Soil classification by the cone penetration test:[1] Discussion

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The discussers were interested in the revised treatment of soil classification from cone penetration testing (CPT) but suggest that a significant factor has nevertheless been missed. Although the case of evaluating CPT data in terms of dimensionless ratios Q, F, and B_q is clear, the fact remains that negative pore-water pressures are limited by an absolute cutoff: cavitation. Such an absolute cutoff can confuse the apparent generality of Q and B_q in terms of soil behaviour.

As noted by the author, the proposed soil classification charts are derived from primarily onshore data from depths of 30 m or less. However, use of the CPT is not limited to onshore applications, and indeed the CPT is often the principal site investigation tool in the offshore. The proposed dual Q–B_q charts are a poor fit to offshore data, as can be seen by some examples.

Soil classification and index data for two offshore sites in the Canadian Beaufort Shelf have been presented in the literature. The two sites are Tarsiut P-45 and Sauvrak F-45, and the required data can be found in Jefferies *et al.* (1985) and Jefferies *et al.* (1987*a*, 1988). Both sites lie in the physiographic region known as the Kringalik Plateau (M.J. O'Connor and Associates 1983) and, as such, are examples of the behaviour exhibited by the stiffer silty clay sediments encountered in the Arctic offshore. The key properties and summarized CPT data for several of the geologic units at both the Tarsiut and Sauvrak sites are presented in Tables 1 and 2, respectively. Hydrometer analyses are only available for the Sauvrak site and show that the clay fraction ranged from a low of 35% in unit B2 to a high of 60% in unit A, with the remainder of the soil particles being essentially silt sized. CPT data were obtained with the piezometric transducer behind the tip. Full details of the CPT geometry are given in Jefferies *et al.* (1987*b*).

The normalized CPT parameters Q and F for the above strata are plotted against the authors' corresponding classification chart in Fig. 1. Most strata are correctly identified as clay to silty clay with the exception of two high-K_o

[1]Paper by P.K. Robertson. 1990. Canadian Geotechnical Journal, **27**: 151–158.

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TABLE 1. Summary of soil characteristics

Site	Geologic unit	Liquid limit (%)	Plasticity index (%)	Liquidity index	OCR	K_o	Legend for Figs. 1–4
Tarsiut P-45 (69°45′56″N; 136°25′04″W)	A	49–55	22–28	0.3–1.1	~7	≈2.7	*a*
	B1	37–45	20–27	0.5–0.9	4–6	≈2.4	*b*
	B2	40–58	27–29	0.2–0.6	~3	≈1.5	*c*
	B3	35–40	20–24	0.5–0.8	~2	≈1.6	*d*
Sauvrak F-45 (69°54′23″N; 136°41′51″W)	A	55–65	24–30	0.5–1.3	na	na	*e*
	B1	45–55	20–30	0.3–0.5	7–9	0.8	*f*
	B2	32–42	12–20	0.2–0.8	4–8	2.6–2.9	*g*
	B3	35–48	15–25	0.1–0.4	3–4	1.5–2.2	*h*

TABLE 2. Summary of dimensionless CPT results

Site	Geologic unit	Q	F (%)	B_q	Legend for Figs. 1–4
Tarsiut P-45	A	~33	~4.5	−0.3±0.03	*a*
	B1	32–28	~2.5	−0.1±0.05	*b*
	B2	18–14	3–4	−0.05±0.05	*c*
	B3	8–11	~2.5	+0.25 to +0.3	*d*
Sauvrak F-45	A	~30	~8	−0.4±0.1	*e*
	B1	~25	8–8.5	+0.1+0.1	*f*
	B2	10–18	6–6.5	−0.35±0.1	*g*
	B3	7–12	4–5	+0.45±0.05	*h*

