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Use of CPTu to Estimate Equivalent SPT N_{60}

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ABSTRACT: Although the CPTu offers many advantages over the SPT, it may be desirable in some instances to use SPT-based experience of soil behavior. An algorithm is presented here for estimation of equivalent N_{60} values directly from the CPTu without resort to soil sampling. The proposed algorithm is based on data and trends reported in the literature; the algorithm is tested against new data obtained for cross-calibration of the CPTu/SPT in a wide variety of soil types, penetration resistances, and depths. As part of the evaluation of the algorithm, replicate trials of both SPT and CPTu were carried out. The data show the CPTu is five times more precise than the SPT. Further, the equivalent N_{60} derived from the CPTu using the proposed algorithm is shown to be at least as reliable as values directly determined by the SPT; the much improved precision of the CPTu outweighs the uncertainty in the CPTu/SPT calibration, and the calibration in itself averages the testing error of the SPT. The proposed algorithm is tested for bias against depth, soil type, penetration resistance, and friction ratio; the algorithm is unbiased. Cumulative probability density functions are given for repeatability of the SPT, the CPTu, and an estimation of equivalent SPT values from the CPTu.

KEYWORDS: cone penetrometer, penetration tests, correlation techniques

Nomenclature

CDF	Cumulative distribution function
E	Measurement uncertainty
ε	Algorithm bias indicator
F	Stress normalized CPTu friction ratio: $F = \dfrac{f_s}{q_T - \sigma_{v0}} \times 100\%$
I_c	Soil classification index
N	Standard penetration test (SPT) blowcount: blows per 300 mm
N_c	Computed SPT blowcount
N_m	Measured SPT blowcount
Q	Stress normalized CPTu tip resistance: $Q = \dfrac{q_T - \sigma_{v0}}{\sigma'_{v0}}$
q_c	Tip resistance
q_T	q_c corrected for any unequal area effects: $q_T = q_c(1 - a \cdot u)$
f_s	Cone penetration test sleeve fraction
a	Unequal end area ratio
u	Dynamic CPTu pore pressure
u_0	Hydrostatic pressure
B_q	CPTu pore pressure ratio: $B_q = \dfrac{u - u_0}{q_T - \sigma_{v0}}$

Introduction

Penetration tests are commonly used to test soils, and there is considerable knowledge relating soil behavior to the Standard Penetration Test [SPT; ASTM Method for Penetration Test and Split-Barrel Sampling of Soils (D 1586)]. However, the incorporation of modern electronics within the instruments used for the cone penetration test [CPTu; ASTM Test Method for Deep, Quasi-Static, Cone and Friction-Cone Penetration Tests of Soil (D 3441)] offers a test with many advantages over the SPT including: precision, repeatability, continuous logging, multiple channel measurements, and ease of use in offshore testing. The CPTu is seeing ever-increasing use and it seems likely that the CPTu will eventually become the accepted reference test for many soils. Nevertheless, it may be desirable to refer to the SPT-based experience record when using the CPTu, for example when carrying out a liquefaction susceptibility analysis, and this requires a mapping between the two types of penetration tests.

The relationship between the CPTu, represented by the tip resistance q_c, and the SPT, represented by the blowcount N, has been determined in a number of studies over the past 30 years (Meigh and Nixon 1961; Thornburn 1970; Schmertmann 1970; Burbidge 1982; Robertson et al. 1982; Seed and de Alba 1984; Burland and Burbidge 1985). The relationship between CPTu and SPT is expressed in terms of the ratio q_c/N (MPa/blows per 300 mm); q_c/N data from data available in the literature is summarized in Fig. 1 against the average particle size of the soils tests. Plotting data in this manner assumes the relationship between the two tests is functionally dependent only upon soil type as characterized by average particle size, a tacit assumption underlying previous studies.

Although Fig. 1 appears to be suitable to estimate SPT results from CPTu data, this is only the case if sampled boreholes are available with grain-size data in the various strata. This also relies on extreme lateral homogeneity of deposits, a geological condition which is not common in natural materials. What is really required is a relationship between SPT and CPTu based on CPTu data alone; such a relationship would permit estimation of SPT resistance without boreholes or samples. A direct relationship based on CPTu parameters alone would also avoid the uncertainty introduced by soil gradation changing between the CPTu data and the supposed corresponding soil sample.

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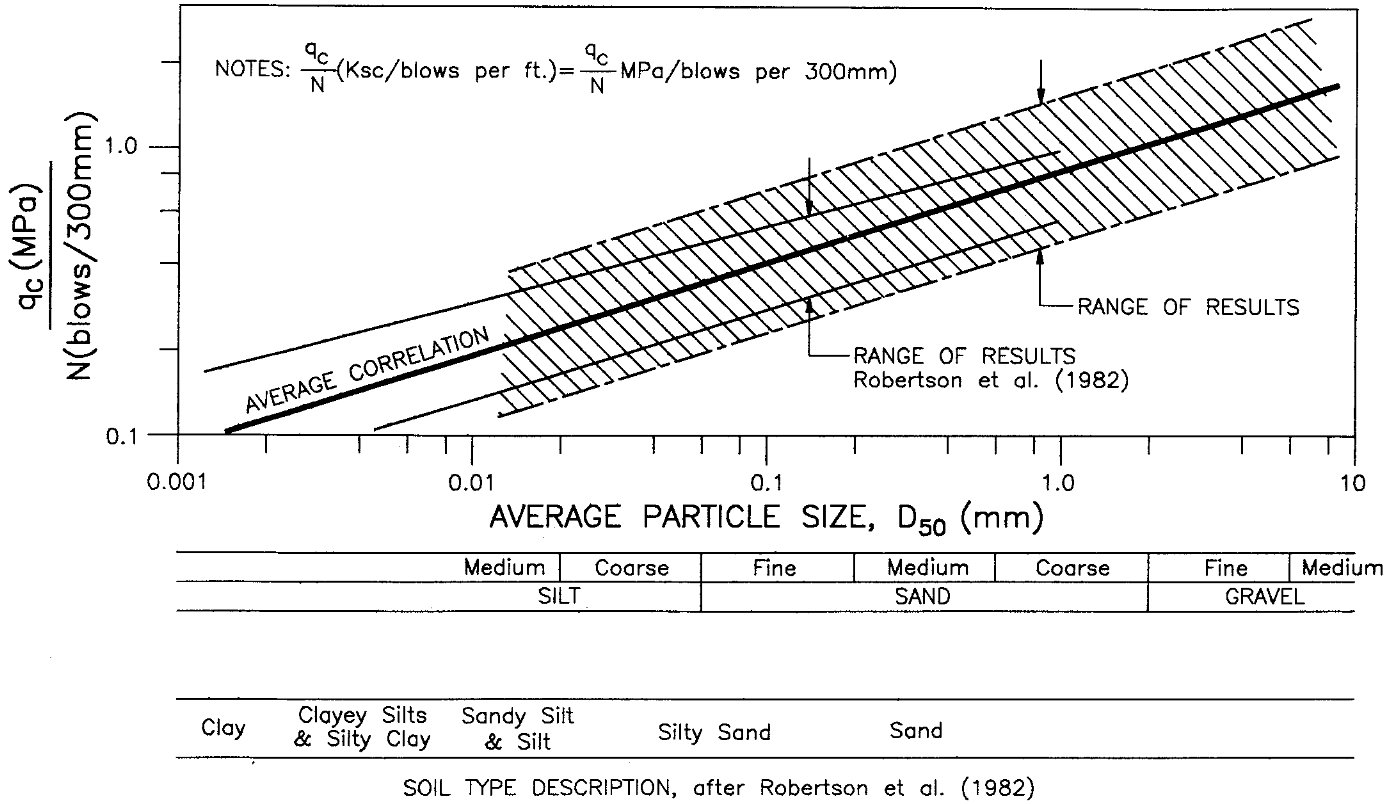


