PROFILING STRESS HISTORY FROM PIEZOCONE SOUNDINGS

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ABSTRACT

A piezocone data base is compiled from 36 well-documented clay sites with known stress histories. Only transducer readings on the cone tip or just behind the tip were considered. The normalized excess pore pressure to effective overburden ratio ($\Delta u/\sigma_{vo}'$) indicated better trends with overconsolidation ratio (OCR) than the parameters (u/q_c) and $B_q = \Delta u/(q_c - \sigma_{vo})$. A direct relationship was also observed between the measured excess pore pressure (Δu) and effective preconsolidation pressure (σ_p'). Positive or negative values of pore pressure can apparently be measured behind the tip in heavily overconsolidated clays, while only positive values can occur at the tip. For the sake of consistency and simplicity of evaluation, this study suggests that standardization of piezocones place the porous element on the cone face. Alternatively, two transducers should be used.

Key words : clay, consolidation, field test, in-situ test, overconsolidation, penetration test, pore pressure, site investigation, sounding (IGC : C 3/D0/D 4/D 6/E1)

INTRODUCTION

At the first European Symposium on Penetration Testing, papers by Janbu and Senneset (1974) and Schmertmann (1974) recognized the importance of monitoring the induced pore pressure during cone penetration. Probes to measure pore pressure during penetration were developed by Torstensson (1975) and Wissa et al (1975), and Schmertmann (1978) attempted to use such a device to measure liquefaction potential in sands. Credit for the concept of the piezocone, a

combination of the pore pressure probe and the electric cone penetrometer, should go to Janbu and Senneset (1974). Since then, Parez et al (1976), and a number of other investigators have further developed the device, so that today its value to site investigations, both onshore and offshore, is widely recognized.

The piezocone is typically a modified standard 60° apex electric cone penetrometer with 10 cm² point and 150 cm² friction sleeve (Fig. 1). In addition to point resistance (q_c) and sleeve friction (f_s), a transducer measure-

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Fig. 1. Definition of piezocone parameters and various filter stone locations for piezocones : (a) Wissa and McClelland types ; (b) Fugro, and (c) ISMES, BAT, and UBC versions. Friction sleeve measurements not shown

ment of induced pore pressures is obtained. The specific location of the porous element on the cone for pore pressure readings has not been standardized. Primarily, these readings are taken on the cone face (tip or midtip) or on the sleeve just behind the tip, although a few prototype models place the sensor on the sleeve several diameters above the tip.

In clean sands, the measured pore pressures (u_{max}) appear to reflect the ambient hydrostatic water table (Jones and Rust, 1983). In clays, however, u_{max} results from a complex interaction of shear, cavity expansion, and/or soil remolding during penetration of the cone. Both total stress analyses (Tavenas et al, 1982) and effective stress methods (Senneset and Janbu, 1982, 1985) have been utilized to interpret piezocone measurements.

An important finding of piezocone research is that all cones (standard electric or mechanical) require a correction factor dependent upon geometry, unequal area projections,

and total pore pressures (Aas et al, 1986 ; Bruzzi and Cestari, 1983). Such corrections applied to previous cone penetration test (CPT) data may possibly reduce some of the large variations observed in the cone bearing factor N_k (Campanella et al, 1982) :

$$N_k = (q_c - \gamma z) / C_u \quad (1)$$

where C_u = the undrained shear strength,

z = the depth, and

γ = the total unit weight.

The corrected cone resistance (q_t) is given by :

$$q_t = q_c + (1 - a)u_{max} \quad (2)$$

where

$$a = \text{area ratio} = d_i^2 / d_o^2$$

u_{max} = measured pore pressure at the junction of unequal areas

d_i = innermost or minimum diameter of cone section

d_o = outermost or maximum diameter of cone section.

For details on the corrections, see Jamiolkowski et al (1985), Lunne et al (1986), and Senneset and Janbu (1985). It is believed that most, but possibly not all, cone resistance values reviewed in this study have been appropriately corrected.

Most prototype piezocones are modified Fugro type electric cones. The location of the porous filter for pore pressure measurement varies, and its position has generated much controversy and discussion. The Wissa, Fugro, and McClelland types favor the cone face, while the UBC, ISMES, and BAT type cones place the element on the sleeve just behind the tip. Theoretical considerations by Wroth (1984) suggest a favorable position at the middle of the friction sleeve. Several studies have investigated the relative effect of different positions on the cone tip or along the sleeve (Roy et al, 1982), Robertson et al (1986), and Lunne et al (1986 a). For example Battaglio and Bruzzi (1984) have shown that the maximum response occurs at the cone apex ; however, this location is especially vulnerable to damage and wear. Therefore, for commercial use, some piezocone designs have incorporated the sensor either midway on the cone tip or on the friction sleeve just behind the cone.

