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Dynamic performance of the Becker hammer drill and penetration test

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ALEX SY and R.G.(DICK) CAMPANELLA

The University of British Columbia
Department of Civil Engineering
2324 Main Mall
Vancouver, B.C., V6T 1Z4

Tel: (604) 822 4266
Fax: (604) 822 6901

ABSTRACT

The Becker penetration test (BPT) blow counts are commonly correlated to the Standard penetration test (SPT) N-values for foundation design and liquefaction potential assessment in coarse-grained soils. Most of the existing correlations, however, do not adequately account for the variable energy output of the ICE 180 diesel hammer used in the Becker system, and the shaft resistance acting on the Becker pipe is often ignored. To obtain reliable BPT-SPT correlations, an extensive study of the BPT has been conducted at several sites in British Columbia. Dynamic measurements of Becker drill rigs and penetration tests were conducted which included hammer combustion and bounce chamber pressures, as well as force and acceleration near the top of the drill pipe. The dynamic field data are presented, including the maximum energy transferred to the top of the Becker pipe (ENTHRU). An energy approach for correcting Becker blow counts to a reference ENTHRU level of 30 % of the hammer rated energy is proposed. Different combustion conditions, different drill rigs, and different pipe sizes are investigated in the study. The test results show that ENTHRU is a fundamental and useful parameter for normalizing the BPT blow counts to account for the variable energy transfer from the diesel hammer.

Key Words: in-situ testing, penetration test, drill rig, dynamic measurement, energy, pile driving, Standard penetration test, diesel hammer, stress wave propagation.

INTRODUCTION

The Becker hammer drill is widely used in western North America for drilling, sampling and penetration testing in coarse granular soils. It consists of driving a double-walled pipe into the ground with a double-acting diesel pile hammer and using an air-injection/cyclone technique to remove the cuttings from the hole. When driven with the pipe close-ended, referred to as the Becker penetration test (BPT), the driving resistances or blow counts give an indication of the density of the soils penetrated. Numerous attempts have been carried out in the past to correlate the BPT blow counts to Standard penetration test (SPT) N-values for foundation design and liquefaction assessment (Harder and Seed, 1986). Most of these correlations, however, had 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 resistances acting on the pipe during driving.

An extensive study of the BPT has been conducted at several sites in Greater Vancouver, British Columbia with the ultimate objective of obtaining reliable BPT-SPT correlations. As part of this study, dynamic measurements of the Becker hammer drill and penetration tests were performed to provide insights into the dynamics of the diesel hammer and the stress wave propagation in the drill pipe.

This paper presents the results of dynamic measurements which include hammer combustion chamber and bounce chamber pressures, as

well as force and acceleration near the top of the Becker pipe during the BPT. An energy approach for normalizing the BPT blow count to account for the variable energy transfer from the diesel hammer is proposed. The effects of variable combustion conditions, different drill rigs, and different pipe sizes on the Becker blow counts are investigated.

BECKER HAMMER DRILL

The Becker hammer drill was developed in 1958 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 granular soils to evaluate density and pile driveability. The drill uses a double-acting diesel pile hammer to drive a specially designed double-walled casing into the ground (Fig. 1). The drive casing is made up of two heavy-walled pipes arranged concentrically, with one male and one female tool joints, and tapered threads, at the ends. In the older design, the two pipes are welded together and separated by four straps or spacers running the length of the casing, and can be handled as one piece of pipe. In the newer design, the inner pipe "floats" inside the outer pipe and only the outer pipe absorbs the direct impact of the hammer. The casings come in 2.4 m or 3.0 m lengths and are available in three standard 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.

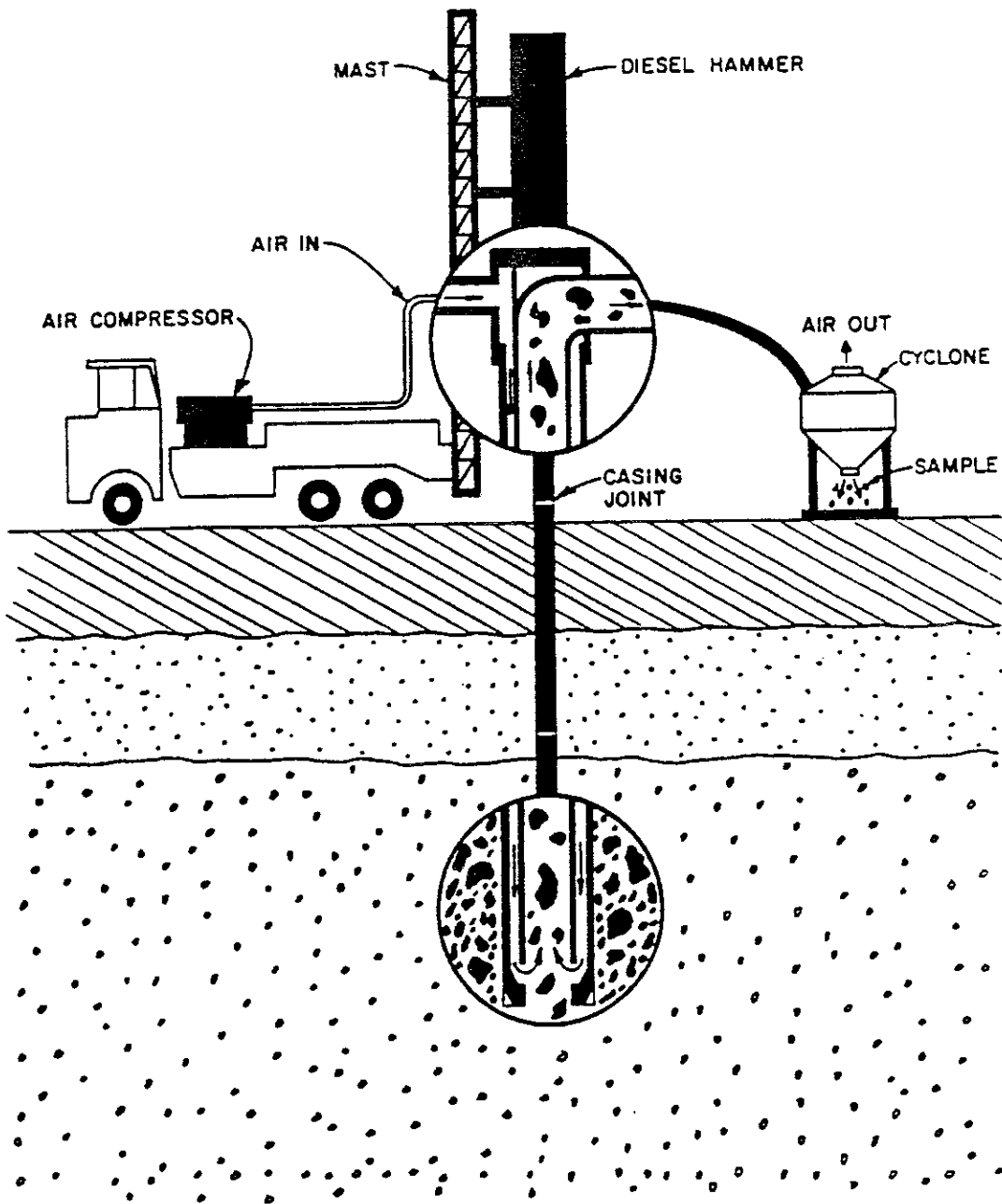


Fig. 1 Becker hammer drill system (from Harder and Seed, 1986)

The Becker casing can be driven open-ended with a hardened drive bit for drilling and sampling, in which case compressed air is forced down the annulus of the casing to flush the cuttings up the centre of the inner pipe to the surface. This drilling technique, also known as the reverse circulation process, is illustrated in Fig. 1. The continuous cuttings or soil particles are collected at the ground surface via a cyclone which dissipates the energy of the fast-moving air/soil stream. At any depth, the drilling can be stopped and the open-ended casing allows access to the bottom of the hole for tube sampling, Standard penetration test or other in-situ tests, or for rock coring to be conducted. On completion of drilling, the casing is withdrawn by a puller system comprising two hydraulic jacks operating in parallel on tapered slips that grip the casing and reacting against the ground.

The Becker casing can also be driven close-ended, without using compressed air, as a large scale penetration test and to model pile driving. In this mode, the driving resistances or blow counts are recorded for each 0.3 m of penetration. The BPT blow counts 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.

There are two basic types of Becker drill rigs: the older HAV180 and the newer AP1000. The main difference between the two rigs is the way the hammer is mounted on the mast and the way the hammer is raised or lowered onto the pipe. The HAV180 has a two-piece

"telescopic" or sliding mast and is a more compact rig. The AP1000 rig is larger, with a single long mast, and is more elaborate, containing several additional features to facilitate drilling and testing. One such feature on the AP1000 is an air blower or supercharger which can be turned on to pump more air into the combustion chamber, thereby increasing the hammer combustion efficiency. Both rigs use the same ICE 180 model diesel hammer but with slightly different driving cap or "spout" design. The spout rests directly on top of the double-walled casing and has an inlet port for air injection into the annulus of the casing and an outlet port for soil retrieval from the drill hole.

The main advantage of the Becker hammer drill is its ability to sample or penetrate relatively coarse grained soil deposits at a fast rate, making it particularly useful for mining explorations or geotechnical investigations in sand, gravel and boulder formations (Anderson, 1968).

