Tests in Alluvial Sand with the PQS Probe

Essais dans le Sable Fluviatile avec la Sonde PQS

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SYNOPSIS The PQS probe, combining the functions of the electric friction cone and the piezometer probe, provides simultaneous measurement of penetration resistance and pore water pressure. Data from cohesionless point bar deposits of the Lower Mississippi Valley indicate that the excess pore pressure induced during probe penetration consists of a component related to the total normal stress at the cone tip and a component related to contractive or dilative response accompanying shear strains induced by the probe. The behavior of the pore pressure after termination of the probe advance is related to the density, permeability, and homogeneity of the soil.

INTRODUCTION

The need of the Corps of Engineers for in situ tests to evaluate the relative density and liquefaction potential of cohesionless soils has led to the development of the PQS probe, which simultaneously measures penetration resistance and pore water pressures induced in the soil by the advance of the probe. Penetration resistance is measured electrically as the axial load on the point (Q) and the shearing force on the friction sleeve (S); the pore pressure (P) is measured through a porous filter element at or near the cone tip.

The design and use of piezometer probes have been described by Wissa et al. (1975) and Torstensson (1975). Schmertmann (1978a) used the Wissa probe to examine the dilation-contraction response of a mine tailings sand in Florida. Baligh et al. (1979) present a considerable body of data from cone penetration tests (CPT) and piezometer probes in three clay deposits. The studies of Schmertmann and Baligh et al. show the value of complementary use of CPT values and pore pressures, though the correlations in those studies were necessarily made between pore pressures and CPT values obtained in different soundings.

THE PQS PROBE

A primary consideration in the design of the PQS probe was the need to adopt a standardized geometry so that direct comparisons could be made with data obtained with the conventional CPT. For this reason the PQS probe was designed to conform to the external geometry for electric cones given in ASTM Tentative Method D 3441-75T (1975).

As shown in Fig. 1, the prototype unit is composed of six pieces, including a mandrel, strain-gauged housing, friction sleeve, pressure cell, cell retainer, and cone tip.

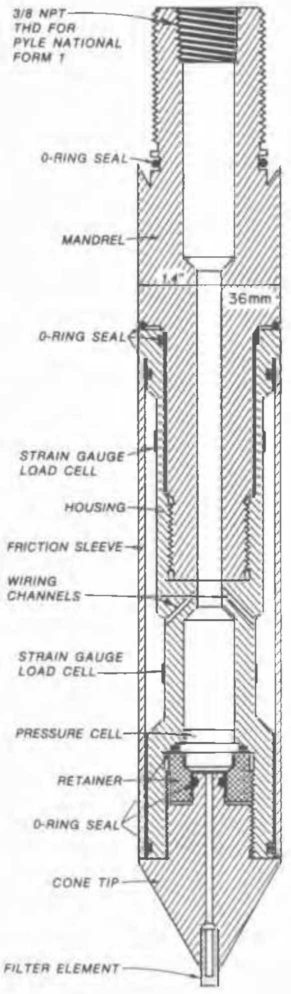

Fig.1 PQS probe, sectional view

The pressure cell retainer is machined from bronze, the mandrel from 1141 CR steel, and the remaining parts from 304 series stainless steel which was selected primarily for its resistance to rust and corrosion during wet storage. The gauge housing provides for independent measurements of sleeve friction and point resistance, and locates the pressure cell as close as possible to the porous tip in order to minimize internal water volume. The skirt of the housing reacts the frictional forces generated during penetration and these forces are measured as a tensile strain in the strain-gauged section of the housing which surrounds the mandrel. Axial forces are measured as compressive strains in the strain-gauged housing section immediately behind the pressure cell. All electrical wiring is brought through the center hole in the mandrel and exits the probe via a Pyle-National sealed fitting. A sealed adapter above the probe houses a cable connector, and the wiring from this connector is routed to the surface inside the jointed drive pipe. Drive forces, both frictional and axial, are transmitted to the mandrel at the flat machined interface between mandrel and housing.

The friction sleeve is provided with sufficient clearance lengthwise so that the tip cannot transfer axial load to the sleeve, and sleeve "O" ring seals as well as special coatings are used to protect the strain-gauged sections from entry of fluids. The interchangeable flanged tip transfers axial penetration loads directly to the machined face of the housing, and a short internal channel communicates pore pressure from the porous element to the 100-psi (690 kPa) rated CEC strain-gauged pressure cell. Interchangeable tips with other placements of the porous element are also used. The stainless steel porous element has a nominal pore size of 2 μm, which has been found to be sufficiently permeable to allow rapid response of the pressure cell while having a sufficiently high air entry pressure to maintain saturation during short periods of exposure of the cone to air.

