Soil Stratification Using the Dual-Pore-Pressure Piezocone Test

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Among in situ testing techniques presently used in soil stratification and identification, the electric quasistatic cone penetration test (QCPT) is recognized as a reliable, simple, fast, and economical test. Installation of pressure transducers inside cone penetrometers to measure pore pressures generated during a sounding has added a new dimension to QCPT—the piezocone penetration test (PCPT). In this paper, some of the major design, testing, de-airing, and interpretive problems with regard to a new piezocone penetrometer with dual pore pressure measurement (DPCPT) are addressed. Results of field investigations indicate that DPCPT provides an enhanced capability of identifying and classifying minute loose or dense sand inclusions in low-permeability clay deposits.

The construction of highway embankments and reclamation projects in deltaic zones often requires continuous soil profiling to establish the stratification of heterogeneous soil deposits. It is of particular significance to identify in these freshly deposited soils the presence of loose sandy layers that could potentially liquefy. The piezocone penetration test (PCPT) offers the unique capability of continuous, detailed, and simultaneous monitoring of the excess pore water pressures generated during penetration, along with the conventional measurements of tip resistance and/or sleeve friction. Therefore, during the last 15 years, PCPT has been extensively used in geotechnical investigations to establish soil stratification.

Significant research has been conducted by several investigators (1-17) to evaluate the effect of the main design, testing, and performance parameters (specifically: the cone shape, diameter and apex angle, and configuration; as well as the location of the piezometric element, and the penetration rate) on the pore water pressures measured during penetration.

Most of these studies have been conducted in fine-grained low-permeability soils. They have demonstrated that the location of the piezometric element has a major effect on the magnitude of pore water pressures measured ($u_0$). The fundamental differences in the strain paths at the cone tip and along the penetrometer shaft result in a significantly different pore water pressure response. At the cone tip, the soil is subjected to both maximum compression and interface shear. The generated pore water pressures ($u_0$) are primarily dominated by the increase of normal stress which can be related to the point resistance. Along the penetrometer shaft, and in particular immediately behind the cone friction sleeve, the soil is subjected mainly to shearing, and the measured pore water pressures depend primarily on the tendency of the saturated soil to dilate or contract during shearing. The pore water pressures measured at the cone tip and the shaft immediately behind the cone tip were found to be highly dependent upon the stress history, sensitivity, and stiffness-to-strength ratio of the soil. Therefore, several charts dealing with soil classification and stress history [i.e., overconsolidation ratio (OCR)] have been developed using the point resistance and the excess pore water pressures measured immediately behind the tip (18-20) and at the cone tip (6,16), respectively.

Interpretation of excess pore water pressures ($\Delta u = u_0 - u_0$, where $u_0$ is hydrostatic water pressure) measured in sandy soils, and their use in soil classification, are more complex because the magnitude of these pore water pressures is highly dependent upon the ratio of the penetration rate to hydraulic conductivity of the soil. However, an attempt has been made to incorporate pore pressures measured in silty fine sands at the standard penetration rate of 2 cm/sec in the classification charts. Moreover, as the pore water pressures measured along the penetrometer shaft immediately behind the tip were found to be highly sensitive to the dilatant/contractive behavior of these soils (20,21), the piezocone appeared to provide a unique testing capability for identifying potentially liquefiable loose sand seams in freshly deposited stratified soils.

To enhance this capability, the concept of a “dual piezocone” was proposed by Tumay and Juran (22); it would allow simultaneous measurement of the pore water pressures at the tip, and along the penetrometer shaft behind the friction sleeve, together with tip resistance and sleeve friction. The LSU/Fugro Dual Pore Pressure Piezocone depicted in Figure 1 was later designed and fabricated (23-25). This paper first presents the design considerations pertaining to the development of the dual-pore-pressure piezocone penetration test (DPCPT) and discusses the results of soundings conducted in Louisiana in normally consolidated clay deposits, and in France in relatively heterogeneous soils of Flandria clay, with inclusions of loose and dense sand layers.