FIG. 1—*Relationship between CPTu and SPT with soil type (adapted from Burland and Burbidge, 1985).*

This note derives an algorithm to estimate SPT N values using only CPTu data. The basis of the algorithm is a soil-type index based on an existing CPTu soil type classification chart; the trend of q_c/N found in earlier studies is then related to the soil type index. The proposed algorithm is thus based on existing data.

The performance of the proposed algorithm is evaluated against new CPTu/SPT data obtained at five sites and comprising a total of 252 data pairs. The use of new data, which was obtained under controlled conditions specifically to provide a cross-calibration, provides an independent trial of the algorithm.

The algorithm presented is based on, and should only be applied to, right circular electronic piezocones conforming to the proposed International Reference Penetrometer configuration (de Beer et al. 1988). Such cone penetrometers also conform to the less restrictive ASTM D 3441 standard. Because the algorithm utilizes the CPTu friction ratio, cone penetrometers should have an independent transducer to measure sleeve friction. Data measured with subtraction cone penetrometers should be processed with the proposed algorithm only if the user is confident that the data are accurate.

Dimensional Similarity of SPT and CPTu

The first step in correlating the two tests is to establish that a functional relationship should exist. A minimum requirement is that the SPT and the CPTu should be dimensionally equivalent in units of mass, length, and time.

Although the SPT blowcount, or N value, is often regarded as an index, this is incorrect. The N value is a count of the number of standard units of energy (hammer drops) applied. Further, the energy applied is measured for unit penetration. Thus, the N value is dimensionally equivalent to energy per unit displacement, which is a force.

The ratio of CPTu penetration resistance, q_c, with SPT N data thus implies an area to the SPT to be dimensionally consistent. This area varies during the SPT test. Initially, an SPT sampler to D 1586 in an unplugged condition (i.e., with the soil moving freely into the sample barrel) presents an area of 1081 mm^2 to the soil; when fully plugged the end area rises to 2043 mm^2, which is a variation of nearly a factor of two.

The SPT is also complicated by the dynamic nature of the loading. Not all energy applied at the anvil is seen by the sampler, and indeed the energy transferred to the ground is a function of the ground impedance. The energy delivered to the sampler is also a function of total rod length and hammer/anvil factors. Commonly, the desired arrangement is one transmitting 60% of the theoretical hammer free fall energy to the rods; a blowcount obtained at this 60% energy ratio is taken as the reference value and referred to as $(N)_{60}$.

If it is assumed for simplicity that all SPT energy is transmitted to the sampler, and if the SPT can be analyzed in a quasi-static manner neglecting both the weight of the hammer/rods and side friction on the sampler, one obtains that the correlation between CPTu and SPT should lie in the range $0.4 < q_c$: MPa/N: blows < 0.8.

The actual relationship between SPT and CPTu will depend not only on the propensity of the sampler to plug, but also on the response of the soil to loading rate, the possibility of drained loading with the CPTu to undrained loading with the SPT, and on the relative importance of side friction to end bearing. These factors should all be functions of the soil type. Thus one may reasonably expect q_c/N to be functionally correlated with soil mechanical response to loading, with this mechanical response being a possibly loose function of soil gradation. The tacit assumption of earlier studies is dimensionally consistent and physically reasonable.

Proposed Algorithm

A first step in estimating equivalent SPT data from the CPTu is to process the CPTu data to represent the longer test interval of the SPT. A CPTu responds to soil and delivers data approximately every 10 to 20 mm, whereas a SPT value is defined over a 300-mm interval. A simple moving window averaging was used to smooth the detail in the CPTu to the coarser SPT; that is, measured data is algebraically averaged over the depth interval corresponding to the SPT on all three CPTu data channels.

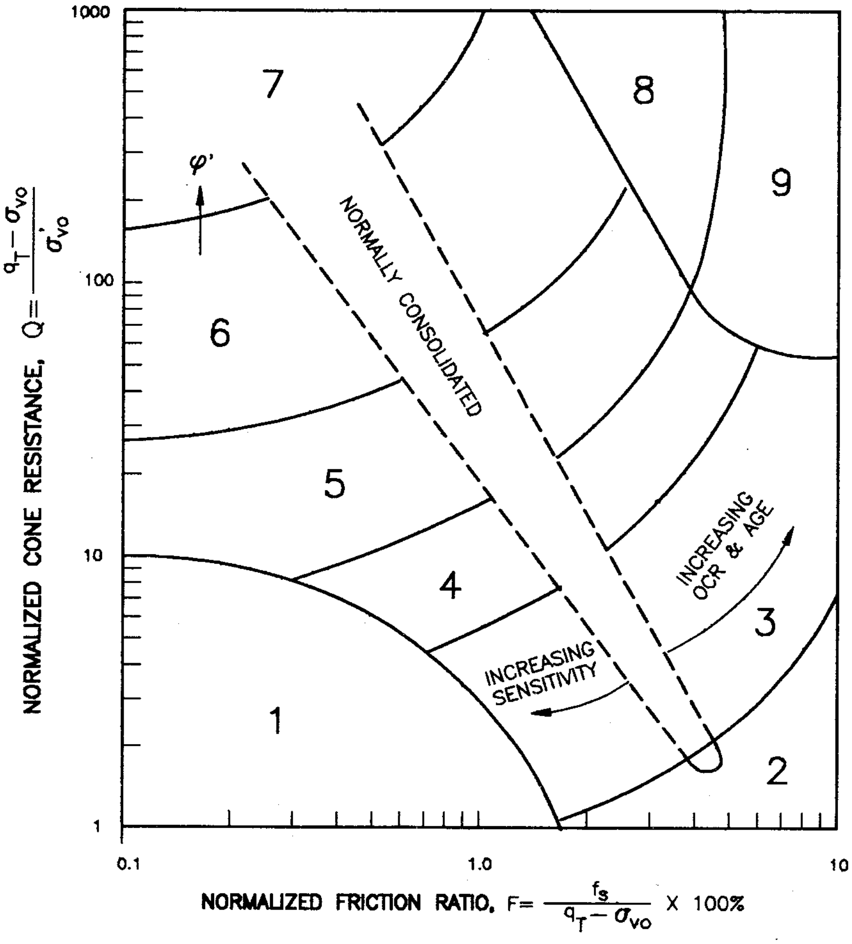
Soil type can be estimated from measured CPTu data using interpretation charts, a recent example of which is shown in Fig. 2 with soil types being indicated. Thus, estimation of SPT N values strictly from CPTu data may be accomplished in principle by combining Fig. 1 with Fig. 2. In fact, this may be preferable to direct use of average particle size data as Fig. 2 uses measured mechanical response to penetration under standard conditions and it is such response that is anticipated to cause variation in the q_c/N ratio.

