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An Alternative Method of Measuring SPT Energy

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SYNOPSIS: Despite problems associated with its repeatability and reliability, the Standard Penetration Test (SPT) continues to be the most widely used in-situ test for liquefaction potential assessment. There are many factors known to influence the SPT results but the most significant factor affecting the N value is the amount of hammer energy delivered into the drill rods. The existing method of SPT energy measurement consists of attaching a load cell near the top of the drill rods and measuring the force time history during hammer impact. An alternative method of SPT energy determination based on measurement of both force and acceleration time histories is described. It is shown that the proposed method is more fundamental and avoids several shortcomings in the existing method. Field measurements are presented and SPT energies calculated by both methods are compared.

INTRODUCTION

The Standard Penetration Test (SPT) is the most widely used in-situ test in North America and has been correlated to many dynamic soil parameters including shear wave velocity and liquefaction resistance. The well-known Seed's simplified method of liquefaction potential assessment based on field observations of the performance of sites during actual earthquakes, for example, uses the SPT N value as the soil index. Despite continued efforts to standardize the SPT equipment and test procedure (e.g. ASTM D1586), there are still problems associated with its repeatability and reliability. Numerous studies have shown that there are many factors influencing the SPT results, but the most significant factor affecting the N value is the amount of hammer energy delivered into the drill rods. Several investigators have measured the hammer energy in various SPT systems and found considerable variabilities (Schmertmann et al. 1978; Kovacs and Salomone, 1982; Robertson et al. 1983; Riggs et al. 1984).

In their early studies of the SPT energy, Kovacs et al. (1977, 1978) and Kovacs (1979) used light scanner and reflection technique to measure the height of hammer fall and the velocity just before impact. These measurements allowed them to calculate the potential energy of the hammer drop and the kinetic energy of the hammer just before impact. They found that the hammer energy just before impact was always less than the potential energy of the hammer drop due to energy losses in the hammer system. They investigated factors which can affect the hammer energy, such as hammer fall height, rope age, number of wraps of the rope around the cathead, speed of rope release, cathead speed, drill rod inclination and different types of hammer. They found a linear relationship between SPT N value and hammer energy at impact. They proposed that a "standard energy" be established based on US practice and that all drill rigs be calibrated by adjusting the hammer fall height to deliver that "standard energy".

Schmertmann and his co-workers at the University of Florida conducted a comprehensive theoretical and experimental study of the statics and dynamics of the SPT (Schmertmann, 1978 and 1979; Schmertmann and Palacios, 1979). They incorporated hollow-center, strain gauge load cells near the top and bottom of the drill rods to measure the force-time histories of the stress waves. The force data were used to calculate energy transfer in the rods and the energy loss in the sampling process. They found that the hammer and rods remain in contact only until tension cutoff occurs. The tension cutoff point marks the arrival of the tensile wave reflection from the sampler to the anvil, and stops further transfer of energy from hammer to rods. The longer the drill rods, the longer is the hammer-rod contact time and the more hammer energy that enters the rods. The energy in the rod was calculated by integration of the measured force squared within the time limits of the first compression pulse times a rod material constant as shown in Eq. 1.

$$E_n(t) = c/EA \int F^2(t)\ dt \qquad (1)$$

where c is the velocity of longitudinal wave propagation in the rod, E is the Young's modulus of the rod, A is the cross-sectional area of the rod and F(t) is the measured force at a point in the rod. For steel rods, c is typically 16,800 ft/sec and E is about 30,000 ksi. They found that due to energy loss to heat during hammer impact as well as energy trapped in the anvil, the energy in the rods or ENTHRU was less than the hammer impact energy, and it was this ENTHRU, not the energy in the hammer at impact, that produced the sampler penetration that determined the SPT N value. They showed field data to confirm that N value varies inversely with the energy delivered into the drill rods.

