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Standard penetration test energy measurements using a system based on the personal computer:[1] Discussion

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Introduction

The authors described a standard penetration test (SPT) energy measurement system based on the personal computer (PC) and developed at the University of Alberta. The system consists of attaching a strain-gauged AW rod section to the top of the drill rods and measuring the force–time history during hammer impact. The energy entering the top of an ideal infinite rod (E_i) is then calculated from

$$[1] \quad E_i = \frac{cK_1K_2K_c}{EA} \int_0^{\Delta t} [F(t)]^2 \, dt$$

where c is the longitudinal wave speed in the rods; E is Young's modulus of the rods; A is the cross-sectional area of the rods; K_1 and K_2 are theoretical correction factors to account for the load cell position in the rods and the finite length of the drill rods, respectively; K_c is a wave speed correction factor, and $F(t)$ is the measured force–time history. The integration is carried out over the duration of the impact compression pulse, Δt, which is approximately $2L'/c$, where L' is the total length of the drill rods and sampler below the transducer location. This force integration method was proposed by Schmertmann and Palacios (1979) and has been adopted in the ASTM Standard D4633-86 (ASTM 1986) and in the International Reference Test procedure for SPT energy measurement (International Society of Soil Mechanics and Foundation Engineering (ISSMFE) 1988).

The main feature of the proposed SPT energy measurement system is the use of bonded strain gauges, which has several practical advantages. Strain gauges are relatively cheap compared with the piezoelectric load cell, and they do not introduce a change in cross-sectional area of the rod. The PC-based system also displays the force–time history in real time, which allows the operator to view the force wave trace for every blow. The authors show applications of the new system to three projects involving the SPT and one project involving the Becker hammer test (BHT; more commonly known as the Becker penetration test, BPT).

The energy results presented in the paper are interesting, but several conclusions drawn by the authors are not supported by considerations of wave mechanics principles. In addition, the application of the force integration method to the BHT is not appropriate. The authors' SPT and BHT energy data are explored in more detail in this discussion.

Extensive ongoing studies of the SPT and BPT have been conducted by the writers at the University of British Columbia (Sy and Campanella 1991*a*, 1991*b*, 1992*a*, 1992*b*). The research involved performing SPT, BPT, and other in situ tests in a controlled pattern at several sites in British Columbia. Dynamic measurements of the SPT and BPT were carried out to provide insights into the stress wave propagation in the tests. The measurements included force and acceleration near the top of the SPT drill rods and BPT drill pipes, impact velocity of the SPT hammer using radar technology, and bounce-chamber and combustion-chamber pressures in the double-acting diesel hammer during the BPT. Wave equation analyses were performed to explain and verify the trends in the field measurements of the SPT and BPT. Some results from the research studies are presented here to support the writers' comments.

This discussion focuses on three issues: (*i*) limitations of the force integration method for SPT energy calculation, (*ii*) SPT energy data presented in Figs. 8 and 9 of the paper, and (*iii*) BHT energy data presented in Fig. 10 of the paper.

Force integration method

There are several assumptions or limitations in the use of the force integration method for SPT energy determination that are often not stated but should be recognized. Equation 1 assumes that the energy transferred into the rods is contained only within the first compression pulse with a duration of approximately $2L'/c$. The $2L'/c$ is the time it takes for the impact compression wave to travel from the load cell near the top of the rods down to the sampler and return to the load cell location. Except for very dense soils (SPT blow count N-value > 50), the reflected return wave is in tension and causes the top of the rods to momentarily separate from the hammer. For relatively long rods, this assumption of energy cutoff at $2L'/c$ is not bad. For rod lengths less than about 15 m, however, wave equation analyses and field measurements by Morgano and Liang (1992) indicate that significant energy transfer can still occur beyond $2L'/c$, particularly in very soft soils. This energy transfer in short rod length is discussed further in the next section.

Equation [1] further requires determination of one cross-sectional area for the whole rod–sampler system below the anvil, which is difficult for a nonuniform system consisting of rods of variable cross-sectional areas or rods with enlarged ends or couplings. Perhaps more importantly in [1] is the inherent assumption that the force and particle

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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 with no external side resistances. Sy and Campanella (1991*b*) have shown that this assumption does not hold for a typical 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. Changes in rod cross sections cause wave reflections that violate the force–velocity proportionality assumption in [1].

An alternative and more fundamental approach of determining the SPT transferred energy is by measuring force and acceleration near the top of the drill rods (Sy and Campanella 1991*a*). In this approach, the transferred energy is calculated from

$$[2] \quad E_t(t) = \int F(t) \cdot V(t)\, \mathrm{d}t$$

where $E_t(t)$ is the energy transferred into the rods 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 [2] represents that part of the hammer energy available to do work in the drill rods and sampler. This force–velocity integration approach is routinely used in dynamic monitoring of pile driving, as recommended in ASTM D4945-89 (ASTM 1989), and it avoids the shortcomings in the existing force integration method of SPT energy measurement.

Despite its limitations, the force integration method is still sufficiently useful for most SPT applications where the drill rods do not contain significant cross-sectional area changes. In the three SPT projects illustrated in the paper, however, the authors used an instrumented AW rod on top of the drill rods of different cross-sectional areas. Such cross-section changes in a drill-rod string may invalidate the use of the force integration method.

SPT energy data

Figures 8 and 9 in the paper show SPT energy measurements for a "dunut" hammer and a safety hammer, respectively, both using rope and cathead technique at two sites in Vancouver, British Columbia. For the dunut hammer in Fig. 8, the calculated energy ratios (expressed as a percentage of the theoretical free-fall SPT hammer potential energy) increase initially with depth, reaching generally constant average values of 50–60% below 7 m depth. For the safety hammer in Fig. 9, the energy ratios in the upper 9 m again increase with increasing depth, reaching average values of 75–85% below 9 m. These energy data are interesting but they raise two obvious concerns: (*i*) the anomalously low energies at shallow depths; and (*ii*) the unusually high energy ratios for the quoted hammers compared with typical energy ratios compiled by Seed et al. (1985) and Skempton (1986) and presented in Table 1 of the paper, i.e., 45% for donut hammer and 55% for safety hammer.

With regards to the first concern, the energy ratios shown were calculated based on [1] and had, therefore, incorporated the short rod length correction factor, K_2. Despite the correction, the energy profiles still show a dramatic decrease in energy at depths less than 10 m. The authors then suggest that "the current correction factor K_2 cannot fully compensate for short rod lengths."

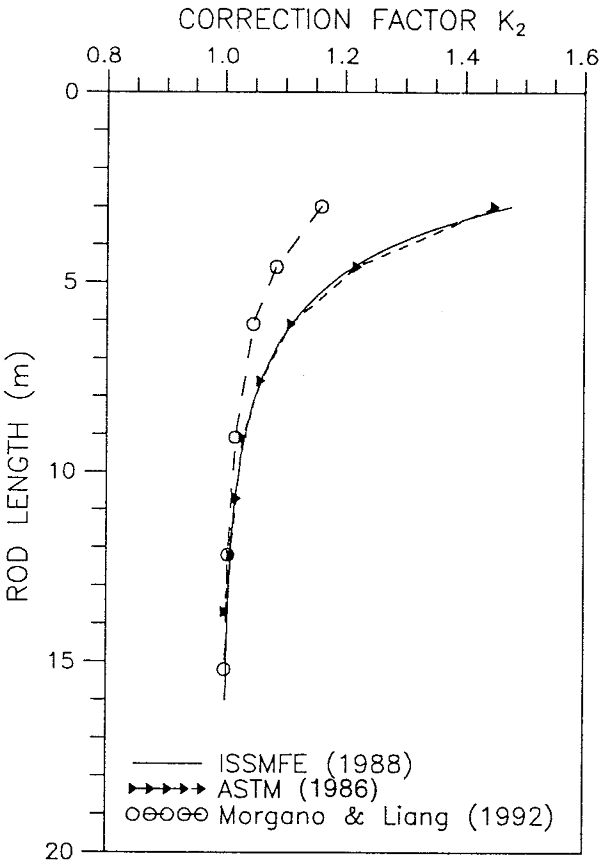

FIG. 1. Comparison of SPT energy correction factors, K_2, for effect of short rod length.

The theoretical short rod length correction factor, K_2, was introduced by Palacios (1977) to account for the fact that the tensile return wave at $2L'/c$ "prematurely" cuts off any further transfer of energy from hammer to rod, compared to an infinitely long rod. The correction factor, therefore, normalizes the measured energy to the ideal infinite rod condition and has values greater than or equal to unity. The values for K_2 recommended in ASTM D4633-86 (ASTM 1986) and in ISSMFE (1988) are based on the theoretical energy transfer derivations by Palacios (1977) and Yokel (1982), respectively. Both derivations are based on the force integration method of energy calculation and do not allow for further energy transfer from hammer to rods beyond $2L'/c$ (duration of the first compression pulse). To the writers' knowledge, no experimental data have been published to support these theoretical K_2 values.