DIESEL HAMMER DETAILS

The hammer used in the Becker system is an International Construction Equipment, Inc. (ICE) Model 180 double-acting atomized fuel injection diesel pile hammer. Fig. 2 shows the operating principle of the double-acting, or closed-top, diesel hammer. On the downstroke and just before ram impact, a high pressure fuel injection system atomizes the fuel as it is injected into the

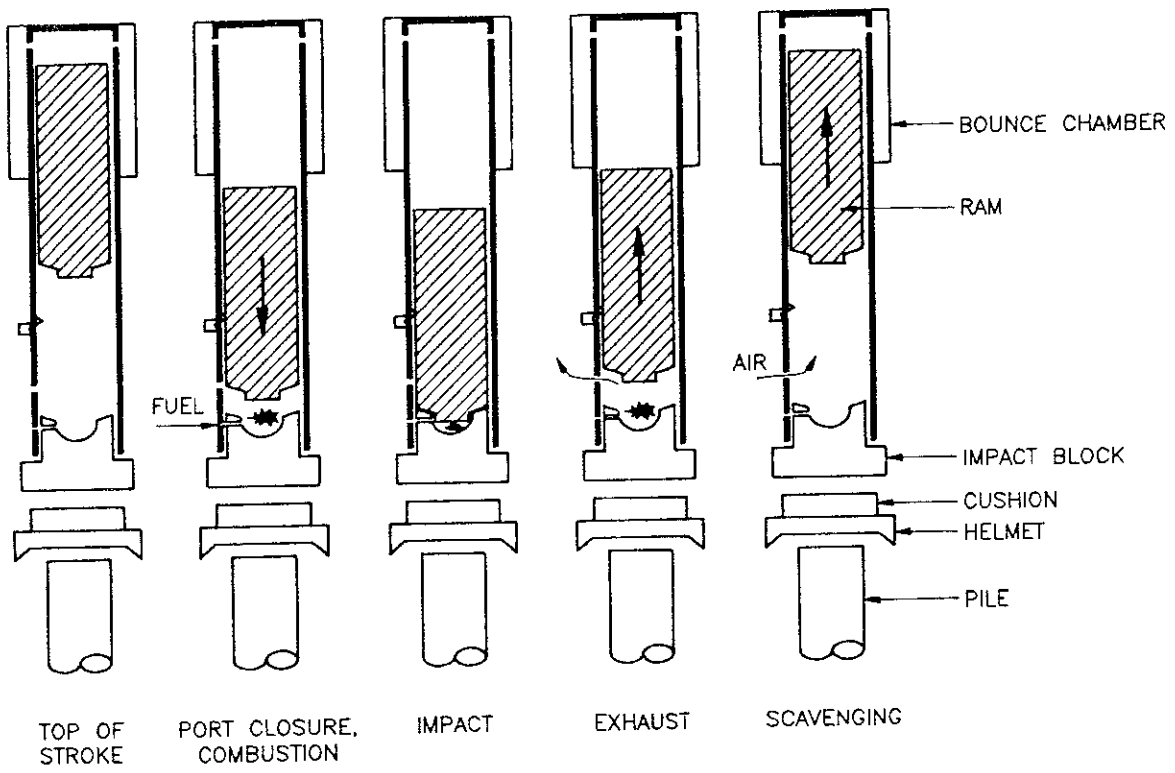


Fig. 2 Operating principle of double-acting atomized fuel injection diesel hammer

combustion chamber. Combustion starts immediately and imparts energy to drive the impact block (or anvil) and to lift the ram up to the top of its stroke for the next cycle. The top of the hammer housing is closed off and connected to compression tanks, such that as the ram rises on the upward stroke, it compresses the air trapped in the "bounce chamber". The air in the bounce chamber acts like a spring, storing energy on the upstroke and imparting it to the ram on the downstroke. The bounce chamber also shortens the stroke, which leads to an increase in blow rate compared to an open-top condition.

The Becker hammer, like all diesel hammers, gives variable energy output depending on the combustion conditions and soil resistances. Anything that affects combustion, such as air-fuel mixture, temperature and pressure, will affect the hammer energy output. In fact, the Becker rig has an adjustable lever or throttle control which allows the operator to control the amount of fuel injected into the combustion chamber. Even if constant combustion conditions can be maintained, the hammer energy output will still depend on the soil resistance. In soft ground driving or a low soil resistance condition, a large portion of the combustion gas energy is expended to accelerate the anvil downward, reducing the energy available for lifting the ram. This will result in lower stroke or lower bounce chamber pressure for the next cycle. On the other hand, in hard driving condition, the anvil movement decreases and more gas energy is available to propel the ram upward, resulting in a higher stroke or higher bounce chamber pressure.

The ICE 180 hammer has a ram weight of 7.67 kN and a maximum physical stroke of 0.96 m. The hammer operates at a blow rate of 90 to 95 blows per minute at maximum stroke. The manufacturer's rated energy for the hammer is 11.0 kJ, equivalent to a single-acting hammer stroke of 1.43 m. ICE closed-top diesel hammers are rated by the manufacturer in a manner similar to that used for double-acting steam/air hammers, in which the potential energy of the actual ram stroke is added to the energy of the steam/air force applied to the ram on its downstroke, to obtain the total potential energy of the hammer. For the diesel hammer, the rated energy is equal to the weight of the ram multiplied by the actual stroke plus the energy stored in the bounce chamber that accelerates the ram downward. This stored energy is calculated by using gas laws for adiabatic conditions, given the dimensions of the bounce chamber and the maximum bounce chamber pressure. The maximum bounce chamber pressure and, therefore, the maximum physical stroke, is controlled by the weight of the hammer housing and is reached when the housing lifts or "racks" on the upstroke. The effect of combustion is ignored in the calculations.

Based on the above assumption that total potential energy is the sum of the actual ram stroke energy and the energy stored in the bounce chamber, the hammer manufacturer develops charts relating peak bounce chamber pressure to the equivalent total potential energy at the top of ram stroke, for different lengths of hose used in recording the bounce chamber pressure. Harder and Seed (1986), however, indicated 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. Using gas laws and again ignoring the effect of combustion, they calculated this energy loss due to compression of gases in the combustion chamber. They found that the calculated net kinetic energy at impact is substantially reduced, and it is this kinetic energy at impact, not the total potential energy of the ram, that appears to control the resulting blow count or penetration resistance of the Becker casing.

BECKER BLOW COUNT CORRECTION

Neglecting the variable energy output of the diesel hammer is one reason why many of the previous BPT-SPT correlations do not generally work. Harder and Seed (1986) have proposed an empirical but ingenious method of using the peak bounce chamber pressure to correct the BPT field blow counts to a common reference level for use in BPT-SPT correlations. Their proposed normalizing procedure is illustrated in Fig. 3. 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 shown in Fig. 3. At constant combustion condition, however, bounce chamber pressure increases with increasing blow count, the points tending to lie on lines somewhat parallel to Line A-A shown. They

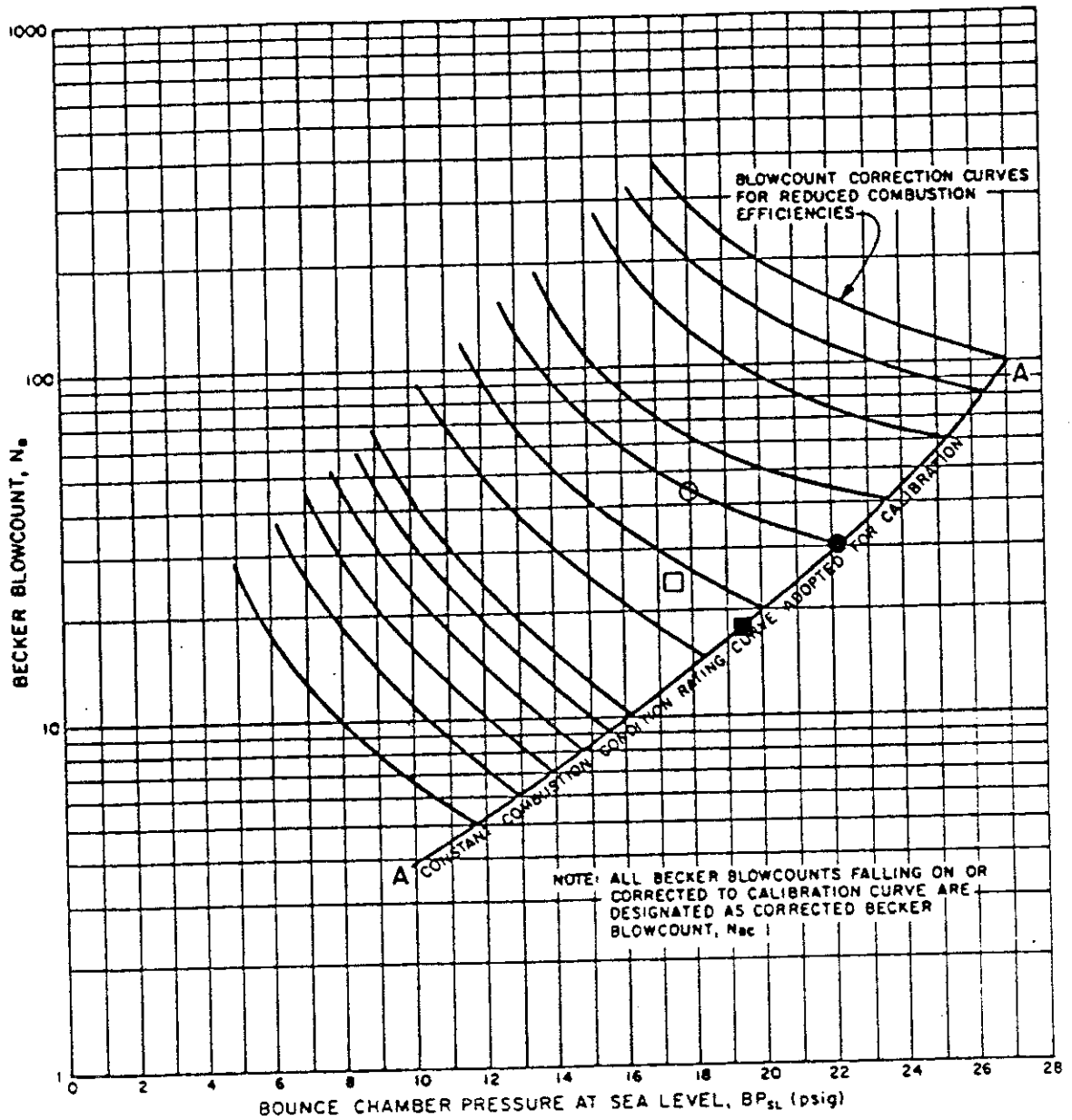


Fig. 3

BPT blow count correction chart based on bounce chamber pressure
(from Harder and Seed, 1986)