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Schmertmann and Palacios (1979) also introduced two theoretical correction factors to the measured ENTHRU values so that the corrected energies refer to the ideal case of an infinitely long rod and can be compared between different SPT systems. The two factors account for the fact that the measuring point in the rods is some distance below the anvil and that the rods have a finite length. Both effects result in apparent cutoff times less than the ideal cutoff times, and consequently, the multiplication factors are greater than unity.

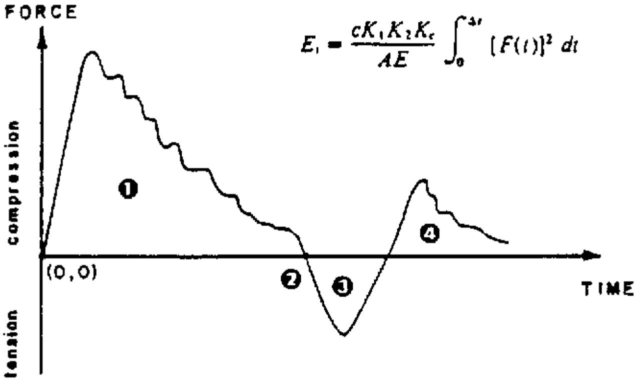
A commercially available SPT energy calibrator has been developed by Binary Instruments, Inc. (Hall, 1982). The system consists of a load cell attached near the top of the drill rods and a data processing instrument which calculates the energy at the transducer location in the rods. The transferred energy for each hammer blow is read directly from the instrument as a percentage of the theoretical free fall hammer energy of 350 ft-lb. The SPT calibrator uses Eq. 1 to calculate the energy in the rods and requires the input of the appropriate cross-sectional area of the drill rods.

Riggs et al. (1983) reported problems with the SPT calibrator in their study comparing the energy performances of a new automatic hammer and a string-cut free fall safety hammer. Their measured energy values were erratic with some recorded energy ratios well over 100 %. They subsequently suggested the need for "calibration of the calibrator".

In a discussion to Riggs et al. (1983), Kovacs (1984) suggested that the erratic calibrator energy values could be due to premature tensile wave reflections or hard driving compression reflections from the sampler, both of which would yield unrealistic integration times for calculating the energy in the rods. In the former case, the apparent integration time would be too short, resulting in too low an energy value, while in the latter case, the integration time would be too long, resulting in too high an energy. The above illustrates the importance of knowing the actual integration time used in calculating the energy from Eq. 1.

Bosscher and Showers (1987) conducted a wave equation analysis of the SPT in an attempt to study the effect of soil type on the input energy in the drill rods. Their computed transferred energies based on Eq. 1 were much higher than the kinetic energy of the hammer at impact! This anomaly again illustrates the problem in using the force integration method to calculate energy and in the selection of the duration of the first compression pulse for use in Eq. 1.

The existing method of SPT energy measurement as specified in ASTM D4633-86 and ISSMFE (1988) is based on the Schmertmann's force measurement concept. The method consists of attaching a load cell near the top of the drill rods and measuring the force time history during hammer impact. Fig. 1 shows an idealized force-time waveform recorded by a load cell in the drill rods. As shown in the equation in Fig. 1, the energy is calculated based on Eq. 1 but with three correction factors applied. The first two factors, K_1 and K_2, are to correct for the load cell position in the rods and finite rod length, respectively, and are similar in principle to Schmertmann and Palacios' (1979) correction factors. The third factor, K_c, is to correct the theoretical wave speed, c, to the so-called "actual" wave speed, c'. This stress wave speed correction was also introduced by Schmertmann (1982) in his SPT calibration work for the Florida Department of Transportation.



