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JOHN ELIAS BALDACCI
GOVERNOR

DAVID A. COLE
COMMISSIONER

July 13, 2007
Subject: **Geotechnical Drilling**
Project No. N/A
Pin No. N/A
Amendment No. 1

Dear Sir/Ms:

Please make the following change to the Bid Documents:

In the Bid Book, ADD the attached: "Standard Test Method for Energy Measurement for Dynamic Penetrometers" seven pages total.

The following questions have been received.

Question: Could I get a copy of test method ASTM D4633-05?

Response: Yes, see change made earlier in this amendment.

Question: Who is qualified to perform ASTM 4633-05 "Energy Measurement for Dynamic Penetrometers"?

Response: Contractors who perform this type of energy testing/hammer calibration are:

GRL Engineers
4535 Renaissance Parkway
Cleveland Ohio 44128
216-831-6131

GZA GeoEnvironmental
4 Free St
Portland ME

207- 879-9190
Soil and Rock Instrumentation Division
Norwood Office
(781) 278-3700

Consider this change and information prior to submitting your bid on July 18, 2007.

Sincerely,

Scott Bickford
Contracts & Specifications Engineer

Designation: D 4633 – 05

Standard Test Method for Energy Measurement for Dynamic Penetrometers[1]

1. Scope

1.1 This test method describes procedures for measuring the energy that enters the penetrometer drill rod string during dynamic penetrometer testing of soil due to the hammer impact.

1.2 This test has particular application to the comparative evaluation of N-values obtained from the Standard Penetration Tests (SPT) of soils in an open hole as in Test Method D 1586 and Practice D 6066. This procedure may also be applicable to other dynamic penetrometer tests.

1.3 *Limitations*—This test method applies to penetrometers driven from above the ground surface. It is not intended for use with down-hole hammers.

1.4 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D 6026.

1.5 The method used to specify how data are collected, calculated, or recorded in this standard is not directly related to how the data can be applied in design or other uses, since that is beyond its scope. Practice D 6066 specifies how these data may be normalized.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:* [2]

D 1586 Test Method for Penetration Test and Split-Barrel Sampling of Soils

D 3740 Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D 6026 Practice for Using Significant Digits in Calculating and Reporting Geotechnical Test Data

D 6066 Practice for Determining the Normalized Penetration Resistance of Sands for Evaluation of Liquefaction Potential

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *acceleration transducer, or accelerometer*—instrument attached on, around, or within a continuous column of drill rods to measure the time-varying acceleration generated in the drill rods by the impact of the hammer.

3.1.2 *anvil*—the mass at the top of the drill rods that is struck by the hammer.

3.1.3 *drill rods*—the steel rods connecting the hammer system above the ground surface to the sampler below the surface.

3.1.4 *force transducer*—a section of drill rod instrumented with strain gages and inserted into the continuous column of drill rods to measure the time-varying force generated in the drill rods by the impact of the hammer.

3.1.5 *hammer*—an impact mass that is raised and dropped to create an impact on the drill rods.

3.1.6 *impedance (of the drill rod)*—a property of the drill rod equal to the drill rod elastic modulus times the cross sectional area divided by the velocity of wave propagation.

3.1.7 *instrumented subassembly*—a short section of drill rod instrumented to measure force and acceleration which is inserted at the top of the drill rod and below the anvil.

3.1.8 *penetrometer*—any sampler, cone, blade, or other instrument placed at the bottom of the drill rods.

3.2 *Symbols*:

EFV = the energy transmitted to the drill rod from the hammer during the impact event (see 7.10).

$ETR = (EFV / PE)$ – ratio of the measured energy transferred to the drill rods to the theoretical potential energy.

L = length between the location of transducers on the instrumented subassembly and the bottom of the penetrometer.

$2L/c$ = the time required for the stress wave (traveling at a known wave speed, c, in steel of 5123 m/s) to travel from the measurement location to the bottom of the penetrometer and return to the measurement location.

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[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.02 on Sampling and Related Field Testing for Soil Evaluations.

Current edition approved Nov. 1, 2005. Published November 2005.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

N-value = the number of hammer blows required to advance the sampler the last 12 in. (0.3 m) of the 18 in. (0.45 m) driven during an SPT test.

PE = the theoretical potential energy of the hammer positioned at the specified height above the impact surface.

4. Significance and Use

4.1 Various driven in situ penetrometers are used to evaluate the engineering behavior of soils. The Standard Penetration Test is the most common type. Engineering properties can be estimated on the basis of empirical correlations between N-values and soil density, strength or stiffness. Alternatively, the N-value can be used directly in foundation design using correlations to design parameters such as allowable bearing pressure or pile capacity. The N-value depends on the soil properties but also on the mass, geometry, stroke, anvil, and operating efficiency of the hammer. This energy measurement procedure can evaluate variations of N-value resulting from differences in the hammer system. See also Refs **(1-6)**.[3]

4.2 There is an approximate, linear relationship between the incremental penetration of a penetrometer and the energy from the hammer that enters the drill rods, and therefore an approximate inverse relationship between the N-value and the energy delivered to the drill rods.

NOTE 1—Since the measured energy includes the extra potential energy effect due to the set per blow, tests for energy evaluation of the hammer systems should be limited to moderate N-value ranges between 5 and 50.

4.3 Stress wave energy measurements on penetrometers may evaluate both operator-dependent cathead and rope hammer systems and relatively operator-independent automatic systems.

4.4 The energy measurement has direct application for liquefaction evaluation for sands as referenced in Practice D 6066.

4.5 This test method is useful for comparing the N-values produced by different equipment or operators performing SPT testing at the same site, aiding the design of penetrometer systems, training of dynamic penetrometer system operators, and developing conversion factors between different types of dynamic penetration tests.