suggested that Line A-A, 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 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.

To use the Harder and Seed's chart in Fig. 3, 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. 3, the open circle and open square representing two measured data, and the closed circle and closed square giving the corresponding blow counts after correction. The attractiveness of this procedure is that peak bounce chamber pressure can easily be measured in the field without sophisticated equipment. The method, however, appears to have some limitations, as it could not be consistently applied to different Becker rigs (Harder and Seed, 1986).

Bounce chamber pressure is useful as an indicator of diesel hammer performance but it can not account for energy losses within the hammer or in the driving system (helmet, cushion, etc.) below the anvil. An alternative and more fundamental approach of characterizing the Becker hammer energy output is by measuring the energy actually transferred to the top of the drill pipe during

hammer impact. The transferred energy in the BPT can be determined with force and velocity measurements, similar to the procedure used in dynamic monitoring of pile driving (ASTM D4945-89). Sy and Campanella (1992) have shown that bounce chamber pressure (and hence the calculated kinetic energy at impact) can not be directly correlated to the maximum transferred energy, ENTHRU, and it is the ENTHRU that directly affects the driving resistance or blow count of the Becker pipe. Accordingly, an energy approach for correcting the Becker blow count to account for the variable energy output of the diesel hammer is proposed below.

PROPOSED ENERGY APPROACH FOR NORMALIZING BPT BLOW COUNTS

The importance of ENTHRU is recognized not only in pile driving, but also in the Standard penetration test. It is known that the most important factor affecting the SPT N-value is the amount of hammer energy transferred into the drill rods (Sy and Campanella, 1991). For liquefaction analysis, the measured SPT N-values are routinely corrected to a reference energy level of 60 % of the theoretical free-fall SPT hammer energy. A similar approach for normalizing the measured BPT blow count to a reference ENTHRU level is proposed.

It is proposed that an ENTHRU of 30 % of the rated hammer energy be adopted as a reference energy level for the BPT and that the measured blow counts be corrected using:

$$[1] \quad N_{b30} = N_b \cdot \frac{ENTHRU}{30}$$

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

The ENTHRU correction based on Eq. [1] is simple, and because ENTHRU is an absolute and measurable quantity, the corrected blow count, N_{b30} , has a physical meaning. Dynamic measurements of several BPT's are presented below, and both the Harder and Seed's approach based on bounce chamber data and the proposed energy approach based on ENTHRU data are evaluated.

DYNAMIC FIELD MEASUREMENTS

As part of an extensive in-situ testing program involving cone penetration tests (CPT), SPT and BPT, dynamic measurements of Becker hammer drills and penetration tests were carried out. Representative time histories of combustion chamber pressures and bounce chamber pressures were measured on the ICE 180 hammer to evaluate the diesel hammer performance. These measurements were performed simultaneously using pressure transducers connected to a

high-speed data acquisition system. In addition, peak bounce chamber pressure for every blow during the BPT was automatically measured with another pressure transducer at the end of a 15 m long hose connected to a computer-based data acquisition system. The Becker casing was also instrumented with strain transducers and accelerometers at 0.4 m below the top of the pipe and monitored using the Pile Driving Analyzer (Goble et al. 1980). The Pile Driving Analyzer (PDA) 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. The PDA force and velocity time histories are displayed in the field for every blow. This allows a check on the quality of the measured data by inspection of the force/velocity proportionality.

Fig. 4 shows time histories of bounce chamber pressure, combustion chamber pressure and force near the top of the drill pipe for three consecutive hammer blows. The bounce chamber pressure time history is essentially a sine wave with a period of approximately 0.63 s. The combustion pressure and force time histories show that one hammer impact event lasts only about 20 ms. Ram impact is characterized by peak force, and as expected, it occurs when the bounce chamber pressure is at its trough and when the combustion pressure is at its peak. A close-up view (50 ms window on the right hand side of Fig. 4) of the combustion pressure and force traces

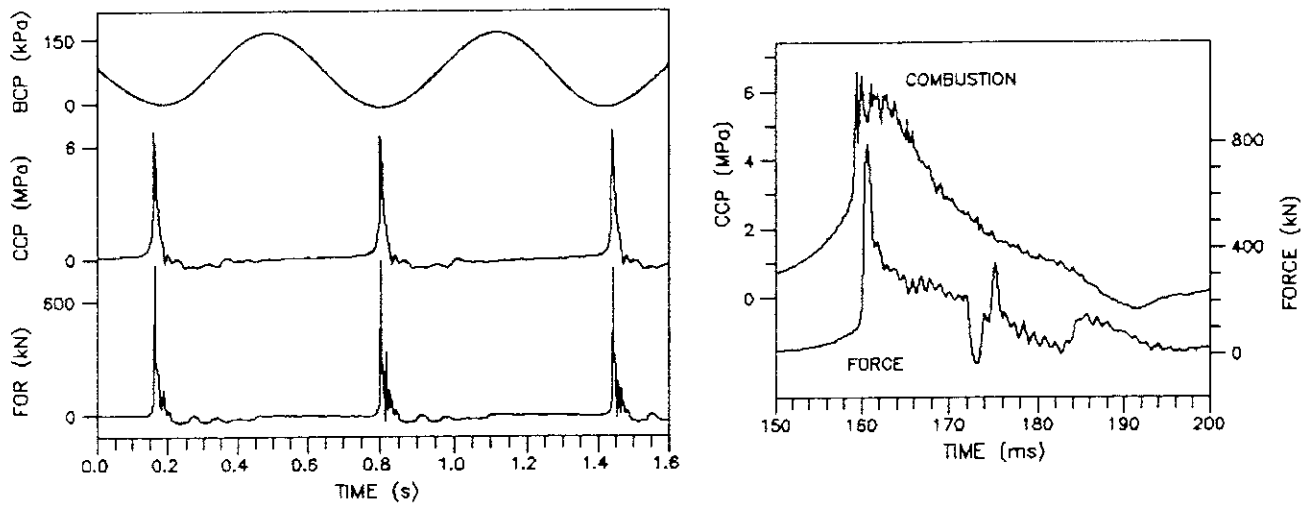


Fig. 4 Bounce chamber pressure (BCP), combustion chamber pressure (CCP) and force (FOR) time histories for three consecutive Becker hammer blows, including an expanded view of one blow on right hand side

reveals that, in fact, the peak combustion pressure of 6.5 MPa occurs about 2 ms before impact and the maximum pressure is maintained for a duration of about 8 to 10 ms. This preignition is a particular feature of atomized fuel injection diesel hammers.

At a test site in Richmond, British Columbia, a series of BPT's, SPT's and CPT's were performed in a controlled pattern. Fig. 5 shows a cone penetration test data. The site is underlain by 25 m of fine to medium grained sands overlying interbedded sand and silt deposits. The top 10 m of the soil profile was densified by dynamic compaction prior to the field test program (Naesgaard et al. 1992).

Table 1 summarizes the various characteristics of the four BPT's conducted as part of the test program. The effects of various factors on the Becker blow counts can be investigated by comparing appropriate pairs of BPT data. BPT 3 and 4 allow an evaluation of variable combustion conditions, BPT 2 and 5 allow an assessment of different rigs or hammers (but the same ICE 180 hammer model), and BPT 3 and 5 consider the effect of different pipe sizes. Comparisons of these data are discussed below.