NOTE—1 = First compression pulse or wave
2 = Cutoff time at the arrival of the first tension pulse, at $\Delta t = 2L'/cK_c$
3 = First tension pulse (reflected from the penetrometer)
4 = Second compression pulse (reflected from the anvil)

Fig. 1. Idealized Force-Time Waveform Recorded by Load Cell in SPT Drill Rods (After ASTM D 4633-86)

The K_c correction is based on the assumption that the total duration of the first compression pulse (see Fig. 1) is the "actual round trip" time it takes 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. The theoretical round trip time is 2L/c, in which L is the length of the SPT rod and sampler system below the load cell and c is the theoretical wave speed. Invariably, it was found that the "actual" pulse duration was always greater than the theoretical 2L/c, suggesting that the "actual" wave speed was less than 16,800 ft/sec. Hence the K_c factor is used to match the theoretical 2L/c to the measured compression pulse duration. In other words, the measured pulse duration is set equal to 2L/c', in which $c'=cK_c$ is the "actual" wave speed in the rods and K_c is less than unity. Riggs et al. (1984) indicated that this correction causes the complete force trace to be contracted or compressed along the time ordinate. He argued that the longer trip time is a result of secondary compression return at the tail of the curve and not from a slow stress wave velocity. He therefore suggested that the theoretical trip time be maintained and that the compression tail or "blip" beyond that time be discounted in the energy calculation. Riggs et al., however, acknowledged that they did not have evidence to support their suggestion. It will be shown in this paper that the theoretical 2L/c actually corresponds to the time interval between the peak force and the tension cutoff point, not from the start of the force trace to the cutoff point as is commonly assumed, and that the K_c factor is, therefore, unnecessary.

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An alternative method of SPT energy measurement is described in this paper. The approach is based on measurement of both force and acceleration time histories in the drill rods during the SPT. The transferred energy is then calculated by time integration of force times velocity. It will be shown that the proposed approach is more fundamental and avoids the shortcomings in the existing method based on integration of force data only. Field data are presented to compare the two methods of energy calculation.

METHODS OF ENERGY CALCULATION

For a body undergoing motion, the increment of work done over a time interval centered at a time t_1 is given by

$$dW = F_1\ dx \qquad (2)$$

where F_1 is the force in the direction of motion at time t_1 and dx is an increment of displacement. Integration of Eq. 2 yields the total work done in the force-displacement space,

$$W = \int F_1\ dx \qquad (3)$$

Since the hammer impact force in a rod is variable with time, it is more convenient to express the work done, or energy, as a function of time, i.e.

$$E_n(t) = W = \int F(t)\ V(t)\ dt \qquad (4)$$

where $E_n(t)$ is the energy, $F(t)$ is the force and $V(t)=dx/dt$ is the particle velocity, all with reference to a point in the rod. Eq. 4 is the fundamental equation describing energy in a rod as a function of time, and can be calculated if the force and velocity time histories are known at a point in the rod. The maximum value calculated from Eq. 4 is the maximum transferred energy or ENTHRU in the rod.

For impact wave propagation in one direction in a uniform unsupported elastic rod, it can be shown (Timoshenko and Goodier, 1970) that

$$F(t) = V(t)\ EA/c \qquad (5)$$

in which the quantity EA/c is referred to as the impedance of the rod. The impedance is a rod material constant. Consequently, in an elastic rod of uniform cross-section, the particle velocity is proportional to the force at a point, as long as there are no wave reflections from external forces acting on the rod. This proportionality relationship is the basis for evaluating the soil resistance from stress wave measurements in piles (Hussein and Goble, 1987).

For wave propagation in a uniform rod with soil resistance acting only at its tip, the above proportionality relationship will hold only from the time of impact to the time of arrival of the wave reflection from the sampler, i.e. for the time duration of the first compression pulse. For such systems, Eq. 5 can be substituted into Eq. 4, either for force or velocity, to obtain

$$E_n(t) = EA/c \int V^2(t)\ dt \qquad (6)$$

or $$E_n(t) = c/EA \int F^2(t)\ dt \qquad (7)$$

Note that Eq. 7 is the same as Eq. 1 and is referred to in this paper as the force integration method for calculating energy. Eqs. 6 and 7 show that the energy at a point in the rod can be computed given only one measured quantity, i.e. either velocity or force time history. Both equations inherently assume proportionality between force and particle velocity at the measuring point in the rod during the first compression pulse, and require that the time limits of the first compression pulse be predetermined.