Morgano and Liang (1992) recently examined the effect of rod length on the energy transfer in the SPT. They conducted wave equation analyses as well as field experiments for different SPT rod lengths. In their field testing, they measured force and acceleration near the top of the drill rods to determine the transferred energy using [2]. They also measured the hammer velocity just before impact with radar to calculate the hammer kinetic energy at impact. The measurement of the hammer impact velocity takes care of the inherently variable hammer drop height obtained with the rope and cathead technique used in the SPT. The ratio of the maximum transferred energy to the hammer kinetic energy is a measure of the energy-transfer efficiency of the system. Both their numerical and field studies show that

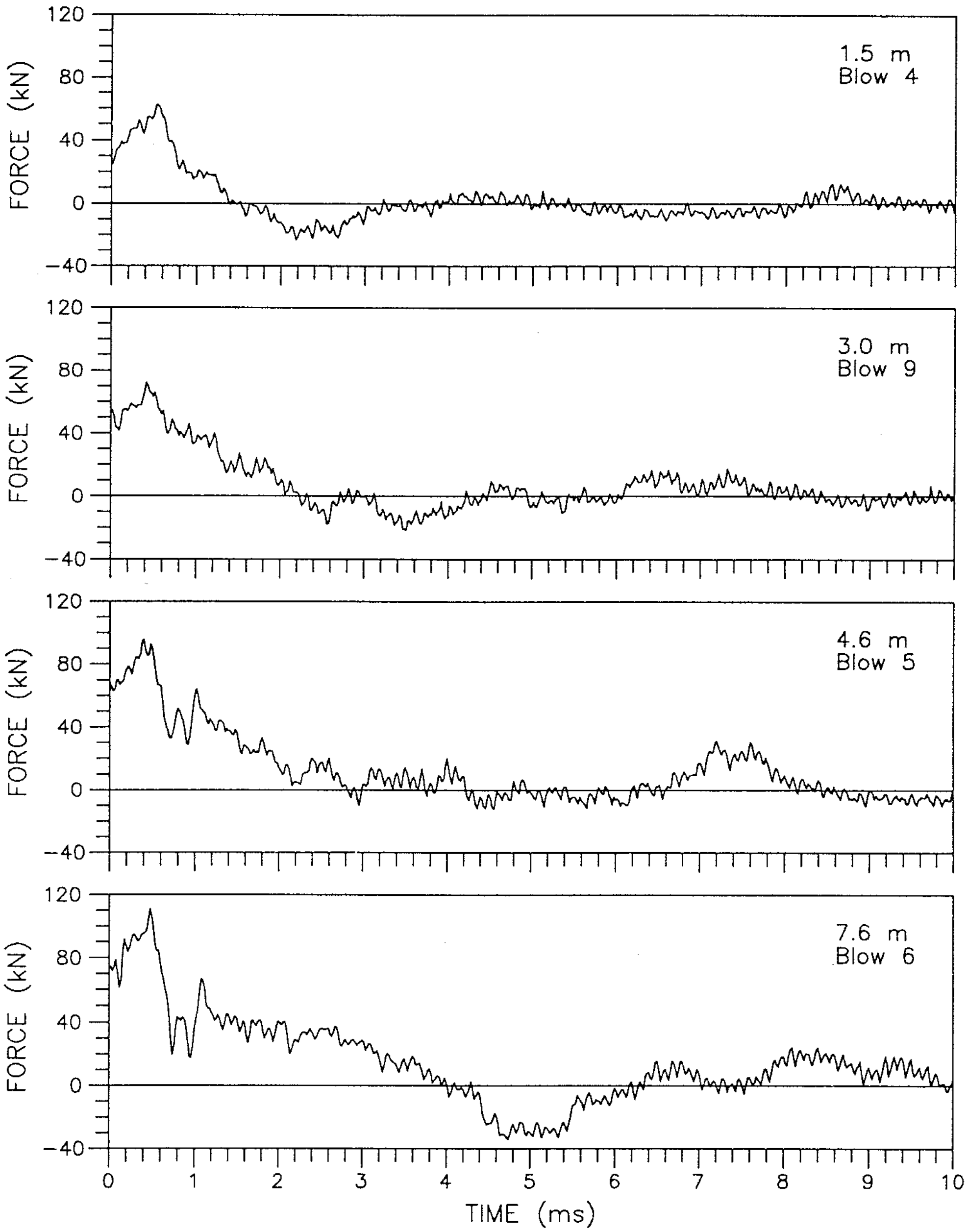

FIG. 2. Measured force–time signals for four representative SPT blows from a safety hammer.

for short rod lengths, significant energy can still be transfered to the rods beyond $2L'/c$ because of secondary or subsequent hammer impacts. Their studies confirm that transferred energy (or the energy-transfer efficiency) increases with increasing rod length, up to about 15 m, but it also depends on the soil resistance. Based on the field measurements at several sites, they propose an average transfer efficiency correction curve (i.e., a measure of K_2) for the effect of short rod length.

Figure 1 compares the theoretical K_2 correction factors from ASTM D4633-86 (ASTM 1986) and ISSMFE (1988) with those proposed by Morgano and Liang (1992) based on field measurements. As expected, the field-derived factors are less than the theoretical values mainly because of the additional energy transfer beyond $2L'/c$ in short rod lengths. Figure 1 shows clearly that the theoretical K_2 factors in ASTM D4633-86 (ASTM 1986) and ISSMFE (1988) are already "upper bound" values, yet they still cannot explain the anomalously low SPT energies at shallow depths in Figs. 8 and 9 of the paper.

The second author has kindly supplied the writers with the measured force–time data for the project illustrated in Fig. 8. Each time signal contains 1000 points at a sampling frequency of 50 kHz. The writers have independently processed the data. The data were, in fact, obtained for a safety hammer, not a donut hammer as indicated in the paper, and with the strain-gauged AW rod attached to BQ drill rods. The cross-sectional areas of the two rod sizes are not very different, being 710 mm^2 for AW rod and 760 mm^2 for BQ rod.

Figure 2 shows the measured force–time histories of four representative blows, one each from 1.5, 3.0, 4.6, and 7.6 m depths. The tensile wave reflection from the tip or sampler occurs at 1.5, 2.2, 2.8, and 4.0 ms, respectively. As expected, these tension reflection times increase with increasing drill-rod length. Note, however, that the peak force also increases

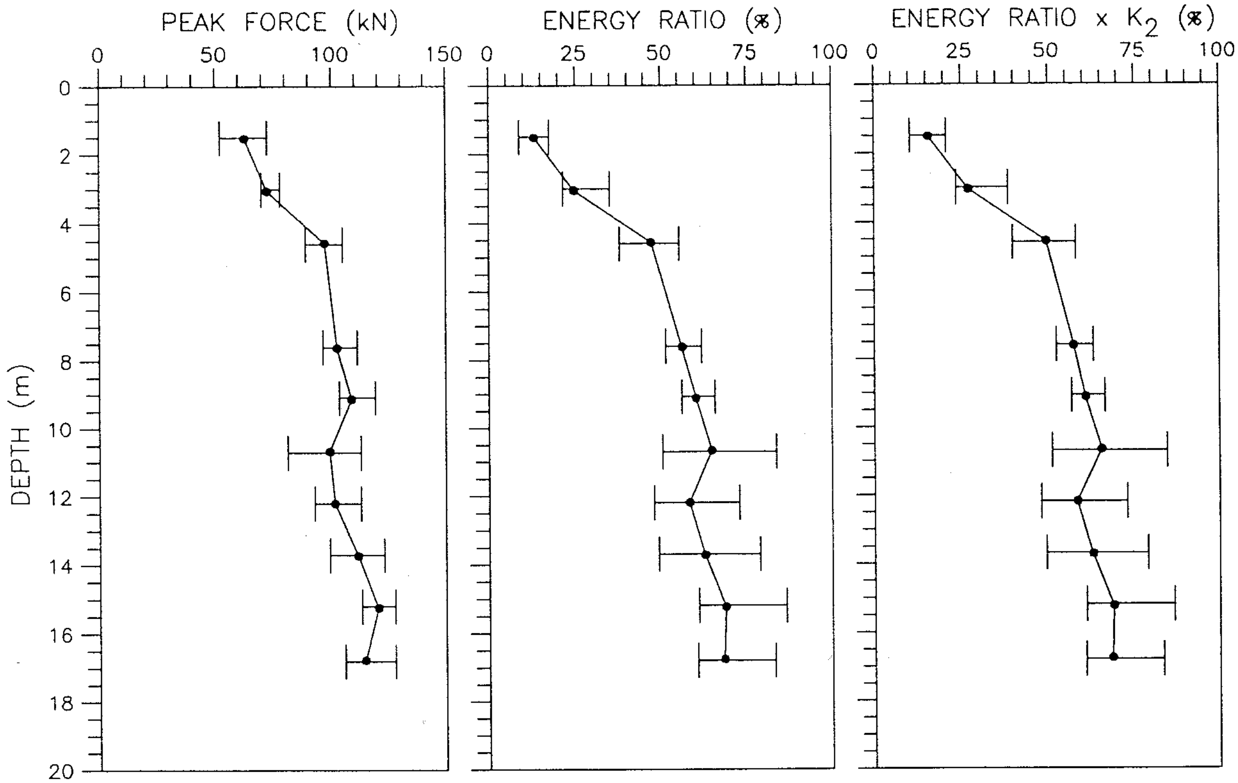

FIG. 3. Minimum–maximum range and average values of SPT peak force and energy ratios for a safety hammer.

with depth and has values of 63, 73, 96, and 111 kN, respectively. The rise time to peak force or impact is typically 0.5 ms. Because the rise time is much shorter than the tension reflection time, the peak force cannot be affected by the wave reflection from the sampler.

