46th Canadian Geotechnical Conference
Saskatoon, Saskatchewan, Sept. 27-29, 1993

#106 BPT-SPT Correlations with Consideration of Casing Friction

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SYNOPSIS

The Becker penetration test (BPT), through correlations with the Standard penetration test (SPT), is widely used for foundation design and liquefaction assessment in gravelly soils. Most of the existing correlations, however, do not adequately account for the variable energy output of the diesel hammer used in the Becker system, and shaft friction on the Becker casing is ignored. An alternative and more rational approach to BPT-SPT correlations is presented, based on experimental and numerical studies conducted at the University of British Columbia. The research involves performing SPT, BPT and other in-situ tests at several sites in British Columbia, and includes dynamic measurements of energy transfer in the SPT and BPT. Stress wave measurements and wave equation analyses are used to evaluate the effect of friction on the BPT blow count. New BPT-SPT correlations are proposed which consider the energy transfer in both tests and which explicitly consider casing friction in the BPT. A recommended procedure for estimating equivalent SPT N_{60} from BPT blow count is presented.

INTRODUCTION

The Standard Penetration Test (SPT) is the most widely used in-situ test in North America for foundation design, liquefaction analysis and compaction control in sandy and silty soils. The well-known Seed's simplified method of liquefaction potential assessment based on field observations of the performance of sites during actual earthquakes, for example, uses the SPT blow count (or N-value) as the soil index. In gravelly soils, however, the SPT N-value becomes unreliable, and often too high, due to the large particle size relative to the sampler diameter.

In coarse-grained soils, a large scale penetration test known as the Becker Penetration Test (BPT) has found useful applications, particularly in western North America. The BPT simulates the driving of a displacement pile, and is commonly used for pile driveability and pile length evaluation, as well as for foundation design, usually through correlations with the SPT (Morrison and Watts, 1985). The BPT is also becoming accepted as a practical tool for liquefaction potential assessment in gravelly sites, again through correlations with the SPT (Harder and Seed, 1986; Cattanach, 1987; Stewart et al. 1990; Harder, 1992).

In order to make use of the large world-wide foundation performance data base currently available for the SPT, such as the SPT-based liquefaction data base, there is a need for reliable BPT-SPT correlations. Numerous attempts have been carried out in the past to correlate the BPT blow counts to the SPT N-values. Most of these correlations, however, have limited applications since they did not take into account the inherent variable output of the diesel hammer used in the Becker system and they ignored the soil friction acting on the Becker casing during driving.

An extensive study of the SPT and BPT has been conducted at the University of British Columbia, and it included dynamic measurements of energy transfer in both the SPT and BPT. Test data from three research sites are presented in this paper, and the effect of casing friction on BPT blow count is evaluated. A rational approach to BPT-SPT correlations, which consider the energy transfer in both tests and which account for casing friction in the BPT, is presented.

PREVIOUS BPT-SPT CORRELATIONS

The Becker hammer drill was developed in the late 1950's initially for exploration in gravel sites. It is now widely used for geotechnical investigations in sand, gravel and cobble formations. The drill uses an ICE 180 double-acting diesel pile hammer to drive a specially designed double-walled casing into the ground. When the casing is driven open-ended, compressed air is forced down the annulus of the casing to continually flush the soil particles or cuttings up the centre of the inner pipe to the ground surface. The casings come in 2.4 m or 3.0 m lengths with threaded ends, and are available in three sizes, viz. 140 mm O.D., 170 mm O.D. and 230 mm O.D., depending on the coarseness of the materials to be sampled or the size of the hole to be drilled. The drill is more or less "standardized", being manufactured by only one company. More details of the Becker hammer drill are given in Anderson (1968) and in Sy and Campanella (1992a).

The idea of driving the Becker casing close-ended like a pipe pile and using the recorded blow counts (blows per 0.3 m) to indicate soil density was introduced in 1972 by Becker Drills Limited of Vancouver (now SDS Drilling Ltd.). That test, then coined as the Becker Denseness Test, is now more commonly referred to as the Becker penetration test (BPT). The BPT has generally been observed to be less sensitive to gravel particle size than the SPT because of the larger Becker pipe (140 mm O.D. or larger) compared to the SPT sampler (51 mm O.D.), and has, therefore, been found to be useful as an indicator of density in gravelly soils.

Numerous correlations have been proposed in the past to correlate the BPT blow counts to SPT N-values. The earliest correlation, shown in Fig. 1, was based on BPT and SPT data compiled from many sites in British Columbia in the 1970's. The sites were underlain by various soil deposits: sand, silt, and gravelly sand. The BPT's were conducted with the 140 mm diameter casing, driven close-ended. Measured blow counts from side-by-side BPT and SPT conducted at the same site were simply plotted as shown in Fig. 1. Although a 1:1 BPT-SPT relationship was suggested, there was considerable scatter in the correlation.

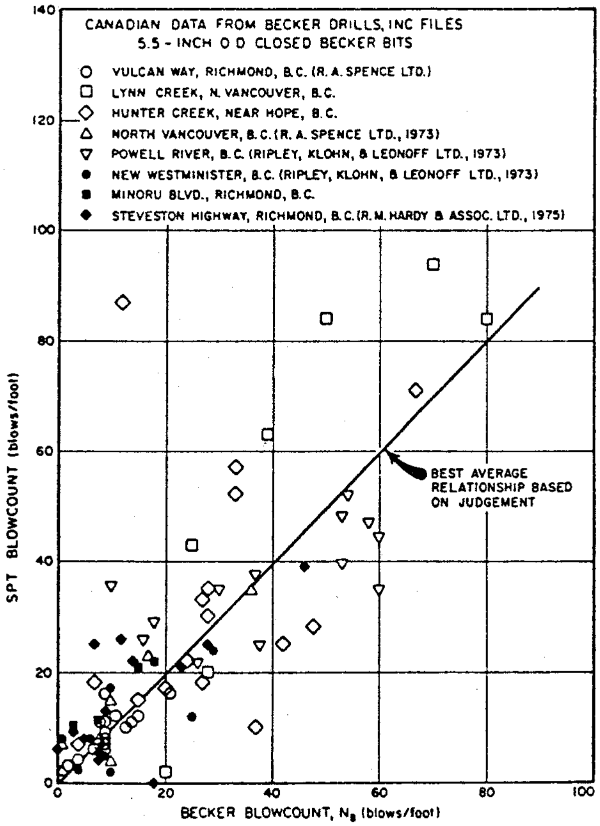

Fig. 1 BPT-SPT correlations by Becker Drills (from Harder and Seed, 1986)

Other early BPT-SPT correlations with similar scatter were summarized by Harder and Seed (1986). A big part of the scatter was due to differences in equipment and procedure used for the SPT and BPT at different sites. Another problem was that some correlations were developed in coarse gravelly subsoils for which the SPT N-values were highly questionable. The variable energies in the SPT, as well as in the BPT, were not always considered.