PIEZOCONE DATABASE

SYMBOL	SITE	(Reference)	SYMBOL	SITE	(Reference)
●	VARENNES ^c	(24)	●	ONTARIO ^c	(24)
●	ONSOY ^{a, b, c}	(16, 27, 28, 31)	▶	SLEIPNER 4 ^{a, b}	(30)
○	BOSTON BLUE ^a	(6, 7)	⊕	RIO DE JANEIRO ^a	(42, 47, 48)
■	SAINT ALBAN ^{a, c}	(49)	⊞	EAST ATCHAFALAYA ^a	(7)
□	PONTIDA ^{a, c}	(16)	▼	NETHERLANDS ^a	(67)
▲	PORTO TOLLE ^a	(14, 16)	◀	LOUISEVILLE ^c	(29, 58)
△	TARANTO ^a	(15, 16)	◀	BASTICAN ^c	(29, 58)
◀	EMMERSTAD ^{a, c}	(1, 26)	▽	SOUTH AFRICA ^b	(18, 19, 20)
◆	GULLFAKS A ^{a, b}	(30)	▽	DRAMMEN ^c	(27, 28)
◇	GULLFAKS C ^{a, b}	(30)	▽	SEA ISLAND ^c	(11, 12, 23)
▷	SLEIPNER 2 ^{a, b}	(30)	⊞	NEW ORLEANS ^b	(61, 62)
△	JAPAN ^c	(55)	⊞	NORTH SEA ^b	(44, 67)
▽	MATAGAMI ^c	(29, 56)	◀	CRAN ^b	(21)
●	EMPIRE ^a	(4)	●	HAGA ^{a, b, c}	(31)
◇	ORINOCO ^a	(3)	⊞	SANTA MARIA ^b	(22, 64)
☆	YORKTOWN ^{c, d}	(40)	△	POTOMAC ^{c, d}	(36, 37)
△	UPPER HONG KONG ^{b, d}	(25)	▶	LOWER HONG KONG ^{b, d}	(25)
△	MIOCENE ^{c, d}	(38)	▶	PLEISTOCENE ^{c, d}	(38)

NOTES: Porous Stone Locations: (a) Tip, (b) Midface, (c) Behind Tip.
All Cones with 10 cm² Tips Except (d) with 15 cm².

Fig. 2. Piezocone symbols, sites, and references for 36 different clay sites reviewed.
All cones with 60° apex and 10 cm² tips, except as noted

In this study, only data from cones with pore pressure measurements made either at the cone apex, midway on the cone tip, or just behind the conesleeve interface (see Fig. 1) have been included. Differences of measurements on the cone tip or midtip of the face are indistinguishable (Lunne et al, 1986). According to several studies, excess pore pressures measured just behind the tip average about 80 percent of those on the tip for soft clays with OCR < 3 (Roy et al, 1982; Torstensson, 1982; Jamiolkowski et al, 1985). Data on overconsolidated clays, however, show larger differences between these locations. The ratio apparently decreases from about 60% for OCRs on the order of 5 (Aas et al, 1986; Jamiolkowski et al, 1985) to 40% for OCRs of 10 to 20 (Lunne et al, 1986). In fact, in some overconsolidated clays, negative pore pressures may be recorded in piezocones with porous elements behind

the tip. Campanella et al (1986) show that the relative size and width of the porous element behind the tip can affect whether positive or negative pore pressures are measured. For cones with tip or face elements, positive pore pressures are observed for all clays, soft to hard (Lunne et al, 1986 a, b).

The results of piezocone soundings have been proposed for the in situ determination of several important soil parameters, such as undrained shear strength (C_u), effective friction angle (ϕ'), overconsolidation ratio ($OCR = \sigma_p' / \sigma_{vo}'$), coefficient of consolidation (c_v), permeability (k), as well as soil classification. The purpose of this study is to evaluate the use of piezocone data for characterizing the stress history of clay deposits. Several different pore pressure parameters have been proposed (e.g., u/q_c , B_q , $\Delta u / \sigma_{vo}'$); however, it is not clear which parameter best describes the variation of OCR with

depth.

A total of 36 well documented clay sites were reviewed. The sites, symbols, and data sources are given in Fig. 2. The position of the porous element (tip, mid-tip, or behind the tip) is also noted. Plasticity indices ranged from 3 to 90 for these soils. As determined from laboratory oedometer tests on samples taken from adjacent borings, the in situ stress states ranged from normally consolidated ($OCR=1$) to heavily overconsolidated ($OCR=40$). For a few sites, the sources of data indicated that OCR was estimated from undrained strength data and index properties (Lunne et al, 1985). Measured values of σ_p' varied from 20 to 4700 kPa.

Measured cone resistances (q_c) ranged from 0.1 to 6 MPa and penetration pore pressures

(u_{max}) varied from 0.05 to 3 MPa. Although miniature laboratory cone tests have been conducted, e.g. by Smits (1982) and Almeida and Parry (1985), our study generally considers only field tests using standard 10 cm² piezocones. Two recent sites investigated by the primary author involved use of a 15 cm² piezocone.