Figure 3 summarizes the measured peak force and the calculated energy ratios, with and without ASTM (1986) K_2 correction factor applied. The minimum–maximum range and the average values are shown. The calculated energies in Fig. 3 did not include the other two correction factors, K_1 and K_c, but their effects were negligible. Figure 3 also shows that the effect of K_2 is practically negligible. The results clearly show that the apparent low energies at depths less than 6 m are due to the anomalously low measured peak forces, and not short rod length effect as the authors suggested.

It is well known from wave-mechanics theory that for an impact wave travelling in one direction, the force (F) and particle velocity (V) at any point in a uniform rod are proportional (Timoshenko and Goodier 1970; Palacios 1977; Clayton 1990), i.e.,

$$[3] \quad F(t) = V(t)\cdot\frac{EA}{C}$$

in which the quantity EA/c is referred to as the impedance of the rod and is a material constant. Consequently, the peak force near the top of the SPT rods will be proportional to the peak particle velocity.

The peak particle velocity, on the other hand, is directly related to the hammer impact velocity (V_i) through

$$[4] \quad V = \frac{1}{1+\alpha}\cdot V_i$$

where α is the hammer to rod impedance or area ratio. Equation [4] is obtained by consideration of force equilibrium and velocity compatibility across the plane of contact when a cylindrical hammer strikes a bar of similar material (Fairhurst 1961).

Finally, from conservation of potential energy and kinetic energy during hammer fall, the impact velocity is related to the square root of the hammer stroke or drop height by

$$[5] \quad V_i = \sqrt{2gh\epsilon}$$

where g is the gravitational acceleration, h is the hammer drop height, and ϵ is an energy-loss factor during hammer fall. The above relationships, therefore, suggest that for a given SPT system, the peak force is proportional to the square root of the hammer drop height. If the drop height is constant (i.e., 0.76 m in the SPT), the peak force at the top of the drill rods will be constant, regardless of the length of the rods or soil conditions. Data from dynamic measurements of pile driving (e.g., Hussein et al. 1992) and SPT (e.g., Palacios 1977) have consistently confirmed the above theoretical concepts.

The above principles can be applied to the data in Fig. 3 to back-calculate the apparent stroke or hammer drop height. Assuming that an average peak force of about 105 kN corresponds to the standard drop height of 0.76 m and that the energy loss in the hammer is constant, the average measured peak force of 63 kN at 1.5 m depth would suggest an effective drop height of only 0.27 m, or 36% of the standard hammer drop height. Similarly, at 3.0 m depth, the average peak force of 72 kN would suggest a drop height of only 0.36 m, or 47% of the nominal SPT drop height. Even allowing for the fact that the hammer drop heights by rope and cathead technique are quite variable, such apparent hammer drop heights are unrealistically low and improbable. The writers, therefore, conclude that the anomalously low measured peak forces and, hence, low transferred energies at shallow depths are likely due to instrumentation or data-

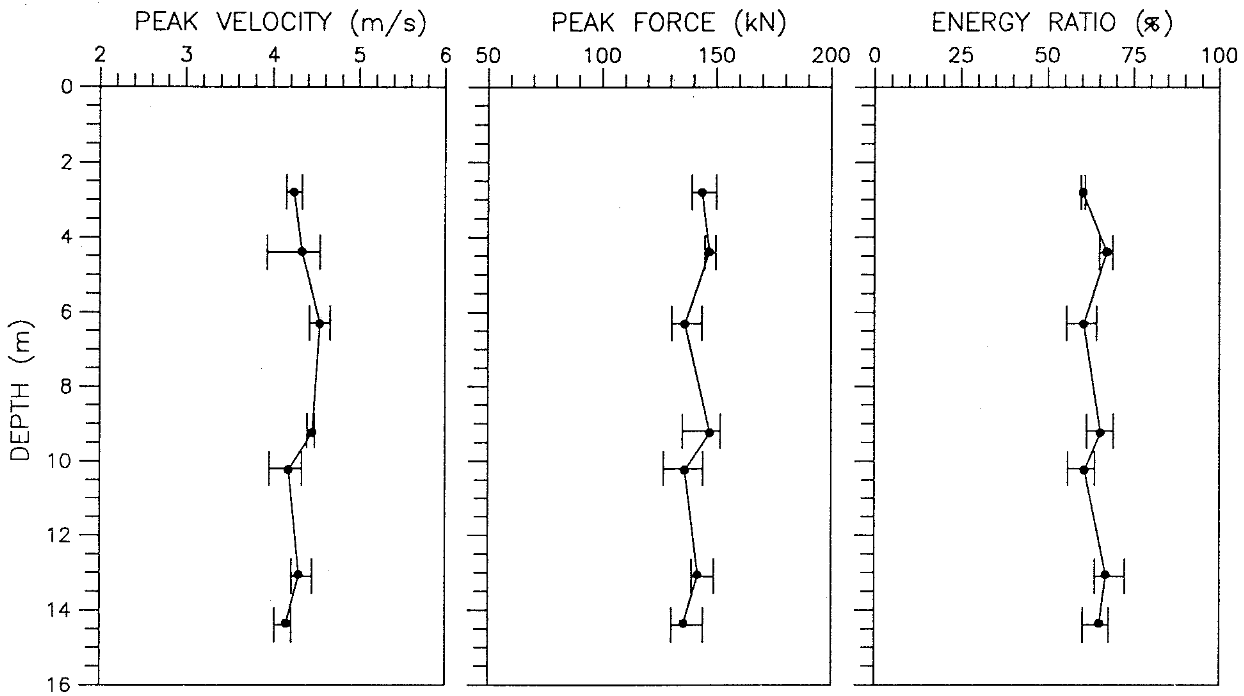

FIG. 4. Minimum–maximum range and average values of SPT peak velocity, peak force, and energy ratio for an automatic trip hammer, Delta, British Columbia.

acquisition problems or some peculiar arrangement of the instrumented rod. This conclusion is further supported by the writers' own data from another site as discussed below.

Figure 4 shows results of SPT energy measurements conducted by the writers at a research site approximately 3 km from the site illustrated in Fig. 3 above (or Fig. 8 of the paper). Both sites have similar soil conditions, being within the Fraser River delta region. For the test data in Fig. 4, an automatic SPT trip hammer was used with AW drill rods. The instrumentation consisted of a piezoelectric load cell coupled with an accelerometer placed 0.6 m below the top of the drill rods, as described in Sy and Campanella (1991*b*). The minimum–maximum range, as well as the average values, of peak velocity, peak force, and transferred energy ratio are presented. The energy ratios were calculated by the force integration method, i.e., [1], but without the three *K*-correction factors. The measured peak force data show a generally consistent average value of 140 kN, regardless of the SPT depth or rod length. The data also show good proportionality between peak force and peak velocity, which provides a check on the reliability of the measured data. The calculated average energy ratio is about 65%, again independent of depth or rod length.

The above paragraphs illustrate the importance of reviewing the force–time histories and examining the peak forces in the SPT. The consistency of peak force, regardless of depth or SPT *N*-value, will provide a check on the quality of the measured force data. Even if the force data are measured correctly, the reliability of the calculated energy by the force integration method will still depend on the validity of the assumptions inherent in the approach.

The second concern raised earlier with regards to the data in Figs. 8 and 9 is the unusually high calculated energy ratios compared with published values in the literature for the same types of hammers. As mentioned above, the SPT hammer used for the project in Fig. 8 is actually a safety hammer with BQ rods, and not a donut hammer as reported in the paper. Consequently, the average energy ratios of 50–60% at depth in Fig. 8 are not unusual for this type of hammer. The hammer used for the project in Fig. 9 is apparently another safety hammer but with BW rods. The average energy ratios of 75–85% in Fig. 9, however, are surprisingly high. The authors did not offer a clear explanation for the high calculated energies other than that the BW rods are heavier (implying larger cross-sectional area) than the more commonly used AW rods. One possible reason for the unusually high energy ratios is discussed below.

Wave-mechanics principles indicate that when an incident wave approaches an interface between the two different cross-sectional areas in a rod, part of the wave is reflected back in the first section and part of it is transmitted to the second section (Palacios 1977). The theory suggests that attaching an instrumented rod to a drill rod with larger cross-sectional area causes compressive-wave reflections at the interface, resulting in increased force and decreased particle velocity in the instrumented rod section. It is possible, then, that the apparently high transferred energy of the safety hammer in Fig. 9 is due to this increased force caused by wave reflections. Such changes in rod areas cause wave reflections that may invalidate the energy calculated by the force integration method. The loss of force–velocity proportionality and its effect on energy calculated by the force integration method can be readily confirmed by wave equation analysis.

