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RECENT DEVELOPMENTS IN ENERGY CALIBRATION OF PENETRATION TESTS AT UBC

DEVELOPPEMENTS RECENTS EN CALIBRATION D'ENERGIE POUR LES ESSAIS DE PENETRATION A LA RESISTANCE DE RUPTURE

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SYNOPSIS: The Standard penetration test (SPT) and Becker penetration test (BPT) are two of the most widely used in-situ tests in North America. The SPT is most commonly used in sands and silty sands, while the BPT, being a large-scale penetration test, is more useful in gravelly soils. Both tests involve hammer impact on penetration rods, and the resulting penetration resistance or blow count is strongly influenced by the amount of hammer energy actually transferred into the rods. Research at the University of British Columbia has shown that the existing methods of SPT and BPT energy calibrations have some serious limitations, and that a more fundamental and direct approach of determining the transferred energy, based on force and acceleration measurements near the top of the drill rods or pipes, should be adopted. The proposed approach provides a unified method of measuring transferred energies in the SPT and BPT, similar in principle to that used in pile driving. The measured energy data can then be used in a consistent manner to correct the recorded blow counts to a reference energy level for each test and allow reliable correlations between SPT and BPT to be established.

INTRODUCTION

Despite problems associated with its repeatability and reliability, the Standard Penetration Test (SPT) continues to be the most widely used in-situ test for foundation design, liquefaction potential assessment and compaction control in sands and silty sands. It is known that the most important factor affecting the SPT blow count (or N-value) is the amount of hammer energy actually transferred into the drill rods. For liquefaction analysis, for example, the measured N-values are commonly corrected to a reference energy level of 60% of the theoretical free-fall SPT hammer potential energy. The transferred energy is currently determined by attaching a load cell near the top of the drill rods and measuring the force time history during hammer impact. This method, however, has some shortcomings as indicated by several investigators in recent years.

In gravelly soils where the SPT N-value is not reliable due to the large particle size relative to the sampler diameter, the Becker Penetration Test (BPT) has found useful applications, particularly in western North America. The BPT consists of driving a specially designed double-walled, closed-end pipe into the ground with a double-acting diesel pile hammer and recording the driving resistance or blow count per 0.3 m of pipe penetration. The BPT simulates the driving of a displacement pile and is like a large-scale continuous penetration test. Numerous attempts have been carried out in the past to correlate the BPT blow counts to the SPT N-values, in order to make use of the large foundation performance data base currently available for the SPT. Most of the BPT-SPT 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 shaft friction acting on the pipe during driving.

An extensive study of the SPT and BPT has been conducted at the University of British Columbia (UBC) with the ultimate objective of obtaining reliable correlations between the two tests. The research project involved performing SPT, BPT and other in-situ tests in a controlled pattern at several sites in British Columbia, Canada. As part of the field testing, dynamic measurements were carried out which included force and acceleration near the top of the SPT drill rods and BPT drill pipes, as well as bounce chamber pressure in the double-acting diesel hammer during the BPT.

Recent developments in energy calibration of the SPT and BPT are described in this paper, together with the main findings from the UBC research study.

CURRENT SPT ENERGY CALIBRATION

The existing method of SPT energy measurement as specified in ASTM Standard D4633-86 and in the ISSMFE (1988) International Reference Test procedure is based on the force measurement approach developed by Schmertmann and Palacios (1979). The method consists of attaching a load cell near the top of the drill rods and measuring the force time history during hammer impact as shown schematically in Fig. 1. On hammer impact, a compression stress wave is generated which travels down the drill rods at a constant speed of about 5120 m/s in steel. Upon reaching the bottom of the sampler, the compression wave reflects as a tension wave back up the drill rods. At the top of the drill rods (or anvil), the upward travelling tension wave reflects once again with opposite sign, this time from tension to compression. The reflected compression wave from the anvil then travels down the drill rods a second time, but with much reduced amplitude.

An idealized force time history recorded by a load cell near the top of the SPT drill rods is shown in Fig. 2. The sign convention is positive force for compression wave, in which the particle motion is in the same direction as the direction of wave propagation, and negative force for tension wave, in which particle motion is in the opposite direction to wave propagation. Zone 1 is the impact compression pulse sensed by the load cell. It has a duration of approximately 2L'/c, where L' is the total length of the drill rods and sampler below the load cell and c is the speed of wave propagation in the rods. The 2L'/c is the time it takes for the impact wave to travel from the load cell near the top of the rods down to the sampler and return to the load cell location. This time also marks the arrival of the tensile wave reflection from the sampler and is commonly referred to as the "tension cutoff time" (Point 2). Schmertmann and Palacios (1979) found that after hammer impact, the hammer and rods remain in contact until the arrival of the tensile wave reflection from the sampler, which causes the rods to pull away from the hammer and effectively stops further transfer of energy from hammer to rods. The longer the drill rods, the longer is the hammer-rod contact time and the more hammer energy that enters the rods.