In an effort to come up with a practical technique for evaluating liquefaction potential in gravelly soils, Harder and Seed (1986) conducted an extensive research on the Becker penetration test and proposed an improved correlation between the BPT and SPT. The correlation was developed from test data at three sites in sand and silt subsoils, where the SPT N-values would not be affected by large gravel particles. They realized that the Becker hammer, like all diesel hammers, gives variable energy output depending on combustion condition and soil resistance. Accordingly, they proposed an empirical but ingenious method of using the peak bounce chamber pressure to correct the BPT blow counts to a reference combustion condition. Their proposed blow count correction procedure is shown in Fig. 2. Using blow count and bounce chamber data collected at various sites, they observed that as the combustion efficiency increases, i.e. as bounce chamber pressure or hammer energy increases, the blow count decreases according to the paths (blow count correction curves) shown in Fig. 2. Each curve represents a constant resistance condition, i.e. all points lying on the same curve have the same soil resistance but different hammer combustion or energy efficiencies. At constant combustion condition, however, bounce chamber pressure increases with increasing blow count, and the data points tend to lie on lines somewhat parallel to Line A-A shown. Harder and Seed suggested that Line A-A, which they called the constant combustion condition rating curve, be used as the reference line for correcting the field blow counts obtained on 170 mm diameter pipe with AP1000 type Becker drill rig. Since the bounce chamber pressure is affected by atmospheric pressure, they further proposed a correction for atmospheric pressure other than the standard 100 kPa at sea level.

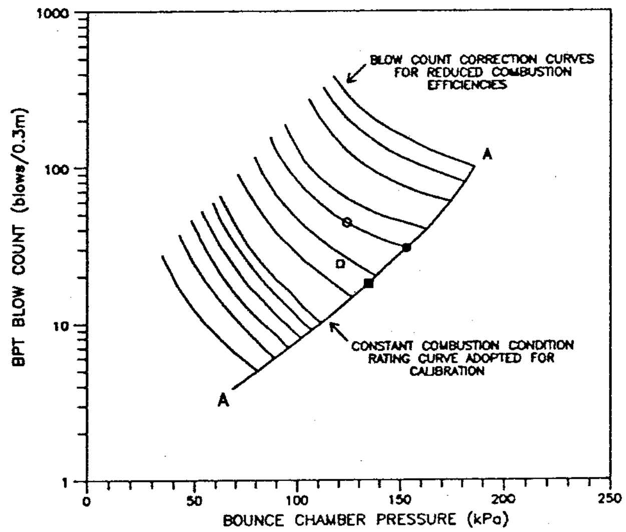

Fig. 2 BPT blow count correction chart based on bounce chamber pressure (after Harder and Seed, 1986)

To use the Harder and Seed's BPT blow count correction chart in Fig. 2, the field data point is first located on the graph, using the measured blow count and corresponding peak bounce chamber pressure at sea level, then following the appropriate correction curve or path down to the rating curve A-A, the corrected blow count, N_{bc}, is obtained. Two examples are shown in Fig. 2, the empty circle and empty square representing two measured data, and the filled circle and filled square giving the corresponding blow counts after correction. The corrected BPT blow count, N_{bc}, is then used to determine the equivalent corrected SPT blow count, N_{60}, using the correlation shown in Fig. 3.

The attractiveness of the Harder and Seed procedure is that peak bounce chamber pressure can easily be measured in the field without sophisticated equipment. The method, however, has some limitations. Since the reference combustion line in Fig. 2 is specific for the particular drill rig/hammer used, the method could not be generally applied to different Becker rigs or hammers (Sy and Campanella, 1992b). Also, the BPT-SPT correlation in Fig. 3 was based on test data to only 15 m depth and did not explicitly consider soil friction on the Becker casing.

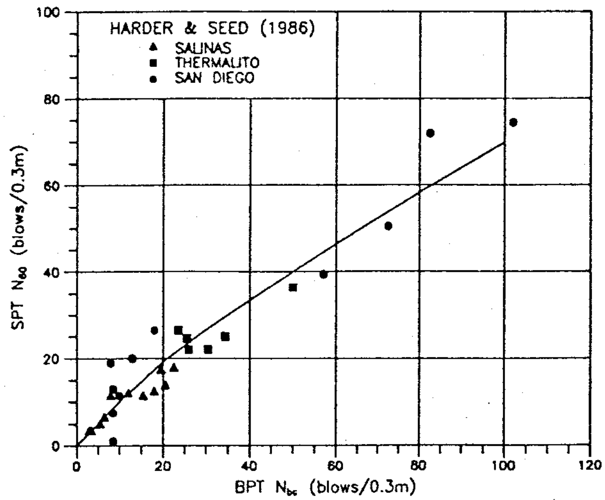

Fig. 3 **Correlation between BPT N_{bc} and SPT N_{60} (after Harder and Seed, 1986)**

DYNAMIC MEASUREMENTS OF SPT AND BPT

At three research sites in Greater Vancouver, SPT, BPT and other in-situ tests were performed in a controlled pattern, and dynamic measurements of the SPT and BPT were conducted. The SPT's were carried out in mud rotary drill holes. The dynamic measurements were made with a piezoelectric load cell coupled with an accelerometer attached near the top of the drill rods as described in Sy and Campanella (1991a). The transferred energies were calculated using both the force integration method as recommended in ASTM D4633-86 and the more fundamental force-velocity integration approach as outlined in Sy and Campanella (1991b). For the SPT systems used in this study, the calculated energies by the two methods were generally close.

The measured SPT N-values were corrected to a reference energy level of 60% of the theoretical free-fall SPT hammer potential energy (Seed et al. 1985; Skempton, 1986), using:

[1] $$N_{60} = N \cdot \frac{ER_i}{60}$$

where N_{60} is the N-value corrected to 60% reference energy level, N is the measured SPT N-value, and ER_i is the measured energy ratio expressed in percent of the theoretical free-fall SPT hammer potential energy of 475 J. This energy correction of SPT blow count is widely accepted in practice.

For the BPT, the Becker casing was instrumented with strain transducers and accelerometers at 0.4 m below the top of the pipe and monitored using the Pile Driving Analyzer, similar to the procedure currently used in dynamic testing of pile driving (ASTM D4945-89). The Pile Driving Analyzer (Goble et al. 1980) measures strain (to determine force) and acceleration for each hammer blow, integrates the acceleration time history to obtain velocity, and computes quantities of interest including peak force, peak velocity and maximum transferred energy, ENTHRU. The transferred energy is calculated by time integration of force times velocity. In addition, peak bounce chamber pressure for every blow during the BPT was automatically measured with a pressure transducer connected to the end of a 15 m long hose and to a computer-based data acquisition system.

The measured BPT blow counts were corrected to a reference ENTHRU level of 30 % of the manufacturer's rated energy for the ICE 180 hammer (Sy and Campanella, 1992b), using:

[2] $$N_{b30} = N_b \cdot \frac{ENTHRU}{30}$$

where N_{b30} is the BPT blow count normalized to the 30% reference energy level, N_b is the measured blow count, and ENTHRU is the measured maximum transferred energy expressed as percent of the rated hammer energy of 11.0 kJ.

