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Dynamic measurements of the Becker penetration test with implications for pile driving analysis

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ABSTRACT: The Becker penetration test consists of driving a double-walled, close-ended pipe into the ground with a double-acting diesel hammer and recording the blows for each 0.3 m of pipe penetration. The test models the driving of a displacement pile. Dynamic measurements were conducted which included hammer bounce chamber pressure, and force and acceleration near the top of the Becker pipe. Different combustion conditions were investigated in the study. The field measurements show that peak bounce chamber pressure can not be correlated to the energy transferred into the pipe during hammer impact, and it is this transferred energy that is the important factor affecting the driving resistance of the pipe. The data also suggest that hammer energy loss due to combustion can be significant. The use of bounce chamber pressure to estimate equivalent hammer potential energy, which neglects the effect of combustion, for use in dynamic pile driving formulae can be misleading.

1 INTRODUCTION

The Becker hammer drill is widely used in 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, 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 resistances acting on the pipe during driving. The Becker penetration test also simulates the driving of a displacement pile and is often used for pile driveability evaluations (e.g. Morrison and Watts, 1985).

A field program was carried out at a site in Richmond, British Columbia, Canada, in which a series of cone penetration tests, Standard penetration tests and Becker penetration tests were conducted in a controlled pattern to allow correlations between the different test methods. As part of this study, dynamic monitoring of the Becker penetration test was performed to provide insights into the stress wave propagation in the BPT.

This paper presents the results of dynamic measurements which include hammer bounce chamber pressure, and force and acceleration near the top of the Becker pipe for every blow during the test. Lessons learned from the field test data and their implications for dynamic pile analysis and for BPT-SPT correlations are discussed.

2 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

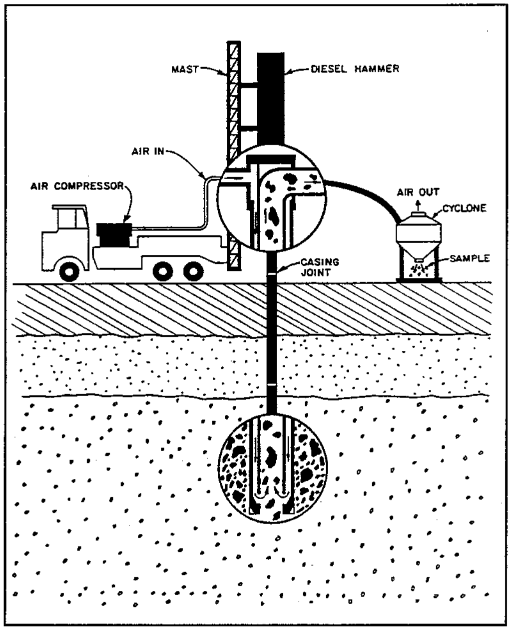

Fig. 1 Becker hammer drill system (from Harder and Seed, 1986)

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.

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 more reliable than SPT N-values in gravelly soils because of the larger pipe diameter to particle size ratio.

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).

3 BECKER 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 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 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

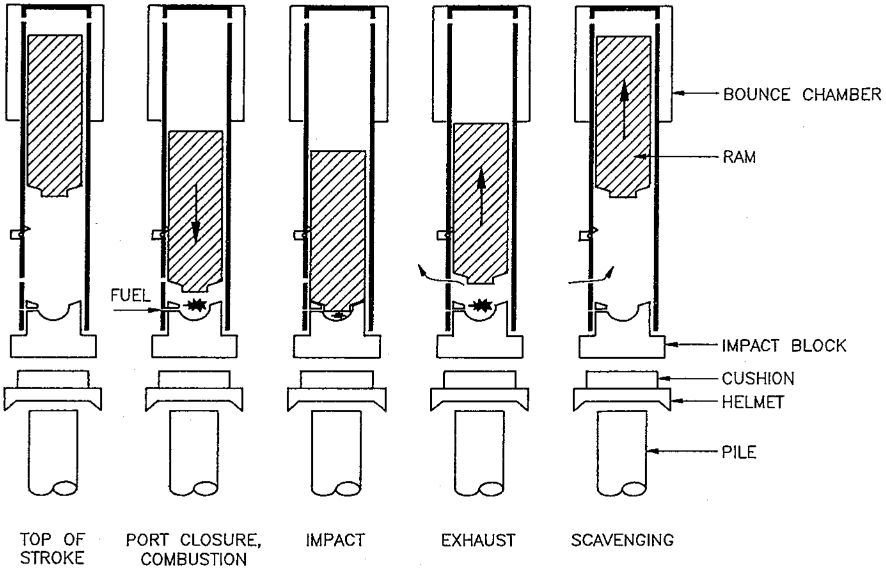

Fig. 2 Operating principle of double-acting atomized fuel injection diesel hammer

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, 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.