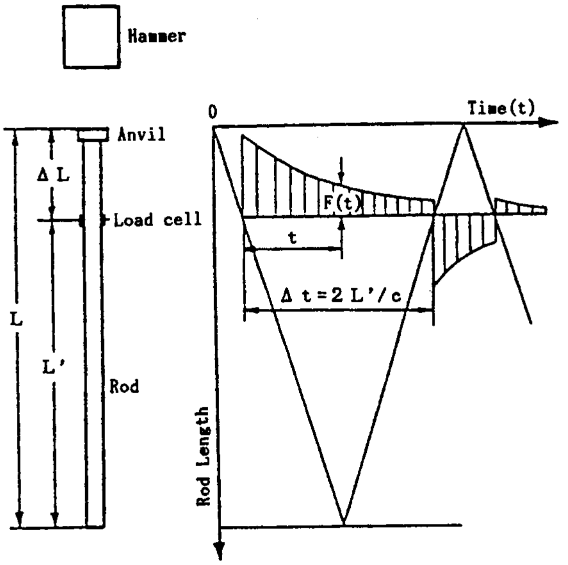

Fig. 1. SPT energy measurement concept using load cell (from ISSMFE, 1988)

Schmertmann and Palacios (1979) showed that the energy entering the drill rods (E_i) can be calculated by integration of the square of the measured force time history within the time limits of the first compression pulse (i.e. integration is valid up to 2L'/c after impact) times a rod material constant:

$$E_i = \frac{c}{EA} \int [F(t)]^2 \, dt \tag{1}$$

where c is the velocity of longitudinal wave propagation in the rod, E is the Young's modulus of the rod, A is the cross-sectional area of the rod and F(t) is the measured force time history. The quantity, EA/c, is a material property, commonly called the impedance of the drill rods.

The force integration method in Eq. 1 assumes that the energy transferred into the rods is contained only within the first compression pulse (Zone 1 in Fig. 2) and that there is no further transfer of energy beyond time 2L'/c. Eq. 1 further requires the cross-sectional area of the whole rod/sampler system below the anvil, which is difficult to determine for a non-uniform system consisting of rods with variable cross-sectional areas or rods with enlarged ends or couplings. Perhaps more importantly in Eq. 1 is the inherent assumption that force and particle velocity at the measurement point are proportional within the first compression pulse, which would be true for wave propagation in an ideal, elastic rod of uniform cross-section. Sy and Campanella (1991a,b) have shown that this assumption does not hold for a typical SPT safety hammer system consisting of the hammer guide rod, drill rods and sampler connected by couplings and adaptors, all of which can have different cross-sectional areas or impedances. Changes in impedance cause wave reflections which violate the force-velocity proportionality assumption in Eq. 1.

In ASTM D4633-86 and ISSMFE (1988), the energy is calculated from:

$$E_i = \frac{cK_1K_2K_c}{EA} \int [F(t)]^2 \, dt \tag{2}$$

which is based on Eq. 1 but with three correction factors applied. K_1 and K_2 are theoretical correction factors to account for the load cell location in the rods and the finite length of the drill rods, respectively. Both effects result in apparent tension cutoff times less than those expected at the top of a uniform, infinitely long rod, and consequently, the multiplication factors are greater than unity. K_c is to correct the theoretical wave speed in steel to the "actual" wave speed as determined from the measured force time history.

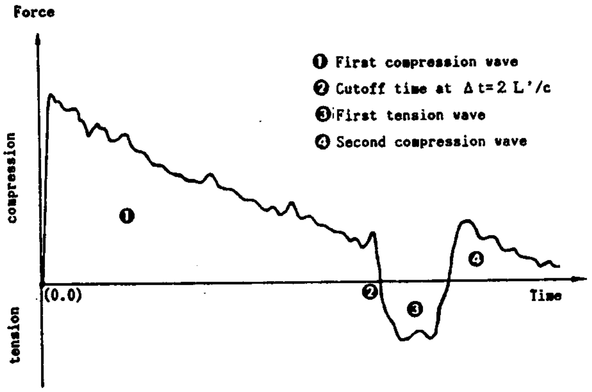

Fig. 2. Idealized force-time waveform recorded by load cell in SPT drill rods (from ISSMFE, 1988)