For comparison, the measured BPT blow counts obtained from AP1000 type Becker drill rigs were also corrected to N_{bc}, following Harder and Seed's procedure shown in Fig. 2.

EXPERIMENTAL TEST RESULTS

The Annacis test site is covered by about 3 m of sand fill over a 2 m thick natural silt stratum overlying fine to medium grained, fairly clean sand to 37 m depth. A transition zone exists between 37 m and 47 m, and comprises sand with interlayered silt. Below 47 m is a soft to firm clayey silt marine deposit which extends to about 90 m depth in this area.

As part of the testing program at the Annacis test site, one cone penetration test (CPT), two drill holes with SPT's, and two Becker penetration tests were conducted. The drill holes, approximately 4 m apart, were carried out using two different drill rigs and SPT hammer systems. In DH90, two automatic trip hammers delivering 65 to 85% of the theoretical free-fall SPT hammer energy were used, whereas in DH92, a donut hammer with an average transferred energy of about 42% was used. Fig. 4 shows the energy-corrected SPT N_{60} values and the CPT tip resistance (Q_t) profile. The recorded CPT tip resistances at 25 mm intervals were averaged over 0.3 m before plotting in Fig. 4. The "erratic" N_{60} values below 27 m reflect the highly variable densities in the river sand deposits as confirmed by the CPT Q_t profile.

The two BPT's, also 4 m apart, were conducted using an AP1000 type Becker hammer drill (Rig No. 102) and 170 mm diameter casing. To investigate the effect of combustion conditions, BPT B1 was conducted to 51.2 m depth with "full throttle" or maximum fuel setting, while B2 was performed to 42.4 m with variable and reduced fuel throttle settings. The measured BPT blow count, N_b, bounce chamber pressure-corrected blow count, N_{bc}, and energy-corrected blow count, N_{b30}, for B1 and B2 are plotted against depth in Fig. 5. A total of 15,000 blows was recorded for B1 and 15,500 blows for B2. As expected, the measured blow counts for the reduced throttle/fuel condition (B2) are higher than those for the full throttle condition (B1). Note the large differences between the two measured blow count profiles, particularly above 15 m and below 25 m, with some recorded blow counts as high as 600 blows per 0.3 m. However, when corrected by either the Harder and Seed (N_{bc}) or the Sy and Campanella (N_{b30}) methods, the two measured

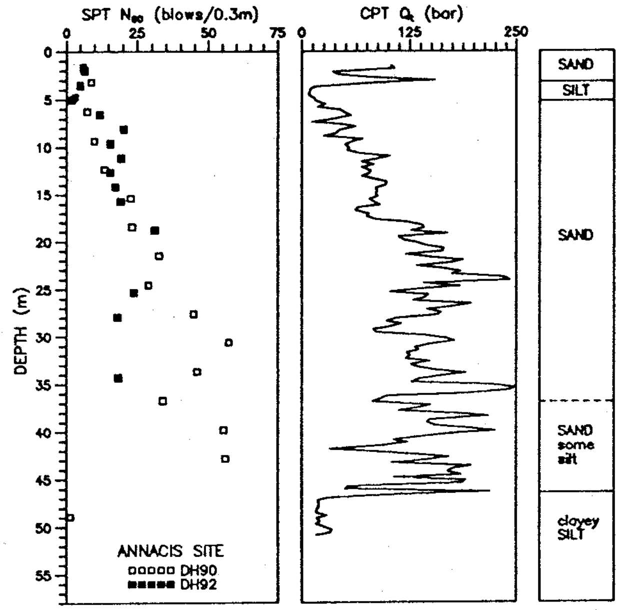

Fig. 4 CPT Q_t and SPT N_{60} data, Annacis site

profiles virtually collapse into one, as shown in Fig. 5. The N_{bc} values are consistently lower than the N_{b30} values, suggesting that the Harder and Seed's calibration Line A-A (Fig. 2) corresponds to some energy transfer higher than the 30% adopted by Sy and Campanella (1992b).

Another interesting observation is in the clayey silt below 47 m. Whereas the CPT Q_t and SPT N_{60} both show significant drop in values (Fig. 4), the BPT blow counts do not. The measured BPT blow counts are more than 200 in this zone compared to a SPT N_{60} of only 2 at 49 m depth, obviously a result of skin friction built-up on the Becker casing at large depth.

The Richmond test site is underlain by 25 m of fine to medium grained, fairly clean sands overlying interbedded sand and silt deposits. The top 10 m of the soil profile was densified by dynamic compaction prior to the field testing program (Naesgaard et al. 1992). Two drill holes, approximately 3 m apart, were carried out using the same drill rig and SPT's were conducted to 24 m with an automatic trip hammer which gave average measured transferred energies of 55 to 60%. A BPT was conducted nearby, also to 24 m depth, using an AP1000 drill rig (No. 107) with full throttle and 170 mm diameter casing. The corrected SPT and BPT blow counts are shown in Fig. 6. The effect of the densified zone is reflected by the increasing SPT N_{60} trend, and somewhat higher N_{60} values, in the top 10 m of the soil profile. Again, the bounce chamber pressure-corrected N_{bc} values are consistently less than the energy-corrected N_{b30} values. More details of the tests at the Richmond site are given in Sy and Campanella (1992b).