Several important factors were beyond the scope of this study. These include differences in clay mineralogy, sensitivity, equipment, degree of saturation of porous element, temperature, geologic origin, etc. In addition, some error was likely incurred in scaling data from original graphs as published. For comparison purposes, data from all sites were processed at approximately one-meter intervals, similar to the procedures outlined by Wroth (1984).

Fig. 3. Results of piezocone sounding in soft organic alluvial clay in Washington, D.C.

Fig. 4. Results of piezocone sounding in stiff sensitive fine sandy clay in Newport News, Virginia

PIEZOCONE PROFILING

The results of a recent piezocone sounding (designated CPTU) in a 25 meter thick deposit of soft organic alluvial clay from the Potomac River in Washington, D.C. is shown in Fig. 3. Three widely spaced CPTUs gave almost identical readings. These tests were performed with a 15-cm² cone having a 60° apex and the transducer measurements taken just behind the tip. Cone resistances shown have not been corrected.

The stress history profile determined from oedometer tests is given by Mayne (1987). Below a thin sandy fill layer, the apparent

OCR in the organic clay decreases from about 2.5 near the surface to approximately 1.5 at the bottom of the deposit. It is observed that the effective preconsolidation pressure, point resistance, and measured pore pressures all increase with depth in this soft clay.

For comparison, a CPTU sounding using the same piezocone in a stiff sensitive fine sandy clay from Newport News, Virginia, is presented in Fig. 4. It is observed that the measured pore pressures are considerably higher here than in the soft clay discussed previously. The clay, known as the Yorktown Formation, has approximately 50% fines and 50% fine sand fraction with shell fragments. Index properties are: LL=31,

Fig. 5. Logarithm of normalized pore pressure $u_{\max}/q_c$ versus logarithm of overconsolidation ratio, OCR

Fig. 6. Logarithm of pore pressure parameter B_q versus logarithm of overconsolidation ratio, OCR

PI=4, and $w_n=31\%$. The Yorktown exhibits some unusual properties, behaving in part like clay and also like sand. Limited field vane tests indicate sensitivities of about

4 to 8. Standard penetration tests from 60 borings indicate N -values of about 14 ± 4 blows/30 cm. Oedometer tests, triaxial tests, and field dilatometer soundings determined in situ preconsolidation pressures between 800 to 900 kPa in this marine deposit. Consequently, the OCR decreases from about 9 at a depth of 8 m to approximately 4 at 18 m.

OCR TRENDS FROM PIEZOCONE DATA

Baligh et al (1980, 1981) found that for a given clay deposit, the ratio of the measured total pore pressure to cone resistance ($u_{\max}/q_c$) varied inversely proportionally with the OCR. Data from Boston Blue Clay and East Atchafalaya supported these findings. If additional sites are included in the database (Fig. 5), it is apparent that these relationships must be very site specific. Although there appears to be a general trend of decreasing (u/q_c) with increasing OCR, the observed range is large. For example, at a given value of $u/q_c=0.6$, the OCR may vary from 1 to 10.

An alternative way to present CPTU data has been suggested by Wroth (1984), Jamiolkowski et al (1985) and Lunne et al (1985). Analogous to the Henkel pore pressure parameter, the term B_q is defined as:

$$B_q = \frac{\Delta u}{q_c - \sigma_{v0}} \quad (3)$$

where Δu = excess pore pressure = $u_{\max} - u_0$

$u_{\max}$ = measured total pore pressure

u_0 = hydrostatic pressure

q_c = corrected cone resistance

σ_{v0} = total overburden stress

The available data base for B_q vs log OCR is presented in Fig. 6. Again, a wide range of OCRs is observed for a specific values of B_q .

Consequently, B_q also appears to be very site specific and requires detailed calibration with high quality samples and oedometer tests, as noted by Jamiolkowski et al (1985), Keaveny and Mitchell (1986), and Robertson et al (1986).

Other normalized pore pressure parameters, similar to u/q_c and B_q , have been proposed for indexing OCR in clays. Smits (1982) suggests the parameter $\Delta u/(q_c - u_0)$ and Tumay et al (1982, 1985) propose the use of $\Delta u/q_c$. However, these parameters have not been investigated in the present study.

The advance of a cone penetrometer into the ground is analogous to the driving of a pile. Several effective stress methods and critical state models are available for describing pile installation effects in clay. For example, Randolph, Carter, and Wroth (1979) indicate that a first order approximation of the excess pore pressure generated at the tip during driving in an elastic-plastic soil is:

$$\Delta u/\sigma_{v0}' = C_u/\sigma_{v0}' \ln (G/C_u) \quad (4)$$

where C_u/σ_{v0}' = normalized undrained strength ratio

C_u = undrained shear strength

σ_{v0}' = effective overburden stress

G = undrained shear modulus

G/C_u = rigidity index.