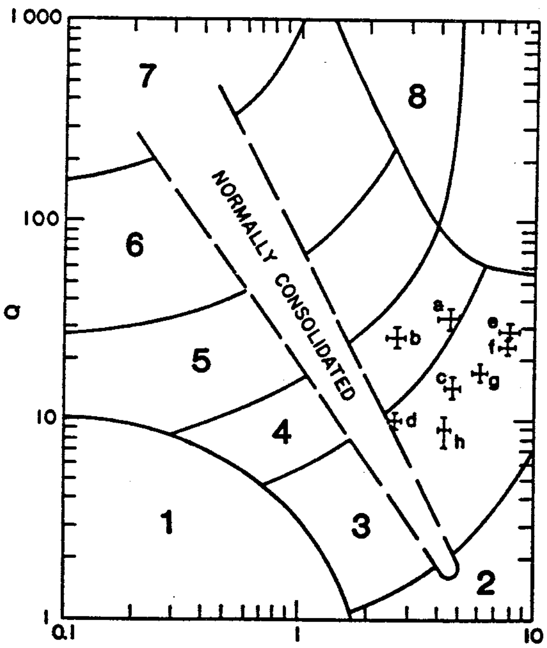

FIG. 1. Proposed soil behaviour type classification chart by Robertson (1990) based on normalized CPT and CPTU data. Zones are as follows: 1, sensitive, fine grained; 2, organic soils — peats; 3, clays — clay to silty clay; 4, silt mixtures; 5, sand mixtures; 6, sands; 7, gravelly sand to sand; 8, very stiff sand to clayey sand.

strata, which are identified as somewhat siltier than the other strata, which is to be expected. The proposed chart also closely estimates the over consolidation ratio (OCR) values with a slight tendency to overestimate for the near-normally consolidated B3 strata; again, the slight overestimation of OCR is unsurprising given the greater than usual geostatic stress in these sediments. Overall, the correspondence of the proposed classification chart to the data is excellent.

A very different pattern of behaviour emerges when the data are compared with the proposed classification chart using Q and B_q parameters (Fig. 2). One-half of the data plots off the domain of the proposed chart and nearly all strata are misclassified to a greater or lesser extent. Overall, the performance of the proposed soil classification chart using Q and B_q is very poor.

The reason for the poor performance of the Q–B_q chart lies in the phenomenon of cavitation and the bias of the chart to shallow, wet clays. In fact, the Q–B_q chart reasonably identifies the two B3 strata with substantial positive pore pressures during sounding. The difficulty arises with the very dilatant Recent and Transgressive sediments. The nature of the dilatancy exhibited by these sediments can be observed in the stress paths presented for these clays in triaxial compression (Jefferies *et al.* 1985, 1988).

The occurrence of cavitation during cone penetration can be observed on the CPT sounding previously presented for the Tarsiut P-45 site (Jefferies *et al.* 1988). The occurrence of substantial undrained dilation, and its cutoff by cavitation, has two effects. First, the observed B_q value is determined by the cavitation pressure, not the undrained response of the soil; thus, B_q becomes decoupled from soil behaviour. A decoupled parameter is obviously of minimal use in classification. Second, if the piezometric response is controlled by the cavitation pressure, then Q will also be controlled by the cavitation pressure because of the effective

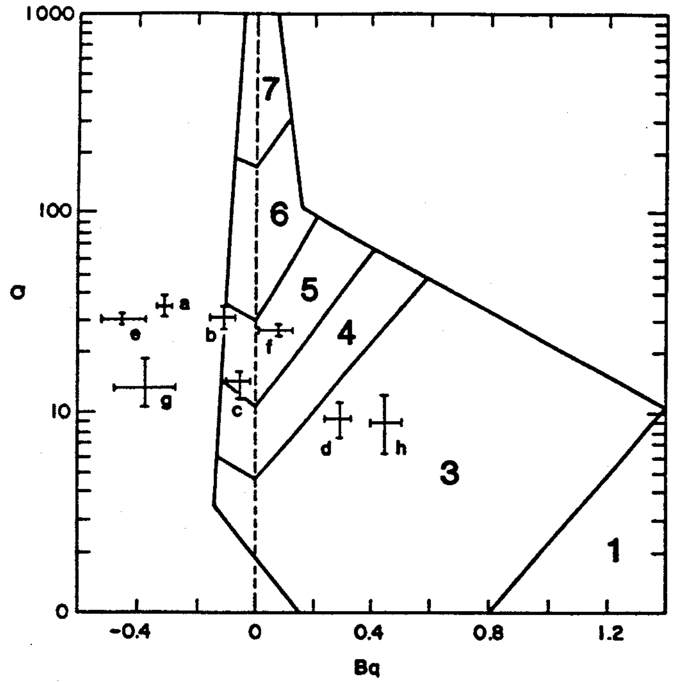

FIG. 2. Proposed classification chart by Robertson (1990) using Q and B_q parameters. Zones as in Fig. 1.