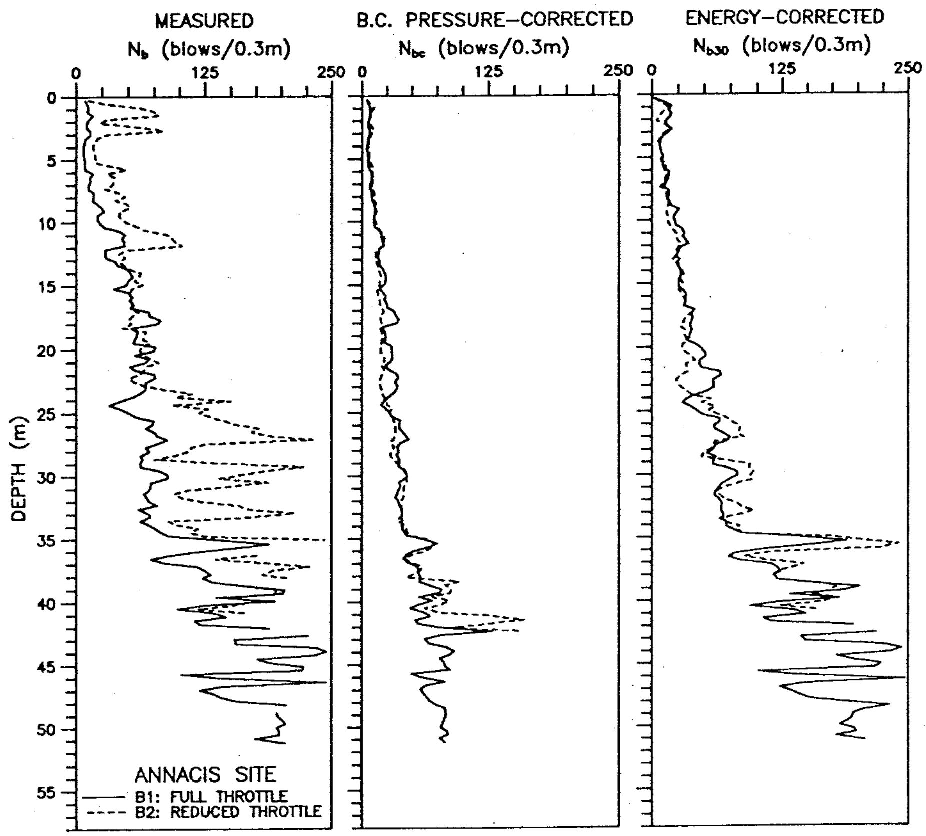

Fig. 5 Measured and corrected BPT blow counts versus depth, Annacis site

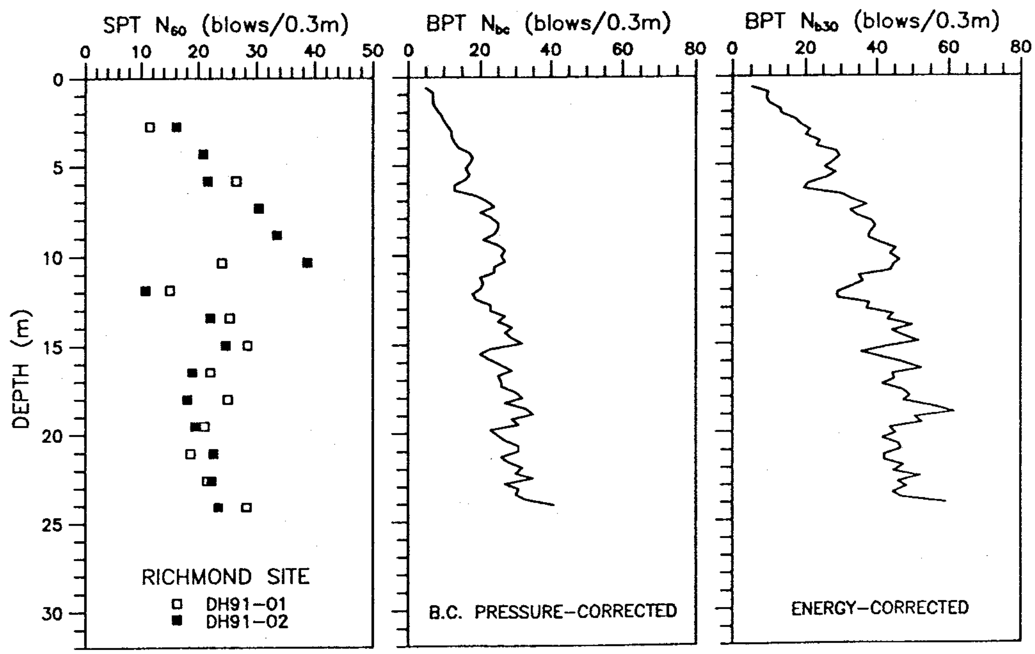

Fig. 6 Corrected SPT and BPT blow counts versus depth, Richmond site

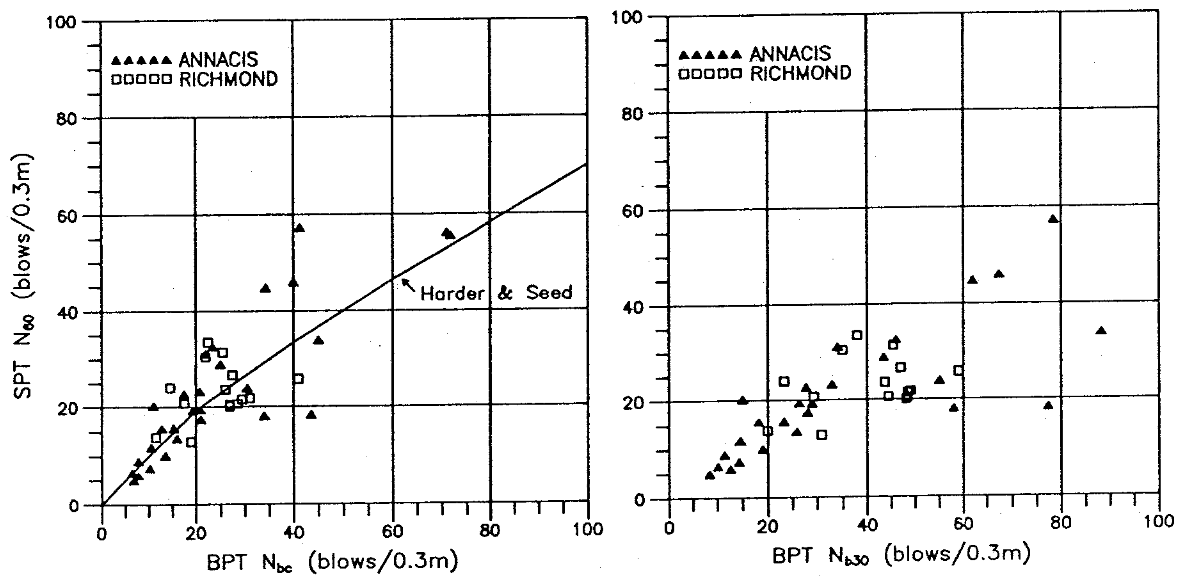

Fig. 7 SPT N_{60} versus BPT N_{bc} and BPT N_{b30}, Annacis and Richmond sites

The SPT and BPT blow counts from the Annacis and Richmond test sites are shown together in Fig. 7, with SPT N_{60} plotted against both N_{bc} and N_{b30} values at the corresponding SPT depth. Only SPT's in sands are presented in Fig. 7. For the Richmond site, the average of two SPT's at the same depth is plotted. In the N_{b30} versus N_{60} plot, two data points with N_{b30} greater than 100 from the Annacis site are not shown. The data points in Fig. 7 cover BPT-SPT data in sands to 43 m, BPT blow counts obtained on 170 mm diameter casing, and SPT N_{60} values up to about 60. Both plots show similar vertical spread in the data but the N_{b30} values are "stretched" in the X-axis relative to the N_{bc} values. Also shown in the N_{bc} versus N_{60} plot is Harder and Seed's BPT-SPT correlation which appears to fit nicely through the middle of the data points, albeit with some large scatter.

EFFECT OF CASING FRICTION AND PROPOSED BPT-SPT CORRELATIONS

In their study of the BPT, Harder and Seed (1986) suggested that casing friction has a minimal effect on the Becker blow count and, hence, friction was not considered in their BPT-SPT correlation. The Harder and Seed data base, although limited to 15 m depth, can be replotted as shown in Fig. 8, with the blow count ratio, N_{bc}/N_{60}, against depth. Note the increasing trend in the blow count ratio with depth, which would suggest increasing friction on the Becker casing as the embedment increases. The effect of casing friction would also explain the bending down or concave shape of their proposed BPT-SPT correlation in Fig. 3.