One approach would be to combine Figs. 1 and 2 using a look-up table. However, the use of such an approach is undesirable as it would lead to arbitrary jumps in q_c/N when crossing a soil type boundary. Since the soil clearly has no cognizance of the classification boundary, a continuum approach of fitting an equation to the trend is desirable.

The influence of drainage on penetration response can be incorporated provided a piezocone is used for the CPTu. Piezocones (denoted by CPTu) measure the pore water pressure induced during penetration as well as the conventional tip resistance and friction. The additional data provided by a CPTu sounding is incorporated into the soil classification scheme using the grouping $Q(1 - B_q)$, this grouping having been simultaneously proposed for unification of CPTu data by Houlsby (1988) and Been et al. (1988); a modification of Fig. 2 using this revised grouping is presented in Fig. 3. The effect of incorporating pore pressure data from the CPTu is to expand the interpretation range in finer soils while leaving the interpretation in sands unchanged.

The boundaries between soil behavior type zones in Fig. 3 can be approximated as concentric circles, as illustrated, if the vertical and horizontal scales are distorted by using differing length scales. Within this approximation, soil type is indicated by circle radius, and the radius may be used as a soil behavior type index. A soil classification index I_c is defined (noting that Q and B_q are dimensionless and that F is given in per cent)

$$I_c = \sqrt{\{3 - \log (Q (1 - B_q))\}^2 + [1.5 + 1.3 (\log F)]^2} \quad (1)$$



NOTES:

1. SENSITIVE FINE GRAINED
2. ORGANIC SOILS – PEATS
3. CLAYS – CLAY TO SILTY CLAY
4. SILT 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
8. VERY STIFF SAND TO CLAYEY* SAND
9. VERY STIFF FINE GRAINED*

*HEAVILY OVERCONSOLIDATED OR CEMENTED

FIG. 2—*Classification of soil behavior types from CPTu data (after Robertson, 1990).*

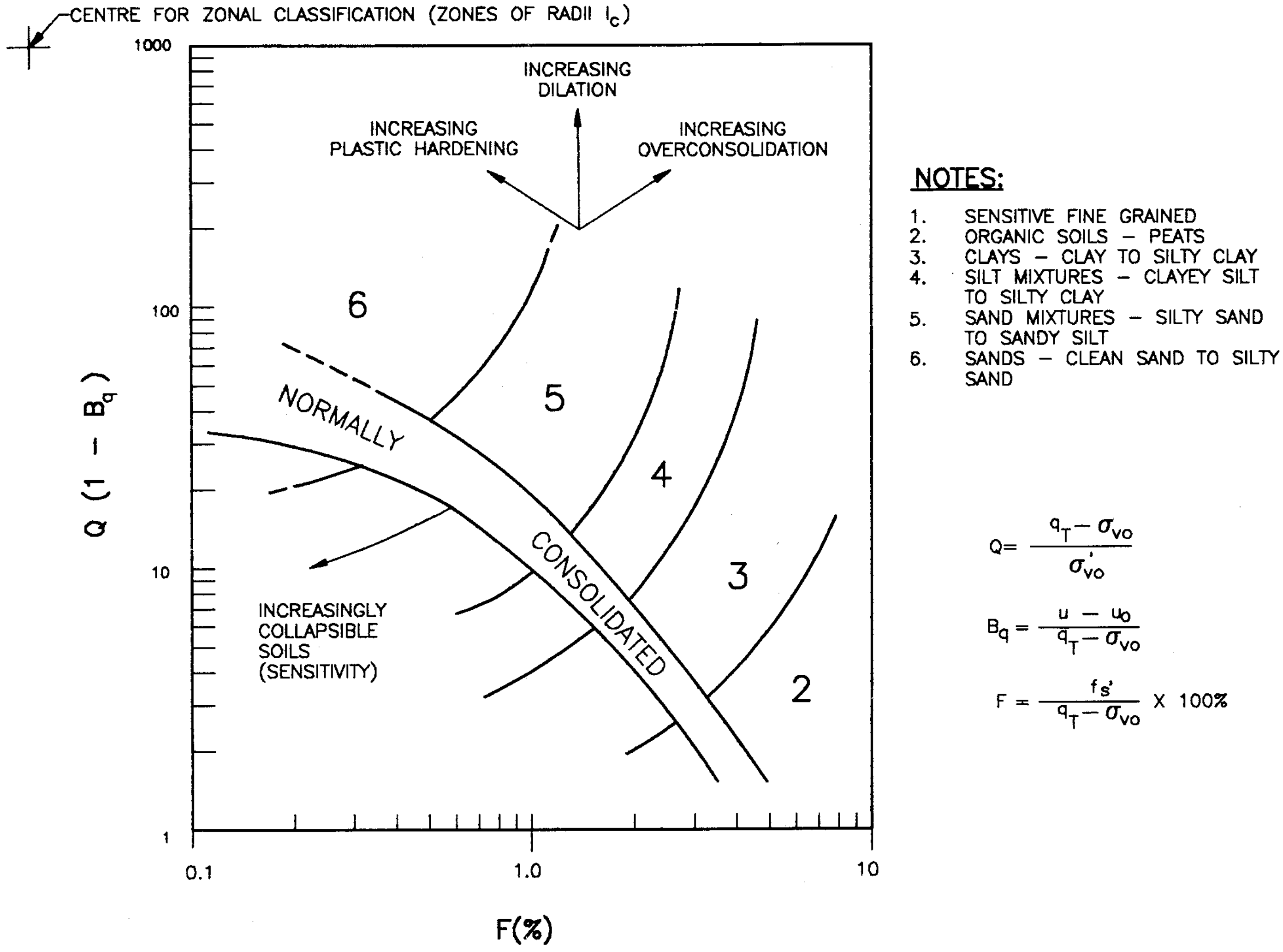


FIG. 3—*Extended soil classification chart for piezometric CPTu data (after Jefferies and Davies, 1991).*

In Eq 1, the factor 1.3 is the mapping used to obtain a plot with concentric circles, and the center of the circles is $\log(Q) = 3$, $\log(F) = -1.5$. The logarithms used are base 10. Within this classification of CPTu data, soil behavior types are attributed from I_c as summarized in Table 1.

The description of soil behavior type used in Table 1 follows Robertson (1990). Note that Zone 7 by Robertson (1990) does not appear in Fig. 3; we feel that this zone is an artificial distinction (Jefferies and Davies 1991) but include it because of its popular use. Also, the reliability of the SPT in this zone is doubtful. The same simplified description of soil behavior type is given in the CPTu/SPT relationship study of Robertson et al. (1982), as indicated in Fig. 1. Assuming consistency in soil type description between these two studies then leads to a relation of q_c/N and I_c as plotted in Fig. 4.