BHT energy data

The authors also used the PC-based SPT energy measurement system to monitor the Becker hammer test (BHT) or penetration test (BPT). In the BPT, a double-acting diesel pile hammer is used to drive a specially designed, close-ended, double-walled casing or pipe into the ground. The authors strain gauged a short pipe section that was placed on

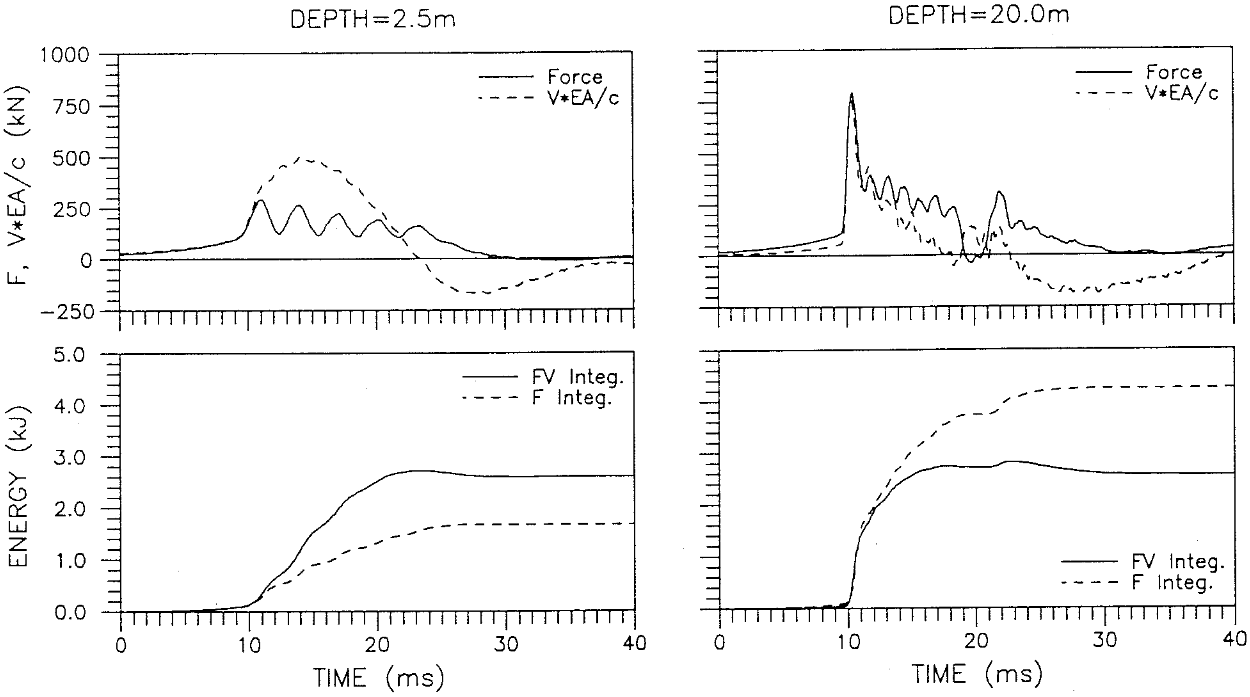

FIG. 5. BPT wave traces and transferred energies at 2.5 and 20.0 m from a site in Richmond, British Columbia. F Iteg., force integration method; FV Iteg., force–velocity integration method.

top of the Becker pipes during testing. In addition, conventional force and acceleration transducers used in dynamic pile testing were also attached to the strain-gauged pipe section and monitored using a pile driving analyzer (Goble et al. 1980). Transferred energies were calculated from both systems: the strain-gauged system being based on the SPT force integration method or [1], and pile driving analyzer (PDA) system based on the force–velocity integration method in [2]. The authors compared the calculated energy ratios (expressed as a percentage of the manufacturer's rated energy of 11.0 kJ for the diesel hammer) for both systems in their Fig. 10. Although limited data are presented in the figure, there are two obvious trends. The average energy ratios from the PDA system are somewhat constant at about 40%, whereas those from the PC-based strain-gauged system generally increase with depth. At shallow depths, the PC-based system gives lower energy ratios than the PDA system, whereas at depth the reverse trend is observed. The authors, however, conclude that "both systems appear to have recorded similar energy values" and further suggest that "the basic SPT energy measurement system can also measure the energy during a Becker hammer test."

The authors' use of the force integration method with the PC-based SPT system to determine the transferred energy in the BPT violates wave-propagation fundamentals. In the BPT, just like in pile driving, soil resistances act along the pipe shaft and toe. The soil resistances, similar to changes in cross-sectional areas along the pipe, cause wave reflections that affect the measured force and velocity at the top of the pipe. Consequently, the force–velocity proportionality, i.e., [3], does not hold and the force integration method becomes invalid. This conclusion is further supported by the writers' data as discussed below.

Figure 5 shows dynamic measurements of two typical BPT blows: one at 2.5 m depth in soft driving, and one at 20.0 m depth in harder driving at a site in Richmond, British Columbia. Both force and acceleration were measured near the top of the Becker pipe using a PDA. Details of the site and dynamic measurements can be found in Sy and Campanella (1992*a*). The top plot for each blow shows the measured force trace and the velocity normalized by the impedance of the 170-mm o.d. Becker pipe, $EA/c = 313.4\ \text{kN}\cdot(\text{m/s})^{-1}$. The bottom plot shows the calculated transferred energy by the force–velocity integration method. For comparison purposes, the calculated "energy" by the force integration method is also shown.

For the BPT blow at 2.5 m, the energy by the force integration method is significantly lower that the true transferred energy obtained by the force–velocity integration method. Note that the maximum energy transferred to the pipe occurs at 23.4 ms, after the impact wave has propagated down and up the pipe for many cycles, as shown in the force trace in the upper plot. The theoretical $2L'/c$ for this pipe length is only 1.4 ms. Another difficulty in using the force integration method here is the selection of the limit of integration, since there is no obvious tension cutoff point in the force trace. Indeed, the characteristic behaviour of diesel hammers renders the tension cutoff approach unworkable.

For the BPT blow at 20.0 m, the separation of the force and velocity in the upper plot is a measure of the dynamic shaft resistance acting on the pipe. Due to soil resistance, the measured force near the top of the pipe increases while the velocity decreases. As a result, the energy calculated by the force integration method is significantly higher than the true energy transferred into the pipe. In this case, the maximum transferred energy occurs at 22.8 ms, and the theoretical $2L'/c$ for this pipe length is 8.5 ms.

The examples in Fig. 5 illustrate why the authors' "energies" from the PC-based SPT system are too low at shallow depths and too high at greater depths where significant shaft resistances are acting. Both wave-mechanics theory and stress-wave data clearly show that force measurement alone is not sufficient to determine the transferred energy. Both force and velocity are required for energy measurement of the BPT, similar to pile driving.

Summary and conclusions

The proposed PC-based system using a short strain-gauged rod section is a practical and useful approach for SPT energy measurement in accordance with ASTM D4633-86 (ASTM 1986) and ISSMFE (1988) test procedures. The limitations and assumptions of the existing force integration approach, however, should be recognized. The force integration method gives approximate energy values provided the drill rods do not contain significant cross-sectional area changes. It is recommended that the instrumented rod be exactly the same size as the rest of the drill rods to avoid wave reflections that may invalidate the force integration method.

The writers agree with the authors that SPT energy measurement must depart for the "black-box" approach. The measured force traces should be examined in the field by an operator with some background in basic wave mechanics. It is recommended that the peak forces be reported with the calculated energy values. The consistency of the measured peak force should be checked. Unusual values of peak force may indicate unreliable force measurement or unusual hammer behaviour.

The force integration method cannot be used to determine the energy transfer in the Becker hammer or penetration test. Both force and velocity are needed for a rational determination of the transferred energy in the BPT.

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Standard penetration test energy measurements using a system based on the personal computer:[1] Reply

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The authors appreciate the thoughtful and detailed discussion provided by Sy and Campanella. As the discussers have concluded, the PC-based system is practical and useful and is in accordance with the ASTM (1991) and ISSMFE (1988) test procedures. The limitations and assumptions of the existing force integration approach are recognized and well described by the writers and others. The authors agree that the force integration method provides an approximate measure of the actual standard penetration test (SPT) energy and that the peak force should be monitored and reviewed to aid in interpretation. The PC-based system allows the user to monitor the peak force and the complete force time record. The peak force values are printed for each SPT blow count. The discussers' detailed processing of the authors measured data, shown in Fig. 2 illustrates the significant amount and accuracy of the data obtained using PC-based system.

The authors agree that the force–velocity method is generally more reliable than the force integration method. However, experience with the SPT using both methods suggests that the force–velocity method is generally within 10% of the energy calculated using the more complicated force–velocity method. This was confirmed by data presented by the discussers (Sy and Campanella 1991).