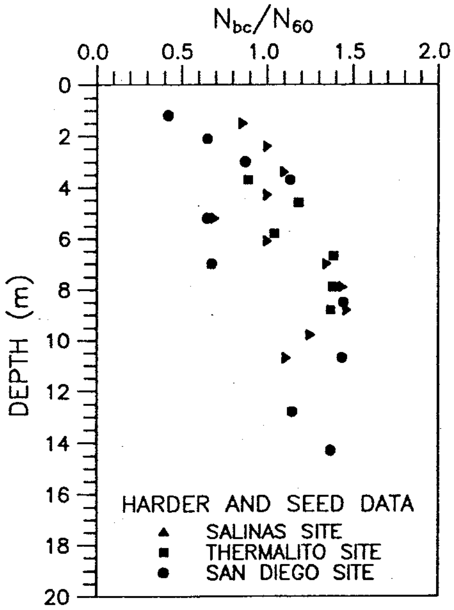

Fig. 8 Harder and Seed's blow count ratio, N_{bc}/N_{60}, versus depth

Stewart et al. (1990) found that casing friction can have a significant effect on the BPT blow count. At one test site, McDonald's Farm, appreciable friction had built up to such an extent that a distinct stratigraphic unit change from dense sand to soft silt at 15 m could not be detected by the BPT. This change was apparently marked by a sharp drop in both CPT tip resistance and SPT N-values, similar to the observation noted above at the Annacis test site below 47 m. At another reported test site, Duncan Dam, large diameter casings were installed in three holes to 5 m, 40 m and 55 m depths and BPT's were conducted through the pre-cased holes. Not surprisingly, the blow counts at the same depth reduced with increased cased length, again, due to the effect of friction on the uncased or embedded portion of the Becker pipe.

Clearly, casing friction in the BPT can not be ignored if reliable and useful BPT-SPT correlations are to be established, particularly for use at large depth. Also, the frictional effects must be quantified if the correlations developed on sand sites are to be applicable to gravelly sites.

Another way of looking at friction on the Becker pipe, and, in fact, a more direct way, is through stress wave measurements and application of wave mechanics principles. Fig. 9 shows measured wave traces of representative hammer blows at 15 m, 30 m, 43 m and 49 m depths

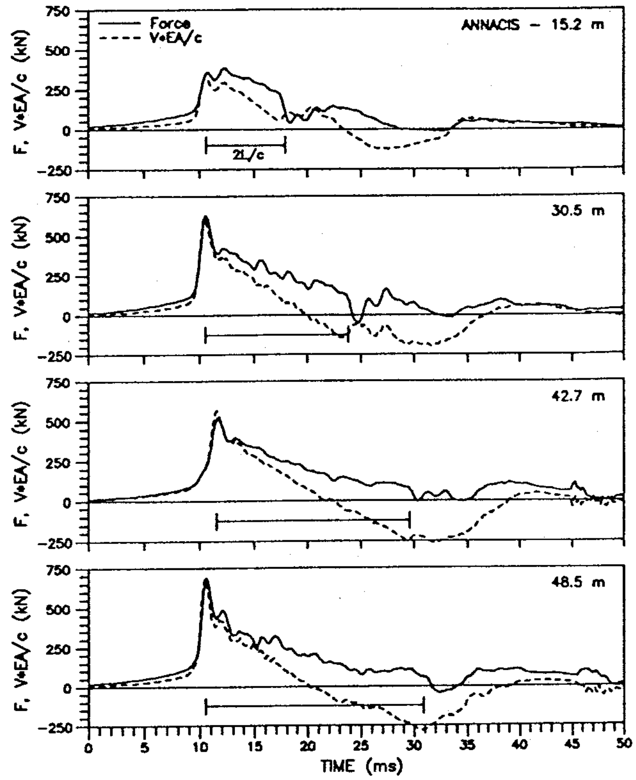

Fig. 9 Measured BPT wave traces, Annacis site

from BPT B1 at the Annacis test site. The wave traces shown are the force and the velocity normalized by the pipe impedance, EA/c (i.e. the product of the Young's modulus times the cross-sectional area over the wave speed). For the 170 mm diameter casing used in the BPT, the impedance, EA/c = 322 kN/m/s. The sign convention used in the plot is positive force for compression and negative force for tension, and positive velocity for downward motion and negative velocity for upward motion.

This type of proportional stress wave plot is commonly used in dynamic pile testing and is convenient to illustrate the effect of soil resistance acting on the pipe during the BPT. For impact wave propagation in one direction in a uniform unsupported elastic rod, the force at a point in the rod is equal to the particle velocity at that point times the impedance. Therefore, when the force and the velocity times impedance are plotted to the same scale, the two traces will plot on top of each other until upward travelling reflections reach the measurement location. For a rod of uniform cross section having no soil resistance, the first upward travelling wave will be from the toe and will arrive at time 2L/c after impact, where L = length of pipe below transducer location and c = wave speed in steel (5100 m/s). External soil resistance will also cause upward travelling reflection that will arrive at time 2X/c, where X is the distance from the measurement point to the location of the soil resistance. The upward travelling wave due to soil resistance will be compressive, with an amplitude proportional to the magnitude of the soil resistance. These upward travelling compressive waves will cause an increase in force and a decrease in velocity recorded near the top of the pipe, i.e. a separation of force and velocity. The greater the separation, the greater is the shaft resistance.

In the wave traces shown in Fig. 9, the wave return period after impact, 2L/c, is indicated by the horizontal bar, the far end of which marks the wave reflection from the pipe toe. The wave traces clearly show increasing force-velocity separation, i.e. pipe friction, with increasing pipe penetration or embedment.

The soil friction and its distribution along the Becker pipe can also be quantified by CAPWAP analysis (Rausche et al., 1985), another recognized technique used in pile dynamics. CAPWAP is a computer program which uses the force and velocity traces obtained with the Pile Driving Analyzer to evaluate the pile and soil boundary conditions through a trial and error process of signal matching in a wave equation analysis. The boundary conditions are the pile impedances, soil resistance distribution, soil quake and damping characteristics. The results of CAPWAP analyses of five selected blows from different depths in BPT B1 at the Annacis site are summarized in Table 1. Also shown in Table 1 are the measured BPT N_{b30} and SPT N_{60} values at the five depths analyzed.

TABLE 1

Summary of CAPWAP resistances and measured BPT/SPT blow counts, Annacis site

Pipe Embed-ment (m)	Shaft Resist-ance (kN)	Toe Resist-ance (kN)	Total Resist-ance (kN)	Measured BPT N_{b30}	Measured SPT N_{60}
9.1	120	31	151	19	10
12.2	147	53	200	26	14
15.2	156	44	200	28	23
21.3	188	66	254	46	33
42.7	356	111	467	181	56

As shown in Table 1, the CAPWAP-computed total shaft resistance increases with increasing embedment or pipe penetration. The shaft resistances, even at shallow depths, are 3 to 4 times the corresponding toe resistances, indicating the significant effect of pipe friction in the BPT. The relative differences between the N_{b30} and corresponding N_{60} values also provide another indication of the effect of friction, particularly at large depth. One could postulate, then, that if shaft resistances were somehow absent, the Becker blow counts would reduce significantly. The SPT blow counts would, of course, remain unchanged. Fortunately, the effect of friction on the BPT blow count can be evaluated theoretically by wave equation analysis as described below.