The overall design was based on a maximum allowable stress of 30,000 psi (207 MPa) in the 304 stainless steel structural elements, and 70,000 psi (483 MPa) in the 1141 CR steel mandrel. This equates to a maximum allowable force limit of 15,000 lb (67 kN), or a maximum of 9000 lb (40 kN) force on the tip (q = 400 tsf, or 38 MPa) plus 6000-lb (27-kN) force on the friction sleeve (i.e. a friction ratio of 1 percent at maximum tip load). Design details are given by Cooper and Franklin (1981).

The pressure cell, sleeve friction, and point penetration load cells were calibrated by independent loadings, but all channels were monitored during each loading cycle so as to detect any crosstalk between channels. Tests included application of axial (point penetration) loading to the fully assembled and saturated probe. Calibration test results indicate that all three sensors of the PQS probe have linear response to within ±1/2 percent up to maximum capacity, and that mechanical and electrical crosstalk between sensors is typically within 1.5 percent to maximum capacity. Bench tests of dynamic response indicate that pressure impulses with rise times of 1.5 msec to 10 psi (69 kPa) can be accurately measured with the PQS probe using a 2-μm porous element in the tip.

Complete saturation of the internal water channels and porous filter of the probe is essential. This is accomplished by evacuating the probe in a vacuum chamber, saturating with de-aired water, and capping the tip with a plastic cover filled with de-aired water during storage periods prior to use. Saturation is checked in the field before and after soundings by measuring the response to a brief impulsive pressure load of 10 to 15 psi (70 to 100 kPa).

TEST RESULTS IN POINT BAR DEPOSITS

The recent point bar deposits of the Lower Mississippi River typically consist of fine quartz sand with intercalated bodies of fine-grained, plastic slough deposits. These sands have a wide range of densities, and in places are subject to flow slides. Fig. 2 shows an example of a record obtained in these materials. The cone bearing capacity, q (the "Q" curve), and the friction ratio, f , are the same as in the conventional CPT. The "P" curve shows the pore water pressure, p , measured at the cone tip during and after the advance of the probe. Next to the friction ratio curve is a curve showing the ratio u/q of the excess pore pressure to the cone bearing capacity. Also noted on the P curve are the time intervals between increments of probe advance. The duration of the interval is governed in most

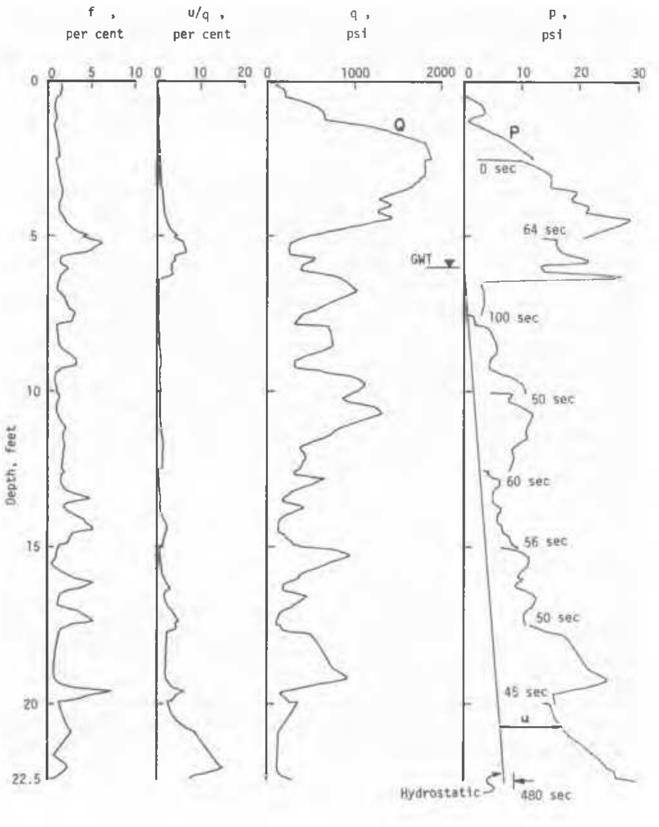

Fig. 2. Log of sounding at Delta, La. (NOTE: 1 ft = 0.3048 m; 1 psi = 6.895 kPa)

instances by the time required to add a length of drill rod to the string, approximately 50 to 60 sec. The probe was pushed in 2.5-ft (76.2 cm) increments, at a rate of 2 cm/sec, to a depth of 22.5 ft (6.86 m).