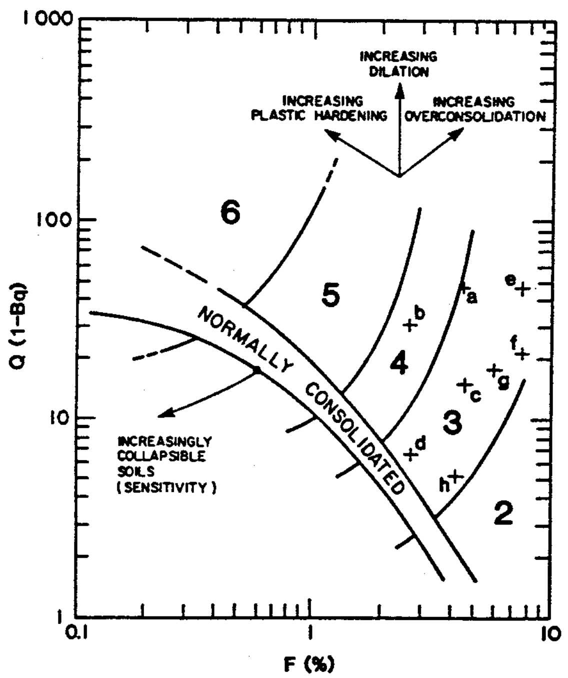

FIG. 3. Proposed classification chart using $Q(1 - B_q)$ and F parameters. Zones as in Fig. 1.

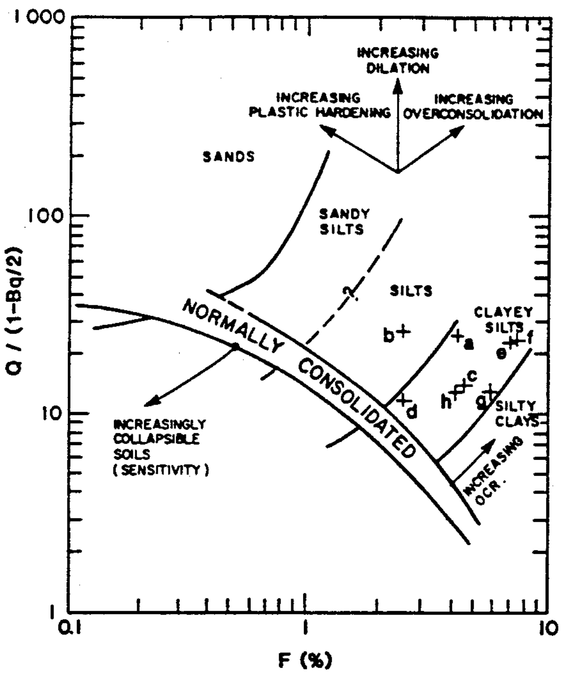

FIG. 4. Proposed classification chart using $Q/(1 - B_q/2)$ and F parameters. Zones as in Fig. 1.

stress principle. The more negative the permitted B_q, the greater the value of Q will be, even for the same soil. More negative B_q values are encountered in the offshore because the water depth at the site can provide a substantial to even very great back pressure.

The effect of back pressure and cavitation can readily be shown by example. Consider the Tarsiut P-45 site and stratum A in particular. The CPT solidly cavitated between the depths of 4 and 6 m, that is, the measured u_c was approximately −100 kPa gauge. On land, the excess pore pressure would have been approximately −150 kPa, assuming the groundwater table was at the ground surface. However, at the Tarsiut site the water depth was 26 m, so the excess pressure was approximately −400 kPa. Thus, the suppression of cavitation by the water depth at the site allowed a near tripling of the excess pore-water pressure and consequently a tripling of the calculated B_q value.