The wave equation analysis is a numerical solution of the pile driving process. For this study, the GRLWEAP program developed by Goble Rausche Likins and Associates, Inc. (1992) was used. The program is based on the Smith (1960) one-dimensional wave equation model for pile driving analysis. The program models the three components of the pile driving problem: driving system, pile and soil. The driving system (i.e. hammer, cushion and helmet) and pile (or pipe) are represented by a series of masses, springs and dashpots. The soil is represented by a series of elastic-plastic springs and linear dashpots attached to the pile mass elements. The analysis gives the blow count (i.e. inverse of set or displacement) for the given hammer-pile-soil input parameters. The program also computes the maximum energy transferred (ENTHRU) into the pile.

Wave equation analyses of the BPT were conducted at the five selected depths for which CAPWAP analyses were performed. As a first step, each wave equation model was calibrated as follows. The results of the CAPWAP analyses were used to provide the pipe and soil input parameters in the wave equation analysis. It should be noted that the CAPWAP analytical model is similar to the wave equation model except that the former does not include the driving system. Another input parameter in the wave equation program is the hammer efficiency which accounts for energy losses in the hammer and which is used to calculate the hammer impact velocity to start the dynamic analysis. The hammer efficiency was varied in the wave equation analysis until the computed ENTHRU matched the field measured ENTHRU. In all cases, the computed blow counts were found to be close to the field recorded blow counts.

After the wave equation model was calibrated, the shaft or side resistance component was removed in the subsequent analysis and a "frictionless" BPT blow count predicted. The computed blow count was normalized to ENTHRU of 30% using Eq. [2]. For the five depths analyzed, the measured N_{b30} and corresponding computed "frictionless" N_{b30} are plotted against SPT N_{60} in Fig. 10. The CAPWAP computed total shaft resistances (Rs) are also shown for the five measured data points. Note the significant drop in BPT blow counts when the shaft resistances are removed in the wave equation analysis. Also, the computed zero shaft resistance (Rs=0) blow counts fall almost in a straight line, with a slope of approximately 2.5 to 1. These results have important implications, and illustrate that for a given SPT N_{60}, there is a wide range of possible BPT N_{b30} values depending on the amount of shaft friction acting on the Becker pipe.

The wave equation analyses were carried one step further by assigning a series of total shaft resistances, i.e. Rs = 45, 90, 135, ... 360 kN, to each BPT model and computing the blow count corresponding to each given Rs. From these analyses, contours of equal Rs can be drawn as shown in Fig. 11. It is interesting to note that the shape of the Rs contour is bending upward or convex, as opposed to Harder and Seed's correlation curve which is bending downward or concave. Although the Harder and Seed's correlation curve is based on N_{bc}, it is not hard to imagine that it would "pass" or "cut" through increasing Rs contours as the blow count increases, suggesting that their correlation has embedded site-specific friction effects, the magnitude of which appears to increase with increasing blow count. Because their correlation was developed on sites having sand and silt subsoils, its application to other sites with different frictional characteristics, e.g. in gravelly soils, may not be appropriate.

Sensitivity analyses were also performed by varying the key input parameters in the wave equation models, including hammer efficiency, pipe length, shaft resistance distribution, and soil damping. It was found that the theoretical curves in Fig. 11 were reasonably robust for the average expected conditions on granular soil sites, and as such, could provide a rational basis for BPT-SPT correlations with consideration of casing friction. It should be noted that Rs refers to the total shaft resistance mobilized on a 170 mm O.D. Becker pipe during the BPT.

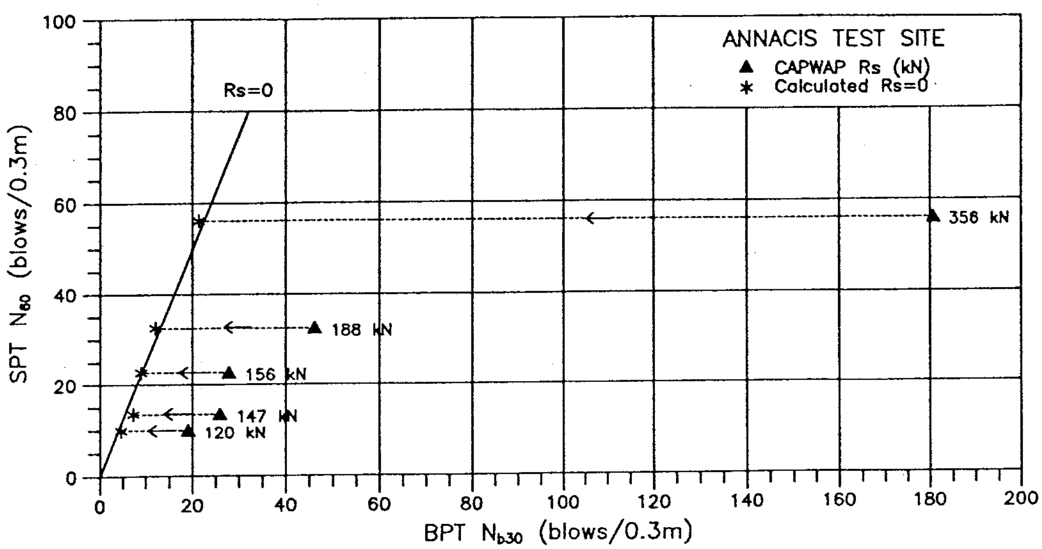

Fig. 10 Effect of casing friction, Annacis site

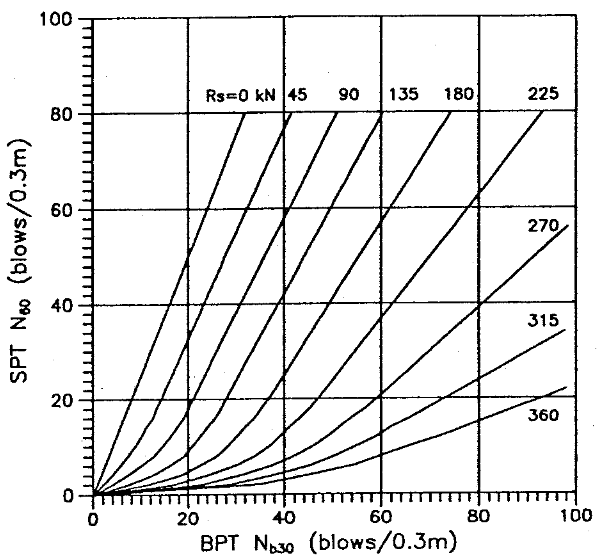

Fig. 11 Computed BPT-SPT correlations for different BPT shaft resistances

VERIFICATION OF BPT-SPT CORRELATIONS

An opportunity arose for independent verification of the above BPT-SPT correlations in a research project conducted by Foundex Explorations Ltd. at the Delta test site to investigate a new BPT technique (Wightman et al. 1993). In the newly developed technique, called the Foundex Becker penetration test (FBPT), bentonite drilling mud is pumped down the Becker pipe and comes out through a series of holes just behind an oversized sleeved close-ended pipe section. In this manner, the shaft friction is substantially reduced compared to a conventional BPT.