TABLE 1—*Soil behavior type from classification index* I_c.

CPTu Index I_c	Zone	Soil Classification
$I_c < 1.25$	7	Gravelly sands
$1.25 < I_c < 1.90$	6	Sands—clean sand to silty sand
$1.90 < I_c < 2.54$	5	Sand mixture—silty sand to sandy silt
$2.54 < I_c < 2.82$	4	Silt mixtures—clayey silt to silty clay
$2.82 < I_c < 3.22$	3	Clays

Subsequent calibration of the proposed relation against new test data, discussed in the next section, gave improved precision with minor modification of the estimated trend. The best fit with data was given by the relation

$$\frac{q_c\text{:MPa}}{N_{60}\text{·blows/300 mm}} = 0.85\,(1 - I_c/4.75) \qquad (2)$$

Also plotted in Fig. 4 is the inferred range of data from the Robertson (1990) soil behavior type classification. The fact that the calibrated relationship was found to be somewhat higher than most published relationships is not surprising to experienced CPTu researchers; a bias towards finer-grained materials is common. A proposed correlation to this fines content bias is beyond the scope of this paper but is noted for completeness.

Equations 1 and 2 form the proposed algorithm for estimating SPT data from the CPTu. The parameter values used as characteristic of the CPTu are the measured values averaged over the 300-mm interval corresponding to the SPT.

A further advantage of using the proposed algorithm over previous efforts exists in the computational simplicity. Equations

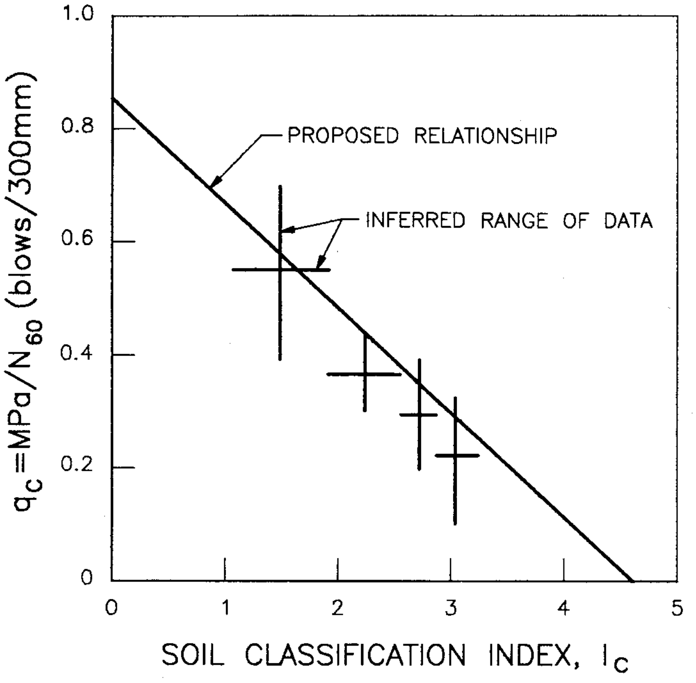


FIG. 4—*Relationship between SPT and CPTu as a function of soil classification.*

1 and 2 can be combined into a single expression to yield N_{60} values from CPTu data during automated evaluations. The combined expression can be placed in existing CPTu analyses codes or, perhaps less elegantly, within a spreadsheet. Earlier methods do not offer this ease of automation feature.

Repeatability of CPTu and SPT

General

The performance of the proposed algorithm was assessed by comparing $(N)_{60}$ values estimated from the algorithm with those measured in an adjacent borehole. Many such trials were carried out in a variety of conditions. The performance of the algorithm was defined in terms of the deviation between estimated and measured values, expressed as a cumulative distribution function (CDF) of uncertainty because of the scatter in the SPT itself. The adequacy of the algorithm is evaluated by comparing the algorithm CDF with the CDF for SPT repeatability. As the starting point for the evaluation of the proposed algorithm, replicate testing of SPT and CPTu were undertaken to estimate the CDF of each test repeatability.

Replicate CPTu

Repeatability of CPTu data was established by carrying out multiple soundings in the same ground. The horizontal spacing between adjacent soundings was reduced in steps until essentially the same response was measured throughout both tests; the spacing was 1.5 m for a similar response. Thus, the replicate soundings were effectively isolated from natural variation in ground properties.

The replicate CPTu soundings were carried out in hydraulically placed sandfill 22 m thick with a groundwater table at a depth of about 4 m. The sand was a uniform predominantly quartz material with less than 2% silt and with a median grain size of 320 μm.

Different cone penetrometers were used for each sounding to incorporate transducer inaccuracy in the derived uncertainty function. However, all penetrometers were right cylindrical piezocones conforming to the proposed International Reference Penetrometer configuration (a more restrictive standard than D 3441). The quoted combined nonlinearity, hysteresis, and accuracy for q_c measurement with the equipment used was 1% of a full scale of 50 MPa.

An example of the replicate data obtained is shown on Fig. 5*a* as plots of q_c versus depth; the repeatability in q_c is remarkable. The q_c values from each test at equal depths are cross-plotted on Fig. 5*b* to emphasize the highly correlated relation-