VARIABLE COMBUSTION CONDITIONS

The difference between BPT 3 and 4 is the combustion condition. BPT 3 was performed with the maximum throttle setting (i.e. full

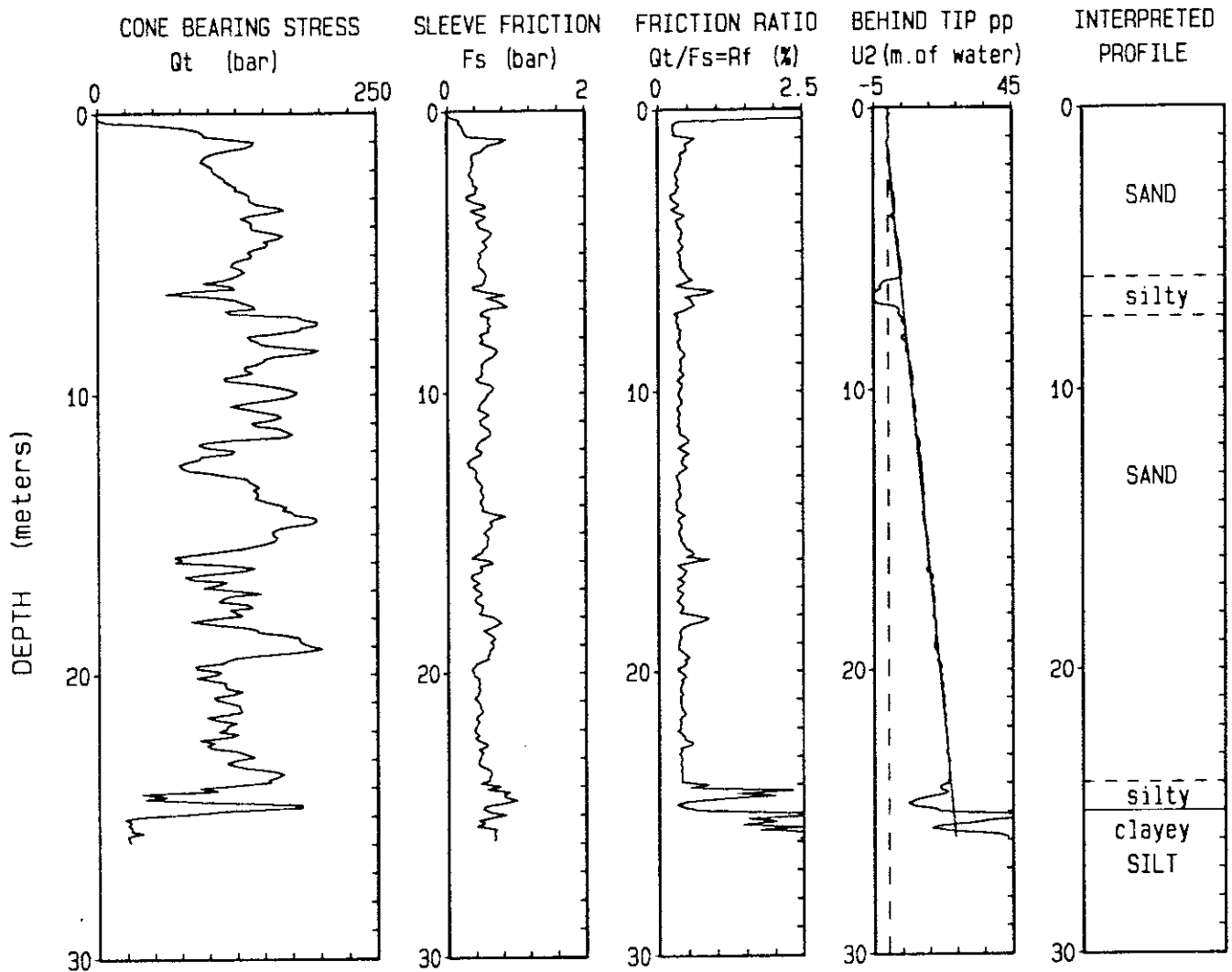


Fig. 5

Cone penetration test data, Richmond, B.C.

TABLE 1. Characteristics of BPT's at Richmond test site

Test No.	Max.	Fuel Throttle	Casing		Drill Rig No. (Type)
	Depth (m)		O.D. (mm)	Inner Pipe Type	
BPT 2	24.1	Full	140	Fixed	Rig F1 (HAV180)
BPT 3	24.1	Full	170	Floating	Rig 107 (AP1000)
BPT 4	8.8	Reduced	170	Floating	Rig 107 (AP1000)
BPT 5	28.0	Full	140	Floating	Rig 107 (AP1000)

combustion condition), whereas in BPT 4, the throttle was reduced and varied several times during the test to achieve various combustion conditions. Both BPT 3 and 4 were conducted with Rig 107 (AP1000 type) using 170 mm diameter floating pipe. The results of the dynamic measurements for BPT 3 (full throttle) and BPT 4 (reduced throttle) are summarized in Fig. 6, which shows the measured blow count, peak bounce chamber pressure (BP), 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 value is shown as a percentage of the manufacturer's rated energy of 11.0 kJ for the ICE 180 hammer. As expected, the blow counts for 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).

For 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 maximum transferred energy, 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

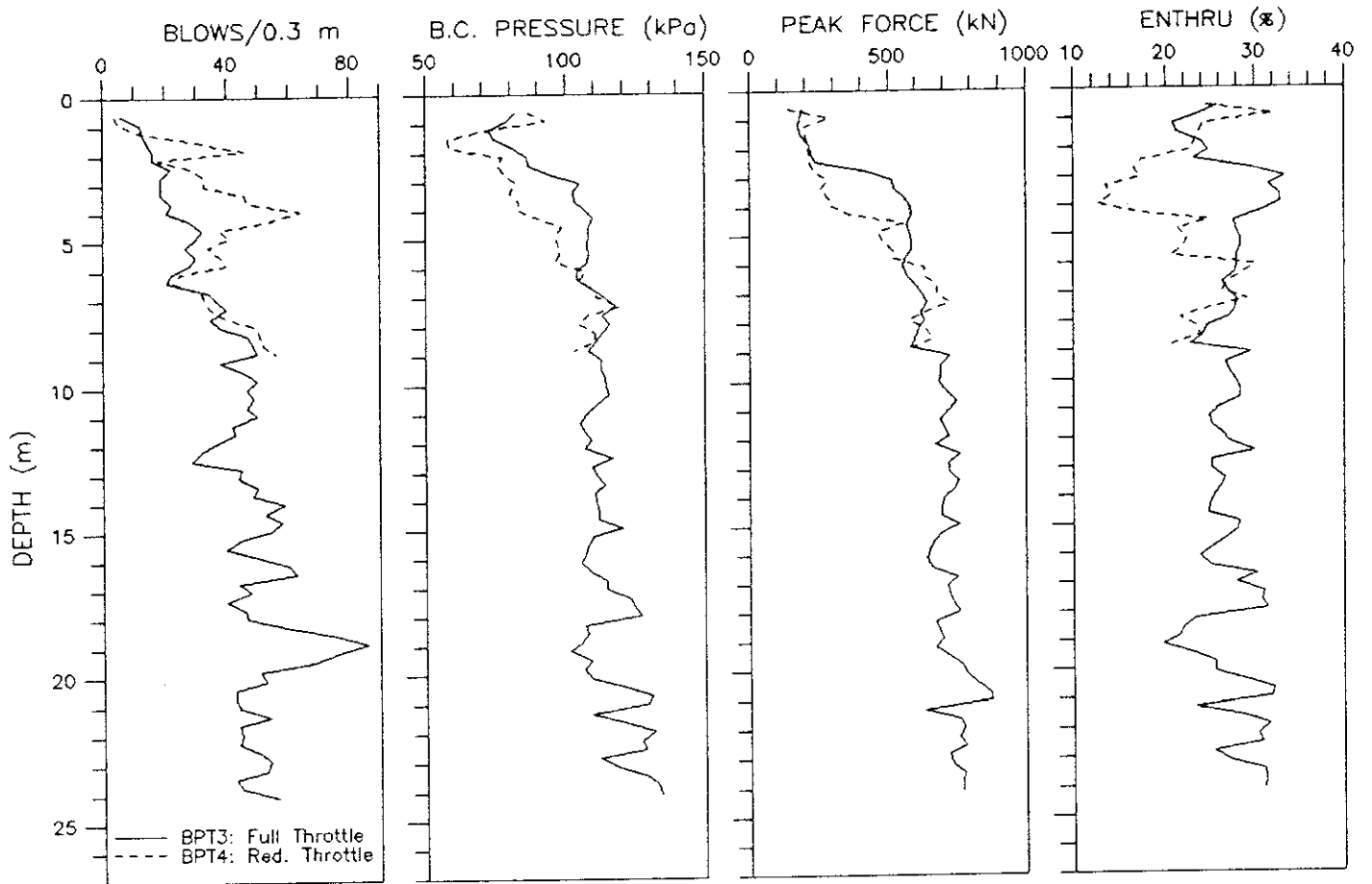


Fig. 6 BPT 3 and 4: blow count, bounce chamber pressure, peak force and ENTHRU versus depth

product of which makes up the work done (or transferred energy) on the Becker pipe.

Fig. 7 shows the BP and ENTHRU data for the first 8.8 m depth from BPT 3 and 4 plotted against the measured blow count, N_b . As expected, the reduced combustion (BPT 4) data points plot above and to the left of the full combustion (BPT 3) data points in both graphs, since blow count increases and bounce chamber pressure decreases with decreasing combustion efficiency or ENTHRU. For comparison, Harder and Seed's calibration curve A-A is also shown on the BP- N_b graph. The trend of the full combustion (BPT 3) data points on this graph, as indicated by the dashed line, is to the left of and parallel to A-A line, suggesting that Harder and Seed's calibration line corresponds to a higher combustion efficiency, or higher ENTHRU, than that measured in this study. This is not surprising since the A-A line was determined from a hammer with an air blower or supercharger on, which increases the combustion efficiency by increasing the oxygen intake into the combustion chamber. The air blower, although equipped on Rig 107, was not used for these tests.