The first two factors, K_1 and K_2, "correct" the measured energies to the ideal infinite rod condition so that the corrected energies can be compared between different SPT systems. These two factors, however, should not be applied indiscriminately, since the corrected energies may not be compatible with the end use of the SPT data. The third correction factor, K_c, has been controversial for some time and has caused confusion (Riggs et al. 1984; Clayton, 1990). Using force and acceleration measurements on the SPT, Sy and Campanella (1991a) showed clearly that there is no rational basis for the wave speed correction, and that K_c should, therefore, not be used in Eq. 2. If only force is measured to determine SPT energy, the authors recommend that the transferred energies be calculated by Eq. 1 and that the results be reported without the use of the three correction factors above.

The measured energies, E_i, are commonly expressed as energy ratios, ER_i, or percentages of the theoretical free fall SPT hammer potential energy of 475 J. Schmertmann and Palacios (1979) have shown that the SPT N-value is approximately inversely proportional to the transferred energy in the rods. Seed et al. (1985) further proposed that for liquefaction potential analysis, the SPT N-values should be corrected to an energy level of 60% of the theoretical potential energy of the SPT hammer, using:

$$N_{60} = N \cdot \frac{ER_i}{60} \tag{3}$$

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 or estimated energy ratio in percent. The 60% energy ratio appears to represent a historical average for the different SPT systems used in most of the SPT-based empirical correlations (Seed et al. 1985; Skempton, 1986).

BECKER DIESEL HAMMER ENERGY CONSIDERATION

The Becker hammer drill was developed in the late 1950's in Alberta, Canada initially for seismic oil exploration in gravel sites. The drill is now widely used in geotechnical investigations for drilling, sampling and penetration testing in coarse granular soils. The drill uses a double-acting diesel pile hammer to drive a specially designed double-walled pipe or casing into the ground. The casings come in 2.4 m or 3.0 m lengths and are available in three sizes: 140 mm O.D. by 83 mm I.D., 170 mm O.D. by 110 mm I.D. and 230 mm O.D. by 150 mm I.D. For drilling and sampling, the casing is driven open-ended with a hardened drive bit and compressed air is forced down the annulus of the casing to bring the drill cuttings up the centre of the inner pipe to the ground surface, as illustrated in Fig. 3.

The Becker casing can also be driven close-ended, without using compressed air, as a large scale penetration test to evaluate density and pile driveability. In this case, the BPT blow counts (per 0.3 m) are generally regarded as more reliable than SPT N-values in gravelly soils because of the larger Becker pipe diameter relative to the soil particle size.

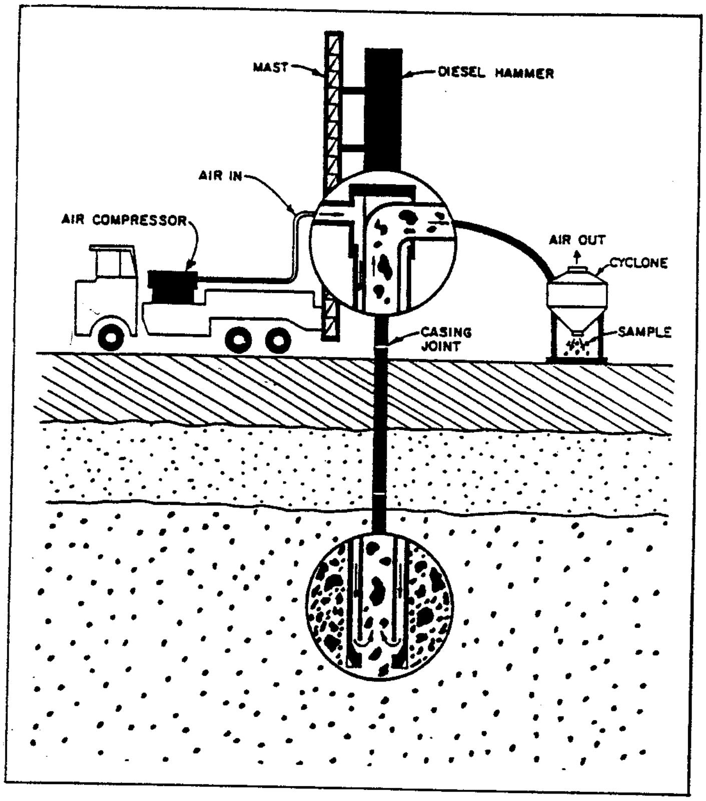

Fig. 3. Becker hammer drill system (from Harder and Seed, 1986)

The hammer used in the Becker system is an International Construction Equipment (ICE) Model 180 double-acting atomized fuel injection diesel pile hammer, with a manufacturer's rated energy of 11.0 kJ. The main feature of the double-acting diesel hammer is that the top of the hammer housing is closed and is connected to a "bounce chamber". As the ram rises on the upward stroke, it compresses the air trapped in the bounce chamber. The trapped air acts like a spring to shorten the upward stroke of the ram and to accelerate it on the downstroke, thereby increasing the blow rate relative to the more conventional open-top condition. The hammer operates at a blow rate of 90 to 95 blows per minute at maximum stroke.