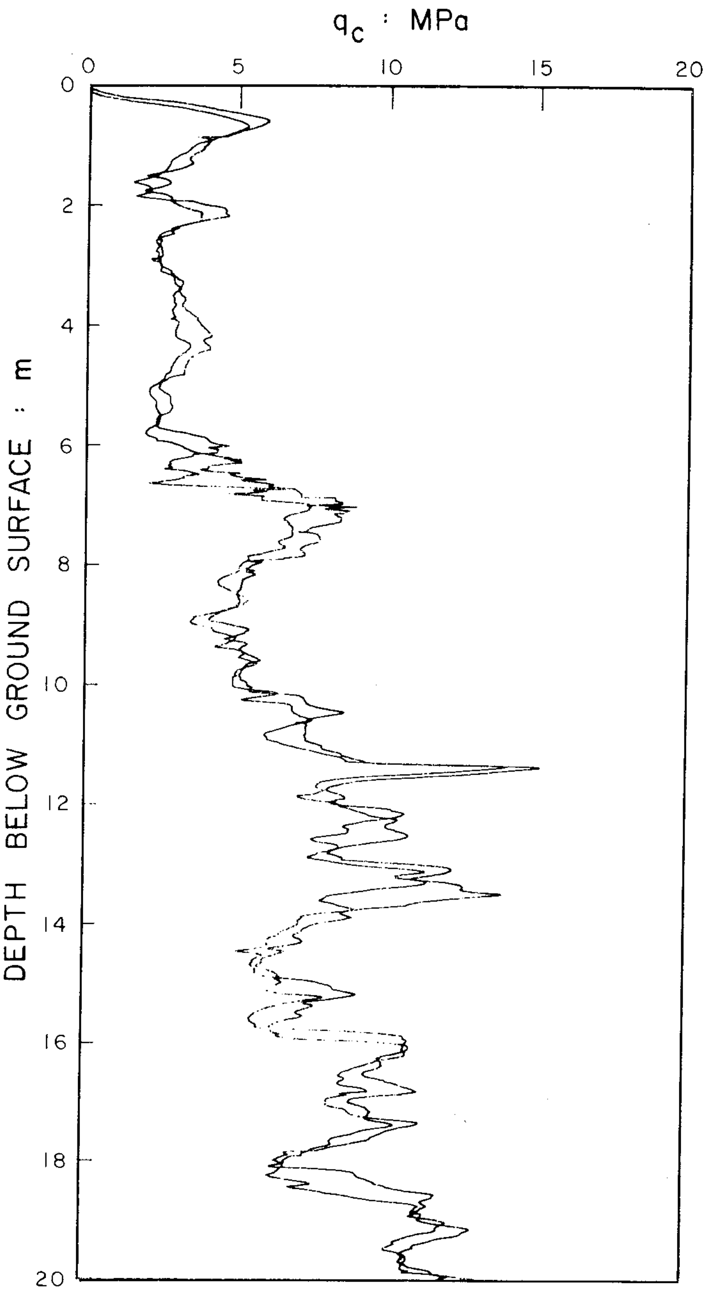


FIG. 5*a*—*Repeatability of CPTu—two adjacent soundings.*

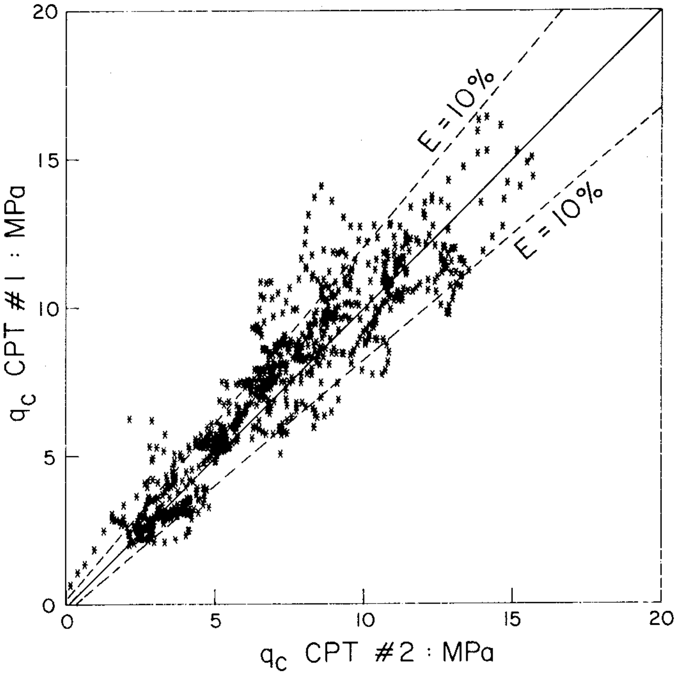


FIG. 5*b*—*Repeatability of CPTu—cross plot.*

ship. The uncertainty in q_c between the two tests is probably overstated in Fig. 5*b* as detailed examination of Fig. 5*a* suggests there is occasional depth mismatching between the two soundings, as judged from marker features in the record; depth mismatch can occur because neither test was corrected for verticality or horizontal location—although the two soundings were close at ground surface, CPTu's naturally deviate or spiral with depth, which introduces both a slight depth error as well as allowing for natural ground variability to intrude at depth.

The average of two replicate soundings was taken as ground truth, q_{truth}. Deviation from ground truth appears proportional to q_c judging from Fig. 5*b*. An uncertainty, E, was defined to express the variance between data and ground truth

$$E = \frac{q_c - q_{\text{truth}}}{q_{\text{truth}}} \qquad (3)$$

The CPTu sounding data were processed using Ref *3* to calculate a cumulative probability, $p\ (E > E_r)$, that the uncertainty, E, would exceed a chosen reference value, E_r. The computed probability function is shown on Fig. 6. The computed CDF is based on 785 points and thus should be a close approximation to the true CDF of replicate CPTu soundings.

Figure 6 shows q_c values are repeatable with an error $E = 6\%$ at the 50% confidence level; since the average q_c value was only 10 MPa, or roughly one fifth of the rated transducer capacity, the combined nonlinearity, hysteresis, and accuracy of the transducer approaches the median repeatability of the test. The estimated uncertainty of q_c in the ground is also comparable to the quoted repeatability of the CPTu in D 3441.

Replicate SPT

Repeatability of SPT data was established in exactly the same manner as for the CPTu by carrying out replicate tests on a given site. The horizontal spacing between adjacent borings for the individual SPTs was 2 m (i.e., similar to the spacing found to be required for repeatable CPTu soundings), and the SPT were carried out at identical depths. SPT procedures conformed to D 1586.

A source of error in SPTs is variation in energy delivered to the rods. This error was minimized in the replicate testing by use of an automatic trip hammer calibrated using ASTM Test Method for Stress Wave Energy Measurement for Dynamic Penetrometer Testing Systems (D 4633) to deliver 285 N·m per blow (i.e. 60% of the theoretical free fall energy of the rope and cathead arrangement). Further, energy monitoring as per D 4633 was used for each test with the blowcounts corrected to $(N)_{60}$

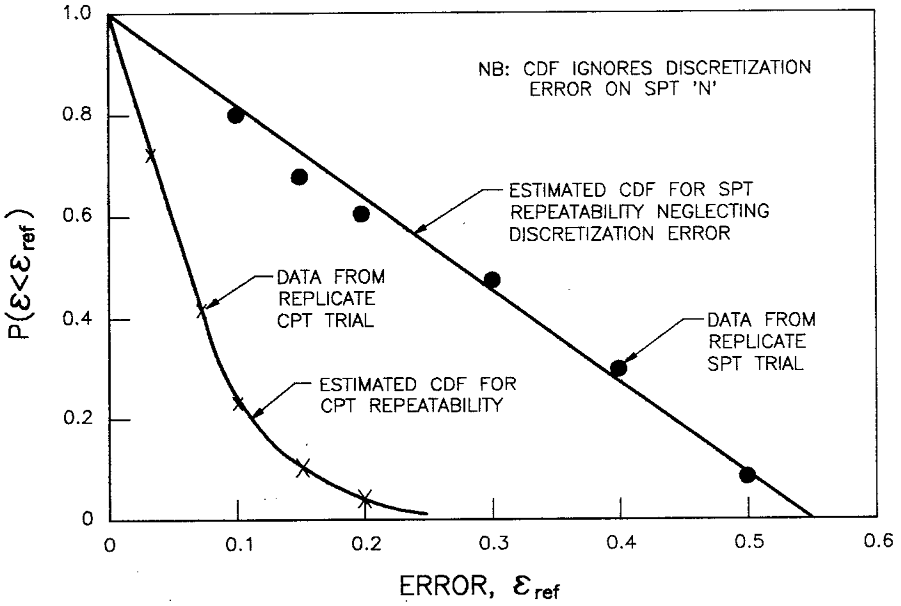


FIG. 6—*Distribution of CPTu and SPT repeatability.*

values, although these corrections were small because of the relatively constant output of the automatic hammer.