Fig. 8 shows the measured blow counts (N_b), the bounce chamber pressure-corrected blow counts (N_{bc}) and the energy-corrected blow counts (N_{b30}) for BPT 3 and 4. As shown, the two measured profiles virtually collapse into one when the blow counts are corrected by either methods. This illustrates that both the BP-correction and the energy-correction methods can adequately account for the effect

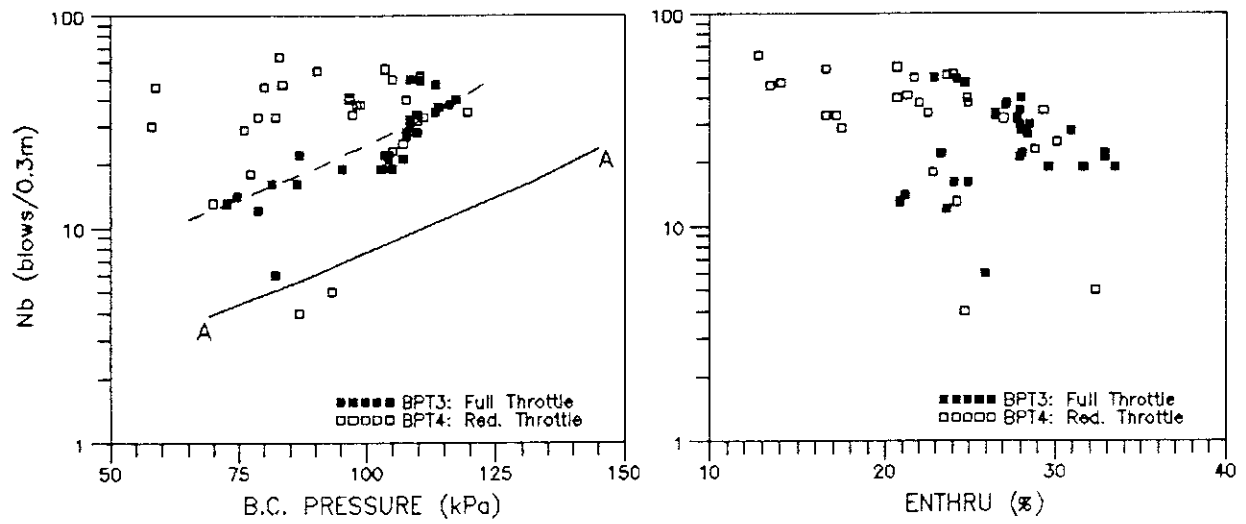


Fig. 7 BPT 3 and 4: bounce chamber pressure and ENTHRU versus blow count

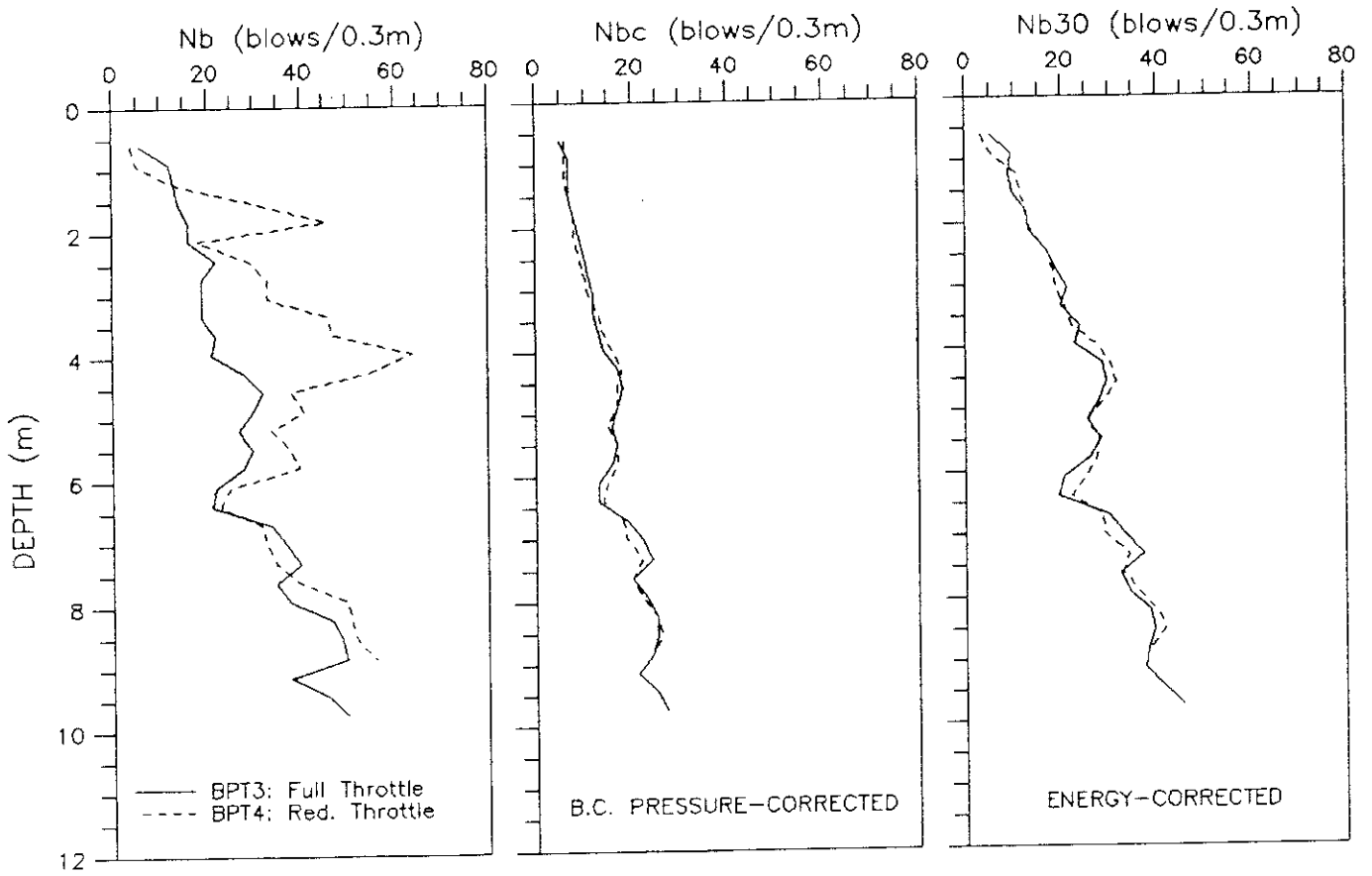


Fig. 8 BPT 3 and 4: measured and corrected blow counts versus depth

of variable combustion conditions on the Becker blow counts. The N_{bc} values, however, are much lower than the N_{b30} values, again suggesting that the Harder and Seed's A-A line corresponds to some combustion efficiency or energy transfer higher than an ENTHRU of 30 %.

DIFFERENT DRILL RIGS/HAMMERS

The effect of different drill rigs/hammers can be evaluated by comparing BPT 2 and 5. BPT 2 was carried out using Rig F1, a HAV180 type drill, while BPT 5 was conducted with Rig 107, an AP1000 type drill. The same sized pipe, 140 mm O.D., was used, but BPT 2 had fixed inner pipe and BPT 5 had floating inner pipe. Both hammers were operated at full throttle condition.

Fig. 9 compares the measured blow count, bounce chamber pressure, peak force and ENTHRU for the two rigs/hammers. The blow counts for BPT 2 are consistently lower than those in BPT 5, suggesting that Rig F1 (BPT 2) was more efficient. This is indeed confirmed by the ENTHRU data which show values for BPT 2 consistently higher than those for BPT 5. The bounce chamber pressure data, however, do not show the same trend. At the same depth, the more efficient BPT 2 has BP readings lower than those for BPT 5, inconsistent with the expectation that for the same resistance, increasing combustion efficiency or increasing BP should be associated with decreasing blow count (refer to Fig. 3).