The SPT, however, is a more complex dynamic system. From the point of hammer impact on the anvil in a typical safety hammer system, the stress wave travels through a hammer guide rod, drill rods, sampler and couplings or adaptors connecting the different parts, all of which can have different cross-sectional areas or impedances. When a stress wave encounters a sudden change in cross-sectional area, part of the wave is reflected back from the interface and part is transmitted. The sign of the reflected wave depends on the sign of the initial wave and whether or not the area is increased or decreased. Thus the different impedances in the SPT drill rod system cause various wave reflections in the system. The hammer/anvil geometries and soil resistances also affect the stress wave propagating in the drill rods. Therefore, the theoretical force-velocity proportionality relationship does not hold for the SPT drill rods and sampler system, and both force and velocity measurements are needed to calculate the energy entering the rods. Sy and Campanella (1991) have also shown that both force and velocity time histories are also needed to fully characterize the stress wave propagation in the SPT system.

Aside from problems associated with the selection of the integration time, the force integration method for calculating SPT energy also requires input of the cross-sectional area of the rods which is not uniform in practice.

In summary, the force-velocity integration method as given in Eq. 4 is the more fundamental method for calculating energy in a rod due to hammer impact and is recommended for the SPT system. The maximum value calculated from Eq. 4 is the maximum transferred energy at the measuring point in the drill rods. Eq. 4 avoids the force-velocity proportionality assumption inherent in Eq. 1, and does not require predetermination of the integration time nor input of E, A or c, all of which are needed in the existing force integration method as given by Eq. 1. This basic force-velocity approach to energy measurement is not new and is, in fact, the standard practice in dynamic monitoring of piles during driving (ASTM D4945-89).

FIELD WORK

The field work was conducted at the UBC in-situ testing research site in McDonald's Farm, an abandoned farm on Sea Island, the site of the Vancouver International Airport south of Vancouver, British Columbia, Canada. Sea Island is located in the Fraser River delta and is contained by a system of dykes to prevent flooding. The site is approximately level. The

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mean groundwater table at the site is about 5 ft below ground surface and varies with the tidal fluctuations of the adjacent Fraser River.

The soil conditions at McDonald's Farm consist of 7 ft (2 m) of soft organic silty clay overlying an 8 ft (2.5 m) thick zone of silty fine sand underlain by about 36 ft (11 m) of medium to coarse sand. The sand stratum is variable in density with occasional seams of silt. Underlying the sand is a deep deposit of normally consolidated clayey silt which extends to a depth of about 350 ft (105 m) above very dense glacial deposits. Fig. 2 shows the piezometer cone penetration test data and soil profile at the site. Full details of the research test site are given in Campanella et al. (1983).

The SPT's were conducted at 5 ft intervals between 5 ft and 30 ft depths in a mud rotary drill hole using a Gardner Denver 1000 drill rig. The SPT was performed in accordance with ASTM D 1586-84 using a safety hammer with two turns of rope around the cathead. Fig. 3 shows dimensions of the safety hammer used. A modified Binary Instruments Inc. SPT calibrator (Hall, 1982) was used to measure the force-time histories of the impact waves in the drill rods with a load cell. In addition to the force transducer, an accelerometer was attached adjacent to the load cell to record accelerations in the rods. Both instruments are piezoelectric type transducers which are robust, stable and have fast dynamic response. The transducers were attached 5.8 ft below the anvil location. The force and acceleration measurements of the SPT blows were recorded on a Nicolet 4094 digital oscilloscope with a 15 bit A/D resolution. For both channels, data samples were obtained at a time interval of 0.01 ms.