The boreholes used were drilled with 80-mm outside-diameter drillpipe using the mud-rotary method. SPT sampler details were as per ASTM D 1586.

The replicate SPT trials were carried out in a sandfill overlying a natural deltaic sand deposit. Both soils comprised fine to medium sand with a trace of silt. The sands extended from ground surface to a depth of 24 m, where they were underlain by silt and other deltaic deposits.

Individual $(N)_{60}$ values are plotted against depth in Fig. 7*a* and plotted against each other for equal depths on Fig. 7*b*. In an identical manner to the CPTu, the mean of the two SPT values is taken as the best estimate of the true penetration resistance (ground truth) and the error computed. The computed cumulative probability of error is shown on Fig. 6, although this CDF is a less precise estimate than that for the CPTu, the CDF for the SPT being based on only 15 replicate trials. Nevertheless, it is readily apparent that the SPT, even when carried out in the most controlled manner, is five times more variable than the CPTu. Half the SPT data has an error worse than $E = 28\%$.

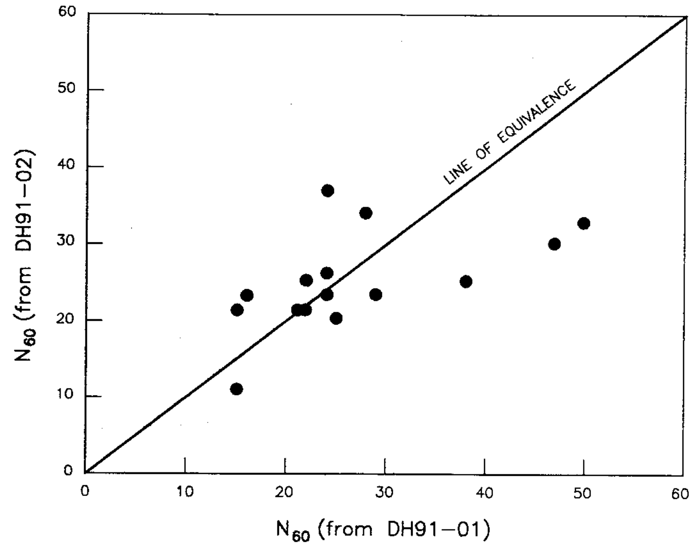


FIG. 7*b*—*Repeatability of SPT—cross plot.*

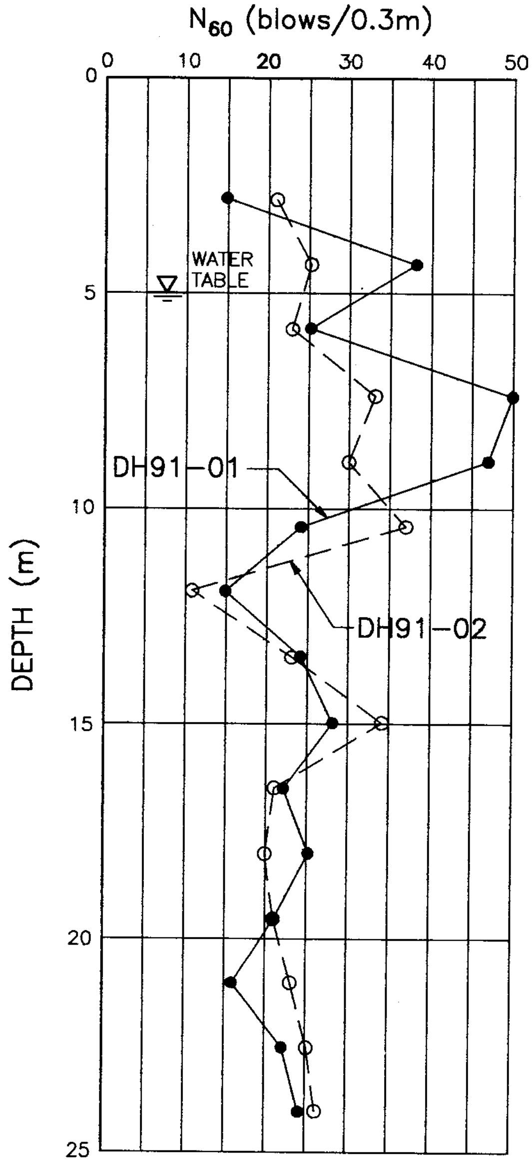


FIG. 7*a*—*Repeatability of SPT—depth plot.*

Discretization error with the SPT has been neglected in the present work. However, even in the range of $(N)_{60}$ encountered in this study, discretization of the SPT is equivalent to about $E = 5\%$ and will increase as $N \rightarrow 0$. The CDF computed for the SPT will underestimate the error in the SPT at low blowcounts.

Performance of Proposed Algorithm

New Test Data

The algorithm to estimate $(N)_{60}$ from the CPTu was derived from published data and trends. New test data was obtained to evaluate the performance of the proposed algorithm in a variety of soil types and circumstances. Since these new data are unconnected with the derivation of the algorithm, it truly forms an independent check.

Five sites have been tested with comparison SPT/CPTu pairs. Each pair comprised a CPTu sounding and a boring with SPT tests, the boring and sounding being typically 3 m apart to minimize the influence of natural variation in the ground. A total of nine CPTu/SPT pairs were available, and the comparison data extend to a maximum depth of 50 m below ground surface. The soils tested included natural deltaic sands to silts and mine tailings ranging from medium sand with little fines to silt. The data base comprises 185 individual SPTs.

CPTu soundings were carried out using right cylindrical piezocones conforming to the proposed International Reference Penetrometer configuration. Three different cone testing systems were used, the soundings were carried out by different drillers, and different drill rigs were used to push the cones. Different transducers were also used within any system. Data were stored in digital form on microcomputer floppy disk with a sampling rate of between 15 and 50 mm per electronic scan of readings, depending upon the system used. The range of CPTu equipment and procedures is representative of achievable standardization in the commercial marketplace.

All SPT data were obtained in mud-rotary boreholes. The SPT procedures complied with D 1586. Both rope/cathead and automatic hammers were used, but in all cases reported here energy calibration to D 4633 was undertaken with the measured blowcounts being corrected to $(N)_{60}$ equivalents (60% of the theoretical energy of 474 N·m).

Accuracy of Algorithm

The comparison of SPT values computed from the CPTu using the proposed algorithm and the corresponding measured SPT is presented in Fig. 8 for all data at all sites. A total of 195 data pairs are plotted. On average, the $(N)_{60}$ computed with the proposed algorithm has a one-to-one correspondence with the $(N)_{60}$ actually measured by SPT. However, a second order bias may be apparent for $N_m > 25$. This bias, if it actually exists, would be conservative as it would result in a slightly lower N_c for an actual N_m. The importance of this potential bias at $N_m > 25$ is uncertain. For essentially all engineering applications, N values of 25 or greater can be considered "good" soil, and usually the need to have engineering properties is limited beyond this level of blowcount. It is of much greater importance that the correlation perform well for potential engineering problem soils; i.e., N_m values of 15 or less.