The effect of measured excess pore pressure on Q is more difficult to calculate, since the pressure will vary with distance from the CPT; a full boundary value problem must be solved. In addition, at such high excess pore pressures, the location, size, and nature of the piezometer element becomes extremely important. Even at low excess penetration pressures, the piezometer geometry has a very significant effect on measured response (as correctly noted by the author). However, it would be reasonable to estimate that a tripling of negative excess pore pressure at the CPT might double the measured tip resistance. Interestingly, if an "onshore" equivalent of Tarsiut unit A is estimated as $B_q \simeq -0.3/3$ and $Q \simeq 33/2$, then it is found that the "onshore equivalent" indeed correctly plots on the proposed Q and B_q classification chart.

The purpose of normalized classification charts is that such charts should provide a first estimate in any situation. Clearly, the proposed Q and B_q chart does not meet this criteria, as there is a missed systematic variable: initial hydrostatic pressure.

Although it might be argued that the proposed chart is "good enough" for most purposes, such an argument is unsatisfactory for the simple reason that it presupposes all users will have a working familiarity with its limitations, which are significant. It is also unsatisfactory because if something is not correct, then it is an error. If something is erroneous, it should not be used. A correct solution should be found. In fact, some steps toward a possibly correct classification scheme have been taken.

One complication of the proposed charts is the separation of the three groups Q, F, and B_q. This separation is not necessary. Houlsby (1988) noted that the grouping $Q(1 - B_q) + 1$ might prove a useful indicator of soil type, whereas Been *et al.* (1988) concurrently used a similar expression (but defined in terms of mean rather than vertical stress) to show the parameter grouping $Q(1 - B_q)$ would be a quantitative measure suitable for sands, silts, and clays. Use of $Q(1 - B_q)$ folds two of the independent normalized parameter groups together.

The expression $Q(1 - B_q)$ is plotted against F in Fig. 3, and for those cases where B_q is near zero it is similar to the first universal classification chart proposed by the author. However, there is an expansion of the silt and clay region to permit greater differentiation of these soils. Nevertheless, the revised interpretation chart still suffers from an inability to correctly deal with negative B_q values where the controlling factor is cavitation.

A combination of normalized ratios that compensates for cavitation effects is the grouping $Q/(1 - B_q/2)$. The theoretical meaning of this combination is not at all clear, and the term $Q/(1 - B_q/2)$ is presently proposed only on the basis of being an algebraic combination of permissible dimensionless variables; the factor of 2 on B_q is introduced as a "damping" coefficient to prevent very soft clays producing sign changes in the grouping, which would be inconvenient in logarithmic plots.

The grouping $Q/(1 - B_q/2)$ is plotted against F in Fig. 4. As can be seen, the chart does improve the grouping of the data given in Tables 1 and 2. Whether the grouping is universally acceptable remains to be seen.

It would be interesting if the author would plot some of his data against Figs. 3 and 4 and extend them if possible. If reliable classification is achieved, an extended version of either chart would be an improvement on the authors present proposal. If reliable classification is not achieved, it must be concluded that soil classification should be limited to only the Q versus F plot for the present. As noted by Houlsby (1988), in comparison with other soil tests, the interpretation of the piezocone is still in its infancy. At this early stage of development, it is essential that any interpretation methods developed are based on sound principles that incorporate the observed behaviour of all soils.

BEEN, K., COOKS, J.H.A., and JEFFERIES, M.G. 1988. Interpretation of material state from the CPT in sands and clays. Proceedings, Institution of Civil Engineers, Conference on Penetration Testing, Birmingham, U.K., pp. 215-218.

HOULSBY, G.T. 1988. Introduction to Papers 14-19. Proceedings, Institution of Civil Engineers Conference on Penetration Testing, Birmingham, U.K., pp. 141-146.

JEFFERIES, M.G., RUFFEL, J.P., CROOKS, J.H.A., and HUGHES, J.M.O. 1985. Some aspects of the behaviour of Beaufort Sea clays. *In* In situ strength testing of marine sediments. American Society for Testing and Materials, Special Technical Publication 883, pp. 487-514.