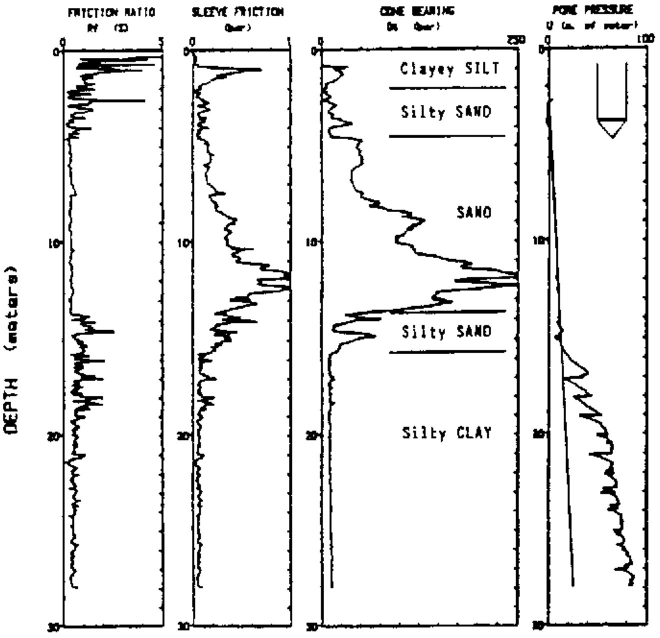

Fig. 2. Cone Penetration Test Profile

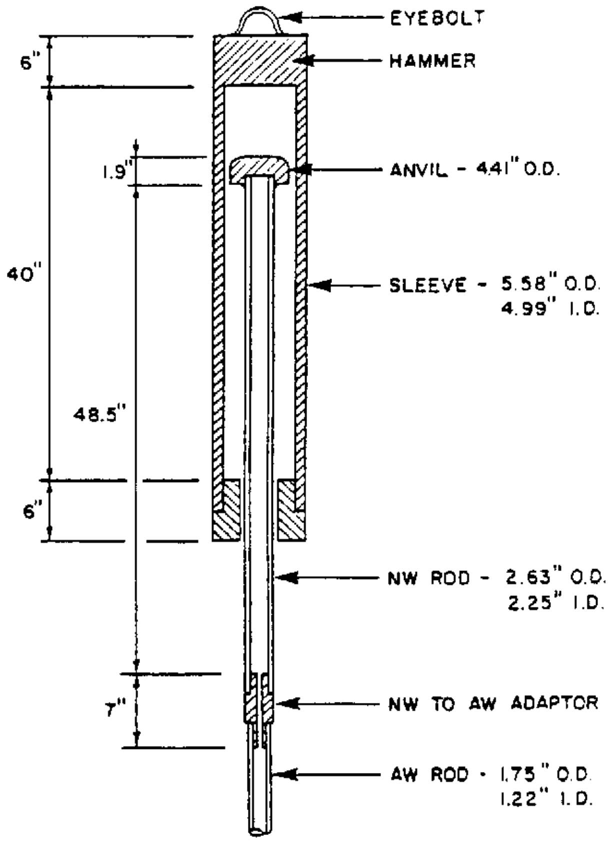

Fig. 3. Safety Hammer Used in this Study

MEASURED STRESS WAVES AND ENERGIES

Data from three selected SPT blows at 5 ft, 15 ft and 30 ft depths in soft clayey silt (SPT N=2), loose sand (N=8) and medium dense sand (N=21), respectively, are presented and discussed in detail below.

Fig. 4 shows the stress wave measurements for the first blow of the SPT at 5 ft depth in the soft clayey silt deposit. The SPT sampler penetrated 8 inches during this blow. The top plot is the recorded force (F) and the calculated velocity times impedance (VEA/c) wave traces. The velocity was derived from integration of the recorded acceleration time history. To calculate the impedance, the cross-sectional area of the AW rod, rather than that of the larger NW rod or the load cell, was arbitrarily selected (see Fig. 3). The sign convention used is positive force for compression wave and negative force for tension wave, and positive velocity for downward motion and negative velocity for upward motion. This type of proportional stress wave plot is commonly used in pile driving monitoring and it illustrates several key features. First of all, if force and velocity are proportional within the first compression pulse as would be expected for wave propagation in a uniform rod with only tip resistance, they will plot on top of each other.