A chart developed by the manufacturer of the Model 180 hammer is shown in Fig. 3, which relates 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. In pile driving analysis, the estimated energies from Fig. 3 are often used in a dynamic formula, such as the Engineering News Formula, and often with a hammer efficiency factor of one, to determine the pile capacity for a given set (pile displacement per blow).

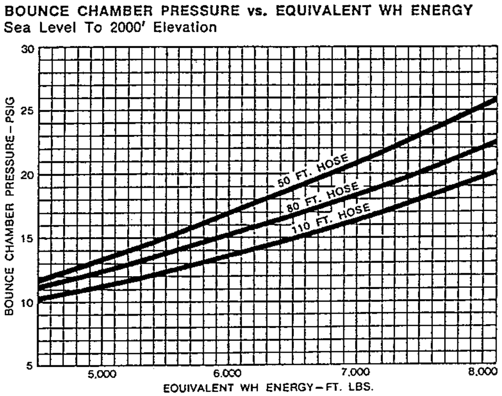

Fig. 3 Energy chart for ICE Model 180 diesel hammer (International Construction Equipment, Inc.). [1 ft = 0.305 m; 1 psi = 6.9 kPa; 1 ft lb = 1.356 J]

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. It will be shown in this paper that the effect of combustion gas energy on hammer energy transfer can be significant and should not be ignored in pile driving analysis.

4 FIELD PROGRAM

The test site is located in Richmond, British Columbia, Canada and within the Fraser river delta. The delta is underlain by a very thick sequence of clayey silts, silty sands and sands overlying glacial till. The natural soil profile at the test site consists of a 3 m thick clayey silt overlying fine to medium grained sands to 25 m over interbedded sand and silt deposits which likely extend to about 150 m at this location. As part of the foundation preparation for a new college, the surficial topsoil and the 3 m thick clayey silt layer were excavated and backfilled with truck-dumped fine grained sand. Prior to the test program described below, the sand fill and underlying loose native sands were densified in-place to an effective depth of approximately 10 m by the dynamic compaction process (Naesgaard et al. 1992).

As part of an extensive field program, two Becker penetration tests were conducted 2 m apart using a Model AP1000 Becker drill rig. 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 two tests were conducted with 170 mm O.D., floating inner pipe casings supplied in 3.0 m lengths. 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 casing was also instrumented with transducers at 0.4 m below the top of the pipe and dynamically 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. A total of 3249 blows was recorded for BPT 3 and 1012 blows for BPT 4.

5 TEST RESULTS AND DISCUSSIONS

Fig. 4 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, EA/c (i.e., the product of the Young's modulus times the cross-sectional over the wave speed), 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. 4 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. 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 tensile (negative force and positive velocity) toe reflection is captured at 19 ms in the record, followed by the return wave reflecting from the top of the pipe and going down the pipe a second time with much reduced amplitude. 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 for the hammer.

The results of the dynamic measurements for BPT 3 (full throttle) and BPT 4 (reduced throttle) are summarized in Fig. 5, 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 percentage of the manufacturer's rated energy of 11 kJ for the ICE 180 hammer. As expected, the blow counts for reduced throttle/fuel condition are higher, while the bounce chamber pressures, peak forces and ENTHRU values are lower,