The PC-based system is also capable of performing the more complicated force–velocity method. However, the procedure is more complicated and requires consistent measurement of velocity, which is usually accomplished using miniature accelerometers. Experience and research by the authors and others has shown that it is difficult to obtain, install, and maintain accelerometers that can withstand the very high accelerations experienced during an SPT. Also, the cost of the equipment, its maintenance, and the time for interpretation is considerably increased when using accelerometers and the force–velocity method. Experience has also shown that engineers are generally reluctant to pay the additional cost associated with the added sophistication of the force–velocity method, especially considering the many other limitations of the SPT. Engineers have also been very reluctant to perform complete wave equation analyses on every blow of an SPT or Becker Penetration Test (BPT) to understand the details of the wave mechanics. Generally, engineers are interested only in the average SPT energy to aid in the correction process. The PC-based system significantly aids in this process and is more reliable than the global correction factors suggested by Skempton (1986) and Seed et al. (1985).

Since the preparation of the original paper (June 1991), the PC-based system has been improved to incorporate many of the topics covered by the writers.

The authors have considerable experience performing SPT energy measurements and are convinced that the geotechnical profession should move away from using such a complex, dynamic test with all its many limitations. The BPT is more complex because of the soil resistance along the shaft of the pipe during driving. Any engineer or researcher that has made measurements of the energy delivered during the SPT or BPT will appreciate the level of complexity associated with such dynamic testing and would therefore recognize and appreciate the extreme limitations of such tests. The discussion should assist in this appreciation.

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Standard penetration test energy measurements using a system based on the personal computer

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According to the International Reference Test procedure for the standard penetration test (SPT), in situations where comparisons of SPT results are important, calibrations should be made to evaluate the efficiency of the equipment in terms of energy transfer. However, equipment to measure the energy transfer of the hammer anvil system is not commonly available. Ten years ago a system was developed and made commercially available. However, this system is no longer available. An SPT energy calibration system is described that has been developed based on a microcomputer. The load cell to measure the compressive stress wave beneath the SPT anvil consists of a 0.5-m length of strain-gauged AW rod. Specialized software has been developed to record the force–time record for each hammer blow on a portable microcomputer. Examples of energy measurements are presented and discussed.

Key words: standard penetration test, *in situ*, microcomputer, energy.

Selon la procédure d'évaluation de la référence internationale pour les essais normalisés de pénétration (SPT), dans les situations où des comparaisons des résultats du SPT sont importantes, des étalonnages devront être réalisés pour évaluer l'efficacité de l'équipement en terme de transfert d'énergie. Cependant, l'équipement pour mesurer le transfert d'énergie du système marteau enclume n'est pas couramment disponible. Il y a dix ans, un système a été développé et rendu disponible commercialement. Cependant, il ne l'est plus. L'on décrit un système d'étalonnage de l'énergie du SPT qui a été développé avec un micro-ordinateur comme base. La cellule de charge pour mesurer l'onde de compression sous l'enclume du SPT consiste en une longueur de 0.5 m de tige AW munie de jauges de déformation. Un programme spécial a été développé pour enregistrer sur un micro-ordinateur portatif les données force–temps pour chaque coup de marteau. Des exemples de mesures d'énergie sont présentés et discutés.

Mots clés : essai normalisé de pénétration, *in situ*, micro-ordinateur, énergie.

[Traduit par la rédaction]

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Introduction

The standard penetration test (SPT) was developed in the United States in 1927 and is used worldwide to a greater extent than any other *in situ* test. The SPT has several significant advantages: (*i*) the equipment is relatively simple and rugged, (*ii*) the procedure is easy to carry out and permits frequent tests, (*iii*) a sample of the soil is usually obtained, (*iv*) tests can be carried out in most soil types, and (*v*) many useful correlations have been developed. No other *in situ* test combines this range of flexibility.

The test is made by dropping a free-falling hammer weighing 63.5 kg (140 lb) onto the drill rods from a height of 760 mm (30 in.). The number of blows (*N*) necessary to achieve a penetration of 300 mm (below a seating drive of 150 mm) of a standard sample tube is termed the penetration resistance or *N*-value.

Details of the SPT procedure and sampler are given by ASTM (1991*a*). Many countries have similar standards. An International Reference Test procedure is also available that is similar to the ASTM standard (ISSMFE 1988).

Figure 1 shows a sketch of the basic SPT setup using a "cathead" and rope system along with a donut hammer. To raise the hammer, the operator pulls the rope in towards himself until the hammer is lifted to the prescribed fall height. To drop the weight, the operator rapidly slackens the rope on the cathead. It is usual to have two turns of the rope on the cathead for lifting the hammer, although sometimes three turns and rarely one turn have been used. The operator has the responsibility to ensure a 760-mm fall usually with the aid of a mark on the guide rod.

Unfortunately, there is a wide variability in equipment and test procedures encountered in practice throughout the world. Considerable research on individual aspects of the equipment and procedures has been carried out in North America and Japan in an effort to better understand the factors affecting the test (Schmertmann 1979; Kovacs and Salomone 1982; Yoshimi and Tokimatsu 1983).

To obtain reliable results the International Reference Test procedure (ISSMFE 1988) recommends that the SPT should be carried out under the following conditions: (*i*) the use of wash boring with a side-discharge bit or rotary drilling with a tricone drill bit and mud flush, (*ii*) the use of casing and (or) drilling mud to support the borehole, (*iii*) drilling mud to be maintained up to groundwater level, (*iv*) borehole diameter between 63.5 and 150 mm and preferably not more than 115 mm, and (*v*) blow count (*N*-value) recorded between 150 mm (6 in.) and 450 mm (18 in.) penetration, with the first 150 mm (6 in.) regarded as a seating drive.

Even with good site control the method of hammer release and type of anvil play a major role in the reliability of the results. Several hammer types and release systems exist. In general the three main hammer types are donut, safety, and trip hammers (ISSMFE 1988).

The four main methods of lifting and releasing the hammer are as follows: (*i*) manual lifting and release of the rope passing over the crown sheave (i.e., no winch cathead);

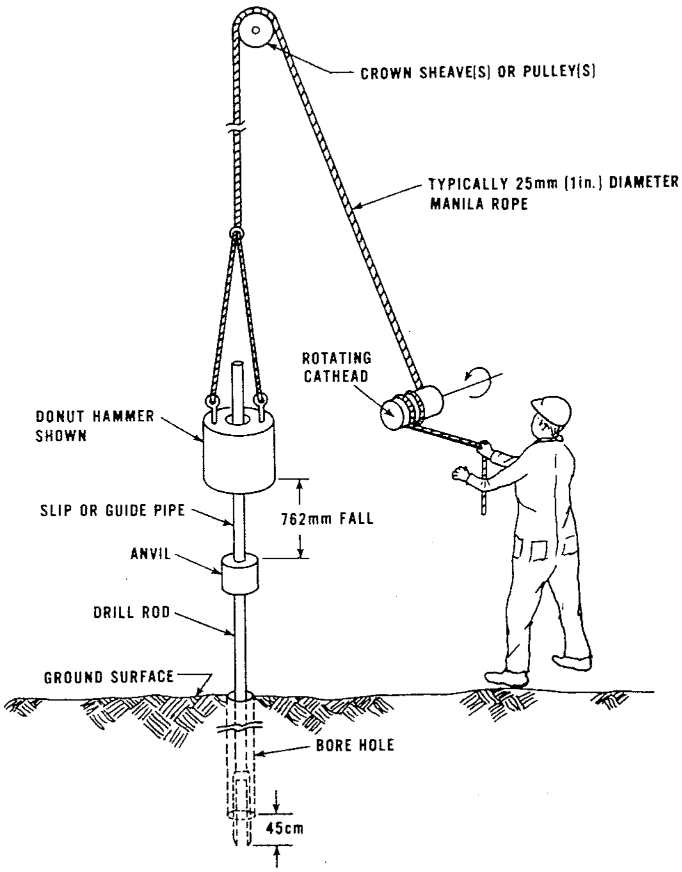

FIG. 1. Sketch showing typical SPT procedure using manual release and donut hammer (adapted from Kovacs and Salomone 1982). Crown sheave(s) and cathead can be either drill-rig or tripod mounted.

(*ii*) "slip-rope" or "rope and cathead" method (as shown in Fig. 1); (*iii*) trip hammer, such as the Pilcon or Dando hammers; and (*iv*) automatic trigger mechanism, such as the Central Mining Equipment (CME) automatic hammer and the Japanese "Tombi" system.

Many tests worldwide are still made using the rope and cathead release with generally two turns of the rope and visual control of the drop height.

In any *in situ* test procedure it is very important to have the ability to reproduce results. In the case of the SPT, the ability to obtain reproduceable and reliable results depends on the equipment, procedures, and operator characteristics. The most significant factor affecting the measured N-value is the amount of energy delivered to the drill rods from the hammer and anvil system.

