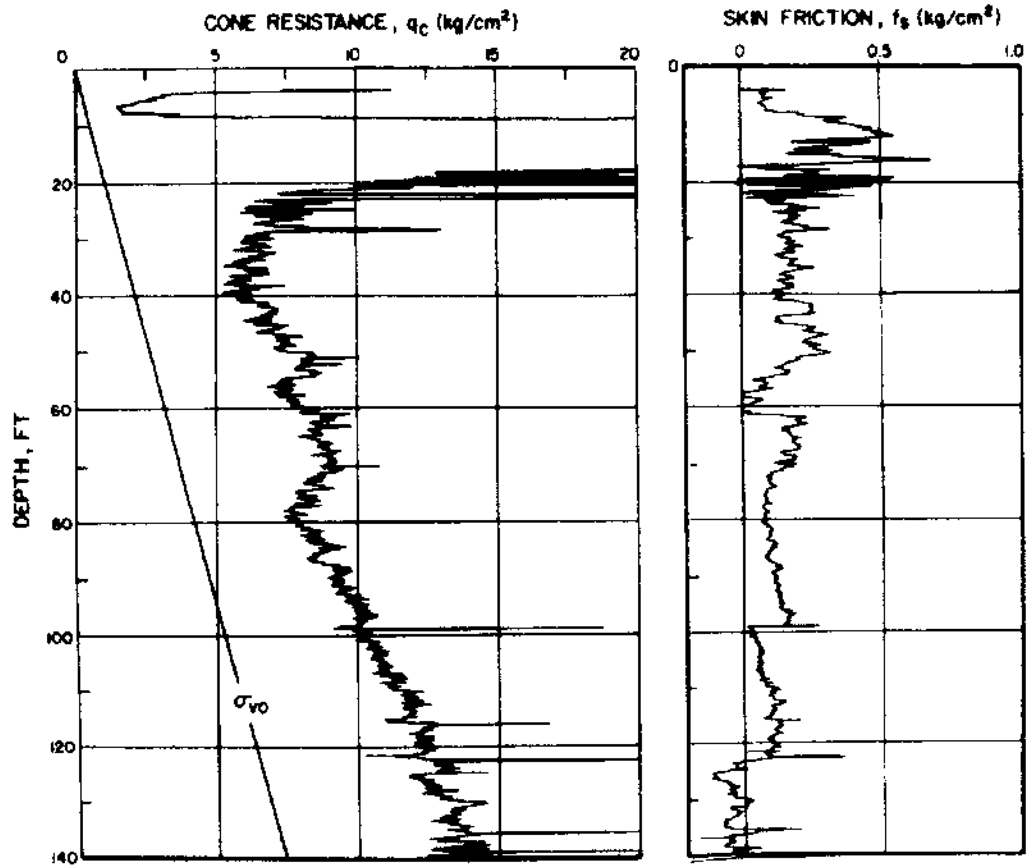


Fig. 6: Simultaneous cone resistance and skin friction data.