There are several noteworthy features on this record. First, the pore pressure ratio u/q is generally quite low, on the order of 1 to 2 percent, in the sand intervals. Peaks as high as 5 to 7 percent occur in zones where low cone bearing and high friction ratio values indicate cohesive soils. Torstensson (1975) also noted that excess pore pressures measured in clay were several times greater than in sand. Baligh et al. (1979) show piezometer tip pore pressures in Boston Blue clay and Atchafalaya Basin clay that approach, and even exceed, q . Pore pressure ratios greater than 1.0 are attributed to inaccuracies in q measurements, and it is noted that pore pressures acting behind the tip lead to underestimation of the actual cone resistance. This may also affect measurements with the PQS probe, though in clean sands it cannot be important with the magnitudes of pore pressures so far observed.

In sands of intermediate density, the P and Q curves typically show a distinct tendency to parallelism. Fig. 3 shows the 17.5 to 22.5 ft (5.33 to 6.86 m) interval of the same record, plotted on a time scale and showing the instrumental records for the time intervals between advances of the probe as well as during the advances. The parallelism of the P and Q curves in the 17.5 to 20 ft (5.33 to 6.10 m) interval is particularly striking. From the correlations given by Schmertmann (1978b), the 17.5 to 19.5 ft (5.33 to 5.94 m) interval should be sand with a relative density in the range of 45 to 75 percent, while a thin cohesive soil zone appears in the 19.5 to 20 ft (5.94 to 6.10 m) interval. The parallelism does not hold for the 20 to 22.5 ft (6.10 to 6.86 m) interval. The evidence indicates that the soil from 20 to 22 ft (6.10 to 6.71 m) is a very loose sand which collapses as it is disturbed by the probe. The P curve builds up steadily with penetration to about 26 psi (179 kPa), while q drops to a value of 115 psi (793 kPa). The friction ratio is about 2 percent. According to the same correlations, such values are indicative of loose sand or sand-silt mixtures, and if sand, with a relative density of the order of 5 percent. The pore pressure ratio reaches a value of about 16 percent and appears to stabilize until the character of the soil changes at 22 ft (6.71 m).

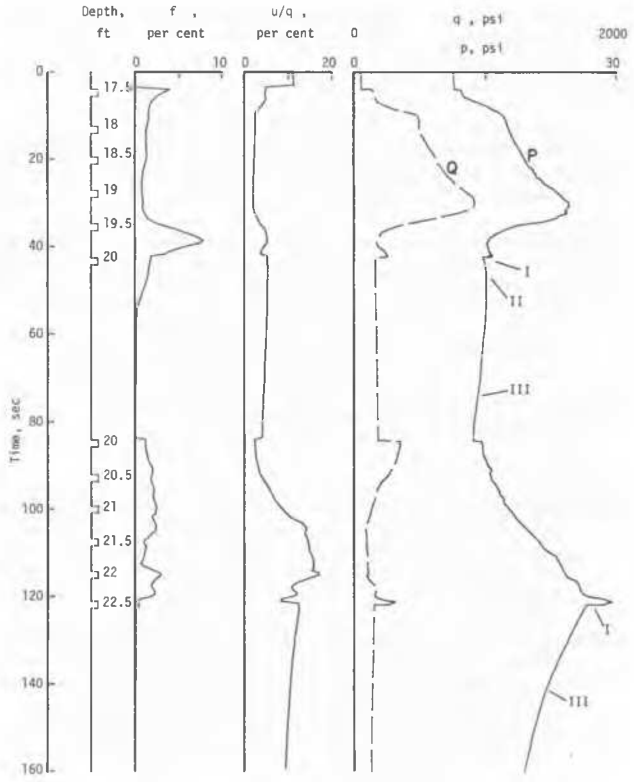

Fig. 3. Time record of a segment of the Delta sounding

Additional insight into the behavior of the soil can be gained from examination of the pore pressure curve in the interval between advances of the probe. From the data observed so far, it is found that the pore pressure curve during this interval can in general be described in terms of three phases of response. Phase I (see Fig. 3) consists of a rapid drop in pore pressure which accompanies a similar drop in the Q curve. This occurs within a few milliseconds after the probe stops, and in all cases seen so far is in the negative direction. This is interpreted as volumetric elastic rebound of the pore water. Taken together with the tendency to parallelism of the P and Q curves, this is evidence that a major component of the pore pressure response, and the dominant one in the 17.5 to 20 ft (5.33 to 6.10 m) interval, is volumetric response of the pore water at the face of the cone to the increase in total mean normal stress. By contrast, the pore pressure response in the 20 to 22 ft (6.10 to 6.71 m) interval is dominated by the collapse response to shear deformations caused by the probe.