Evaluation of accuracy of the algorithm was based on accepting the $(N)_{60}$ measured by the SPT as ground truth, despite the large uncertainty in the SPT shown in Fig. 6. An uncertainty is then computed in the same manner as in Ref *3*, the computation being carried out for the entire data base of the new test to obtain a CDF for probability that the $(N)_{60}$ measured by SPT would fall within the chosen error band. The computed CDF is shown in Fig. 9.

The precision with which the computed SPT compares to the measured SPT is about $E = 30\%$ at the 90% confidence level; the algorithm appears more precise than the repeatability of the SPT itself as shown in Fig. 6. It is unclear whether the estimated CDF for SPT repeatability has been overestimated because of too few data points or whether the algorithm is truly more precise because of the excellent repeatability of the CPTu itself combined with a reduction in the variability of the SPT implicit in using averaged trends as the backbone to the algorithm.

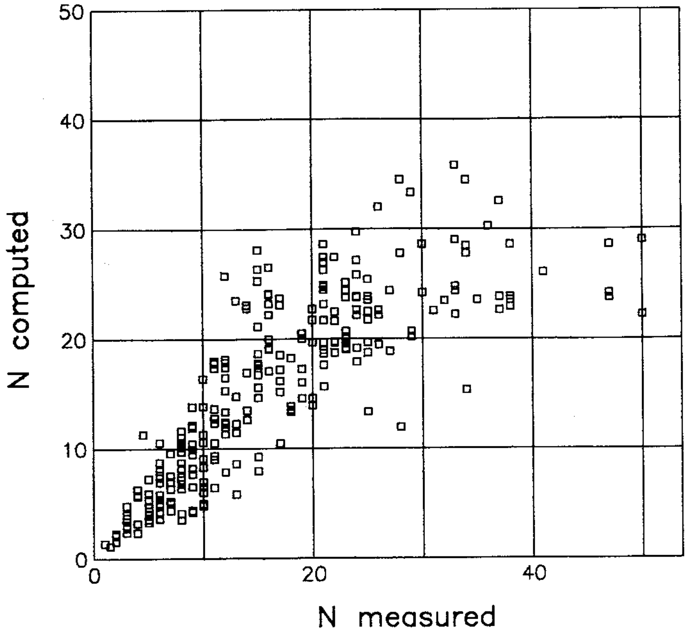


FIG. 8—*Performance of algorithm.*

Bias in Algorithm

The relationship between $(N)_{60}$ computed from CPTu data and the actual $(N)_{60}$ from SPT was tested for bias against three conditions: depth, Q, and F. The dependent (i.e., $N_c - N_m$) variable was taken to be a measure of computed blowcount to measured blowcount; $\varepsilon = (N_c/N_m)/N_m$.

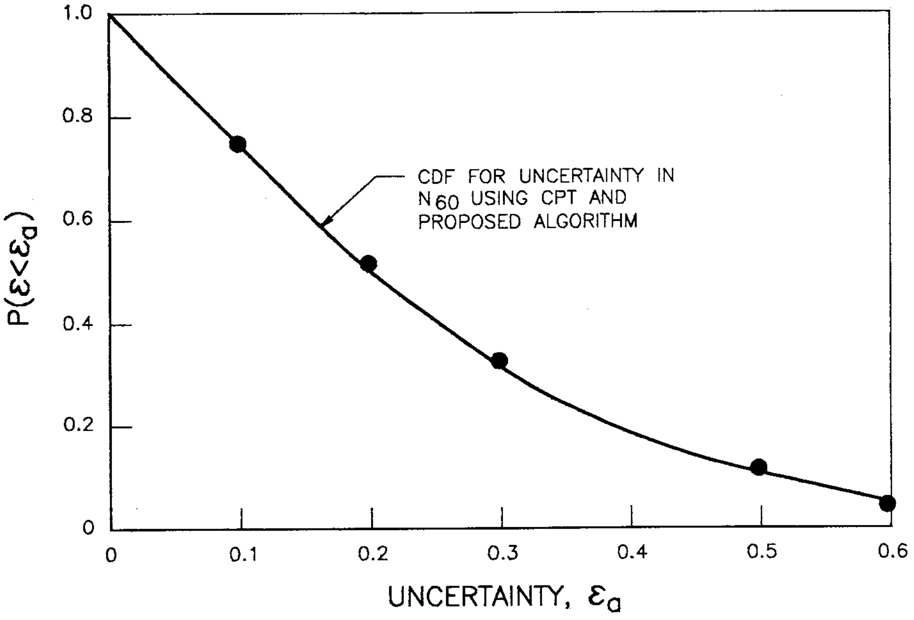


FIG. 9—*Cumulative distribution of uncertainty with proposed algorithm.*

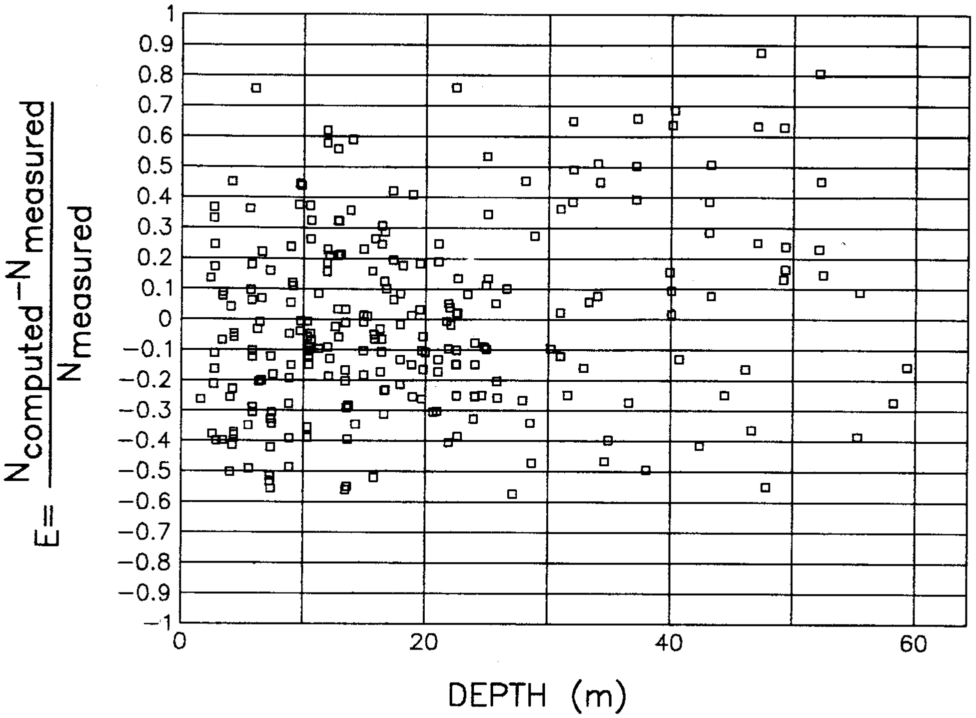


FIG. 10—*Bias of proposed procedure with depth.*

The value ε is plotted with depth in Fig. 10. The proposed algorithm is unbiased at least to 30 m; there may be a slight tendency to underestimate measured SPT data at depths of 50 m. However, as no rod-length correction has been applied to the SPT data itself, this secondary bias may be a reflection of the energy transmission deficiencies of the SPT rather than the proposed algorithm.