Hammer manufacturers have realized that bounce chamber pressure, which is easily measured in the field with a pressure gauge, can be used to estimate the potential energy of the ram, based on the assumption that the total potential energy is the sum of the actual ram stroke energy (ram weight times stroke) and the energy stored in the bounce chamber (which can be calculated from gas laws). A chart developed by the manufacturer for the Model 180 hammer is shown in Fig. 4. This chart allows one to estimate the total potential energy of the hammer given the peak bounce chamber pressure recorded at sea level (note that bounce chamber pressure is affected by atmospheric pressure). Harder and Seed (1986) indicated, however, that just as the air in the bounce chamber acts as a spring in storing potential energy on the upstroke, the air-fuel mixture in the combustion chamber acts as a cushion during the downstroke, slowing down the ram and resulting in energy loss. They calculated the net kinetic energy at impact and found that it is substantially less than the total potential energy of the ram. They suggested that it is this kinetic energy at impact, not the total potential energy of the ram, that appears to control the resulting penetration resistance or blow count of the Becker pipe.

The Becker hammer, like all diesel hammers, gives variable energy output depending on the combustion conditions and soil resistances. Neglecting this variable hammer energy is one reason why many of the previous BPT-SPT correlations do not work. Harder and Seed (1986) have proposed a method of using the peak bounce chamber pressure to correct the BPT field blow counts to a so-called "constant full combustion condition". The corrected BPT blow counts are then correlated to corrected SPT N-values for liquefaction potential evaluation. Their bounce chamber pressure correction method, however, can not account for energy losses in the driving system (helmet, cushion, etc.) below the anvil, and can not, therefore, be generally applied to different Becker rigs or hammers (Sy and Campanella, 1992b).

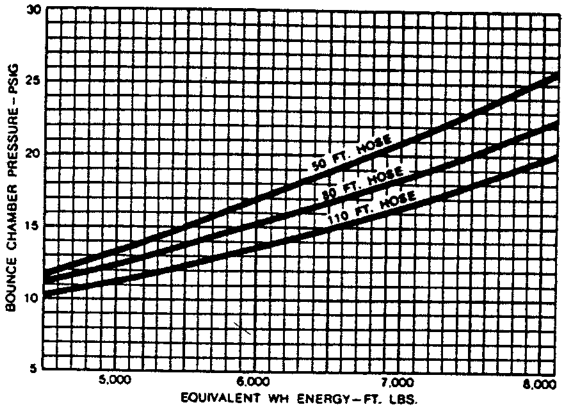

Fig. 4. Energy chart at sea level for ICE Model 180 diesel hammer [1 ft = 0.305 m; 1 psi = 6.9 kPa; 1 ft lb = 1.356 J]

ENERGIES IN IMPACT PENETRATION SYSTEMS

In the existing method of SPT energy measurement (i.e. Eq. 2), the transferred energy is determined by force measurement and the two correction factors, K_1 and K_2, "correct" the measured energy to that at the top of an ideal, infinitely long rod. This procedure is analogous to determining the kinetic energy of the SPT hammer impact on the anvil, such that it is independent of rod length. In other words, the corrected energies may not be the actual energies transferred into the drill rods. In a similar manner, the Harder and Seed's approach for normalizing BPT blow counts based on bounce chamber pressure measurement assumes that the kinetic energy of the Becker diesel hammer directly affects the resulting blow count.

There are three basic methods of characterizing energy in pile driving: potential energy of the ram, kinetic energy of the ram at impact, and energy transferred into the pile. Extensive experience from piling, however, indicates that it is the energy actually transferred into the pile, rather than the potential or kinetic energy of the ram, that directly affects the driving resistance or blow count of the pile. Dynamic monitoring of pile driving is well-established (ASTM D4945-89). The transferred energy is determined by measuring force and acceleration near the pile head for each hammer blow, and using the fundamental energy equation,

$$E_i(t) = \int F(t) \cdot V(t)\, dt \qquad (4)$$

where $E_i(t)$ is the energy transferred into the pile as a function of time, $F(t)$ is the measured force time history, and $V(t)$ is the velocity time history obtained by integration of the measured acceleration time signal. The maximum transferred energy from Eq. 4, commonly called ENTHRU, represents that part of the hammer energy available to do work on the pile.