Eq. (4) considers only the excess pore pressure due to change in octahedral stress during cylindrical cavity expansion. For spherical cavity expansion, the right hand term is 4/3 times larger. Only positive pore pressures are possible for cavity expansion, since the quantity $\ln G/C_u > 0$ and the ratio C_u/σ_{v0}' increases with OCR.

Randolph et al (1979) also consider a contribution of the pore pressures due to undrained shear, analogous to the triaxial A_f parameter, which may either be positive or negative. However, it turns out that the magnitude of pore pressures due to shear are relatively small when compared with those caused by cavity expansion (Baligh, 1986).

Furthermore the results of enumerable laboratory programs using tests have misled many into expecting negative pore pressures for most overconsolidated clays. For example, isotropic triaxial compression tests on Weald Clay indicate positive values of A_f for $OCR < 4$ and negative A_f for $OCR > 4$ (Wroth, 1984). Available data for anisotropic

triaxial compression tests on natural clays, however, exhibit negative pore pressures only at very high values of OCR. For example, heavily-overconsolidated Taranto clay ($25 < OCR < 40$) and AGS clay ($OCR < 8$) show small yet generally positive pore pressures in CAUC triaxial tests (Jamiolkowski et al, 1985).

Baligh et al (1981) have suggested that $\Delta u/\sigma_{v0}'$ from CPTU tests is an indicator of soil type. This ratio may also be used as an index of OCR. The normalized undrained strength may be expressed as:

$$C_u/\sigma_{v0}' = C_u/\sigma_{vnc}' OCR^A \quad (5)$$

where C_u/σ_{vnc}' = normalized strength for $OCR = 1$

A = strength rebound parameter
(Mayne and Swanson, 1981)

Combining Eq. (7) with Eq. (6), we obtain an estimate of overconsolidation ratio for spherical and cylindrical cavity expansion:

$$OCR = \left[\frac{0.75 \Delta u/\sigma_{v0}'}{C_u/\sigma_{vnc}' \ln (G/C_u)} \right]^{1/A} \quad (6a)$$

cylindrical:

$$OCR = \left[\frac{\Delta u/\sigma_{v0}'}{C_u/\sigma_{vnc}' \ln (G/C_u)} \right]^{1/A} \quad (6b)$$

The ratio (G/C_u) is the rigidity index and it may typically vary from 20 to 1000 in clays (Vesic, 1972). However, the natural logarithm of (G/C_u) ranges from only 3 to 7. Assuming typical values $C_u/\sigma_{vnc}' = 0.35$ and $A = 0.7$ for triaxial compression (Mayne, 1985 a, b) and average value of $\ln (G/C_u) = 6$, we obtain:

$$\text{spherical: } OCR = [0.38 (\Delta u/\sigma_{v0}')]^{1.43} \quad (7a)$$

$$\text{cylindrical: } OCR = [0.48 (\Delta u/\sigma_{v0}')]^{1.43} \quad (7b)$$

These estimates compare favorably with linear regression analysis for the direct relationship between $\log (\Delta u/\sigma_{v0}')$ and $\log OCR$ shown in Fig. 7, which indicates:

$$OCR = [0.42 (\Delta u/\sigma_{v0}')]^{1.35} \quad (8)$$

In fact, the sample correlation coefficient (r) between $\Delta u/\sigma_{v0}'$ and OCR is 0.88 assuming the log-log relationship. For comparison, regression analyses in terms of u/q_c and

Fig. 7. Logarithm of normalized excess pore pressure versus logarithm of overconsolidation ratio, OCR

B_q gave correlation coefficients of -0.63 and -0.60 , respectively.

The apparent less scatter in Fig. 7 than in the u_{max}/q_c (Fig. 5) or B_q (Fig. 6) relationships vs OCR may occur because these parameters utilize two measurements from the CPTU, which may possibly compound the error.

DIRECT CORRELATION APPROACH

Tavenas and Leroueil (1979) presented a direct relationship between the preconsolidation pressure ($\sigma'_{p'}$) and cone resistance for two Canadian clays. Subsequently, Mayne (1986) reviewed data from 42 clay sites tested by standard electrical and mechanical cones and found that :

$$\sigma'_{p'} = q_c / \beta \quad (9)$$

where the parameter β generally ranged from 2 to 8. This range is no greater than the observed range in N_k value from Eq. (1) as noted by Robertson and Campanella (1983) and Lunne et al (1985).