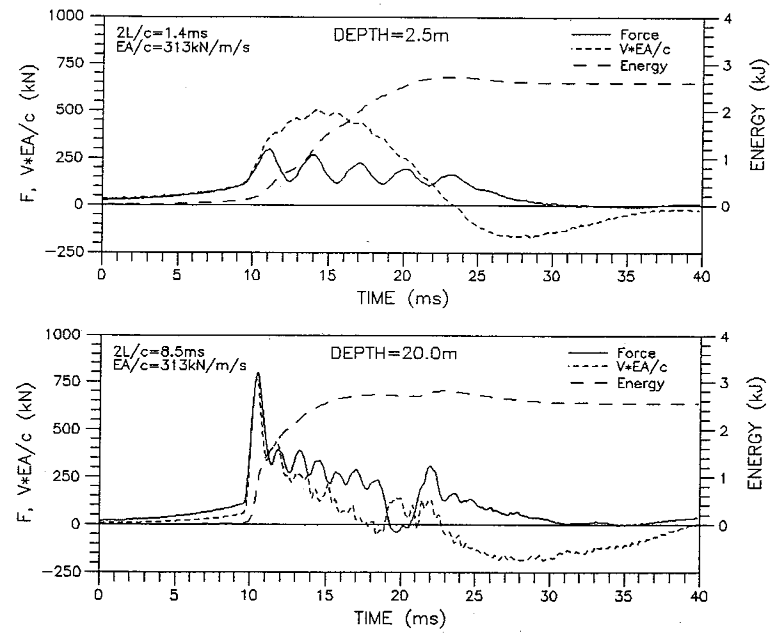

Fig. 4 Wave traces at 2.5 m and 20.0 m in BPT 3

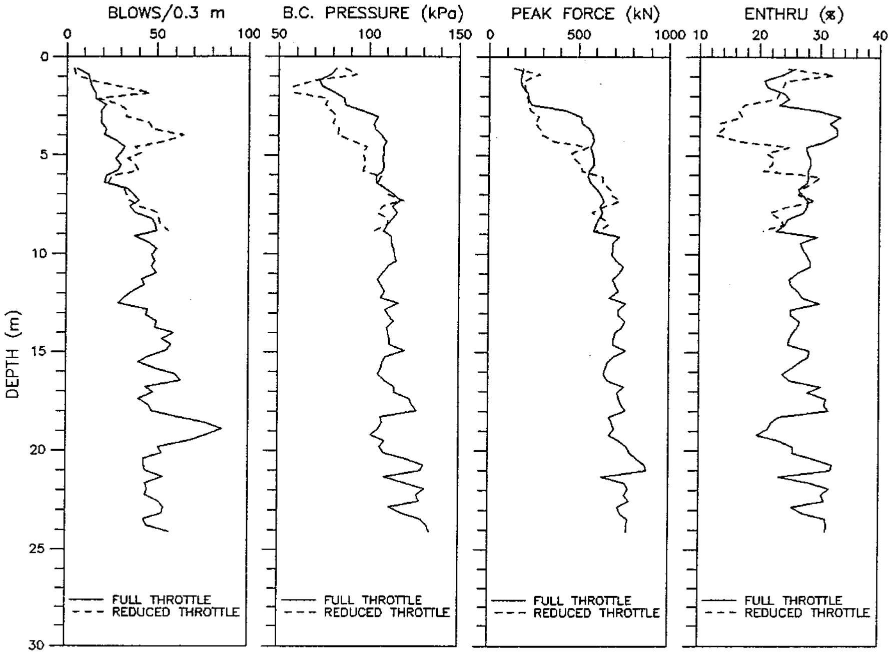

Fig. 5 Measured blow count, peak bounce chamber pressure, peak force and ENTHRU versus depth

than those for the full throttle condition.

For the full throttle condition shown in Fig. 5, 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 practically constant with depth. This observation is interesting, since it indicates that even though the hammer was apparently delivering more energy (i.e. higher bounce chamber pressure) with increasing depth or driving resistance, the maximum transferred energy to the top of the pipe remained 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. The constant ENTHRU of 27 % for this hammer is lower than the mean value observed for other double-acting diesel pile hammers as compiled in Rausche et al. (1985).

The ENTHRU and peak force from the PDA measurements at the top of the Becker pipe are plotted against peak hammer bounce chamber pressure in Fig. 6. These quantities are, again, averaged over 0.3 m depth interval. There is no reliable direct relationship between ENTHRU and bounce chamber pressure, but a relationship clearly exists between peak force and bounce chamber pressure. This is not surprising, since bounce chamber pressure is related to stroke, which controls impact velocity or pile top peak particle velocity, and from one-dimensional wave propagation theory, peak particle velocity is proportional to peak force at the top of a uniform pile. Consequently, peak bounce chamber pressure and peak force are both closely related to hammer performance, whereas ENTHRU depends on the interaction of the hammer/pipe/soil system during the stress wave propagation in the pipe. Bounce chamber pressure, therefore, can not be directly correlated to ENTHRU and it is the ENTHRU that is the important factor affecting the driving resistance or blow count of the Becker pipe.

6 IMPLICATIONS OF DYNAMIC MEASUREMENTS

As discussed earlier, bounce chamber pressure is often measured on double-acting diesel hammers to provide an estimate of the equivalent potential energy of the hammer for use in dynamic pile driving analysis. The field measurements shown in Fig. 5 for the full throttle BPT 3 indicate bounce chamber pressures reaching 120 kPa in hard driving with blow counts of about 50. For this bounce chamber pressure, Fig. 3 indicates an equivalent potential energy of 8.4 kJ, or 76 % of the manufacturer's rated energy for the hammer. The measured ENTHRU, however, is only 27 %. The equivalent total potential energy is almost three times higher than ENTHRU. This substantial energy difference is not only due to energy losses in the driving system (anvil, cushion and helmet) during impact, but suggests that the energy loss due to the "cushioning" effect of the compression of the air-fuel mixture in the combustion chamber and the combustion of the atomized fuel in the ICE 180 hammer is significant. The use of the estimated total potential energy in a pile driving formula to determine pile capacity will, therefore, be