The SPT and BPT, like all dynamic penetration test systems, involve stress wave propagation in a slender rod due to hammer impact, similar to pile driving. Thus the principles of wave mechanics or pile dynamics should be applicable to these dynamic penetration tests. Consequently, transferred energies due to hammer impacts in these tests should ideally be determined by force and acceleration measurements. This approach will avoid several shortcomings inherent in the existing methods, and will also provide a unified approach for determining the transferred energies in all impact penetration systems i.e. pile driving, Standard penetration test, Becker penetration test, and other dynamic cone penetration tests. Results of UBC's published research on dynamic measurements of the SPT and BPT using force and acceleration transducers are summarized below.

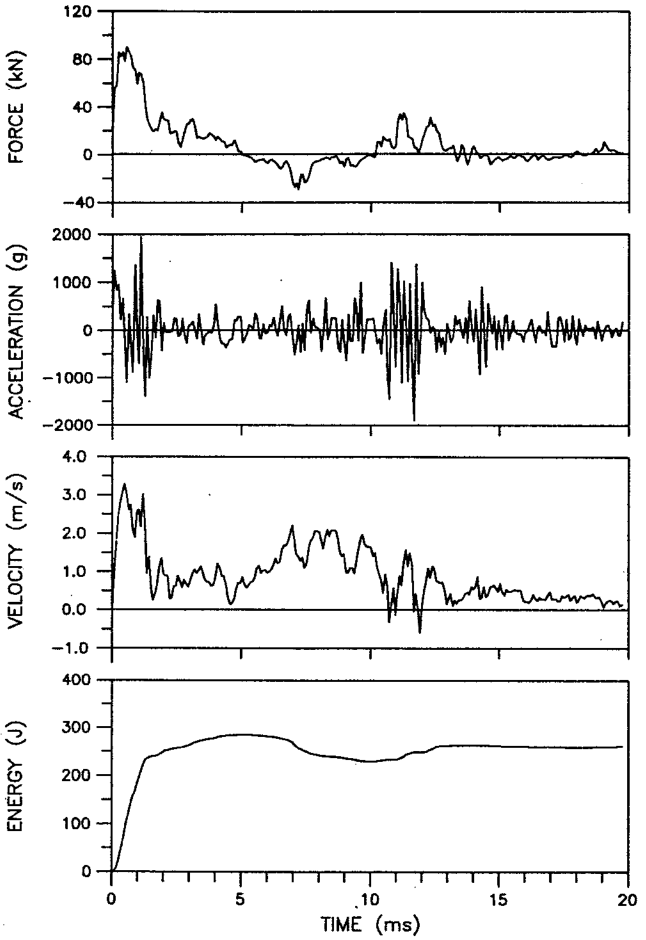

Fig. 5. Force, acceleration, velocity and energy time histories for SPT blow at 9.1 m depth

SPT TRANSFERRED ENERGIES

Fig. 5 shows dynamic measurements for a SPT hammer blow at 9.1 m depth in fine to medium grained sand in which the recorded N value was 21. The measurements were made with a piezoelectric load cell coupled with a piezoelectric accelerometer attached near the top of AW (44.5 mm OD/ 31.0 mm ID) drill rods below a safety hammer (Sy and Campanella, 1991b). The four time histories in Fig. 5 are the measured force, measured acceleration, velocity obtained by integration of the recorded acceleration wave trace, and calculated energy from time integration of force times velocity. The sign convention used is positive force for compression wave and negative force for tension wave, and positive acceleration or velocity for downward motion and negative acceleration or velocity for upward motion. The measured peak compression force is 89 kN and the maximum acceleration is about 2000 g. The peak velocity at impact is 3.4 m/s. Finally, the maximum energy, ENTHRU, is 285 J, which is 60 % of the theoretical free fall hammer energy of 475 J. Note that this maximum energy occurs at 5.0 ms, when the tensile reflection from the sampler bottom reaches the transducer location in the drill rods.

The same blow above is replotted in the top part of Fig. 6 showing the force (F) and velocity times impedance (VEA/c) wave traces. To calculate the impedance, the cross-sectional area of the AW rod was used. This type of proportional stress wave plot is commonly used in piling. If force and velocity are proportional within the first compression pulse, as would be expected for wave propagation in a uniform rod with only tip resistance, they will plot on top of each other. Fig. 6 shows, however, that force and velocity are not proportional within the first compression pulse due to reflections from the different impedances in the SPT rod system used.