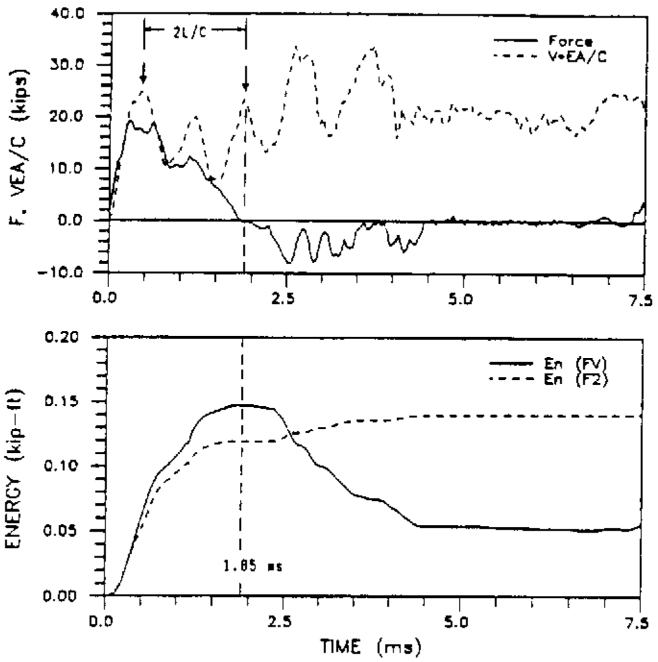

Fig. 4. Measured Force, Velocity and Energy Traces for SPT Blow 1 at 5 ft Depth

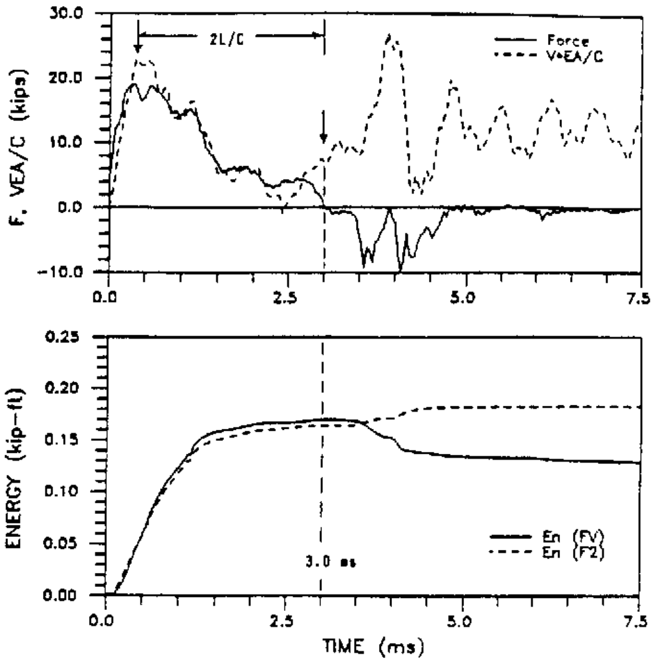

Fig. 5. Measured Force, Velocity and Energy Traces for SPT Blow 4 at 15 ft Depth

Fig. 4 shows that proportionality does not exist at the first two velocity peaks in the primary compression pulse. The separation of the force and velocity peaks in this region is mainly caused by wave reflections from the different impedances in the SPT rods and sampler system. The third velocity peak at 1.85 ms is the tensile reflection of the impact compression wave from the sampler. The relatively large magnitude of this peak reflects the very small soil resistance acting on the sampler. As expected, the tension force cutoff also occurs at this time.