Attempts to physically measure SPT hammer anvil energies began in the early 1970s (ISSMFE 1988). Studies on hammer fall velocity during the SPT were performed by Kovacs *et al.* (1975). Palacios (1977) developed a method of measuring stress-wave energy in drill rods immediately below the anvil. Results showed that the majority of energy for sample penetration was delivered in the first energy pulse down the rods. Force–time histories of stress waves were first measured at locations just below the anvil and just above the sampler. After confirmation by theoretical studies, the method was simplified to measure the energy content in the first compression wave measured just below the anvil. Based on the work by Palacios (1977) a commercial SPT energy-measurement system was first introduced in the early 1980s (Hall 1982). The system consists of a piezoelectric load cell attached near the top of the drill rods and a data-processing instrument that calculates the energy at the load-cell location. The energy for each hammer blow is read directly from the instrument as a percentage of the theoretical free-fall hammer energy of 475 J (4200 in·lb) in terms of a rod energy ratio ($\mathrm{ER_i}$). The methodology developed by Palacios (1977) and incorporated into the commercial system by Hall (1982) has been successfully applied for many years. However, several disadvantages with the system have been observed. (*i*) The connectors to the load cell were easily damaged and required frequent repair. (*ii*) The piezoelectric load cell required special dynamic calibration procedures. (*iii*) The integration times and the nature of the force–time histories of the stress waves were not easily verified without the aid of an ocsilloscope.

The commercial system (Hall 1982) has often been regarded as a "black-box" system that allowed little flexibility for verifying the results. Surprisingly very few of the SPT energy-measuring systems were sold and used in practice. This may be a reflection of the black-box nature of the device.

Energy measurements in the last decade have shown that the energy delivered to the rods during an SPT can vary from about 30 to 90% (Kovacs and Salomone 1982; Robertson *et al.* 1983). The energy delivered to the drill stem varies with the releasing-system, hammer, anvil, and operator characteristics. The type of hammer and anvil appears to influence the energy-transfer mechanism.

Palacios (1977) has shown that the SPT blow count is approximately inversely proportioned to the delivered energy. Kovacs *et al.* (1984), Seed *et al.* (1985), and Robertson *et al.* (1983) have suggested that an energy level of 60% appears to represent a reasonable historical average for most SPT-based empirical correlations. Seed *et al.* (1985) clearly suggested that for liquifaction analyses the SPT N-values must be corrected to an energy level of 60%.

N-values measured with a known or estimated $\mathrm{ER_i}$ value can be normalized to an energy level of 60% by the conversion

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

Based on data summarized by Skempton (1986) and Seed *et al.* (1985), recommended generalized energy ratios and conversion for SPT practice are given in Table 1. These values represent broad global corrections and should be used with caution.

Further adjustments are also needed for the effects of rod length, sampler type, and borehole diameter. Wave-equation studies (Schmertmann and Palacios 1979) show that the theoretical maximum energy ratio decreases with decreasing rod length. This decrease in measured energy is due in part to the rapid return of the tension wave before all the hammer energy can be transferred to the drill rods. Studies by Schmertmann (1979) also found that removing the liners from a SPT sampler designed for liners improved sample recovery but reduced the measured blow count by about 20%. Therefore, if the SPT sampler has no liners the N-value should be increased by a factor of about 1.2.

Although good modern practice has the SPT performed

TABLE 1. Generalized SPT energy ratios

Location	Hammer	Release[a]	ER_i (%)	$ER_i/60$
North and South America	Donut, safety	2TR	45	0.75
	Automatic	2TR	55	0.92
		Trip	55–83	0.92–1.38
Japan	Donut	2TR	65	1.08
	Donut	Auto-trigger	78	1.30
China	Donut	2TR	50	0.83
	Automatic	Trip	60	1
United Kingdom	Safety	2TR	50	0.83
	Automatic	Trip	60	1
Italy	Donut	Trip	65	1.08

NOTE: Based on Seed *et al.* (1985) and Skempton (1986).
[a] 2TR, two turns on rope.

TABLE 2. Approximate corrections to measured SPT *N*-values (after Skempton 1986)

Rod length	
≥10 m	1.0
6–10 m	0.95
4–6 m	0.85
3–4 m	0.70
Standard sampler	1.0
U.S. sampler without liners	1.2
Borehole diameter	
65–115 mm	1.0
150 mm	1.05
200 mm	1.15

in a borehole with a diameter between 65 and 115 mm, many countries allow testing in boreholes of up to 200 mm. The effect of testing within relatively large diameter boreholes can be significant in sands and probably negligible in clays. Approximate correction factors for rod length, sample liners, and borehole diameter are given in Table 2.

The actual energy level at which different systems (hammer, anvil, release rods, sampler, drillhole, operator) are made to operate is very important. Of equal importance is the need for the variation in energy levels using the individual system to remain consistent. Table 1 provides only a guide to anticipated average energy levels. In situations where comparisons of SPT results are important or where project requirements merit, energy measurements should be made.

In recent years other systems based on the same basic principle have been developed to measure SPT energy (Clayton 1990; Sy and Campanella 1991*a*, 1991*b*). This paper describes a new system that was developed at the University of Alberta in early 1990. The system is based on the same basic principles used by Palaçios (1977) but utilizes recent advances in microelectronics and computing.

Energy measurements

The recommended method for SPT energy measurement is specified in ASTM (1991*b*) and ISSMFE (1988) and is based on the force-measurement concept developed by Palacios (1977). The method consists of attaching a load cell near the top of the drill rods and below the anvil and measuring the force–time history of the stress wave during hammer impact. The basic principle of the stress-wave force integration method is shown in Fig. 2. An idealized force–time wave form recorded by a load cell in the drill rods is shown in Fig. 3. The stress-wave force integration method to determine the energy uses the following formula:

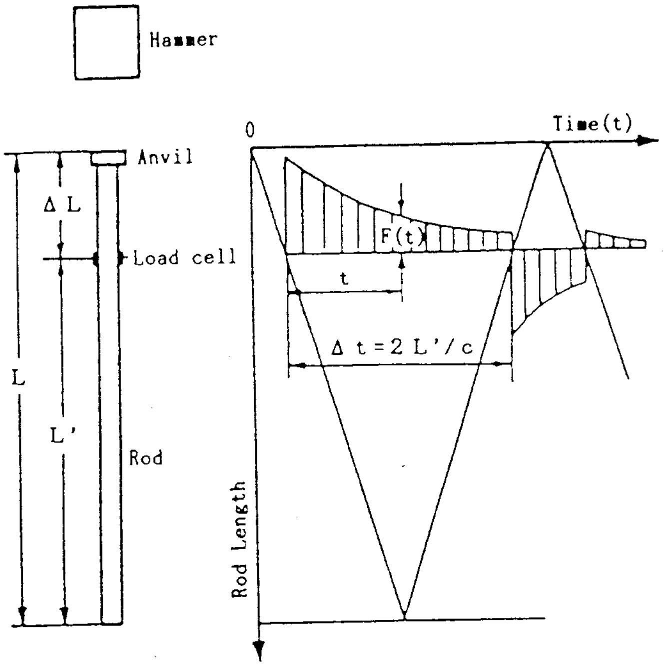

FIG. 2. Principle of SPT energy measurement (after ISSMFE 1988).

$$[2] \quad E_i = \frac{cK_1K_2K_c}{AE}\int_0^{\Delta t} [F(t)]^2 \, dt$$

where $F(t)$ is dynamic compressive force in the drill rods as a function of time t, E_i is energy content in the first compression wave for the ideal case, Δt is time duration of the first compressive wave starting at $t = 0$, A is cross-sectional area of the connector rods above and below the load cell, E is Young's modulus of the connector rods, and c is theoretical velocity of compression wave in connector rods (usually $c = 5120$ m/s). K_1 and K_2 are correction factors to account for the load-cell position in the rods and the finite length of the drill rods, respectively. The K_c correction is

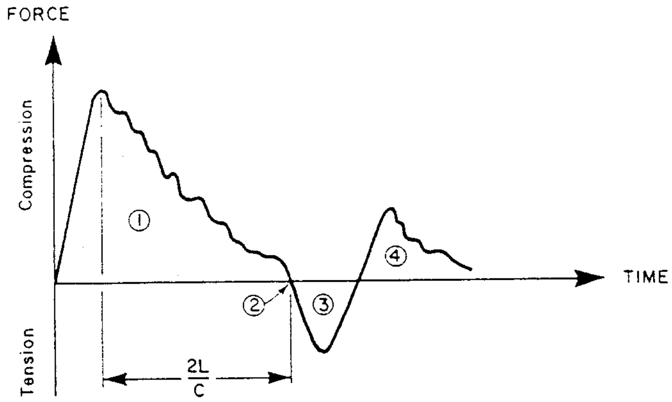

FIG. 3. Idealized force–time SPT wave form (modified from ASTM 1991*b*). 1, first compression pulse or wave; 2, cutoff time at the arrival of the first tension pulse; 3, first tension pulse reflected from the sampler; 4, second compression pulse reflected from the anvil.

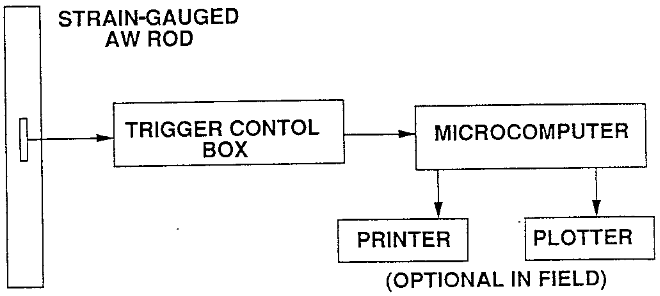

FIG. 4. PC-based SPT energy-measurement system.

based on the assumption that the total duration of the first compression pulse from $t = 0$ is the round-trip time for the stress wave to travel from the load cell near the top of the drill rods to the sampler bottom and return to the load-cell location. Hence

$$[3] \quad \Delta t = \frac{2L'}{cK_c}$$

where L' is the length of rod between the load cell and the bottom of the SPT sampler.