For the piezocone database, a similar trend is seen in Fig. 8, where $\log \sigma'_{p'}$ is plotted vs the log of net cone resistance. The expres-

sion :

$$\sigma'_{p'} = 0.4 (q_c - \gamma z) \quad (10)$$

appears reasonable over a very wide range of net cone resistances [$0.2 \text{ MPa} < (q_c - \gamma z) < 6 \text{ MPa}$]. However, the upper and lower

Fig. 8. Logarithm of in situ preconsolidation stress versus logarithm of net cone resistance

Fig. 9. Relation between in situ preconsolidation pressure and excess pore pressure for piezocone transducer measurements taken at cone tip/face

Fig. 10. Relation between in situ preconsolidation pressure and excess pore pressure for piezocones with transducer measurements taken just behind the tip

bounds generally vary by a factor of three. Very hard cemented clay reported by Jamiolkowski et al (1982, 1985) falls above these limits (open triangles in Fig. 8) and has not been included in the following regression analysis.

Similarly, for pore pressures measured only on the tip, an apparent relationship between $\log \sigma'_p$ and $\log \Delta u$ is shown by Fig. 9. The log scales are utilized in order to present data over two orders of magnitude. Fig. 10 presents a similar trend for piezocones with porous elements located just behind the tip. The apparent mean trend for a forced intercept ($b=0$) using regression analyses between these parameters (no log-log relationship assumed) and all piezocone data gives ($r=0.97$):

$$\sigma'_p = 0.521(\Delta u) \quad (11)$$

This trend indicates an apparently smaller bandwidth than in the other relationships presented previously. As shown by Figs. 9 and 10, a general expression for the effective preconsolidation pressure is:

$$\sigma'_p = \Delta u / \delta \quad (12)$$

where δ varies from about 1 for sensitive clays to 4 for insensitive clays. A recent

analysis of piezocone data by Konrad and Law (1987) in 5 Canadian clays indicated that σ'_p is related to the net quantity of cone resistance minus measured pore pressure ($q_t - u_{\max}$). However, a correction factor is required, which depends upon the OCR. Also, only 5 sites were studied.

DISCUSSION

If in fact either positive or negative pore pressures can be measured behind the tip in stiff to hard clays (Campanella et al, 1986), no general correlation may be possible for these cones because of complicated effects of shear and cavity expansion. A logical conclusion is therefore that standardization of the piezocone should require pore pressure measurements on the cone tip. Even though this occurs at the sacrifice of considerable wear and vulnerability, superior data is obtained since positive pore pressures are ensured for all values of OCR.

It should be noted that the determination of σ'_p from consolidation tests on samples from adjacent boreholes in itself requires judgment and presents considerable uncertainty. Also, the sensitivity, sand content, presence of fissures, and degree of saturation can significantly affect CPTU readings. It is recommended that each site be calibrated against OCRs determined from oedometer tests for verification of the observed trends.

All cone data should be corrected for pore pressures acting on unequal areas. The corrections apply to both point and sleeve friction measurements. The net area ratios can be determined for standard electric and mechanical cones, however, the total pore pressures during penetration at the standard rate of 2 cm/sec are not known unless piezocones are used. Finally, the measured pore pressures may be used to profile the undrained shear strength of clay deposits, in a manner as discussed by Tavenas, Leroueil and Roy (1982) and Robertson and Campanella (1983). Returning to Eq. (4), it can be seen that the undrained strength (C_u) may be expressed:

$$C_u = \Delta u / N_p \quad (13)$$

Fig. 11. Observed trend between undrained triaxial compression strength and piezocone excess pore pressure at cone tip/face

Fig. 12. Observed trend between undrained triaxial compression strength and piezocone excess pore pressure measured just behind the tip

where $N_p = \ln(G/C_u)$ for a given clay. Several of the sites listed in Fig. 2 had been sampled and tested using the triaxial shear apparatus in the laboratory to determine the undrained shear strength in compression. As shown by Figs. 11 and 12, the value of N_p generally ranges from about 7 to 15 with

boundary limits apparently extending from 5 to 20. Tavenas et al (1982) suggested that this value varies with the liquidity index of the clay, however, their correlation was made using the field vane strength as a reference.

CONCLUSIONS

This study reviews the results of piezocone soundings at 36 different sites in soft to stiff clays. For piezocones with porous sensors on the tip, face, or behind the tip, the following general trends are indicated:

(1) The normalized pore pressure parameters u/q_c and B_q generally decrease with increasing OCR, although the trends are very site specific.

(2) The normalized parameter $\Delta u/\sigma_{v0}'$ increases with OCR, as expected from critical state and cavity expansion theory for driven piles in clays.

(3) For porous elements on the tip, measured pore pressures are always positive. For porous elements located just behind the tip, pore pressures in heavily overconsolidated clays can apparently be either positive or negative. For the sake of consistency, it would appear that standardization of the porous cone should locate it on the cone face. Unfortunately, this may require regular maintenance and replacement of the tip due to excessive wear and damage. Alternatively, cones should utilize two transducers.

(4) An apparent trend between the pre-consolidation pressure and excess pore pressure is observed.

(5) Piezocone profiling of in-situ OCR in clay deposits should be calibrated against oedometer tests.