DUAL-PORE-PRESSURE PIEZOCONES

PENETROMETER—DESIGN AND DE-AIRING CONSIDERATIONS

Previous experimental and theoretical studies (1,5,6,16,17,26-31) have shown the individual merits of piezocones with pore pressure measurement capabilities on the shaft immediately behind the cone tip or the midsection of the cone tip. It has been proposed that piezometric measurement on the cone tip is best suited for investigations regarding soil classification,
FIGURE 1 Cross-sectional view of DPCPT (23–25).
whereas the pore pressures measured along the shaft tend to reflect the stress history of the sediments penetrated. Theoretical studies by Al-Awkati (26), Tumay and Yilmaz (32), Acar and Tumay (16), and Kiousis et al. (17) have further hypothesized the likelihood of the presence of a significant unloading zone (i.e., tendency toward separation of the soil and shaft interface) immediately behind the cone tip, extending approximately twice to three times the radius of the shaft.

The concept of the dual-pore-pressure piezocone penetration test (DPCPT) has thus evolved from the necessity of making reliable measurements of pore pressures generated during a CPT for proper soil stratification/classification and stress history (OCR) identification. The respective locations of the piezometric elements were initially envisaged to be on the face of the cone tip and at the mid-section of the friction sleeve about 3 cone diameters behind the cone. Observations on the wear of the cone tip and friction sleeve with respect to penetrometer use (5) have demonstrated these locations to be subjected to maximum soil-penetrometer interaction. Due to practical reasons, however, the piezometric element on the shaft was finally emplaced behind the friction sleeve 17 cm behind the tip of a 15-cm$^2$ cone. Figure 1 shows the cross-sectional view of the LSU/Fugro DPCPT. The dual pore pressure measurement configuration of this probe takes into account the basic parameters of design, namely: (a) identical pore pressure transducers, (b) identical material properties (i.e., compressibility, pore size, hydraulic conductivity, etc.) of piezometric elements, (c) equal pore pressure chamber volumes, (d) compressibility and viscosity of pore pressure chamber fluid, (e) equal thickness of piezometric elements, and (f) equal lateral surface area of piezometric elements in contact with soil to ensure compatible and comparable pore measurements at two locations during a sounding. The piezometric elements used in LSU/Fugro DPCPT were ceramic (aerolith 10) with a hydraulic conductivity of $10^{-3}\text{ cm/sec}$ and a nominal filtration grade of 15 microns. Calibration tests conducted in the lab to check compliance proved it unnecessary to use viscous fluids (i.e., glycerin, silicone oil, etc.) instead of water in the pore pressure chamber (25).

One of the most important aspects of the PCPT is the complete saturation of the pressure-sensing cavities (i.e., the piezometric element and the pore pressure chamber). Complete saturation is essential because compressible gas bubbles inside the measuring system would lead to an increase in the response time, affecting the accuracy and repeatability of results. The traditional de-airing technique used for piezometric elements is boiling and/or the application of $10^{-2}$ to $10^{-3}$ mm Hg vacuum. Vacuum saturation of the piezometric element and pressure-sensing cavities using special portable attachments on the cone tip in the field have been successfully used in the past (31). However, with the addition of a second piezometric element, the sheer size of the probe, which needed to be bodily housed in a portable vacuum chamber, became problematic. The saturation of the measuring system has to be done before each test and, in principle, may be influenced by the operator. Thus, a new technique that could easily and repeatedly be carried out in the field was needed.

Figure 2 depicts the Nold DeAerator system, modified to achieve saturation of the DPCPT by mechanically generating the phenomena of nucleation and cavitation, by which gases are removed from their dissolved state at much higher rates than are possible with conventional heat-boiling and vacuum methods (33). The unit consists of a sealed tank, an electric motor, a magnetic clutch, an impeller, and a water-powered aspirator. A vacuum, applied through a hollow support tube, draws water into the tank via an intake valve; the motor is energized, rotating the impeller.