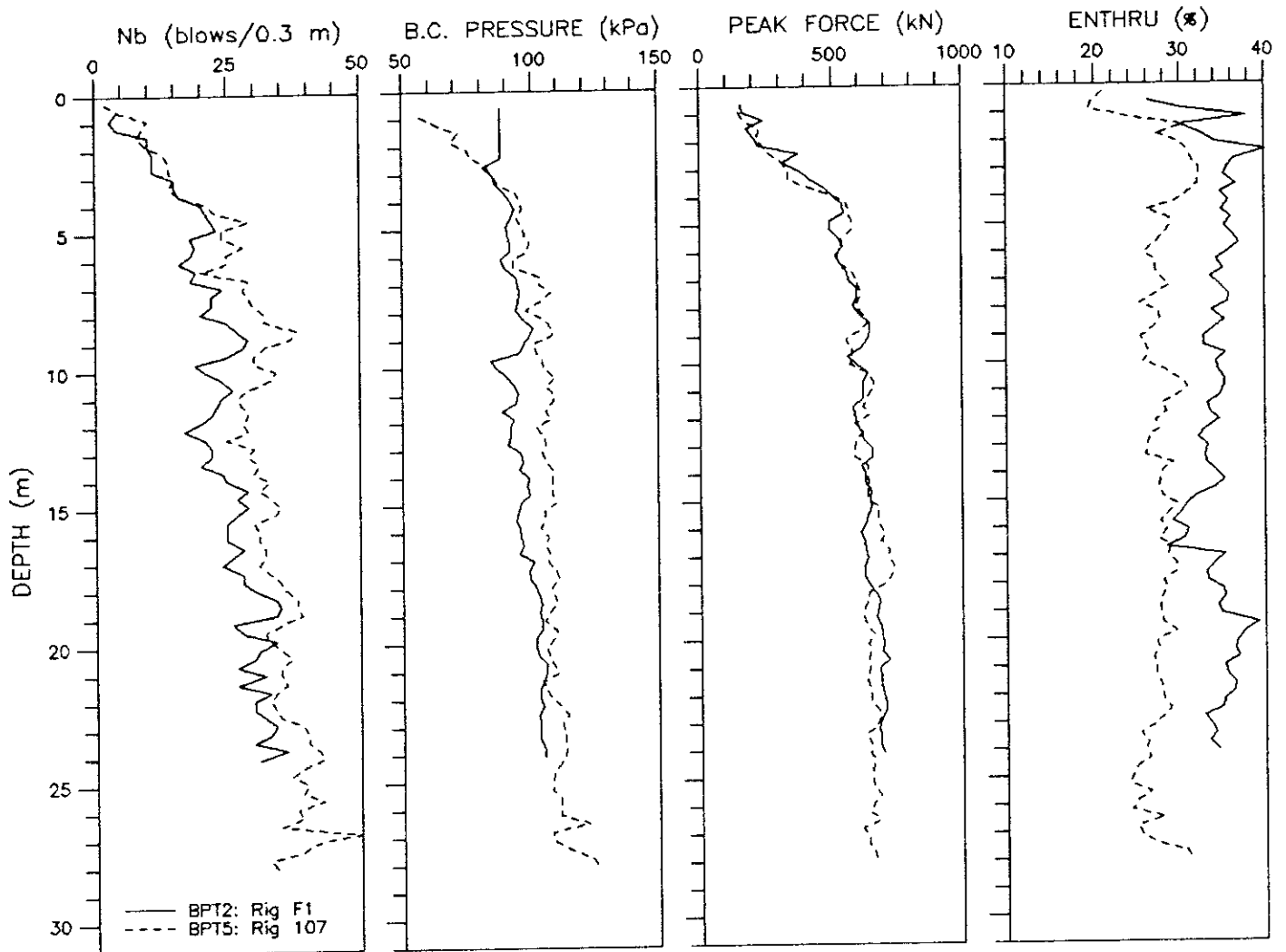


Fig. 9 BPT 2 and 5: blow count, bounce chamber pressure, peak force and ENTHRU versus depth

The BP and ENTHRU data are plotted against N_b in Fig. 10. Except for some scatter at shallow depth, or low blow count, where the diesel hammer was not firing continuously, two trends are evident in Fig. 10. The ENTHRU data are practically independent of blow count (or depth as shown in Fig. 9), being on average about 35 % for BPT 2 and 27 % for BPT 5, whereas the BP data follow a constant combustion trend line almost parallel to A-A line. Note that for both BPT 2 and 5, the bounce chamber data lie on the same trend line, confirming the apparent inconsistency indicated above. The more efficient (or higher ENTHRU) BPT 2 data points are expected to fall in the region between the BPT 5 data and A-A line in the BP- N_b graph. It is not surprising then that when BPT 2 and 5 blow counts are corrected to A-A line using the BP-correction method, the BPT 2 (Rig F1-HAV180) N_{bc} values are still consistently less than BPT 5 (Rig 107-AP1000) values, as shown in Fig. 11. On the other hand, the energy-corrected N_{b30} profiles again practically collapse into one profile.

Harder and Seed (1986) found similar inconsistency when comparing BPT results from a HAV180 (also known as B180) rig and an AP1000 rig. After correcting for hammer combustion efficiencies to A-A line, they found that the AP1000 N_{bc} values were still 1.5 times higher than the HAV180 values. This would suggest that the BP-correction procedure in Fig. 3 is not generally applicable to all Becker rigs or hammers. One possible reason for this discrepancy between the two rigs is difference in energy losses in the driving systems.

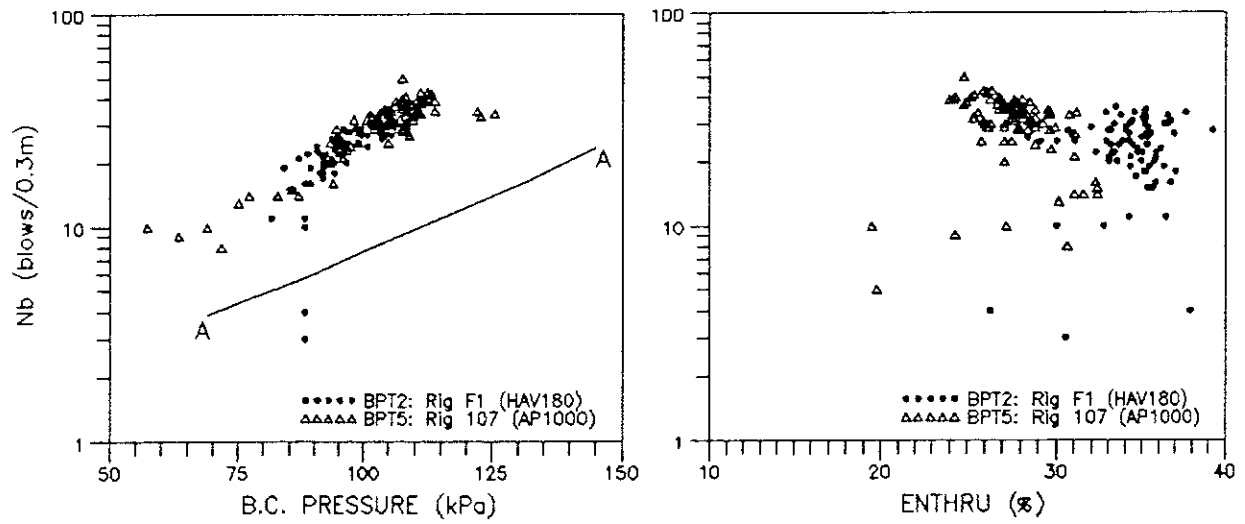


Fig. 10 BPT 2 and 5: bounce chamber pressure and ENTHRU versus blow count

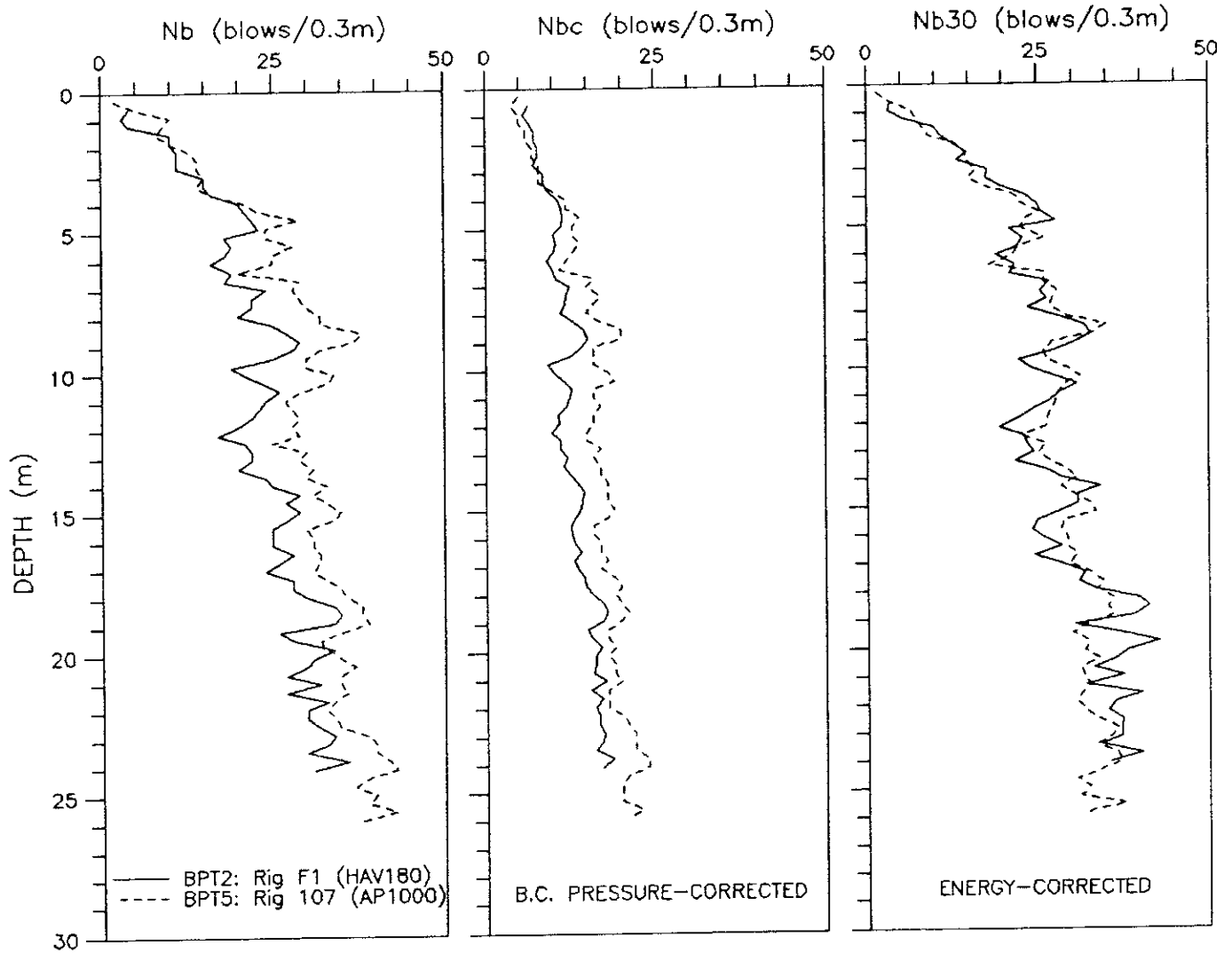


Fig. 11 BPT 2 and 5: measured and corrected blow counts versus depth

As mentioned earlier, BP is only an indicator of the diesel hammer performance above the anvil. When the ram strikes the anvil in the hammer, the impact wave propagates through a striker plate/cushion/helmet system below the anvil and then a driving cap or "spout" resting on top of the pipe. Differences in the cushion makeup and condition, and differences in spout design will affect the energy transmission efficiency between the anvil and the top of the pipe. Such energy losses in the driving system will be reflected in the measured transferred energy near the top of the pipe, but not by the bounce chamber pressure measurements. In other words, two hammers with exactly the same combustion condition but different energy losses through the driving systems would still define the same combustion curve in the BP- N_{bc} plot but yield different transferred energies, as observed in the plots in Fig. 10. Thus the BP-correction method can not provide a consistent approach for normalizing BPT blow counts between different rigs or hammers.