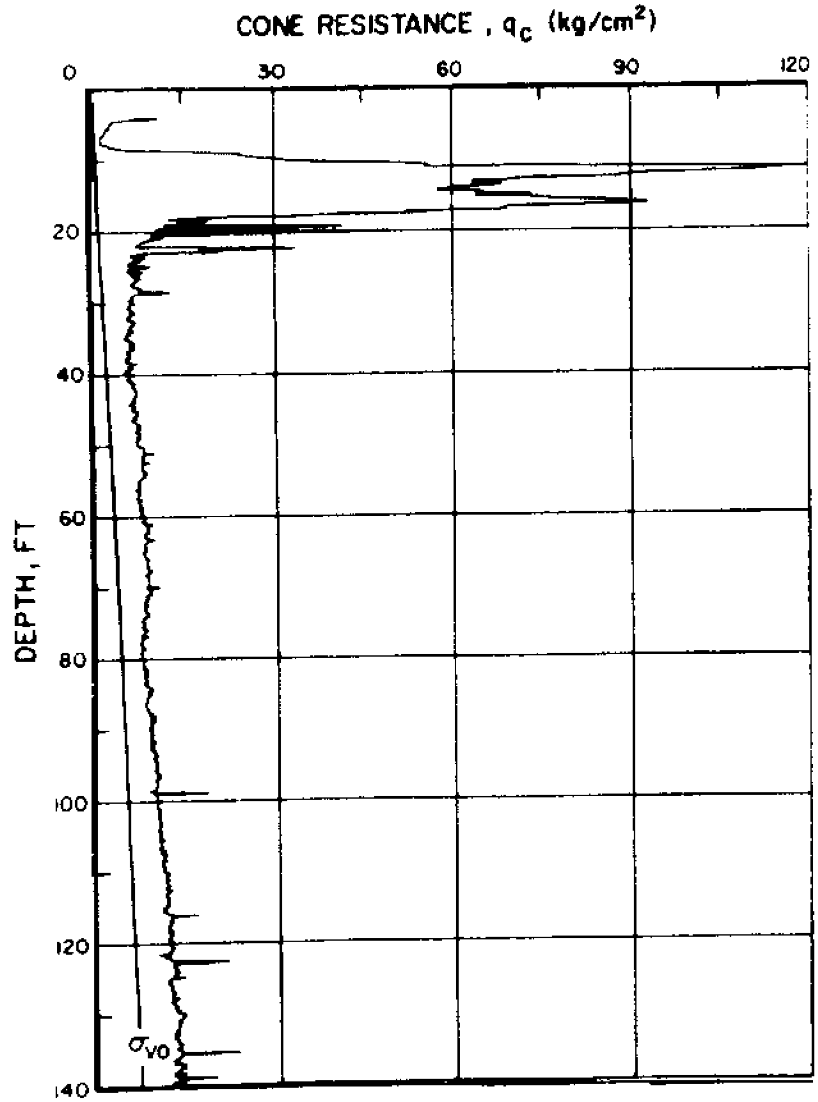


Fig 7: Cone resistance data on an enlarged scale.

(1) The pore pressure data are very similar. Note, however, that the sharp drops, indicating the existence of permeable layers, are not encountered at the same depths which means that such lenses are of limited lateral extent.

(2) The cone resistance records are basically similar down to a depth of about 75 ft, below which the q_c measured by the piezocone is smaller than that measured bythe FUGRO cone. For example, at a depth of 115 ft, q_c in Fig. 4 is approximately 20% higher than that in Fig. 5. This difference can be attributed to the higher response of the FUGRO cone (i.e., the difference between the actual and measured q_c due to the pore pressures acting at the base of the cone is smaller in the case of the FUGRO cone). Clearly, this difference becomes significant where large penetration pore pressures are generated. However, modification of these measurements using the appropriate response factors (67% for the piezocone and about 85% for the FUGRO cone) should lead to essentially identical results.

(B) Soil Stratification

The penetration results in Figs. 5 through 7 show the following:

(1) The porous stone at the tip of the piezocone has no influence on the cone resistance. The q_c data in Fig. 5 and Fig. 6 (below 20 ft) are almost identical.

(2) The upper deposits may be described as follows:

depth (ft)	Characteristics	Description
4 - 8	q_c is low with small variability (Fig. 7)	a layer of peat exists over this depth (see Fig. 3)
8 - 17	sharp increase in q_c (Fig. 7)	sand layer
17 - 30	very clear decrease in mean value of q_c with high variability. u is very low at d=20 ft and increases thereafter with large variability in magnitude.	transition zone starting with clean sand changing to sandy clay with interstitial sand lenses

(3) The underlying clay deposit below 30 ft can be divided into four sublayers as follows:

depth (ft)	Characteristic
30 - 40	u and q_c are essentially constant with some variability
40 - 60	Both u and q_c increase at approximately the same rate
60 - 77	Smaller rate of increase in both u and q_c compared to above
77 - 140	Both u and q_c increase at the same rate with small variability

The above division corresponds well with that suggested from the 1977 testing program as reported by Baligh et al. (2).

(4) At a depth of approximately 140 ft, a sharp increase in q_c accompanied by a sharp decrease in u was recorded. This corresponds to the interface with the glacial till. In fact, the u record in Fig. 5 suggests the presence of a small transition zone overlying the till.

(5) The sharp increase in q_c and decrease in u at depths of 28, 51, 99 and 117 ft suggest the presence of sand lenses at these depths. Such information is essential for the determination of drainage boundaries for problems involving the dissipation of excess pore pressures.

(6) The skin friction profiles shown in Figs. 5 and 6 initially follow the stratification established earlier. f_s in the peat layer is very small, increases substantially within the sand layer and fluctuates within the transition zone. However, in the clay, the readings are erratic and some negative values were recorded. Furthermore, sand

lenses appear to cause a shift in the skin friction output. This is illustrated at depths of 117 and 99 ft in Figs. 5 and 6, respectively. Unreasonable f_s values were also recorded during the 1977 testing program (1) employing the FUGRO cone which yielded negative values of f_s at large depths. Hence, this may suggest that the reliability skin friction measurements in clays is questionable.

(C) Pore Pressure to Cone resistance Ratio, u/q_c

Baligh et al. (2) introduced the ratio u/q_c as a possible soil identification method for deposits where the water table is at or near the ground surface. They suggest that this ratio reflects changes in the degree of overconsolidation within clay deposits.