JEFFERIES, M.G., CROOKS, J.H.A., BECKER, D.E., and HILL, P.R. 1987*a*. Independence of geostatic stress from overconsolidation in some Beaufort Sea clays. Canadian Geotechnical Journal, **24**: 342-356.

JEFFERIES, M.G., JONSSON, L., and BEEN, K. 1987*b*. Experience with measurement of horizontal geostatic stress in sand during cone penetration test profiling. Géotechnique, **371**: 483-498.

JEFFERIES, M.G., CROOKS, J.H.A., BECKER, D.E., and HILL, P.R. 1988. Independence of geostatic stress from overconsolidation in some Beaufort Sea clays: Reply. Canadian Geotechnical Journal, **25**: 624.

O'CONNOR, M.J. AND ASSOCIATES. 1983. Development of a proposed model to account for the surficial geology of the southern Beaufort Sea. Geological Survey of Canada, Open File 954.

List of symbols

$$Q = \frac{q_t - \sigma_{vo}}{\sigma_{vo}}$$

$$F = f_s/(q_t - \sigma_{vo})$$

$$B_q = (u - u_o)/(q_t - \sigma_{vo})$$

Soil classification using the cone penetration test:[1] Reply

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The writers of the discussion have correctly identified a limitation to the proposed empirical soil classification chart for piezocone data. For offshore investigations it is possible to have large hydrostatic back pressures because of the depth of water that can allow large negative pore pressures to develop during cone penetration in some highly dilative soils before cavitation occurs. The writers have also presented some valuable additional data to assist in the modification and improvement of the existing chart.

[1]Discussion by M. G. Jefferies and M. Davies. 1991. Canadian Geotechnical Journal, **28**, this issue.

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The majority of data presented by the writers were correctly identified using the normalized cone penetration test (CPT) parameters Q and F; problems only occurred using the piezocone parameter B_q. Hence, the charts appear to have provided a good first estimate of soil classification.

The domains shown in the Q–B_q chart were based on the author's extensive experience with data from numerous onshore and offshore projects worldwide. The fact that the B_q domain was limited in the negative region is based on the observation that very little data have been obtained in soils that are highly dilatant and where cavitation has not restricted the response. The Q–B_q domains were given defined limits in an effort to guide potential users to recognize potentially unusual data. Data that would fall outside the defined zones should be checked for potential errors, both measurement and calculation. Because of the extensive volume of data produced during cone testing it is common practice to use computers to process the results. Hence, the charts have been designed in a deterministic way to facilitate the application of computer processing. When limits are defined based on previous experience the user is made aware of potentially unusual data if these results fall outside the limits. However, at present there is limited available experience for piezocone data, and the new data presented by the writers indicate that some of the domains should be expanded and adjusted somewhat in the region of negative B_q.

Figure 1 presents a suggested modification to the original Q–B_q chart to incorporate the writers' data. This modification also provides a somewhat better fit to much of the previous experience. Additional data in the form of dissipation rates are required to clarify some of the classifications. It would have provided valuable additional information if the writers had presented and discussed any possible dissipation data. Also included in the modified Q–B_q chart is zone 2 soils (organic soils and peat) that was missing in the original published chart.

The original and modified charts have many limitations in their effort to account for all the complexities of real soils. The charts are proposed as a "guide," knowing that they may need some small adjustments to suit local geologic conditions.

Offshore investigations can present special problems for interpretation of CPTU data. For example, it is common practice in deep-water (>50 m) offshore investigations to zero the CPTU measured parameters at the mud line and hence record everything relative to the values at the mud line. This procedure complicates the interpretation of the data, since the large total stress overburden because of the depth of water is removed. Fortunately, the shallow offshore data presented by the writers did not appear to have this added problem.