Cavitation forms at ultra-high vacuum around the impeller vanes, violently agitating and breaking liquid into a fine, mist-like spray (nucleation). Centrifugal force hurls the released gases (air, hydrogen sulfide, sulfur dioxide, methane, radon, etc.) outward; they then bubble up to the partially evacuated space above the liquid surface and are withdrawn through the vacuum tube (34).

**FIGURE 2** General view of the Nold DeAerator modified for DPCPT de-airing (34).

Field verification and calibration tests of the DPCPT were conducted in Louisiana (24,33,35) and in France (36,37). A series of 19 tests were completed at sites in Dunkerque, France, and Grand Isle and Norco, Louisiana, with four different
types of cone penetrometers: (a) the 10-cm$^2$ Fugro electrical cone measuring the point resistance ($q_c$) and sleeve friction ($f_s$) (QCPT); (b) the 10-cm$^2$ Fugro piezocone measuring pore water pressure ($u$) at the middle of the cone tip, as well as point resistance ($q_c$) (PCPT); (c) the 15-cm$^2$ piezocone measuring $q_c$, $f_s$, and $u$ at the middle of the tip (PCPT); and (d) the 15-cm$^2$ dual-pore-pressure piezocone measuring $q_c$, $f_s$, and $u$ at the middle of the tip and behind the friction sleeve on the penetrometer shaft (DPCPT). The main objective of these penetration tests was to evaluate the effect of the cone diameter, the penetration rate, and the location of the piezometric elements on the measured soil response parameters.

Figure 3 shows the soil profile established by self-boring pressuremeter tests (PMTs) and piezocone penetration tests (PCPTs) in the Dunkerque site. The site consists of an upper sandy layer, 16 m deep, underlain by a Flandria clay layer. The soil profile obtained by DPCPT sounding at the Grand Isle, Louisiana, site is depicted in Figure 4. A 16-m-deep loose and dense sand layer with inclusions of silt and clay, underlain by Belize Delta clay with sand/silt lenses, closely parallels the characteristics of the Dunkerque site. In both soil profiles, the upper part of the clay layer includes loose and dense sand layers that are of specific interest in evaluating the stratification capability of the DPCPT and specifically the sensitivity of dual pore water pressure measurement in loose and dense sand/silt inclusions.

### Effect of Cone Diameter

Figure 5 shows typical CPT and PCPT soil profiles at Dunkerque obtained with the 10-cm$^2$ and 15-cm$^2$ cones. The cone diameter is found to have practically no effect on the point resistance and excess pore water pressures measured at the tip, provided that the cone diameter ($d$) and the shaft diameter ($D$) are the same (i.e., $d/D = 1$). However, cone diameter does affect the measured sleeve friction: the 10-cm$^2$ cone systematically yields values about 20 percent higher than those obtained with the 15-cm$^2$ cone.

### Effect of Penetration Rate

Figure 6 shows the PCPT profiles at Dunkerque of $q_c$ and the excess pore pressure $\Delta u$ obtained with the 15-cm$^2$ cone at penetration rates of 0.2 cm/s and 10 cm/s. The penetration rate is also found to have no appreciable effect on the $q_c$ values recorded in the sand and clay layers. However, it has a significant effect on the pore water pressures measured in the sand. At the penetration rate of 0.2 cm/s, the measured pore water pressures approach the hydrostatic $u_0$, whereas the penetration at the rate of 10 cm/s generates pore water pressures that reach 4 times $u_0$. 

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**FIGURE 3** Soil profiles in the Dunkerque site.
FIGURE 4 (a) Profiles of $q_c$, $f_r$, $q/f_r$, $u_1$, and $u_2$ at Grand Isle, Louisiana. (b) Profiles of $q_c$, $u_1$, $u_2$, $u_1/q_c$, $u_2/q_c$ at Grand Isle, Louisiana.
FIGURE 5 Effect of cone diameter on PCPT profiles in the Dunkerque site.