The top plot in Fig. 4 also shows that the point of impact at 0.4 ms is much better defined by the sharper initial velocity peak than by the initial force peak. The time interval between the first velocity peak (impact) and the third velocity peak (return wave), or the tension cutoff point, is 1.45 ms. This time corresponds to the theoretical 2L/c time for the wave to travel from the load cell to the sampler tip, where L=12.2 ft, and back to the load cell. Thus the 2L/c should not be measured from the beginning of the force-time pulse to the tension cutoff point, as is recommended in ASTM D 4633-86 and ISSMFE (1988).

The bottom plot in Fig. 4 shows the energy traces calculated using the force-velocity integration (FV) method in Eq. 4 and the force integration (F2) method in Eq. 1. For this blow, the maximum energy transfer at the transducer location in the drill rods is 0.147 kip-ft using Eq. 4 and 0.119 kip-ft using Eq. 1. These ENTHRU values correspond to 42 % and 34 %, respectively, of the theoretical free fall hammer energy of 0.35 kip-ft. The 24 % discrepancy between the two ENTHRU values is a result of the non-proportional force and velocity waveforms caused by wave reflections in the SPT system and by the very low soil resistance acting on the sampler. As expected, the maximum energy in the force-velocity integration method occurs at 1.85 ms, when the tensile reflection from the sampler bottom reaches the transducer location, whereas in the force integration method, the tension cutoff point has to be predetermined from the recorded force trace before obtaining the ENTHRU value by Eq. 1.

Fig. 5 shows the measured F and VEA/c traces for the 4th blow of the SPT at 15 ft depth in sand during which the sampler penetrated 2 inches. The two traces are approximately proportional within the first compression pulse except for some local separations of the two wave traces caused by wave reflections in the system. For this blow, the initial peak velocity and peak force both occur at 0.36 ms. The tension force cutoff occurs at 3.0 ms, which is also marked by a small velocity spike that is not as sharp in this particular case. The theoretical 2L/c for this test is 2.64 ms, in which L=22.2 ft, and matches well the time interval between the initial force or velocity peak and the tension cutoff point.

As shown in the bottom plot of Fig. 5, the calculated ENTHRU values are 0.17 kip-ft by the force-velocity integration method and 0.164 kip-ft by the force integration method, corresponding to 49 % and 47 % energy ratios, respectively. The similarity of the ENTHRU values here is because of the nearly proportional force and velocity traces within the first compression pulse recorded for this blow.

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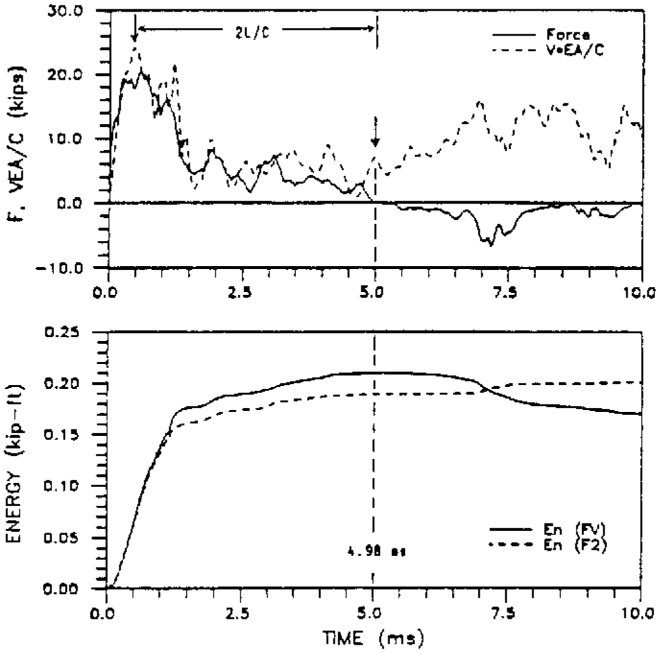

Fig. 6. Measured Force, Velocity and Energy Traces for SPT Blow 28 at 30 ft Depth