Sy and Campanella (1991*b*) have suggested that the theoretical $2L'/c$ corresponds to the time interval between the peak force and the tension cutoff point (as shown in Fig. 3), not from the start of the force trace ($t = 0$) to the cutoff point. Ideally, the rise time for the first compression pulse should be infinitely small (see Fig. 2), and the time difference between the start point and the peak force would be very small. Hence, the K_c correction should be unnecessary.

Based on dynamic monitoring of piles during driving (ASTM 1991*c*), Sy and Campanella (1991*a*) suggested the use of the force–velocity integration method. This method avoids the need to determine the integration time (Δt) and select an appropriate cross-sectional area of the drill rods (A). However, the force–velocity integration method does require the additional measurement of particle velocity (V), usually from the integration of acceleration using accelerometers. The accurate measurement of velocity using accelerometers is extremely difficult due to problems in electrical drift and response time (Poskitt and Wong 1991). The measurements presented by Sy and Campanella (1991*a*) showed that the energy determined from the force–velocity integration method was generally within 5–15% of that determined from the force integration method using [2]. Hence, considering the potential wide variation of energy per blow it would appear that the simpler force integration method specified in ASTM (1991*b*) and ISSMFE (1988) is sufficiently accurate.

New PC-based SPT energy-measurement system

In early 1990 a PC-based SPT energy-measurement system was developed at the University of Alberta to measure SPT energies for a tailings-dam project in China. The system is based on the force integration method but is also capable of performing the force–velocity integration method. A schematic layout of the SPT energy-measurement system is shown in Fig. 4.

The force in the drill rods is measured using a strain-gauged 0.5-m-long section of drill rod (typically AW size). The early work by Palacios (1977) and recently confirmed by Clayton (1990) showed that the force during the first compression wave could be accurately measured using a strain gauge load cell rather than a more expensive piezoelectric load cell. The strain-gauged drill rod has the advantage of being inexpensive, equal in cross-sectional area to the drill rods (typically AW), and simple to statically calibrate. A total of eight strain gauges are placed around the circumference of the drill rod to average the measured force.

The rod load cell is connected to a portable field microcomputer via a small custom-made trigger control box. The trigger control box provides two functions: (*i*) selection of force level to trigger the data-acquisition system, and (*ii*) balance the zero load output of the load cell before each SPT blow count series.

The field microcomputer contains a fast analog to digital (A/D) board to digitize the force measurement as a function of time. Optional printer or plotter can be connected to the microcomputer to obtain hard copies of the data. The data is stored in memory and backed up on disk.

Initially, basic software was developed to record the force–time record $F(t)$. Subsequently, specialized software and signal-conditioning functions were developed by Adara Systems Ltd. to record $F(t)$ as well as the integration time for the first compressive wave (Δt) and to calculate directly the energy (E_i) and rod energy ratio (ER_i) for each SPT hammer blow. The software also records the number of blows and calculates the average ER_i for the SPT. The system allows the operator to select a range of acceptable integration times for the energy calculation. The ISSMFE (1988) International Reference Test Procedure recommends an acceptable range of 0.9–1.2 of the theoretical integration time $2L'/c$.

Example data

The first application of the University of Alberta SPT energy-measurement system was for a tailings-dam investigation in China during April 1990. The site investigation was part of a Sino-Canadian Research project to study the stability of the Dashihe Tailings Dam during the 1976 Tangshan Earthquake. The SPT's were performed using Chinese equipment and procedures in general accordance with ASTM (1991*a*). A total of 175 SPT energy measure-

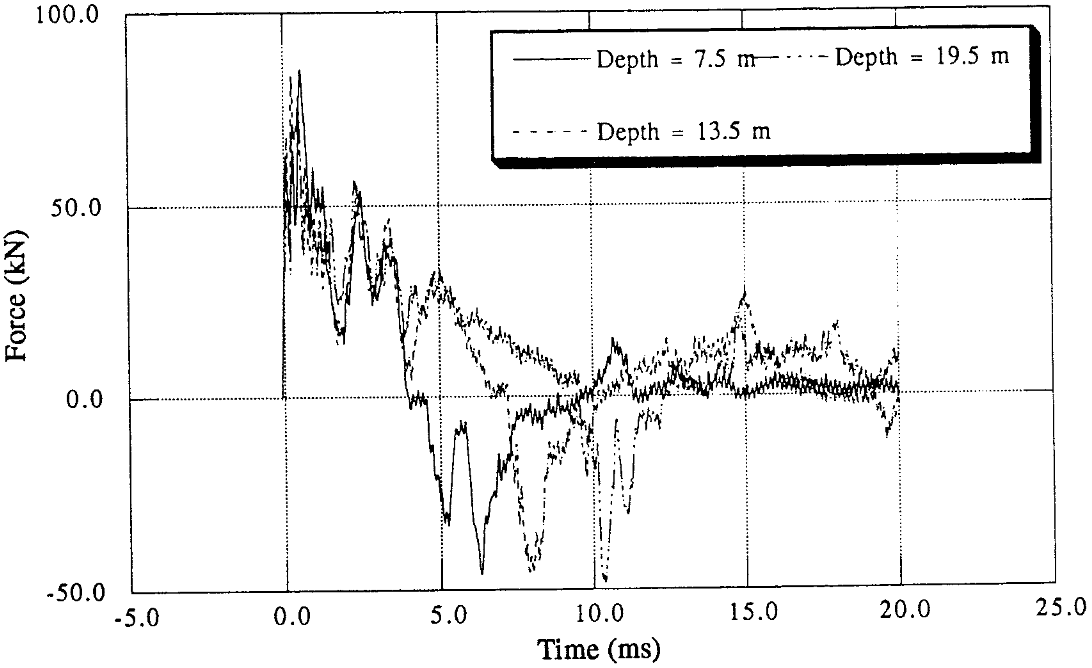

FIG. 5. Typical measured force–time records for Chinese automatic trip hammer.

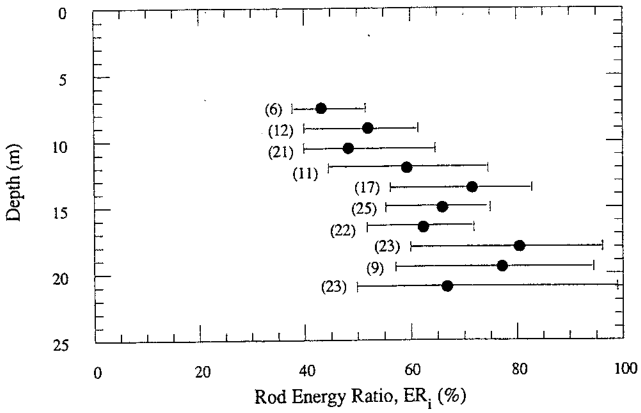

FIG. 6. Variation with depth of average, maximum, and minimum rod energy ratio (ER$_i$) for Chinese automatic trip hammer. SPT *N*-values are in parentheses.

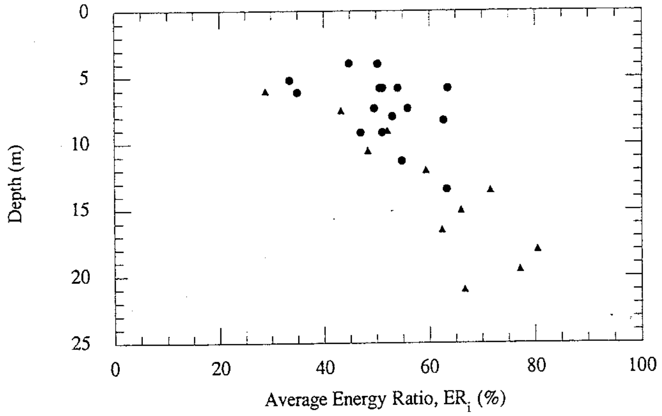

FIG. 7. Comparison of average rod energy ratio (ER$_i$) using PC-based system (▲) and ERTEC Inc. (1985) (●) data for Chinese automatic trip hammer.

ments were made on a Chinese automatic trip hammer. The trip hammer design regulated the height of fall to 760 mm by a mechanical release. During the tests, blows were applied at a rate of about 20 blows per minute. Hammer lift was accomplished by a hydraulic winch and wire cable.

A Chinese split-barrel sampler was used during SPT measurements. The sampler generally conformed to ASTM specifications. The sampler had a constant internal diameter, with no provision for liners. The Chinese drill rods had upset rod joints and therefore varied in cross-sectional area from about 581 mm^2 for the drill-rod shaft to about 2000 mm^2 for the upset-joint sections. A linear summation of rod areas was performed and an equivalent rod area per unit length was calculated (Douglas and Strutyusky 1984).