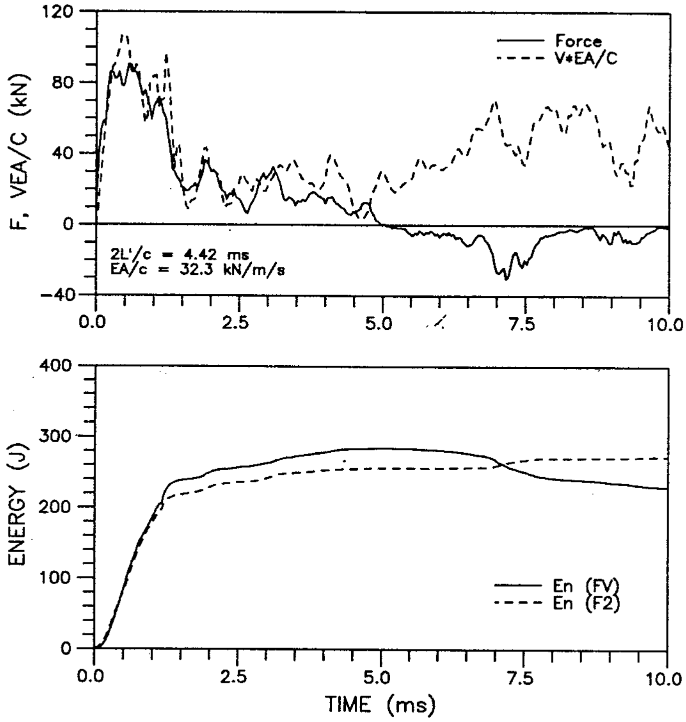

Fig. 6. Force, velocity times impedance and energy traces for SPT blow at 9.1 m depth

The bottom plot in Fig. 6 compares the energy traces calculated using the force-velocity integration (FV) method in Eq. 4 and the force integration (F^2) method in Eq. 1. For this blow, the maximum calculated transferred energies at the transducer location in the drill rods are 285 J using Eq. 4 and 256 J using Eq. 1, corresponding to 60 % and 54 % energy ratios, respectively. The discrepancy between the two energy values is due mainly to the non-proportional force and velocity waveforms caused by wave reflections in the SPT system, and has been verified by wave equation analysis of the SPT (Sy and Campanella, 1991b).

SPT energy measurements using force and acceleration conducted by the authors (Sy and Campanella, 1991b) and by others (Morgano and Liang, 1992) have shown that the existing force integration method gives only approximate ENTHRU values, depending on the changes in cross-sectional areas in the actual anvil-rod-sampler system and on the soil resistances acting on the sampler. The force-velocity integration method is more rational and avoids the force-velocity proportionality assumption inherent in the existing method. The proposed method does not require predetermination of the integration time (tension cutoff point) and also avoids the difficulty of selecting one cross-sectional area of the SPT system for use in the force integration method.

BPT TRANSFERRED ENERGIES

Two BPT's were conducted 2 m apart at a site underlain by 25 m of fine to medium grained sands, the top 10 m of which was densified by dynamic compaction before the penetration tests were conducted (Sy and Campanella, 1992a). In order to investigate the effect of combustion conditions, BPT 3 was carried out to 24.1 m depth with full or maximum throttle setting, while BPT 4 was performed to 8.8 m with variable and reduced throttle settings. The peak bounce chamber pressure for every blow was automatically recorded with a pressure transducer at the end of a 15 m long hose connected to a computer-based data acquisition system. The Becker pipe was also instrumented with strain (force) and acceleration transducers at 0.4 m below the top of the pipe, and dynamically monitored using the Pile Driving Analyzer (Goble et al. 1980).

Fig. 7 shows the stress wave measurements from BPT 3 (full throttle) for two hammer blows, one at shallow depth in soft driving condition and the other at depth in harder driving condition. The wave traces shown are the force, velocity normalized by the pipe impedance, and the calculated energy by integration of the force times velocity time histories. For the 170 mm O.D. pipe used, EA/c = 313.4 kN/m/s. The upper plot in Fig. 7 is for a blow at 2.5 m depth with a driving resistance of 19 blows/300 mm and a total pipe length of 3.9 m, whereas the lower plot is for a blow at 20.0 m with a blow count of 53 and a pipe length during driving of 22.2 m. As shown in the upper plot, the shorter pipe in easy driving behaves somewhat like a rigid body or a "stout pile". This is illustrated by the velocity trace showing the pipe moving down as one unit over a relatively long time period, while the stress wave (force trace) propagates down and up the pipe for several cycles after impact. In the lower plot, the wave traces for the longer pipe show characteristics typical of the driving of a long slender pile. The precompression phase after hammer port closure is recorded in the first 10 ms of the traces, with impact occurring at 10.5 ms and the subsequent compression wave propagating down and returning up the pipe in the next 8.5 ms. The separation of the force (increase) and velocity (decrease) traces between 12 ms and 19 ms suggests substantial shaft friction acting on the 20 m embedded pipe. As expected, the peak force of 292 kN for the softer blow at 2.5 m is much lower than the measured 797 kN peak force for the harder blow at 20 m. The maximum transferred energies, however, are not significantly different, being 2.72 kJ for the softer blow and 2.82 kJ for the harder blow, corresponding to 24.7 % and 25.6 %, respectively, of the manufacturer's rated energy of 11 kJ for the hammer.