Using the values of q_c and u in Fig. 5, the corresponding ratio u/q_c has been calculated and is plotted in Fig. 8, where we note:

(1) u/q_c increases with depth down to approximately 80 ft and then remains constant. Such a trend agrees well with the OCR profile presented in Fig. 3 which shows the OCR to decrease from a value of about 7 at depth 25 ft to about 1.2 at depth 80 ft and remains constant thereafter.

(2) The value of u/q_c shown below a depth of 80 ft is greater than unity which is unrealistic (2). This inaccuracy is a direct result of the pore pressure acting on the portion of the base of the cone tip leading to the reduction in the measured q_c values as discussed earlier.

Based on the results of the extensive testing program carried out in 1977, Baligh et al. (1) show that for this deposit, the pore pressures at the cone base are approximately 10% smaller than those generated at the tip. Combining this and the cone response of 67% as established in Fig. 2, the modified cone resistance is given by:

$$
\left.\begin{aligned}
(q_c)_{mod} &= (q_c)_{meas} + 0.33u_{base} \\
&= (q_c)_{meas} + 0.33(0.90u_{tip}) \\
&= (q_c)_{meas} + 0.30u_{tip}
\end{aligned}\right\} \qquad (1)
$$

The measured q_c record presented in Fig. 5 was modified according to Eq. (1) and the resulting $(u/q_c)_{mod}$ are presented in Fig. 8 from which it can be seen that the ratio in the lower clay is approximately 0.85.

(3) Since u and q_c are measured simultaneously by means of the piezocone, the ratio u/q_c is also useful in the determination of soil stratification. For example, the u/q_c profile clearly detects the sand lenses at depths 51, 99 and 117 as well as the location of the glacial till.

(D) Dissipation of Pore Pressures

Subsequent to penetration, dissipation of the generated pore pressures occurs. Baligh and Levadoux (3) have developed a theory for predicting the consolidation characteristics of soils from measurements of the pore pressure dissipation with time. Using their theory along with the dissipation records obtained by the piezometer probe, they predicted that the coefficient of consolidation in the horizontal direction, c_h, in Boston Blue Clay below a depth of 60 ft is constant with depth and is equal to $0.04 cm^2/sec$.

The normalized dissipation records obtained from the piezocone below 60 ft are plotted versus time in Fig. 9, in which:

u = pore pressure at time t
u_i = pore pressure at the end of penetration
u_o = hydrostatic pore pressure

The predicted dissipation curve obtained by Baligh and Levadoux (3) based on $c_h = 0.04 cm^2/sec$ is shown in Fig. 9 to agree well with the piezocone dissipation records.