The values of ε are plotted against the CPTu penetration resistance in Fig. 11. There is no bias over the range of available data, which is for $Q < 300$. This range of q_c includes situations where the N value may be of engineering importance and only excludes very dense clean sands. The scatter in ε increases at very low penetration resistance because of the discretization error in the measured SPT (a one-blow resolution at $N = 2$ represents a 50% discretization error).

Considerable emphasis is placed on F in the proposed algorithm. The computed results are tested for bias against F in Fig. 12. Again, little if any bias is apparent for the range of materials

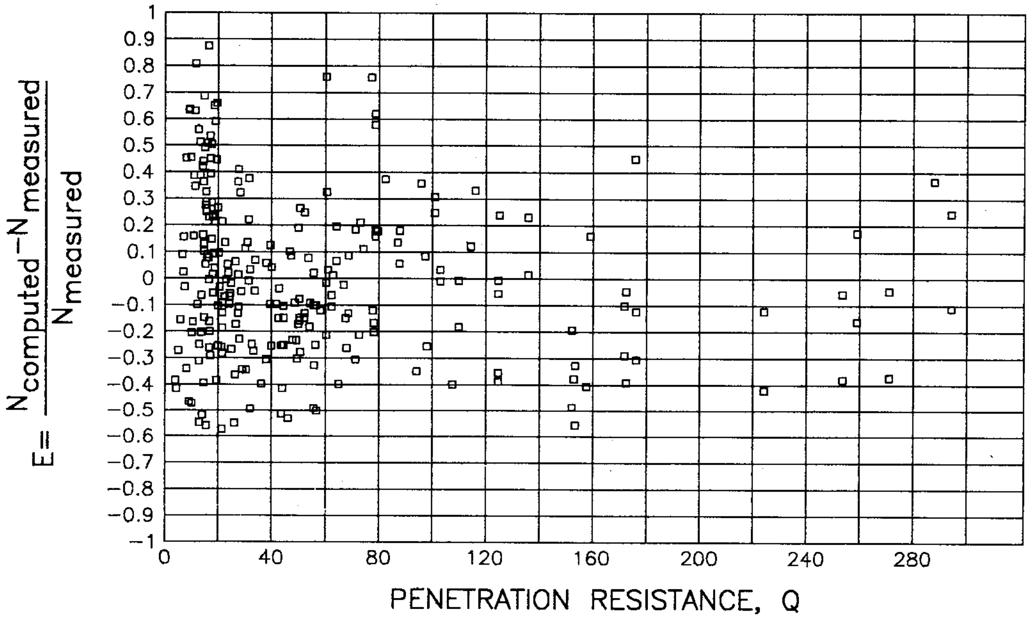


FIG. 11—*Bias of proposed procedure with penetration resistance.*

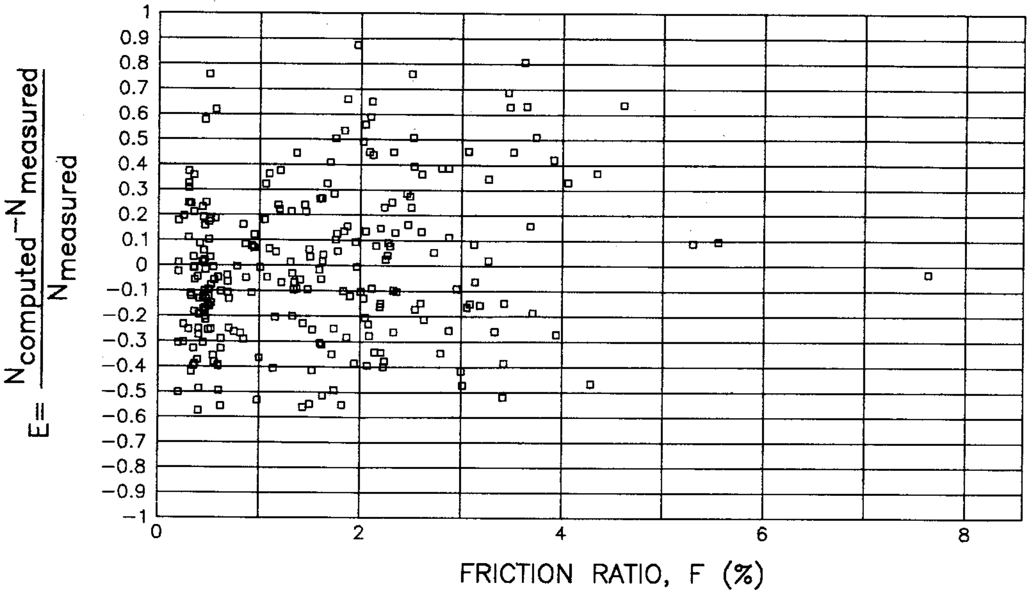


FIG. 12—*Bias of proposed procedure with friction ratio.*

tested. As shown by the density scatter of data, more test results where $F > 2.5\%$ is required to fully evaluate the algorithm into the range of the finest-grained and organic rich soils.

Conclusions

An algorithm for estimation of equivalent SPT blowcount directly from CPTu data and without soil sampling has been developed. The algorithm has been tested against 252 SPT/CPTu data pairs from five sites in a range of soil conditions.

The effectiveness of the algorithm was assessed on the uncertainty defined as the difference between computed and measured N_{60} value. The uncertainty of the SPT itself was estimated by replicate testing to provide a basis for comparison. Replicate CPTu soundings were also made to define the basic test uncertainty.

The proposed algorithm has more certainty of indicating ground truth than by using the SPT itself. This result is apparently caused by the poor repeatability of true SPTs; the CPTu has a five-fold improved precision compared to the SPT, and further averaging is apparently introduced by the algorithm (which is based on trends over a large number of tests).

The median uncertainty in N_{60} computed from CPTu data using the proposed algorithm is less than $E = 0.1$; that is, the true N_{60} will lie within the range $N_c/(1 + E) < N_{60} < (1 + E)/N_c$, where N_c is the computed value at 50% probability. By way of comparison, the repeatability of the SPT itself is significantly worse with $E \sim 0.28$ at the same confidence level.

The proposed algorithm was tested for bias against depth, soil type, penetration resistance, and friction ratio. From the variety of soils tested it is concluded that the algorithm is unbiased. Further validation and perhaps refinement of the algorithm is possible. It is particularly important that the algorithm be tested with more soils of higher friction ratio values, say higher than 2.5%. In addition, the use of the algorithm should be extended to soils other than the hard mineral deltaic soils of this study to check for the degree of global applicability.

An additional advantage of the proposed algorithm to those previously suggested for a SPT estimate from CPTu is the computational ease of applying the algorithm to engineering problems.

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