The Delta test site is underlain by a 1.5 m thick surficial silt layer overlying a fine, fairly clean sand deposit to 41 m depth. Below 41 m is sand with stratified silt layers. As part of the testing program, dynamic measurements of SPT's in two drill holes and of two types of BPT's were conducted. A HAV180 type Becker drill rig was used for the BPT's. FBPT5 was performed with the new mud-injection technique and with a 170 mm diameter by 300 m long shoe at the end of a 140 mm diameter pipe, while BPT10 was a "regular" or conventional BPT conducted with a constant 170 mm diameter pipe. Both tests, therefore, have the same toe diameter or end area.

The measured and energy-corrected BPT and SPT data at the Delta site are presented in Fig. 12. The left plot shows the N_{b30} profiles for FBPT5 and BPT10, as well as the SPT N_{60} values in sand. The horizontal separation between BPT10 and FBPT5 profiles is a measure of the effect of friction. Note how the separation increases with increasing depth, suggesting pipe friction "growing" with embedment. In fact, several silt layers below 40 m depth as identified by FBPT5, and confirmed by adjacent CPT's, were completely "missed" by BPT10. The right plot in Fig. 12 shows the BPT-SPT blow count ratios, N_{b30}/N_{60}, versus depth for FBPT5 and BPT10. These blow count ratios again illustrate the dramatic effect of pipe friction on the BPT blow count.

The BPT N_{b30} values are plotted against the SPT N_{60} values in Fig. 13. For each SPT N_{60}, there are two corresponding N_{b30} values, i.e. one for FBPT5 (filled circle) and one for BPT10 (empty circle). It can be seen that the effect of removing pipe friction is to shift the BPT blow counts to the left, an observed trend in agreement with the computed wave equation results in Fig. 10.

The energy-corrected BPT-SPT data from all three sites in sand are plotted in Fig. 14, together with the computed correlations from Fig. 11. As shown, the Delta mud-injection (FBPT5) data points lie in a reasonably narrow band between Rs curves of 0 and 45 kN. On the other hand, the data points for the regular or conventional BPT's lie to the right of the FBPT data and cover a wide range of Rs values. A closer examination of these BPT data points indicates that most of the

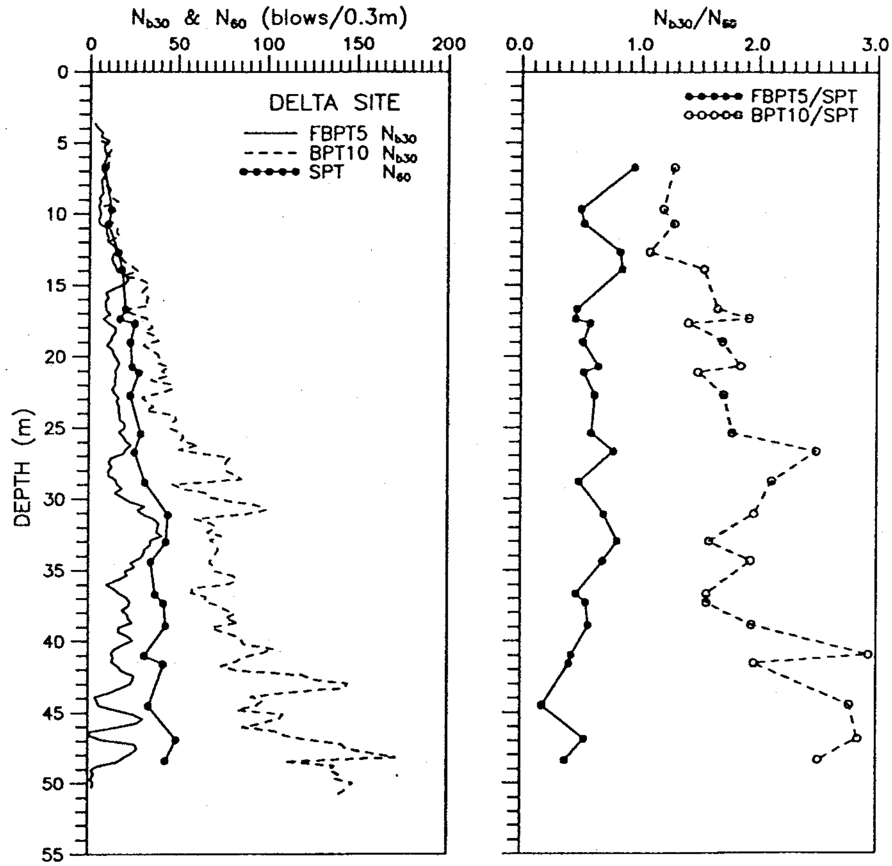

Fig. 12 Corrected SPT and BPT blow counts versus depth, Delta site

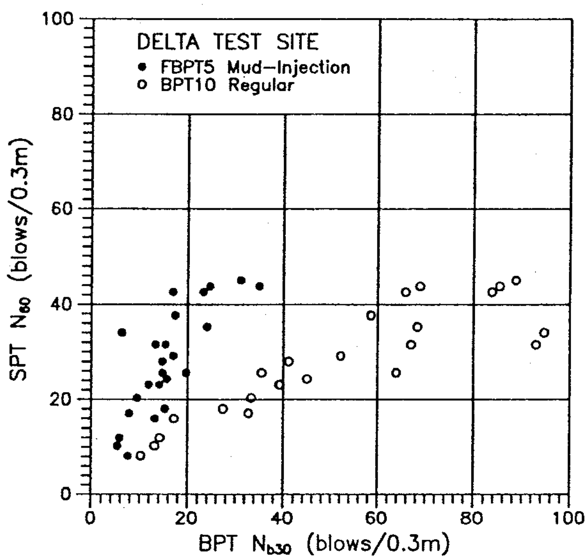

Fig. 13 BPT N_{b30} versus SPT N_{60}, Delta site

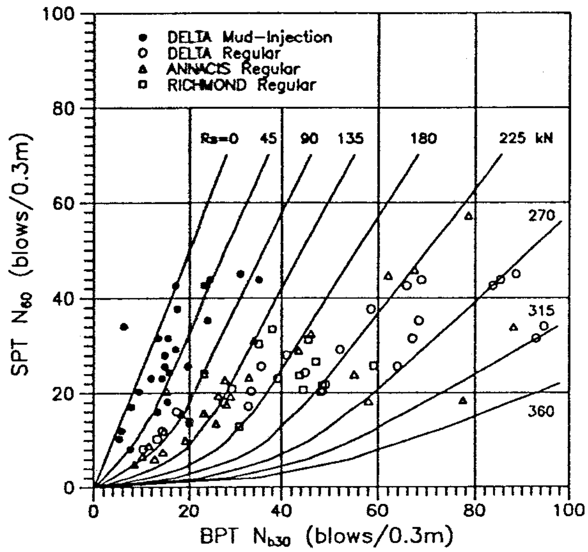

Fig. 14 Computed BPT-SPT correlations with measured data

shallow data, up to 10 m depth, lie between Rs curves of 45 kN and 135 kN, whereas below 20 m depth, most of the data lie beyond Rs of 180 kN. This is not surprising, since total shaft resistance in sands increases with depth or pipe embedment.