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REFERENCES

- 1) Aas, G. et al (1986) : "Use of insitu tests for foundation on clay," *Proceedings In Situ 86*, ASCE Specialty Conference, Blacksburg, Va., 34 pages.
- 2) Almeida, M. and Parry, E. (1985) : "Small cone piezocone tests in clays," *ASTM Geotechnical Testing Journal*, Vol. 8, No. 1, pp. 14-24.
- 3) Azzouz, A., Baligh, M. and Ladd, C. C. (1982) : "Cone penetration and engineering properties of soft Orinoco Clay," *Proceedings 3rd International Conference on Behavior of Offshore Structures*, Vol. 1, MIT, Hemisphere Publishing Co., pp. 161-180.
- 4) Azzouz, A. and Lutz, D. (1986) : "Shaft behavior of pile in plastic empire clay," *Journal of Geotechnical Engineering*, Vol. 112, No. 4, pp. 389-406.
- 5) Baligh, M. (1986) : "Undrained deep penetration : Pore pressures," *Geotechnique*, Vol. 36, No. 4, pp. 487-501.
- 6) Baligh, M. et al (1981) : "The piezocone penetrometer," *Proceedings Cone Penetration Testing and Experience*, ASCE, St. Louis, pp. 247-263.
- 7) Baligh, M., Vivatrat, V. and Ladd, C. C. (1980) : "Cone penetration in soil profiling," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 106, No. GT 4, pp. 447-461.
- 8) Battaglio, M. et al (1981) : "Piezometer probe test in cohesive deposits," *Proceedings Cone Penetration Testing and Experience*, ASCE, St. Louis, pp. 264-302.
- 9) Battaglio, M. and Bruzzi, D. (1984) : as reported by Jamiolkowski et al (1985).
- 10) Bruzzi, D. and Cestari, F. (1983) : "Effects of pore pressure on point resistance in soft clay," *Symposium International In Situ Testing*, Vol. 2, Paris, pp. 227-320.
- 11) Campanella, R. and Robertson, P. (1981) : "Applied cone research," *Proceedings Cone Penetration Testing and Experience*, ASCE, St. Louis, pp. 343-362.
- 12) Campanella R., Gillespie, D. and Robertson, P. (1982) : "Pore pressures during cone penetration," *Proceedings 2nd European Symposium of Penetration Testing*, Vol. 2, Amsterdam, Balkema Books, pp. 507-512.
- 13) Campanella, R., Robertson, P. and Gillespie, D. (1986) : "Factors affecting the pore water pressure around a penetrating cone," *University of British Columbia Report No. 101*, Department of Civil Engineering, 9 pages.
- 14) Jamiolkowski, M. and Lancellotta, R. (1981) : "On piezometer probe and piezocone tests," *Proceedings 10th International Conference on Soil Mechanics*, Vol. 2, Stockholm, pp. 773-774.
- 15) Jamiolkowski, M. et al (1982) : "Undrained strength from CPT," *Proceedings 2nd European Symposium on Penetration Testing*, Vol. 2, Amsterdam, Balkema Publishing Co., pp. 599-606.
- 16) Jamiolkowski, M., Ladd, C. C., Germaine, J. and Lancellotta, R. (1985) : "New developments in field and lab testing of soils," *Proceedings 11th International Conference on Soil Mechanics*, Vol. 1, San Francisco, pp. 57-154.
- 17) Janbu, N. and Senneset, K. (1974) : "Effective stress interpretation of in situ static penetration tests," *Proceedings of the European Symposium on Penetration Testing I*, Stockholm, Vol. 2. 2, pp. 181-193.
- 18) Jones, G. and VanZyl, D. (1981) : "The piezometer probe—A useful tool," *Proceedings 10th International Conference on Soil Mechanics*, Vol. 2, Stockholm, pp. 489-496.
- 19) Jones, G. and Rust, E. (1982) : "Piezometer penetration testing," *Proceedings 2nd European Symposium of Penetration Testing*, Vol. 2, Amsterdam, Balkema, pp. 607-613.
- 20) Jones, G. and Rust, E. (1983) : "Piezometer probe for subsoil identification," *Symposium International In Situ Testing*, Vol. 2, Paris, pp. 303-308.
- 21) Juran, I. et al (1983) : "Application of piezocone penetrometer to in situ soil investigation," *Symposium International In Situ Testing*, Vol. 2, Paris, pp. 309-315.
- 22) Keaveny, J. and Mitchell, J. K. (1986) : "Strength of fine grained soils using the piezocone," *Proceedings Use of In Situ Tests in Geotechnical Engineering*, ASCE, VPI, pp. 668-685.
- 23) Konrad, J., Bozozuk, M. and Law, K. (1985) : "Study of insitu test methods in deltaic silt," *Proceedings 11th International Conference on Soil Mechanics*, Vol. 2, San Francisco, pp. 879-886.
- 24) Konrad, J. and Law, K. (1987) : "Preconsolidation pressure from piezocone tests in marine clays," *Geotechnique*, Vol. 37, No. 2, pp. 177-190.
- 25) Koutsoftas, D., Foott, R. and Handfelt, L. (1987) : "Geotechnical Investigations offshore Hong Kong," *Journal of Geotechnical Engineering*, Vol. 113, No. GT 2, pp. 87-104.