The results of the dynamic measurements for BPT 3 (full throttle) and BPT 4 (reduced throttle) are summarized in Fig. 8, which shows the measured blow count, peak bounce chamber pressure, peak force and maximum transferred energy, ENTHRU, plotted against depth. The latter three quantities are average values for each 0.3 m of pipe penetration. The ENTHRU values are shown as percentages of the manufacturer's rated energy for the ICE 180 hammer. As expected, the blow counts for the reduced throttle/fuel condition (BPT 4) are higher, while the bounce chamber pressures, peak forces and ENTHRU values are lower, than those for the full throttle condition (BPT 3).

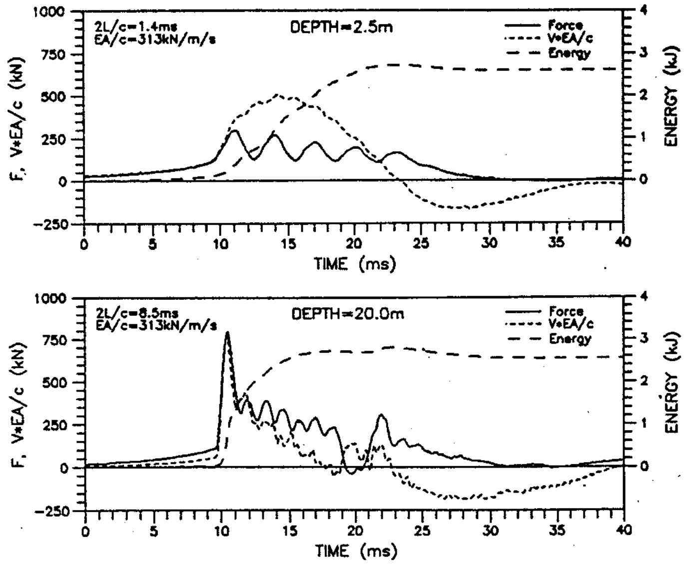

Fig. 7. BPT 3 wave traces at 2.5 m and 20.0 m

For the full throttle condition (BPT 3), the blow count generally increases with depth. Similarly, the bounce chamber pressure and peak force also increase with depth, or with increasing driving resistance. The ENTHRU, however, is surprisingly constant with depth, at about 27 %. This observation suggests that even though the hammer was apparently delivering more kinetic energy (i.e. higher bounce chamber pressure or higher peak force) with increasing depth or driving resistance, the maximum transferred energy to the top of the pipe remained practically constant. This is because the increase in force with driving resistance is equally matched by a decrease in displacement, the product of which makes up the work done (or transferred energy) on the pipe.