The writers also suggest that cavitation of the pore-pressure measurement will control Q because of high effective stresses induced by the negative pore pressures. This is not completely true because negative pore pressures are only recorded immediately behind the cone tip. Figure 2 shows a summary of data presented by Robertson *et al.* (1986). These results illustrate that in highly dilative soils large negative pore pressures can be recorded behind the cone tip, but large positive pore pressures exist on the face of the tip. The large positive pore pressures are strongly controlled by the large increase in total normal stresses induced by cone penetration. The large gradient of pore pressures existing

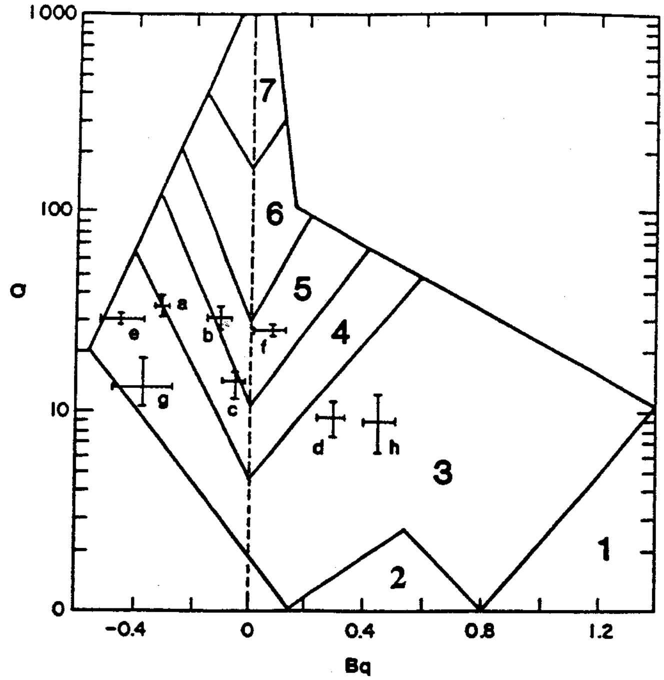

FIG. 1. Proposed modified soil behaviour type classification chart for CPTU data. Zones are as follows: 1, sensitive, fine grained; 2, organic soils — peats; 3, clays — clay to silty clay; 4, silty mixtures — clayey silt to silty clay; 5, sand mixtures — silty sand to sandy silt; 6, sands — clean sand to silty sand; 7, gravelly sand to sand.

around the cone in dilative soils, as shown in Fig. 2, illustrates the complexity of pore-pressure distribution during cone penetration. Hence, it is not "reasonable to assume that a tripling of negative excess pore pressure immediately behind the cone might result in a doubling of the measured tip resistance." The fact that the Q–F chart correctly identified the writers offshore soils illustrates that the measured Q was consistent with similar soils (onshore and offshore) where the measured negative pore pressures behind the tip were generally smaller.

The writers have suggested modified charts based on the complex combined parameters $Q(1 - B_q)$ or $Q/(1 - B_q/2)$. These new charts provide almost no improvement over the existing basic Q–F chart and introduce unnecessary complication. This author is very reluctant to recommend charts that require the measurement of pore pressures, since there still remains some complications with these measurements for some soil conditions. Also, the basic CPT masurements of q_c and f_s are still the most common form of data collected.

The author would like to encourage more people to publish their experiences with piezocone data so that the general data base can expand and empirical charts, such as those proposed, could be improved.

The writers comment rather strongly that the limitations to the charts are significant and that "if something is erroneous, it should not be used." The data presented by the writers show that the Q–F chart is very good and that only minor modifications are needed to the Q–B_q chart to suit their data, as suggested in Fig. 1. If geotechnical engineers in the past had taken the philosophy suggested by