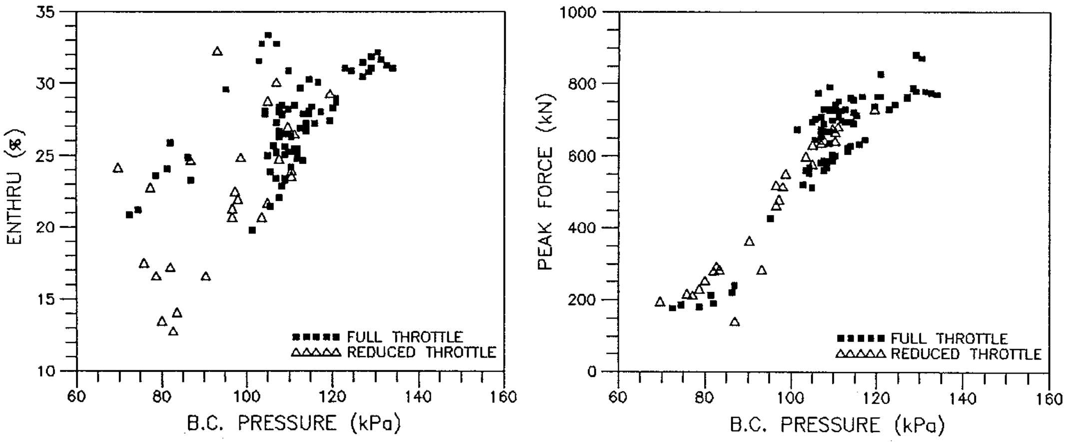

Fig. 6 ENTHRU and peak force versus bounce chamber pressure

misleading. The combustion effect in diesel hammers can be realistically modelled in a wave equation analysis of pile driving (Rempe and Davisson, 1977), but not in simple pile driving formulae.

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. To obtain reliable BPT-SPT correlations, it would seem logical to similarly correct the measured BPT blow counts to account for the variable energy output of the diesel hammer.

Fig. 7 compares the measured blow counts and the energy-corrected blow counts for BPT 3 (full throttle) and BPT 4 (reduced throttle). The energy-corrected blow counts are referenced to a common ENTHRU level of 30 % of the rated hammer energy, using:

$$N_{b30} = N_b \cdot \frac{ENTHRU}{30} \qquad (1)$$

where N_{b30} = blow count corrected to 30 % energy and N_b = measured blow count. As shown in Fig. 7, the two measured lines virtually collapse into one when the blow counts were corrected to one common ENTHRU level. The ENTHRU value can, therefore, be used to correct the measured BPT blow counts to allow meaningful correlations with corrected SPT N-values. The effect of shaft friction on the Becker pipe, however, should also be considered in the BPT-SPT correlations. This topic is currently being studied and will be the subject of subsequent publications.

7 CONCLUSIONS

Dynamic field measurements, which included bounce chamber pressure, and force and acceleration near the top of the pipe for every hammer blow, were conducted on two Becker penetration tests with different combustion conditions. The test data show that bounce chamber pressure can not be directly correlated to the maximum energy transferred to the drill pipe due to hammer impact, but that the bounce chamber pressure can be correlated to peak force. The data also suggest that hammer energy losses due to compression of the air-fuel mixture and combustion in the diesel hammer can be significant and should not be ignored in pile driving analysis. The pitfall of using bounce chamber pressure to estimate equivalent total potential energy, which neglects the effect of combustion, for use in dynamic pile driving formula is illustrated.

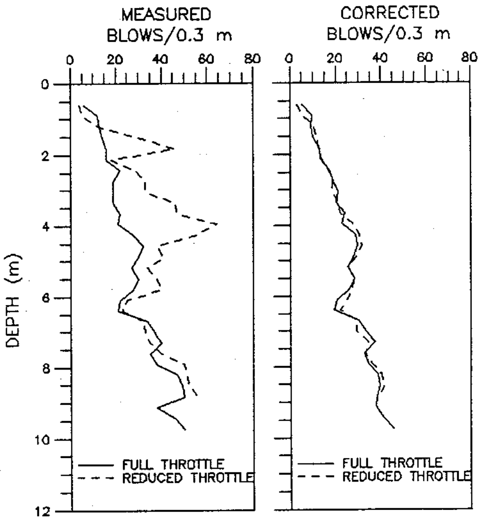

Fig. 7 Measured and energy-corrected blow counts versus depth

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