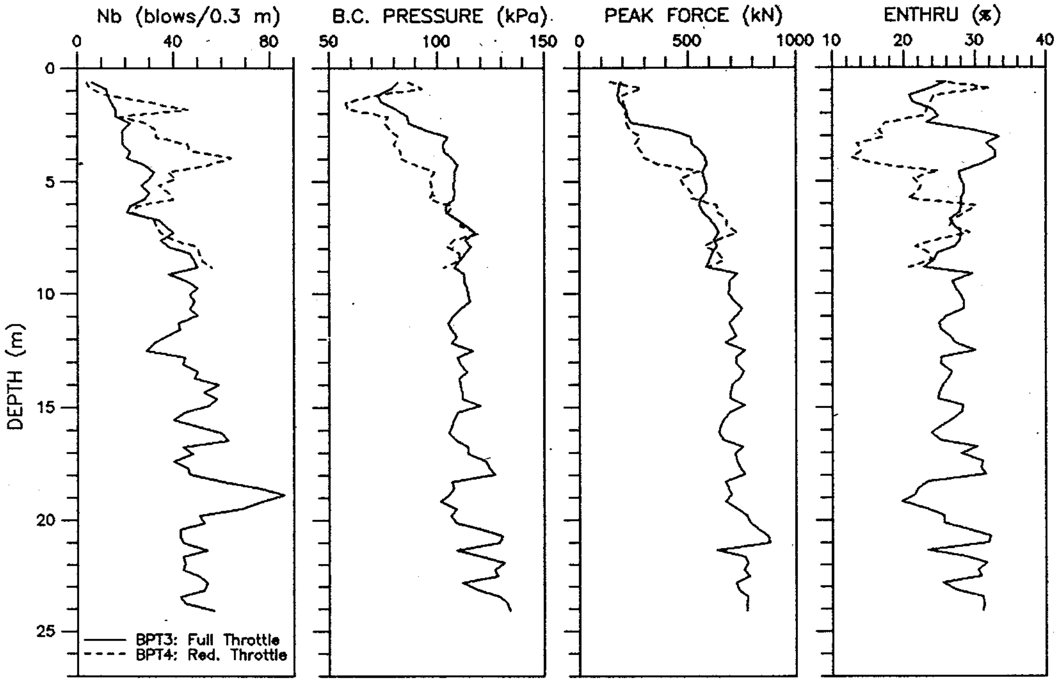

Fig. 8. BPT 3 and BPT 4: blow count, peak bounce chamber pressure, peak force and ENTHRU versus depth

A simple procedure for normalizing the measured BPT blow count to a reference transferred energy level, similar to that used for the SPT, has been proposed by Sy and Campanella (1992b). The measured BPT blow counts are corrected to a common ENTHRU level of 30 % of the rated hammer energy, using:

$$N_{b30} = N_b \cdot \frac{ENTHRU}{30} \qquad (5)$$

where N_{b30} = blow count corrected to 30 % transferred energy ratio (or 3.30 kJ) and N_b = measured blow count. The ENTHRU of 30% represents the average of several Becker rigs measured todate in British Columbia, and is close to the mean efficiency value observed for other double-acting diesel hammers driving steel piles as compiled by Rausche et al. (1985).

Fig. 9 compares the measured blow counts and the energy-corrected blow counts for BPT 3 (full throttle) and BPT 4 (reduced throttle). As shown, the two measured profiles are very different but virtually collapse into one when the blow counts are corrected to a common ENTHRU level of 30 %. The transferred energy can, therefore, be used to correct the measured BPT blow counts to a reference energy level and to allow meaningful correlations with corrected SPT N-values. The effect of shaft friction on the Becker pipe, however, must also be considered in any BPT-SPT correlations. This topic is currently being studied and will be the subject of subsequent publications.

CONCLUSIONS

Recent developments in energy calibrations of the SPT and BPT are summarized in this paper. It is shown that the energy transferred into the SPT drill rods and BPT drill pipes can be determined by force and acceleration measurements, similar in principle to that used in pile driving. The proposed approach provides a fundamental and unified method of measuring transferred energies in the SPT and BPT, and is also applicable to other dynamic cone penetration tests. The measured energy data are then used in a consistent manner to correct the recorded blow counts to a reference energy level in each test. The energy correction allows the SPT and BPT blow counts from different drill rigs or hammers to be compared, and allow more reliable BPT-SPT correlations to be established.

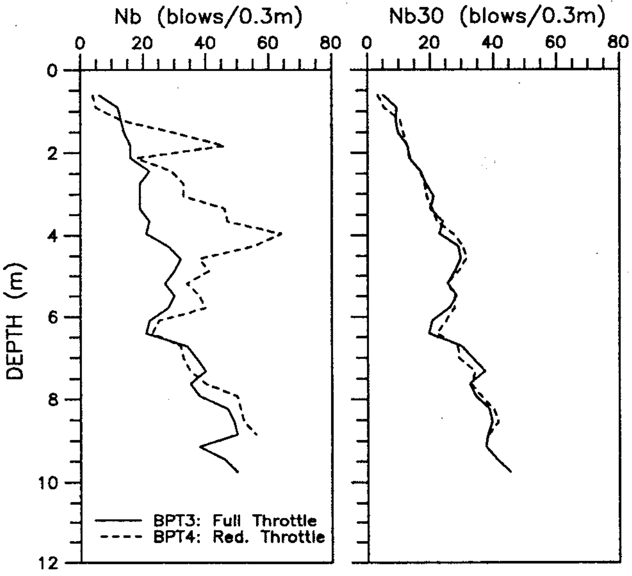

Fig. 9. BPT 3 and BPT 4: measured and energy-corrected blow counts versus depth

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