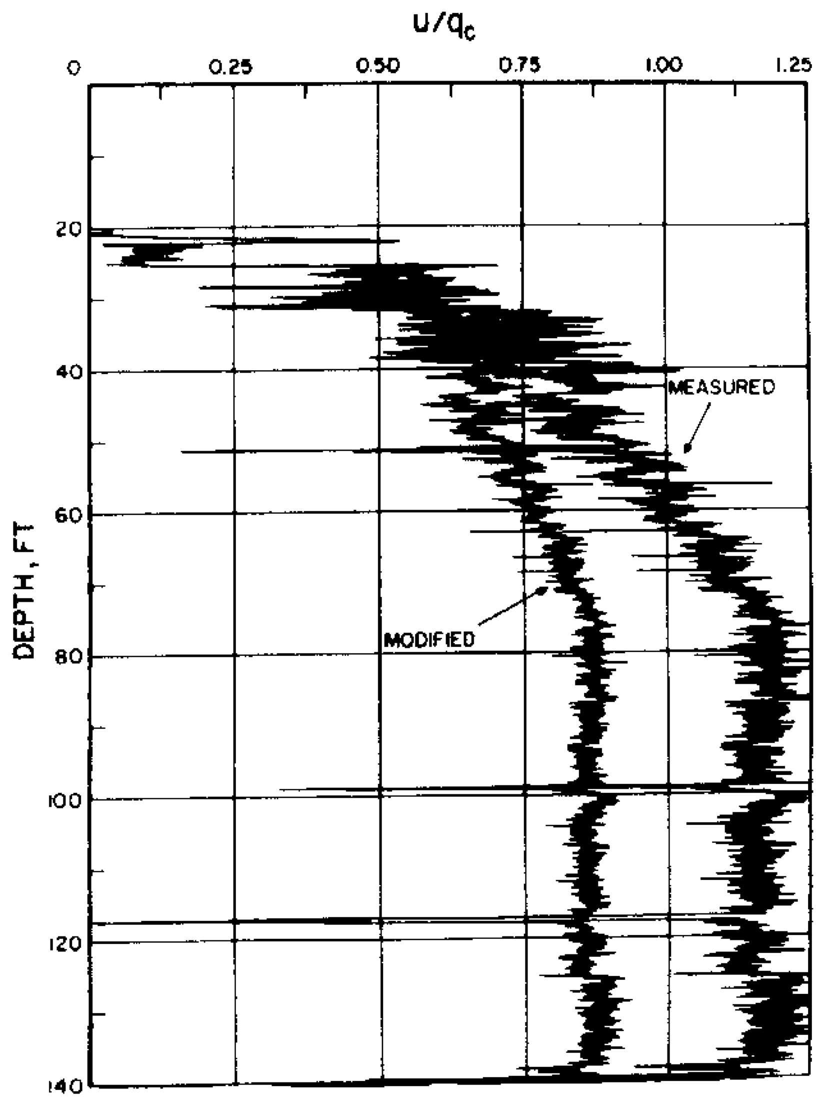


Fig 8: Pore pressure to cone resistance ratio.

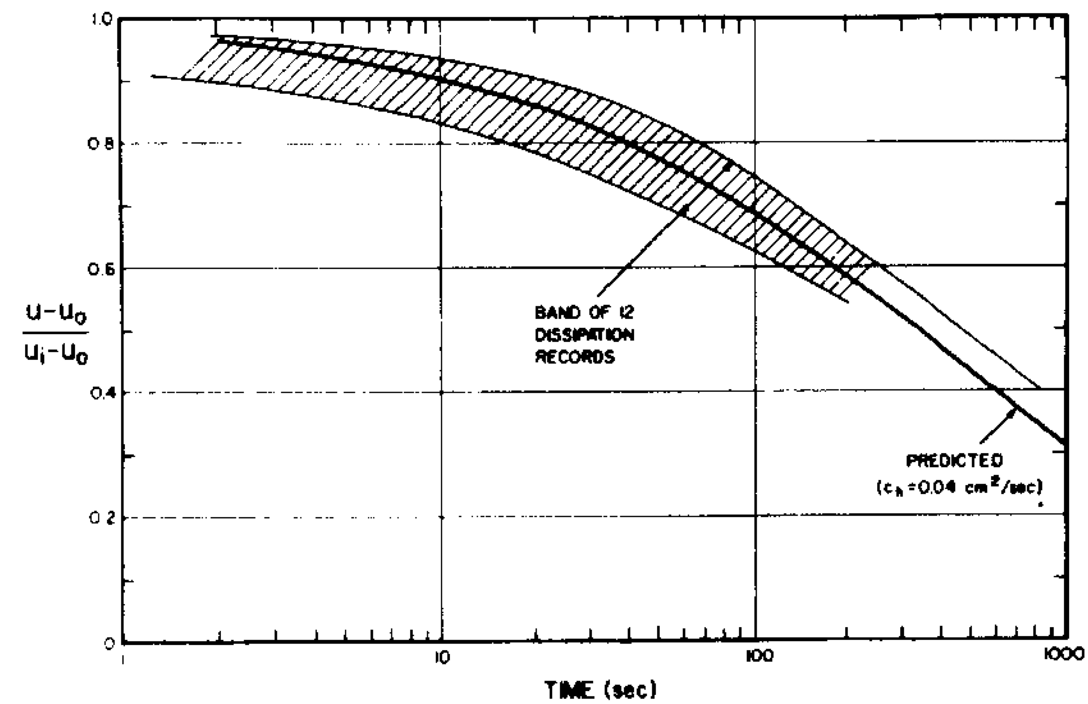


Fig. 9: Normalized dissipation record below 60 ft in Boston Blue Clay.

CONCLUSIONS

This paper presents a new device which is capable of simultaneously measuring the cone resistance, pore pressures and the skin friction during cone penetration. The piezocone penetrometer was evaluated in a marine illitic clay deposit with established engineering properties and where extensive previous cone penetration measurements are available. Based on the results, the following can be concluded:

(1) The cone penetration records obtained by the piezocone are essentially similar to those previously determined separately by the FUGRO electric cone and piezometer probe.

(2) The porous stone located at the tip of the piezocone for measuring the penetration pore pressure has no effect on the cone resistance.

(3) The cone penetration data is repeatable and consistent, and since a continuous record is provided, it allows a good definition of soil variability and stratification.

(4) The piezocone is particularly useful in detecting interstitial layers which can be important in the assessment of stability and drainage boundaries for foundation designs.

(5) With u and q_c being measured simultaneously in the same hole, the ratio u/q_c reflects changes in soil stratification. Furthermore, the ratio may reflect changes in the overconsolidation ratio within a clay deposit.

(6) At the present time, the reliability of skin friction measurements in clay deposits seems to be questionable.

(7) Using the recent theory developed by Baligh and Levadoux (3), and the pore pressure dissipation records obtained after penetration, values of the coefficient of consolidation in the horizontal direction can be obtained.

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