FIGURE 6 Effect of penetration rate on PCPT profiles in the Dunkerque site.
The measured excess pore water pressures ($\Delta u$) are found to be highly sensitive to the existence of loose sand inclusions in the clay layer (at depths of 16 to 23 m at Dunkerque and 16.5 to 26 m at Grand Isle) (Figures 4 through 6). The excess pore water pressures decrease substantially due to dissipation in these highly permeable sand seams (at depths of 17, 18.6, 21, and 22 m at Dunkerque; 18.5, 19.2, and 24.2 m at Grand Isle), which cannot practically be detected using any other of the available in situ soil testing techniques.

**Effect of Location of Porous Stones**

Figures 4 and 7 show typical DPCPT soil profiles obtained at the Grand Isle and Dunkerque sites, respectively, with the dual piezocone at the standard penetration rate of 2 cm/s. The location of the porous stone is found to have a significant effect on the recorded $\Delta u$ profiles. The excess pore water pressures measured at the tip, both in the sand and the clay layers, are systematically positive and higher than those measured at the sleeve. In the upper sand layer, generally positive excess pore water pressures are measured at the tip, whereas those measured at the sleeve correspond to the hydrostatic $u_0$ or somewhat below. In the normally consolidated clay layer (depth, 17 to 22 m at Dunkerque; 20 to 30+ m at Grand Isle), the excess pore water pressures measured at the tip are about double those measured behind the sleeve. It is of particular interest to note that the pore water pressure response in the upper dense sand layer is significantly different from that measured in the dense sand inclusions (depth, 25 to 26 m at Dunkerque; 18.5 to 19.5, and 29.5 m at Grand Isle) located within the clay layer. This major difference is due to the boundary drainage conditions associated with a sand inclusion in a clayey deposit that substantially reduces the rate of dissipation. The excess pore water pressures measured at the tip in the sand inclusion are found to be several times (5 to 10 times) higher than those measured in the upper sand layer (depth, 7 to 12 m at Dunkerque; 1 to 5.5 m at Grand Isle), whereas the $q_c$ and $f_s$ values are about the same. Specifically, the very low to negative excessive pore water pressures measured at the sleeve in the dense sand inclusions illustrate that the effect of the location of the porous stone is much more significant in sand inclusions than in the relatively thick sand deposits. The dual piezocone thus appears to provide a significant and uniquely enhanced capacity to identify sand inclusions situated in clay deposits of low hydraulic conductivity.

**PIEZOCONE TESTING IN STRATIFIED SOIL SYSTEMS OF CLAY DEPOSITS WITH THIN SAND INCLUSIONS**

Figure 8 illustrates the use of the dual piezocone in identifying loose and dense sand inclusions in a silty clay deposit. In the loose sand inclusion (depth, 22 to 23 m), the excess pore water pressures measured both at the tip and the sleeve are positive. In the dense sand inclusion (depth, 25 to 26 m), the high increase in the normal stress on the tip, associated with high $q_c$ values, results in high positive excess pore water pressures (greater than 2 MPa, about 10 times $u_0$) at the tip, whereas the excess pore water pressures measured at the sleeve are negative ($-0.26$ MPa), indicating that the sand tends to dilate.
FIGURE 8 Dual piezocone penetration test profiles in clayey silt with sand inclusion (Dunkerque site).

FIGURE 9 Dissipation tests in the Dunkerque site.

during its shearing. Dissipation tests that provide useful means to evaluate in situ the hydraulic conductivity of the soil can significantly extend the data base for soil stratification. Figure 9 shows the dissipation curves measured in the silty clay layer at both the sleeve and the tip.