Phase II of the pore pressure response curve is a buildup of pore pressure, lasting in this instance for about 9 seconds, before the trend reverses and the pore pressure starts to approach the hydrostatic value. The Phase II buildup seen in Fig. 3 represents about 0.5 psi (3.4 kPa) increase in pore pressure. A sounding made about 5 ft (1.5 m) away, using a penetration rate of 4 cm/sec, or twice the rate represented by Fig. 3, showed the same behavior of both P and Q curves, except that the Phase II buildup amounted to 7 psi (48 kPa), reached in 15 sec. It seems clear that the Phase II behavior is due to pore pressures in the collapsing zone below the cone, and with the cone tip halted just above, or in the top of, the collapsing zone, being communicated to the pressure cell by upward flow of water. It is hypothesized then that Phase II response in general represents shear-induced dilation at some remove from the pore pressure sensor. It could be either positive or negative in sense.

In most cases, Phase II behavior is not seen, and Phase I is immediately followed by Phase III, an asymptotic approach to the equilibrium pore pressure (which normally is the hydrostatic).

This can be seen at 22.5 ft (6.86 m) depth in Fig. 3, where the typical shape of the dissipation curve, resembling a negative exponential curve, is shown. Torstensson (1975) has related the time for 50 percent excess pore pressure dissipation in clay to the coefficient of consolidation. In sands, the permeability is greater and consolidation consequently more rapid. Typical times to 50 percent excess pore pressure dissipation are on the order of a few seconds.

Denser sands were encountered in point bar deposits at a site near LaPlace, Louisiana. Fig. 4 shows a time record of the interval from 50 to 53 ft (15.24 to 16.15 m). The probe was advanced in 1 ft (30.48 cm) increments, at a rate of 1 cm/sec. The groundwater table was at 6 ft (1.8 m). An example of dilatant response can be seen in the pore pressure behavior during the pause at 52 ft (15.85 m). At the end of the probe advance, the pore pressure value is very close to hydrostatic, and the subsequent Phase I response is a decrease of -13 psi (-90 kPa). Phase II is absent, and the Phase III pressure dissipation is relatively rapid, with 50 percent dissipation in 3-1/2 seconds. According to Schmertmann's correlations, the relative density of the sand in the interval of 51 to 52 ft (15.5 to 15.8 m) should be in the range of 60 to 80 percent.

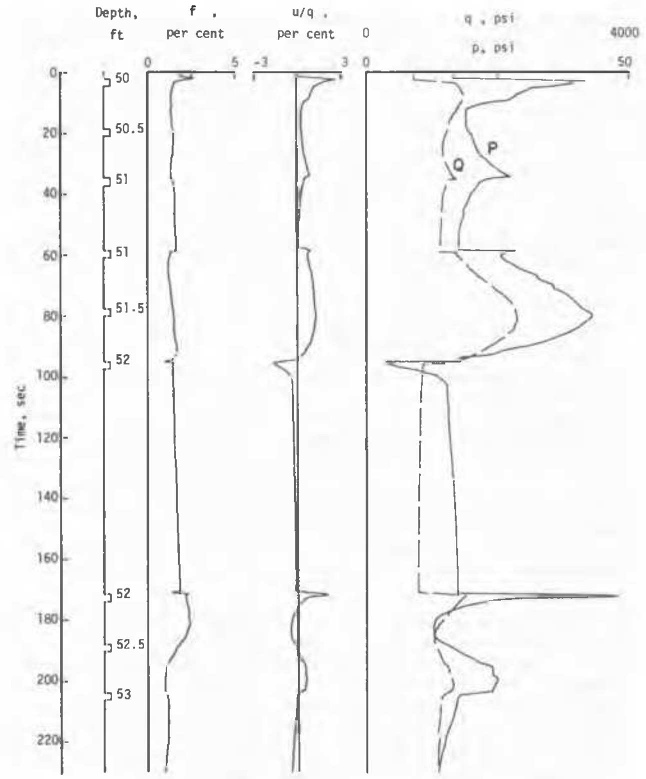

Fig. 4. Time record of a segment of sounding at LaPlace, La.

CONCLUSION

Experiences with the PQS probe in point bar deposits have shown that simultaneous measurement of friction cone penetration parameters and the pore water pressures induced by penetration is reliable and requires little additional effort over that required for the CPT alone. The evidence of these and earlier investigations is that the induced pore pressures are linked to soil conditions or properties, rather than being controlled by details of test procedure. The ratio of the induced excess pore pressure to the cone bearing capacity is much lower in sands than in clays, being usually of the order of a few percent, either positive or negative. It bears an inverse relationship to relative density, although the limited data available to date do not justify the drawing of correlation curves. Simultaneous measurement of penetration resistance and pore pressures at the same location provides a basis for an improved understanding of the mechanisms involved in both kinds of response, and additionally, the pore pressure behavior during pauses between penetration increments, while relatively complex, offers important information on soil behavior.

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