The results shown in Fig. 14 are encouraging and suggest that the BPT-SPT correlations derived from wave equation analyses can provide a useful framework for determining equivalent energy-corrected SPT blow count, N_{60}, from energy-corrected BPT blow count, N_{b30}. Since Becker casing friction or shaft resistance is accounted for, the proposed correlations should also be applicable to gravel sites for which the BPT has proven to be a most practical and economical testing technique. So given a BPT N_{b30} and Rs value at a depth, the equivalent SPT N_{60} can be determined from the appropriate Rs curve in Fig. 11.

RECOMMENDED PROCEDURE FOR ESTIMATING EQUIVALENT SPT N_{60}

The recommended procedure for estimating equivalent SPT N_{60} values given BPT blow counts from a 170 mm O.D. Becker pipe are:

1. Monitor BPT with the Pile Driving Analyzer in accordance with ASTM Standard D4945-89 and correct the recorded blow counts to N_{b30} using Eq. [2].

2. Select representative blows for CAPWAP analysis to determine the total shaft resistances (Rs) at specific depths and estimate or interpolate between computed Rs values for other depths.

3. With the energy-corrected BPT N_{b30} and Rs values, estimate equivalent SPT N_{60} from Fig. 11.

The above procedure is applied to BPT B1 and B2 at the Annacis site (see measured blow count profiles in Fig. 5) and the results are presented in Fig. 15, which show the N_{b30}, Rs and equivalent N_{60} values plotted against depth. For comparison, the measured SPT N_{60} values from adjacent drill holes are also plotted in Fig. 15. As shown, the measured SPT blow counts are in good agreement with the estimated N_{60} values.

SUMMARY AND CONCLUSIONS

Experimental and numerical studies of the BPT and SPT have been conducted with the objective of obtaining reliable BPT-SPT correlations. Side-by-side SPT's and BPT's have been performed at three research sand sites, including dynamic measurements of energy transfer in both tests. An energy approach for correcting the BPT blow counts to account for the variable energy output of the Becker hammer, similar in principle to that used in SPT energy correction, is used. The energy-

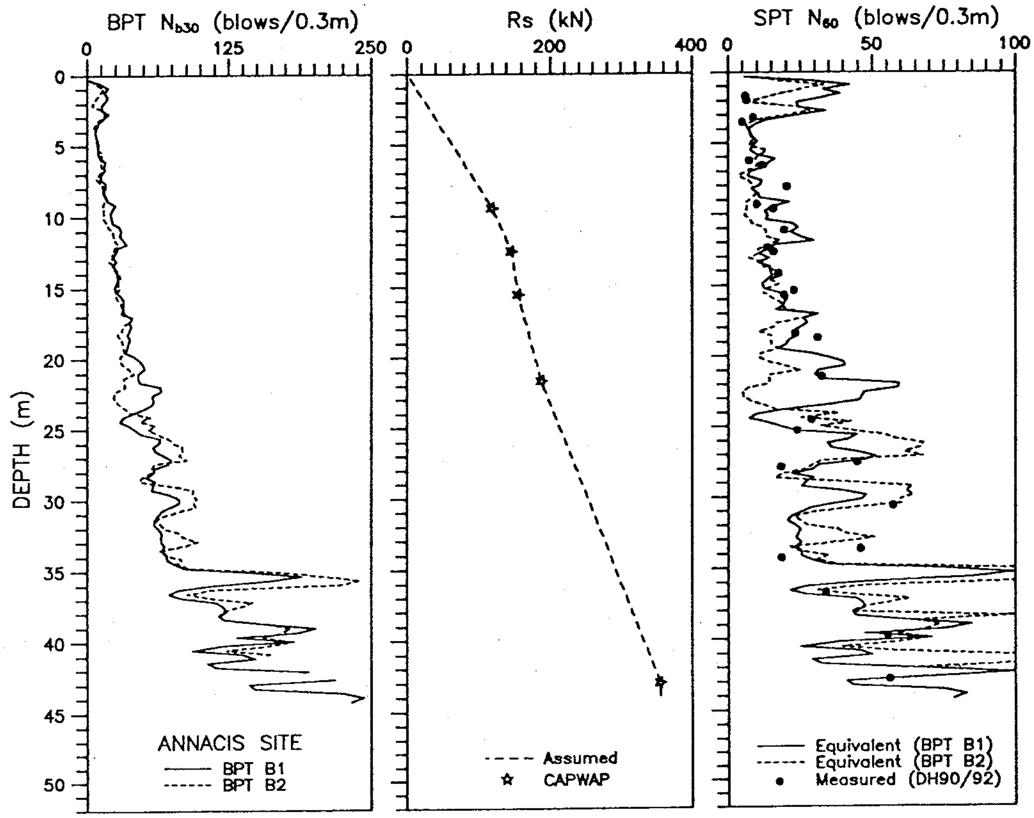

Fig. 15 Corrected BPT blow count, shaft resistance, and equivalent and measured SPT blow counts versus depth, Annacis site

corrected BPT blow counts are correlated to energy-corrected SPT blow counts. It is shown that meaningful BPT-SPT correlations can only be obtained if friction acting on the Becker casing during the BPT is considered. Stress wave measurements and wave equation analyses of the BPT are used to evaluate the effect of shaft friction on the BPT blow count.

A rational procedure for BPT-SPT correlations is presented. It is shown that the proposed BPT-SPT correlations, which consider the energy transfer in both tests and which explicitly consider shaft resistance in the BPT, can provide a useful framework for estimating equivalent SPT N_{60} from BPT blow counts in granular soil sites.

ACKNOWLEDGEMENTS

The first author acknowledges the financial support of the STARS scholarship provided by the Science Council of B.C. in cooperation with Klohn Leonoff Ltd. The support and interest of B.C. Hydro, Klohn Crippen Consultants, Ministry of Transportation and Highways, and Foundex Explorations Ltd. are also acknowledged. Helpful discussions with Li Yan, David Siu, Bert Miner and Lars Anderson are appreciated. CAPWAP analyses performed by GRL and Associates are also appreciated. The valuable assistance of the UBC Civil Engineering technicians and especially Scott Jackson is much appreciated.

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