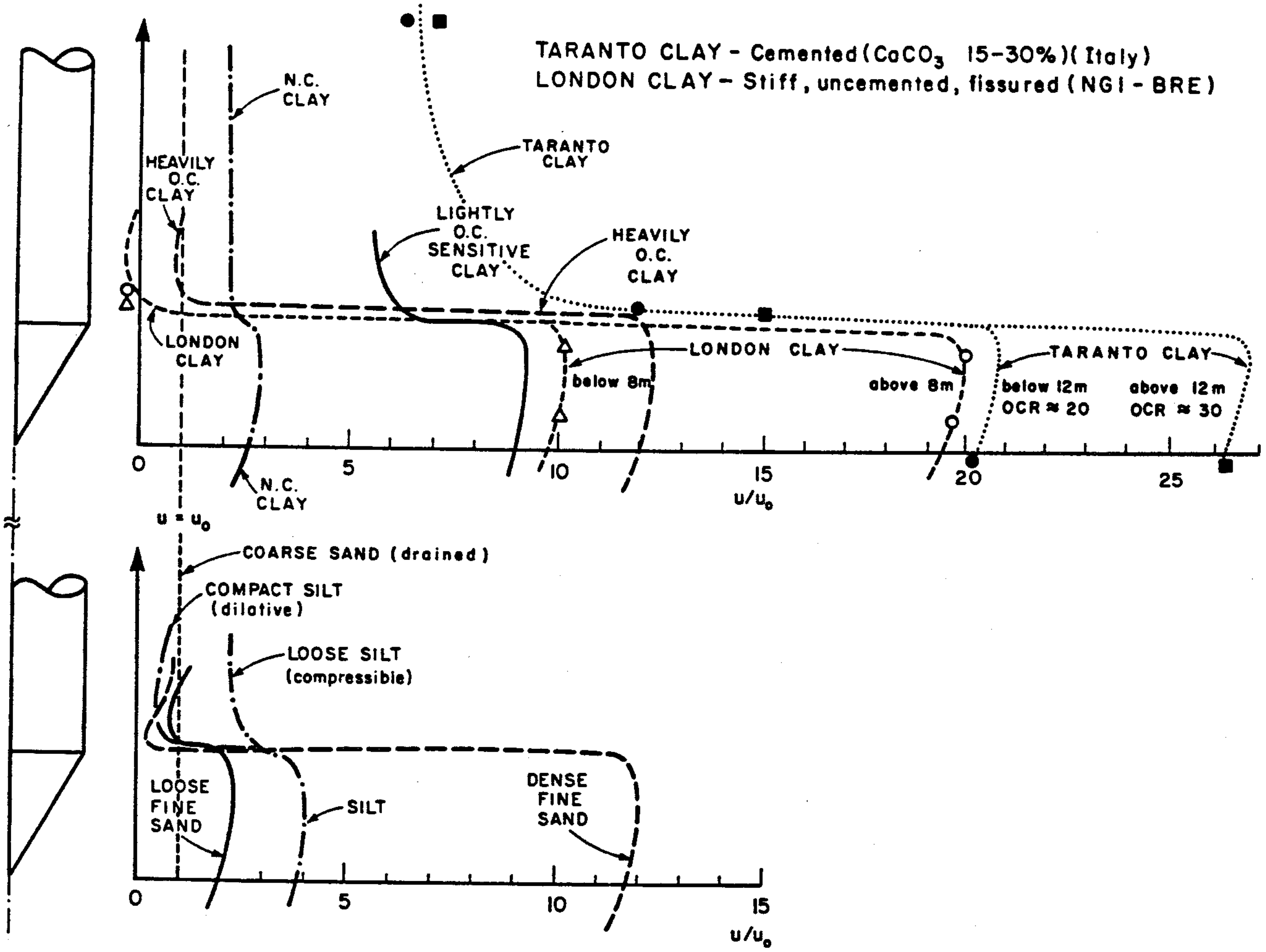

FIG. 2. Distribution of pore pressures around a penetrating cone (after Robertson *et al.* 1986).

the writers, most of the well-established and well-used empirical design rules based on simple tests would not have been developed and their application by subsequent practising engineers would not have been enjoyed. The author respects the purity of thought expressed by the writers but suggests that geotechnical engineering for real soils is not utopia.

ROBERTSON, P.K., CAMPANELLA, R.G., GILLESPIE, D., and GRIEG, J. 1986. Use of piezometer cone data. Proceedings, In Situ '86, ASCE Specialty Conference on Use of In Situ Tests in Geotechnical Engineering, Blacksburg, VA, ASCE, Geotechnical Special Publication 6, pp. 1263–1280.