It is of interest to report at this point the results of a series of piezocone tests in a similar site of a 40-m-deep silty clay layer with inclusions of loose sand seams, namely the Nice harbor site in France. In this site, a conventional 10-cm² piezocone with a porous stone at the middle of the tip has been used (38) to identify potentially liquefiable sand layers that could have caused the quasi-instantaneous sliding collapse of the 10 Mm³-harbor dike. Figure 10 shows typical penetration profiles \( (q, u) \) obtained in this site. These penetration profiles illustrate that subhorizontal loose sand seams less than 10 cm in thickness can be identified using the piezocone. As the penetration reaches a sand seam, there is an increase of the point resistance \( (q_s) \), associated with an increase of positive excess pore water pressure exceeding that measured in the surrounding silty clay layer. Dissipation tests conducted both in the silty clay layer and the sand seams indicated significantly different hydraulic conductivities of the two soil layers (Figure 11) and thereby improved the data base for the soil stratification. However, it should be indicated that the excess pore water pressures measured at the tip in these loose sand inclusions are mainly governed by the soil compression around the penetrating cone and, to a lesser extent, by the mechanical compression of the piezometric element in the cone tip, and
therefore do not reflect their tendency to liquefy under rapid undrained shearing.

Interpretation of piezocone data in a stratified soil system of a clayey soil of low hydraulic conductivity containing loose or dense sand seams is a difficult task. The available classification charts for piezocone data (18,20) have been established for thick soil deposits. The drainage conditions at the boundaries of sand seams significantly reduce the dissipation rate and generally imply horizontal flow. Therefore, the pore water pressure response in such sand seams is significantly different from that measured in thick layers of similar sands at the same relative density (Figures 4 and 7). Figure 12 illustrates an attempt to use the classification charts proposed by Robertson and Campanella (20) depicted in Figure 13, for soil stratification in this site. These charts involve all the piezocone data: $q_c, \Delta u_{\text{sheave}}$ and $f_r$, and use the normalized pore pressure parameter $B_p = (u_i - u_o)/(q_c - \sigma_{vo})$ and the friction ratio $F_r = f/r_c$.

For the sand inclusions specified above, these classification charts indicated that:

- The loose sand layer (depth, 23 m) is identified as a silty sand using the $q_c, F_r$ data, but the high excess pore water pressure data would indicate a rather fine-grained soil (sandy to clayey silt) (Point A); and
- The dense sand layer (depth, 25 to 26 m) can be classified as gravelly sand to sand (Point B).

These charts, and specifically the use of the normalized pore water pressure parameter $B_p$, seem to be better adapted for the classification of sand inclusions in clayey soils. However, it is anticipated that a significant improvement of the data base for soil stratification can be gained by incorporating the difference in the pore water pressures measured at the tip and the sleeve in the classification charts.

CONCLUSIONS

This paper presents a newly developed piezocone probe providing simultaneous measurement of pore pressures generated...
both at the middle of the cone tip and along the penetrometer shaft behind the friction sleeve, together with monitoring of the tip resistance and sleeve friction. Design considerations and a novel de-airing technique are outlined.

The preliminary penetration tests conducted with the dual piezocone penetrometer illustrate that simultaneous measurement of excess pore water pressures at the middle of the cone tip and behind the friction sleeve provides valuable data for soil stratification. The pore water pressure response at both piezometric element locations is highly dependent on the strain path of the surrounding soil. Consequently, substantial differences are observed in the pore water pressures recorded during a sounding. In particular, the excess pore water pressure response at the middle of the tip is primarily governed by the increase of the normal stress and the cone tip, whereas the excess pore water pressure measured along the shaft (4 to 5 diameters behind the tip) is primarily dependent upon the tendency of the soil to contract or dilate during shearing. Therefore, the dual piezocone is of particular interest for the identification of potentially liquefiable loose sand seams often encountered in freshly deposited normally consolidated soils. However, in our present state of knowledge, the available classification charts do not provide appropriate means of identification of such inclusions. An attempt should be made to develop a reliable data base using the dual piezocone for the development of relevant classification charts.

REFERENCES


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FIGURE 13 Classification of sand seams in the Dunkerque site using Robertson and Campanella’s (20,21) classification chart.


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