Another possible reason for the apparent discrepancy in N_{bc} values between BPT 2 and 5 is that the BP readings in BPT 2 are not reliable, i.e. the readings are too low. The peak bounce chamber pressures were measured with a transducer at the end of a 15 m long hydraulic hose. Although easily measured, the bounce chamber pressure reading could be affected by fluid accumulation (oil and water from the bounce chamber) in the hose and possibly by the hose diameter, fittings and adaptors. There was no independent field check on the accuracy of the BP measurement.

The N_{b30} results in Fig. 11 again confirm that ENTHRU is a fundamental and useful parameter for normalizing the BPT blow counts regardless of the Becker rig type, hammer condition or driving system.

DIFFERENT PIPE SIZES

The effect of different pipe sizes can be investigated by comparing BPT 3 and 5, both carried out with the same Rig 107 operating at full throttle. BPT 3 was conducted using 170 mm O.D. casing, whereas BPT 5 used 140 mm O.D. casing, both with floating inner pipes. These two casing sizes are the most commonly used for the BPT.

Fig. 12 compares the test results for BPT 3 and 5. As expected, because of the larger sized pipe, BPT 3 blow counts are greater than those of BPT 5. The BPT 3 BP values are slightly higher BPT 5 values, consistent with the fact that for the same combustion condition, BP increases with increasing blow count. The peak force data also show higher values for BPT 3 relative to BPT 5. This is also expected since higher BP implies higher equivalent hammer stroke and hence results in higher peak force. The ENTHRU values for BPT 3 and 5 are similar, suggesting that the higher force in BPT 3 is compensated by its smaller displacement (i.e. higher blow count) relative to BPT 5, the product of these two quantities determining the transferred energy in the pipe.

One noticeable feature between the two blow count profiles is that the BPT 3 profile is more spiky and would at first glance appear to suggest that the larger diameter pipe is much more sensitive to soil variability than the smaller pipe (BPT 5). A comparison of corresponding N_b and ENTHRU profiles in Fig. 12, however, indicates that the higher N_b values or peaks in BPT 3 are associated with relatively lower ENTHRU values, and conversely, lower N_b values with higher ENTHRU. After correction for hammer efficiencies as shown in Fig. 13, the dominant spikes are a bit more subdued. Thus the apparent spiky blow count profile may not necessarily imply better indication of soil density. Another complicating factor is that the amount of shaft resistance on the two pipe sizes is different and undoubtedly affects the measured blow counts.

As expected, the BP-corrected and ENTHRU-corrected blow counts for the larger pipe (BPT 3) are consistently higher than the corresponding values for the smaller pipe (BPT 5), as shown in Fig. 13. The corrected blow counts are presented in another form in Fig. 14 in order to establish a relationship between the two pipe sizes. Linear regression analyses of the data give the following relationships:

$$[2] \quad N_{bc} (170 \text{ mm}) = 1.45 \times N_{bc} (140 \text{ mm})$$

$$[3] \quad N_{b30} (170 \text{ mm}) = 1.40 \times N_{b30} (140 \text{ mm})$$

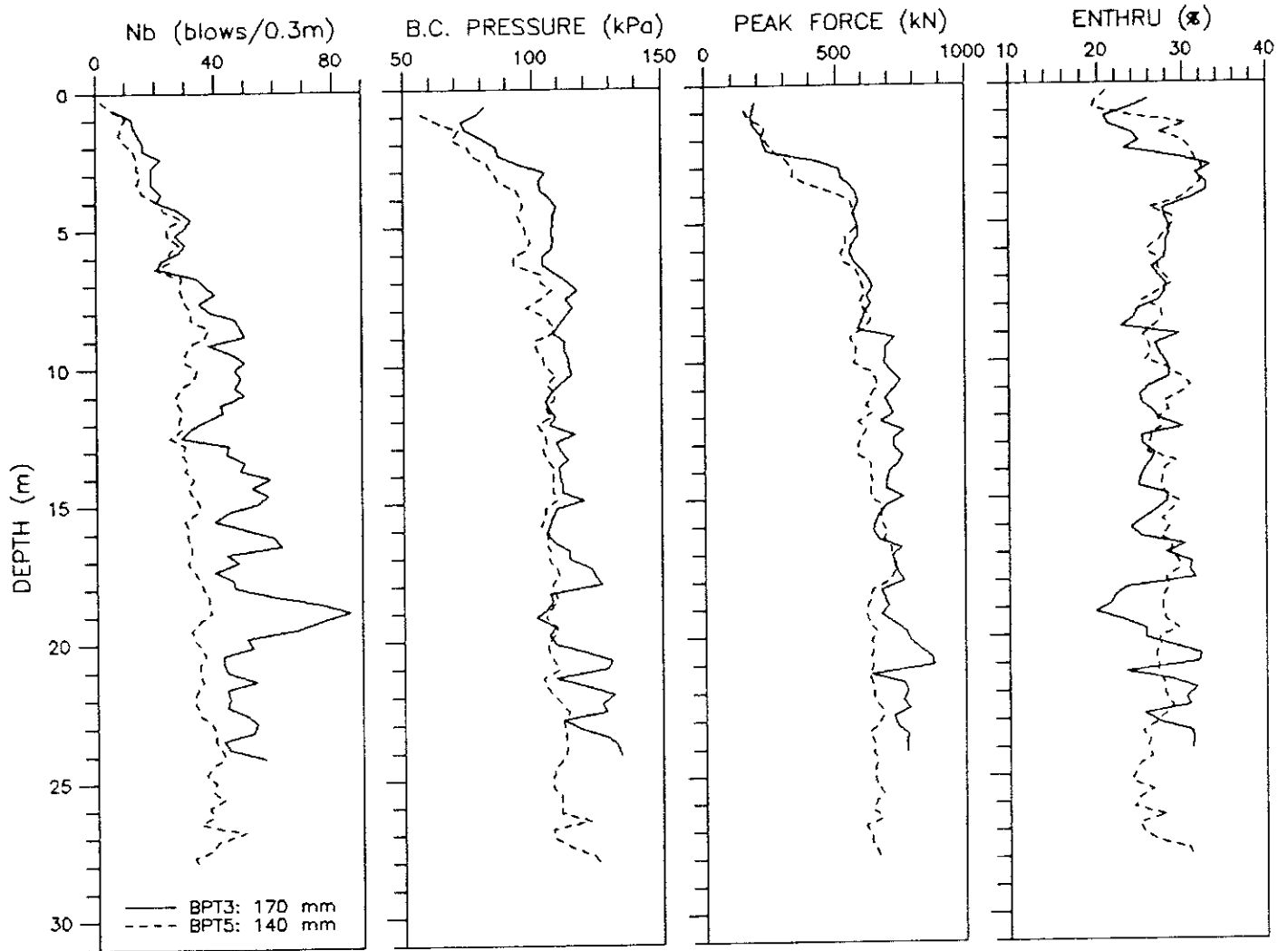


Fig. 12 BPT 3 and 5: blow count, bounce chamber pressure, peak force and ENTHRUS versus depth