Typical force–time histories for three hammer blows at depths of 7.5, 13.5, and 19.5 m below ground surface was shown in Fig. 5. The initial portions of the force–time histories are very repeatable, with a peak force of about 85 kN at a time of about 0.5 ms. The time duration of each compressive wave increases with increasing rod length below the load cell according to the theoretical time of $2L'/c$.

Figure 6 shows a summary of rod energy ratios (ER$_i$) calculated using [2] for the 175 energy measurements made in one borehole during 1 day of investigation in terms of average, maximum, and minimum values of ER$_i$ as a function of depth below ground surface. The numbers in parentheses are the SPT *N*-values. There is a clear trend for the measured ER$_i$ to decrease at depths of less than about 12 m.

In 1984 ERTEC Inc. performed SPT energy measurements in China as part of a joint United States–China study (ERTEC Inc. 1985). The SPT energy measurements made by ERTEC Inc. were performed using the SPT calibrator (Hall 1982) with a piezoelectric load cell. The measurements were made on the same Chinese type of automatic trip hammer operated by the same Chinese contractor. Figure 7 shows a comparison between the average ER$_i$s measured in

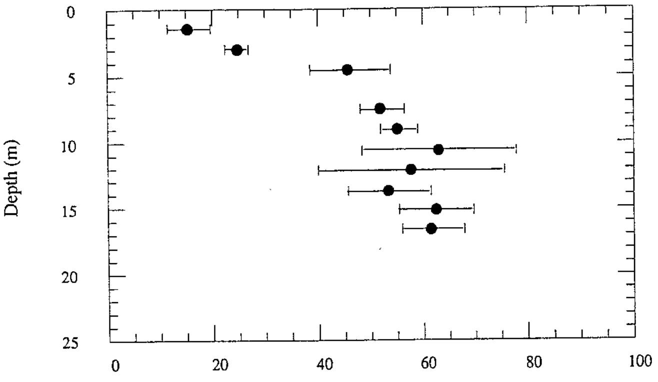

FIG. 8. Variation with depth of average, maximum, and minimum rod energy ratio (ER_i) for dunut hammer, rope, and cathead release SPT system, Vancouver, B.C.

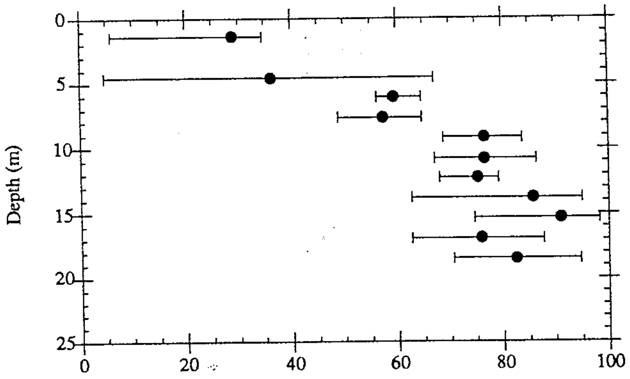

FIG. 9. Variation with depth of average, maximum, and minimum rod energy ratio (ER_i) for safety hammer, rope, and cathead release SPT system, Vancouver, B.C.

1984 by ERTEC Inc. and those measured in 1990 using the University of Alberta system. Although Fig. 7 shows a large range in ER_is, the ERTEC Inc. and University of Alberta data agree reasonably well. The ERTEC Inc. data at depths less than about 8 m are somewhat larger than the PC-based University of Alberta data. Since the intergration times for the ERTEC Inc. data were not recorded, it is not possible to check the 1984 data. However, errors in integration times could explain the differences at these depths. Although the energy measurements shown in Fig. 7 were made at different times, the results indicate generally good agreement between the two SPT energy-measurement systems.

Since the first application in 1990, the University of Alberta SPT energy-measurement system has been improved and used extensively on projects in western Canada. Figure 8 shows the average, maximum, and minimum values of measured ER_i for a donut hammer, rope, and cathead release SPT system in Vancouver, B.C. Figure 8 clearly shows a decrease in energy at depths less than about 12 m. The correction factor K_2 in [2] has been applied to the results in Fig. 8 and should correct the measured energy due to the short length of drill rod. However, Fig. 8 suggests that the current correction factor K_2 cannot fully compensate for short rod lengths.

Figure 9 shows a similar trend of measured rod energy ratios (ER_i) for a safety hammer, rope, and cathead release SPT system. The drill rods were BW, which are heavier than the more commonly used AW rods. The average ER_i at depth is about 80%, and again there is a decrease in energy at depths less than 12 m. The blow count at a depth of 4.6 m was 12; however, the first six blows provided measured ER_is less than 10% owing to the gradual uncoupling of the drill near the anvil. The test was stopped and the rods tightened. Energy values measured after rod tightening were near 60%. This illustrates the importance of procedure, such as loose couplings near the anvil, to provide repeatable SPT results. The software used in the PC-based SPT energy system has been recently upgraded to show the force–time plot in real time on the screen of the computer so that the operator can evaluate the maximum force and intergration time for each blow during the SPT test. The printout after the test includes the maximum force and intergration times for each blow.

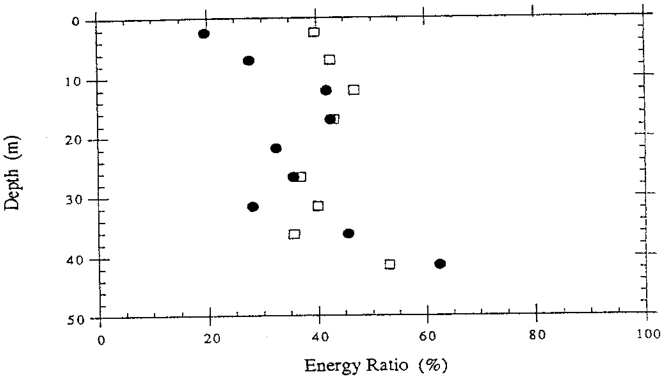

FIG. 10. Comparison of average energy ratio for Becker hammer using PC-based system (●) and pile-driving analyzer (☐).

The results shown in Figs. 8 and 9 illustrate the need to measure SPT energies rather than rely on the global energy ratios provided in Table 1.

In western Canada the Becker hammer test (BHT) is used extensively in areas of gravelly soils and for liquefaction analyses in gravelly soils. The BHT is a large-scale penetration test that uses a Becker hammer drill, which consists of a double-acting diesel pile hammer to drive a double-walled casing. The BHT consists of driving a closed-ended casing and recording the blows for each 300 mm of penetration. The drive casings commonly used are 138 mm (5.5 in.) and 185 mm (6.6 in) outside diameter. The diesel hammer is an International Construction Equipment model 180. The main advantage of the test is its ability to penetrate most dense soil formation at a relatively fast rate, making it particularly useful in gravel and cobble deposits. Like the SPT, the BHT results are strongly controlled by the delivered energy from the hammer. Harder and Seed (1986) proposed an energy correction for liquefaction analyses based on BHT bounce chamber pressure. However, the bounce pressure is also influenced by the soil resistance and ambient atmospheric pressure.

Energy measurements were recently made on a Becker hammer simultaneously using the PC-based SPT energy-measurement system and a commercially available pile driving analyzer (PDA). A short section of double-walled casing was strain gauged and installed below the diesel hammer. Pairs of strain gauges and accelerometers were also installed for the PDA measurements to record the force–time and velocity–time histories for each blow according the ASTM (1991*a*). Figure 10 presents the average measured energy ratios using both systems. The average energy, as a percent of the theoretical rated energy of the hammer, varies from 20 to 60%. Although these results are preliminary, both systems appear to have recorded similar energy values and similar variations of energy for each blow count (i.e., range from maximum to minimum energy) and with depth.

Summary

A PC-based SPT energy-measurement system has been developed based on the basic principles specified in ASTM (1991*b*) and ISSMFE (1988). The system incorporates a short section of strain-gauged drill rod as a load cell connected to a microcomputer via a trigger control box. Specialized software has been developed to record the force–time record of each SPT hammer blow and present the rod energy ratio (ER_i) for acceptable integration times.

Data collected using this PC-based SPT energy-measurement system have shown that the system provides reliable results. The results presented in this paper confirm the observation that the actual energy produced by any hammer anvil system is highly variable. The generalized energy ratios presented in Table 1 should only be used as a guide. For projects where comparisons of SPT results are important, such as liquefaction studies or where major project decisions rely on the SPT, energy measurements should be made.

The data presented have also shown the importance of the rod length correction (Table 2) for rod lengths less than 12 m. For very shallow depths (<5 m) the SPT energy could be significantly less than the generalized values shown in Table 1, and hence the SPT values can significantly overestimate the strength of the tested soil at these shallow depths.

Preliminary measurements have also been presented to suggest that the basic SPT energy-measurement system can also measure the energy during a Becker hammer test.

The PC-based energy-measurement system described has recently been modified to also monitor data from accelerometers so that the force–velocity integration method can be applied to calculate energy. This would enable the PC-based system to monitor pile driving according to ASTM (1991*c*) similar to various pile-driving analyzers.

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