- 26) Lacasse, S., Berre, T. and Lefebvre, G. (1985) : "Block sampling of sensitive clays," *Proceedings 11th International Conference on Soil Mechanics*, Vol.2, San Francisco, pp.887-890.
- 27) Lacasse, S., Jamiolkowski, M. et al. (1981) : "Insitu characteristics of two Norwegian Clays," *Proceedings 10th International Conference on Soil Mechanics*, Vol.2, Stockholm, pp. 507-511.
- 28) Lacasse, S. and Lunne, T. (1982) : "Penetration tests in two Norwegian clays," *Proc. 2nd European Symposium on Penetration Testing*, Vol. 2, Amsterdam pp.661-669.
- 29) Leroueil, S. et al (1983) : "Preconsolidation pressure of Champlain Clays," *Canadian Geotechnical Journal*, Vol.20, No. 4, Nov., pp.803-816.
- 30) Lunne, T., Christoffersen, H. and Jelta, T. (1985) : "Engineering use of piezocone data in North Sea Clays," *Proceedings 11th International Conference on Soil Mechanics*, Vol.2, San Francisco, pp.907-912.
- 31) Lunne, T. et al (1986) : "Laboratory and field evaluation of cone penetrometers," *Proceedings Use of In Situ Tests in Geotechnical Engineering*, ASCE, VPI, pp.714-729.
- 32) Lunne, T., Eidsmoen, T., Powell, J. and Quarterman, R. (1986 b) : "Piezocone testing in overconsolidated clays," *Proceedings 39th Canadian Geotechnical Conference*, Ottawa, pp. 209-218.
- 33) Mayne, P. W. (1985) : "Stress-anisotropy effects on clay strength," *Journal of Geotechnical Engineering*, ASCE, Vol.111, No. 3, pp.356-366.
- 34) Mayne, P. W. (1985) : "A review of undrained strength in direct simple shear," *Soils and Foundations*, Vol.25, No.3, pp.64-72.
- 35) Mayne, P. W. (1986) : "CPT indexing of insitu OCR in clays," *Proceedings Insitu 86*, ASCE, Virginia Polytechnic Institute, Blacksburg, Virginia.
- 36) Mayne, P. (1987) : "Determining preconsolidation pressures from DMT contact pressures," *ASTM Geotechnical Testing Journal*, Vol.10, No. 3, pp.146-150.
- 37) Mayne, P. W. and Frost, D. D. (1986) : "Geotechnical report, WHCA facility, Anacostia, Washington, D. C.," *Law Engineering Report No. W 6-5523 to Wiley & Wilson*, Lynchburg, Virginia.
- 38) Mayne, P. W. and Gordon, D. (1987) : "Geotechnical exploration, Surry waste storage, Bacons Castle, VA," *Law Engineering Report, No. W 7-5768 to Virginia Power*, Richmond, VA, 230 p.
- 39) Mayne, P. W. and Swanson, P. G. (1981) : "Critical-state pore pressure parameter," *Laboratory Shear Strength of Soil*, ASTM STP 740, Chicago, pp.410-430.
- 40) Mayne, P. W. et al (1986) : "Geotechnical report, CEBAF project, Newport News, Virginia," *Law Engineering Report No. NK 5-1182 to DMJM*, Washington, D. C.
- 41) Parez, L., Bachelier, M. and Sechet, B. (1976) : "Pression Interstitielle Developpee au Foncage des Penetrometres," *Proceedings of the VI European Conference on Soil Mechanics and Foundation Engineering*, Vienna, Vol.1.2, pp.533-538.
- 42) Ramalho-Ortigao, J. et al (1983) : "Embankment failure on clay near Rio de Janeiro," *Journal of Geotechnical Engineering*, ASCE, Vol.109, No.11, pp.1460-1479.
- 43) Randolph, M., Carter, J. and Wroth, C. P. (1979) : "Driven piles in clay-effects of installation," *Geotechnique*, Vol.29, No.4, pp.361-393.
- 44) Richards, A. and Zuidberg, H. (1985) : "Insitu determination of the strength of marine soils," *Strength Testing of Marine Sediments*, ASTM STP 883, Philadelphia, pp.11-40.
- 45) Robertson, P. and Campanella, R. (1983) : "Interpretation of cone penetration tests in clay," *Canadian Geotechnical Journal*, Vol.20, No. 4, pp.734-745.
- 46) Robertson, P. et al (1986) : "Use of piezometer cone data," *Proceedings Use of In Situ Tests in Geotechnical Engineering*, ASCE, VPI, Blacksburg, Virginia, pp.1263-1380.
- 47) Rocha Filho, P. (1982) : "Influence of excess pore pressure on cone measurements," *Proceedings 2nd European Symposium of Penetration Testing*, Vol.2, Amsterdam, pp.805-811.
- 48) Rocha Filho, P. and Alencar, J. (1985) : "Piezocone tests in Rio de Janeiro Soft Clay," *Proceedings 11th International Conference on Soil Mechanics*, Vol.2, San Francisco, pp.859-862.
- 49) Roy, M. et al (1982) : "Development of a quasi-static piezocone," *Canadian Geotechnical Journal*, Vol.19, No.2, pp.180-188.
- 50) Schmertmann, J. H. (1978) : "Study of the feasibility of using wissa-type piezometer probe to identify liquefaction potential of saturated fine sands," *Technical Report S-78-2*, 73 pages, USAE Waterways Experiment Station, Vicksburg, Mississippi.
- 51) Schmertmann, J. H. (1974) : "Pore pressures