Fig. 6 shows the measured F and VEA/c traces for the 28th blow of the SPT at 30 ft in medium dense sand. The observed sampler penetration for this blow is 0.5 inch. The force and velocity traces are again not proportional within the first compression pulse due to the reflections from the different impedances in the SPT system. At impact, the velocity peak is sharp and occurs at 0.46 ms, whereas the force peak is again not as well defined. The tensile reflection of the first compression pulse from the sampler occurs at 4.98 ms. Note the reflected velocity peak at this time is relatively small, indicating the larger soil resistance encountered at the sampler. The time interval from the first impact velocity peak to the first return velocity peak, or the tension cutoff, is 4.52 ms, which again corresponds closely to the theoretical 2L/c in which L=37.2 ft for this test.

The ENTHRU values obtained from the bottom plot in Fig. 6 are 0.21 kip-ft by the force-velocity integration method and 0.189 kip-ft by the force integration method, corresponding to 60 % and 54 % energy ratios, respectively.

A comparison of the ENTHRU values for the three blows described above shows, as expected, that the transferred energy increases with the SPT rod length, i.e. 42 %, 49 % and 60 % energy ratios for the SPT at 5 ft, 15 ft and 30 ft depths, respectively. This energy increase can not go on indefinitely. Schmertmann and Palacios (1979) have shown theoretically that this increase is practically zero beyond a rod length of 40 ft. This conclusion is well illustrated in Figs. 4, 5 and 6 which show that the bulk of the energy is coming from the main pulse within the first 1.5 ms of the impact event and that the remaining compression pulse beyond this time contributes very little to the maximum transferred energy.

Another interesting observation from the bottom plots of Figs. 4, 5 and 6 is the shape of the energy curves calculated from the force-velocity integration method. In soft soils, there is a large drop off in energy after the peak value is reached at the tension cutoff point. This is due to the large tensile reflection from the sampler causing a significant increased downward velocity of the rods and pulling away of the rods from the hammer. In denser soils, the energy drop off after the peak value is less pronounced, as the smaller tensile wave reflection results in a more gradual separation of the hammer-rod contact.

Data from the other blows not presented in this paper confirm that the ENTHRU values calculated by the force-velocity integration method are generally higher than those by the force integration method, by about 5 to 15 %. The discrepancy is mainly due to the complicated wave reflections from the different impedances in the actual SPT anvil-rod-sampler system. These are confirmed by wave equation analysis of the SPT (Sy and Campanella, 1991). The difference in ENTHRU values found in this study is likely hammer and soil specific, and more measurements should be conducted for different SPT hammer systems in different soil conditions.

CONCLUSIONS

The SPT is a complex dynamic system. The recorded force and integral of measured acceleration (or particle velocity) traces from the SPT are complicated and show wave reflections from the different impedances in the drill rod and sampler system. It is shown that force and velocity data provide more insight into the dynamics of the SPT and allow a more fundamental approach to calculating transferred energy in the rods.

Field measurements show that the point of impact is better defined by the initial velocity peak rather than by the initial force peak, and that the time interval between the initial velocity peak or force peak and the tension cutoff point corresponds to the theoretical 2L/c time. It is suggested that the stress wave speed correction factor, K_c, in ASTM D4633-86 and ISSMFE (1988) is unnecessary in calculating ENTHRU.

Field measurements also show that the existing force integration method of calculating SPT energy gives only approximate ENTHRU values, which can be low depending on the changes in cross-sectional areas in the actual anvil-rod-sampler system and on the soil resistances acting on the sampler.

An alternative method of measuring SPT energy based on force and acceleration measurements in the drill rods has been proposed. The proposed force-velocity integration method is more rational and avoids the force-velocity proportionality assumption inherent in the existing method. The proposed method does not require predetermination of the integration time and also avoids the difficulty of selecting one cross-sectional area of the SPT system for use in the force integration method.

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