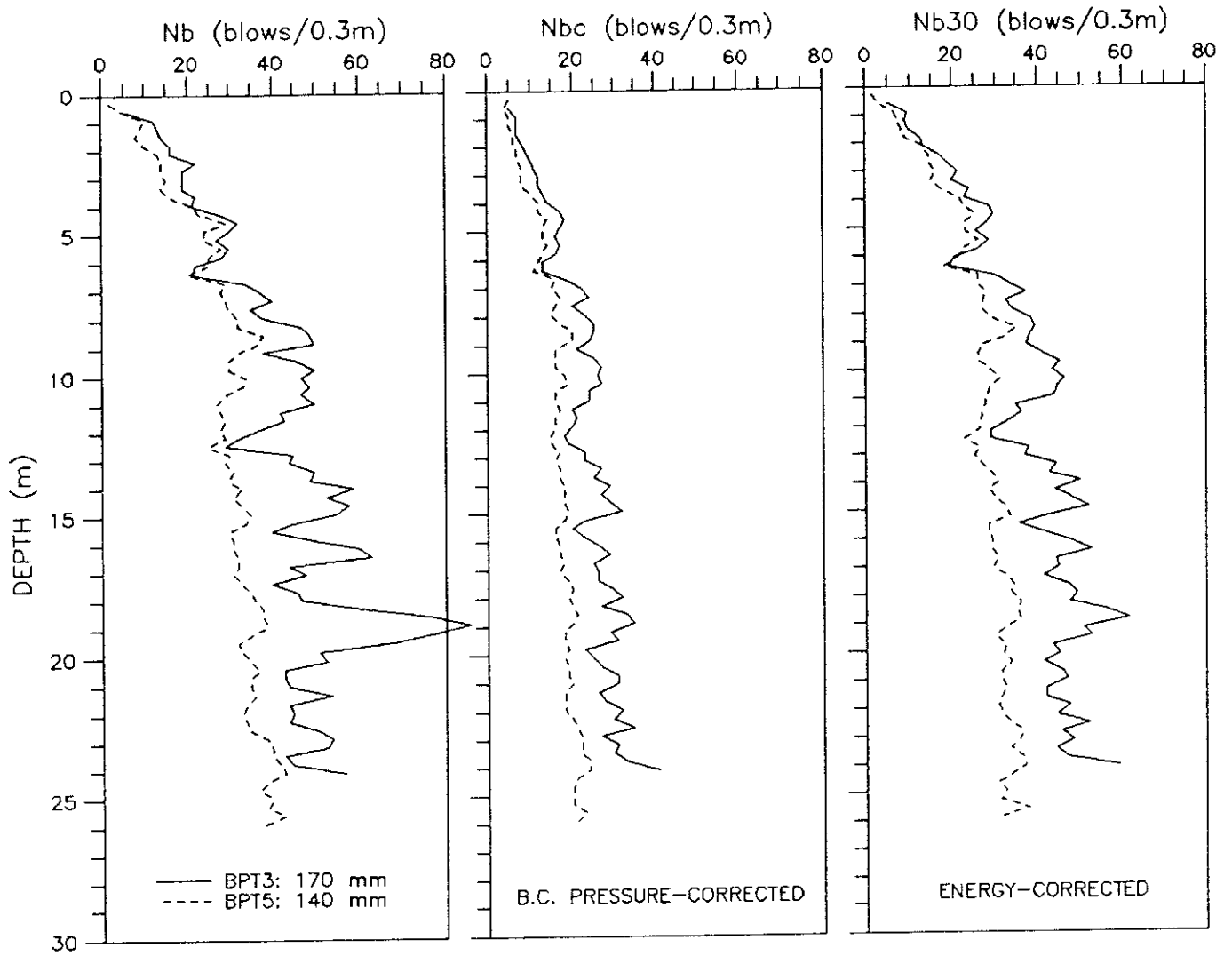


Fig. 13 BPT 3 and 5: measured and corrected blow counts versus depth

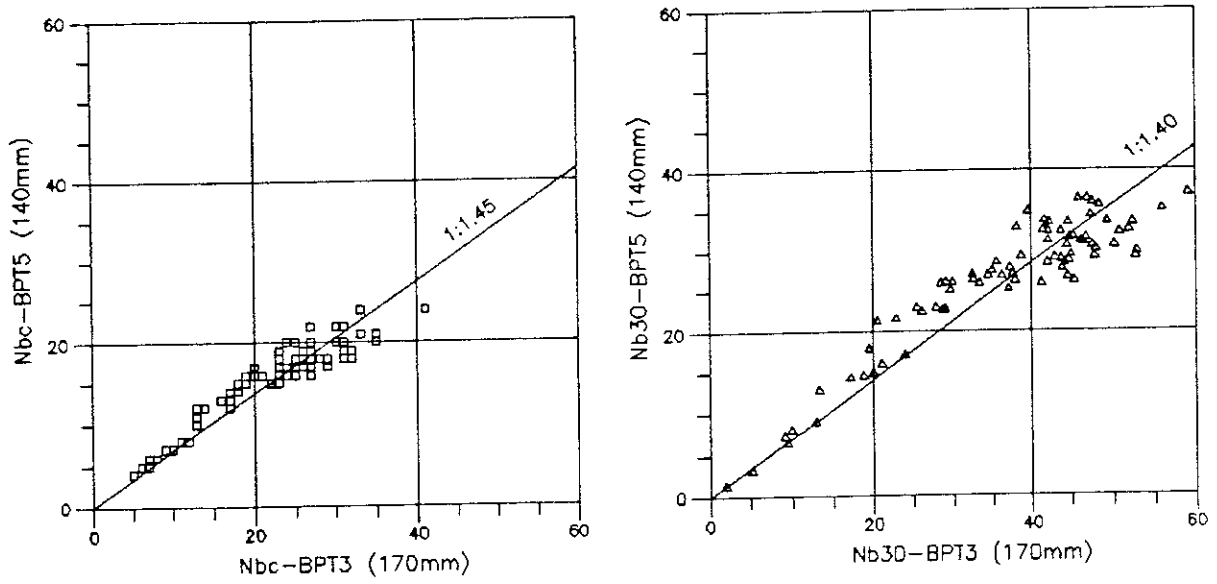


Fig. 14 Corrected blow counts for BPT 3 versus BPT 5

For the same hammer and soil conditions, the blow count or driving resistance is a function of the dynamic soil resistances (shaft and toe) acting on the pipe, the magnitude of which is governed by the pipe/soil contact areas. The larger the pipe, the larger the resistance, and therefore, the higher the blow count. Theoretically, the pipe size factor between the 170 mm and 140 mm diameter pipes should lie between two bounds: one bound controlled by the ratio of the unit pipe shaft areas, i.e. 1.2, for zero toe resistance condition, and the other controlled by the ratio of the pipe toe areas, i.e. 1.5, for zero shaft resistance condition. The pipe size factors in Eqs. [2] and [3] fall within this theoretical bound. Stewart et al. (1990) reported similar pipe size factors at two sites based on BP-corrected blow counts.

CONCLUSIONS

Dynamic measurements of the Becker hammer drill and penetration tests were conducted as part of an extensive study into BPT-SPT correlations. The field measurements included hammer combustion chamber and bounce chamber pressures, as well as force and acceleration near the top of the pipe for every blow during the BPT. The maximum energy transferred to the top of the pipe (ENTHRU) is calculated by time integration of force times velocity measurements. An energy approach for normalizing the BPT blow count to account for the variable diesel hammer energy output is proposed. The blow

counts are corrected to a reference ENTHRU level of 30 % of the manufacturer's rated energy for the hammer, in a manner similar to that used in SPT energy correction.

A series of BPT's was performed to investigate variable combustion conditions, different rigs/hammers and different pipe sizes. The dynamic measurements confirm the variable energy output of the diesel hammer used in the Becker system. Both the Harder and Seed's approach for correcting BPT blow counts based on bounce chamber pressure measurements and the proposed energy approach based on ENTHRU measurements are evaluated. It is shown that the bounce chamber pressure-correction procedure, although conceptually sound for correcting variable hammer combustion conditions, can not consistently be applied to different rigs or hammers. The test data show, however, that the proposed ENTHRU-correction procedure is much simpler, and provides a more fundamental approach to normalizing the Becker blow counts, regardless of combustion conditions or energy losses in the hammer and in the driving system.

The energy-corrected BPT blow counts will then allow meaningful correlations with corrected SPT N-values. The force and velocity measurements will also allow quantification of the shaft resistances acting on the drill pipe during the BPT, the effect of which must be considered in any BPT-SPT correlations. This topic is currently being studied and will be the subject of subsequent publications.

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REFERENCES

- ANDERSON, L.G. 1968. A modern approach to overburden drilling. Western Miner, November.
- ASTM STANDARD D4945-89. Standard test method for high-strain dynamic testing of piles.
- GOBLE, G.G., RAUSCHE, F., and LIKINS, G.E., 1980. The analysis of pile driving - a state-of-the-art. Proceedings of the 1st International Conference on the Application of Stress-Wave Theory on Piles, Stockholm, A.A. Balkema Publishers, pp. 131-161.
- HARDER, L.F. JR., and SEED, H.B. 1986. Determination of penetration resistance for coarse-grained soils using the Becker hammer drill. Report No. UCB/EERC-86/06, University of California, Berkeley, CA, 118 pages.

- NAESGAARD, E., SY, A., and CLAGUE, J.J. 1992. Liquefaction sand dykes at Kwantlen College, Richmond, B.C. 1st Canadian Symposium on Geotechnique and Natural Hazards, Vancouver, B.C.
- RAUSCHE, F., LIKINS, G.E., GOBLE, G.G., and MINER, R. 1985. The performance of pile driving systems. Main report, Volume 1 to 4, Federal Highway Administration contract #DTFH 61-82-C-00059, Washington, D.C.
- STEWART, R.A., KILPATRICK, B.L., and CATTANACH, J.D. 1990. The use of Becker penetration testing for liquefaction assessment of coarse granular overburden. 43rd Canadian Geotechnical Conference, Quebec, 1: 275-283.
- SY, A., and CAMPANELLA, R.G. 1991. An alternative method of measuring SPT energy. Proceedings of the 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, 1: 499-505.
- SY, A., and CAMPANELLA, R.G. 1992. Dynamic measurements of the Becker penetration test with implications for pile driving analysis. Proceedings of the 4th International Conference on the Application of Stress-Wave Theory to Piles, The Netherlands, September 21-24.