- that produce nonconservative q_c data," Discussion, Proceedings of the European Symposium on Penetration Testing I, Stockholm, Vol. 2.2, pp. 245.
- 52) Senneset, K. and Janbu, N. (1985): "Shear strength parameters from static cone penetration tests," Strength Testing of Marine Sediments, ASTM STP 883, Philadelphia, pp. 41-54.
 - 53) Senneset, K., Janbu, N. and Svano, G. (1982): "Strength and deformation parameters from cone penetration," Proceedings 2nd European Symposium of Penetration Testing, Vol. 2, Amsterdam, pp. 863-870.
 - 54) Smits, F. (1982): "Penetration pore pressure measured with piezometer cones," Proceedings 2nd European Symposium of Penetration Testing, Vol. 2, Amsterdam, pp. 871-876.
 - 55) Sugawara, N. and Chikaraishi, M. (1982): "On estimation of ϕ' for mine tailings by pore pressure cone," Proceedings 2nd European Symposium of Penetration Testing, Vol. 2, Amsterdam, pp. 883-888.
 - 56) Tavenas, F., Leroueil, S. and Roy, M. (1982): "The piezocone test in clays: Use and limitations," Proceedings 2nd European Symposium on Penetration Testing, Vol. 2, Amsterdam, Balkema Publishing, pp. 889-894.
 - 57) Tavenas, F. and Leroueil, S. (1979): "Clay behavior and the selection of design parameters," Proceedings 7th European Conference on Soil Mechanics, Vol. 1, Brighton, England, British Geotechnical Society, pp. 281-291.
 - 58) Tavenas, F. (1981): "Advantages and limitations of piezocone," Proceedings 10th International Conference on Soil Mechanics, Vol. 4 Stockholm, pp. 769-773.
 - 59) Torstensson, B. A. (1975): "Pore pressure sounding instrument," Proceedings of the ASCE Specialty Conference on In Situ Measurement of Soil Properties, Raleigh, Vol. 2, pp. 48-54.
 - 60) Torstensson, B. A. (1982): "A combined pore pressure and point resistance probe," Proceedings 2nd European Symposium on Penetration Testing, Vol. 2, Amsterdam, pp. 903-908.
 - 61) Tumay, M. et al (1982): "Soil exploration in soft clays with electric cone penetrometer," Proceedings 2nd European Symposium on Penetration Testing, Vol. 2, Amsterdam, May, pp. 415-421.
 - 62) Tumay, M. and Acar, Y. (1985): "Piezocone penetration testing in soft cohesive soils," Strength Testing of Marine Sediments, ASTM STP 883, pp. 72-82.
 - 63) Vesic, A. (1972): "Expansion of cavities in infinite soil masses," Journal of Soil Mechanics and Foundations Division, Vol. 98, No. SM 3, March, pp. 265-290.
 - 64) Villet, W. and Darragh, R. (1985): "Interpretation of piezometric cone in overconsolidated offshore silts," Proceedings 17th Offshore Technology Conference, Vol. 2, May, Houston, Paper No. 4916, pp. 187-200.
 - 65) Wissa, A. E., Martin, R. T. and Garlanger, J. E. (1975): "The piezometer probe," Proceedings of the ASCE Specialty Conference on In Situ Measurement of Soil Properties, Raleigh, Vol. 1, pp. 536-545.
 - 66) Wroth, C. P. (1984): "The interpretation of in-situ soil tests," Geotechnique, Vol. 34, No. 4, pp. 449-489.
 - 67) Zuidberg, H. et al (1982): "A penetrometer for cone resistance and dynamic pore pressures, Proceedings 2nd European Symposium on Penetration Testing, Vol. 2, Amsterdam, pp. 963-970.