NOTE 2—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D 3740 are generally considered capable of competent and objective testing and inspection. Users of this standard are cautioned that compliance with Practice D 3740 does not in itself assure reliable results. Reliable results depend on many factors: Practice D 3740 provides a means of evaluating some of those factors.

5. Apparatus

5.1 *Apparatus for Measurement*—An instrumented subassembly defined in 3.1.7 shall be inserted at the top of the drill rod string directly below the hammer and anvil system so that the hammer impact is transmitted through the anvil into the instrumented subassembly and then into the drill rods. The subassembly shall be made from the same type of drill rod as used in the drill rod string, shall be at least 600 mm (2 ft) in length. The measurement location shall be located at least 300 mm (1 ft) below the top of the instrumented subassembly, and shall be at least three diameters away from any cross sectional area change.

5.2 *Apparatus to Measure Force*—The force in the drill rods shall be measured by instrumenting the subassembly with foil strain gages in a full bridge circuit. The gages shall be arranged symmetrically such that all bending effects are canceled. The instrumented rod section shall have a minimum of two such full bridge circuits. Transducer systems that insert massive elements or load cells with stiffness properties substantially different than those of the rods themselves are specifically prohibited.

5.3 *Apparatus to Measure Acceleration*—Acceleration data shall be obtained with a minimum of two accelerometers attached on diametrically opposite sides of the drill rod within 100 mm (4 in.) of the force measurement location. The accelerometers shall be aligned axially with the rod in their sensitive direction and shall be bolted, glued, or welded to the rod with small rigid (solid, nearly cubic shape) metal mounts. Overhanging brackets that can bend during impact and plastic mounting blocks are prohibited. Accelerometers shall be linear to at least 10 000 g and have a useable frequency response to at least 4.5 kHz.

NOTE 3—The rigidity of the accelerometer mounting block can be assessed by comparing the rise times of the velocity to the force signal.

5.4 *Apparatus for Recording, Processing and Displaying Data*:

5.4.1 *General*—The force and acceleration signals from the hammer impact shall be transmitted to an instrument for recording, processing, and displaying data to allow determination of the force and velocity versus time. The apparatus shall provide power and signal conditioning for all transducers. There are two forms of data acquisition systems. Analog systems electronically integrate measured acceleration to velocity through electronic circuitry and digitize the resulting velocity. Digital systems acquire acceleration data and digitally integrate acceleration to velocity.

5.4.2 *Analog Systems*—The signal conditioning system shall apply a low-pass filter to both force and velocity with a cutoff frequency of 2 kHz or higher (preferably 5 kHz). Data acquisition sampling rate shall be at least 5 times the low-pass filter frequency to avoid signal aliasing. For analog integration, automatic balancing must be turned off during the impact event.

5.4.3 *Digital Systems*—The signal conditioning shall apply a low-pass filter to both force and acceleration with a cutoff frequency of 5 kHz or higher (preferably 25 kHz). Data acquisition sampling rate shall be at least 10 times the low-pass filter frequency to avoid signal aliasing.

5.4.4 *Apparatus for Recording*—The apparatus shall sample each signal and record the magnitude versus time of each sensor in digital form with a minimum 12-bit resolution. The signals from individual transducers for each blow shall be permanently stored in digital form for a minimum time sample so that the motion has ceased, or 50 milliseconds, whichever is

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[3] The boldface numbers in parentheses refer to the list of references at the end of this standard.

longer. The zero line of the acceleration shall be determined such that the velocity near the end of the sample shall be zero.

5.4.5 *Apparatus for Processing*—The apparatus for processing the data shall be a digital computer or microprocessor capable of analyzing all data and computing results. The measured acceleration shall be integrated to obtain velocity. Small time shifts between the force and velocity should be eliminated by time shifting one signal versus the other to account for small phase shifts up to at most 0.1 milliseconds. Larger time shifts indicate deficiencies in the measurement system and should be corrected.

5.4.6 *Apparatus for Data Display*—The apparatus shall display the force and velocity signals graphically as a function of time. The apparatus shall be capable of reviewing each individual measured signal to confirm data quality during acquisition as described in 7.8. The apparatus for display shall display the $2L/c$ time and the calculated energy result.

6. Calibration

6.1 *Force Transducer*—The instrumented subassembly shall be calibrated both in force and strain, each to an accuracy within ±2 %, The subassembly shall be loaded to at least 70 % of the anticipated force. The strain calibration allows direct comparison of strain with particle velocity. The dual calibration allows determination of the calculated effective rod cross-sectional area, A_c, of the instrumented subassembly from $A_c = (F/E\epsilon)$ where F is the applied measured force, E is the modulus of steel of 206 000 MPa (30 000 ksi), and ϵ is the measured strain at applied force F. If the calculated and measured rod areas at the transducer section differ by more than 5 percent, then the rod should be re-calibrated, or the area re-measured. If differences persist, the calculated area is considered more accurate.

6.2 *Accelerometer Calibration*—The accelerometer shall be calibrated to an accuracy within ±3 % with a shock of at least 2000 g's using a Hopkinson's Bar with a steel to steel impact. The accelerometers shall be attached to the instrumented Hopkinson's Bar measuring strain, and the measured velocity from integration of acceleration compared with the measured strain which is theoretically proportional to velocity to check the acceleration calibration factor. The Hopkinson's Bar shall be steel and be at least 10 m long with no welds or joints. The impacting bar shall also be steel, of the same area as the Hopkinson's Bar, and between 3 and 6 m long.

6.3 *Frequency of Calibration*—Calibrate force and acceleration transducers at regular time periods or at frequency of use as required in the quality assurance plan for the company, project, or as recommended by the manufacturer, or every three years whichever is least.

7. Procedure

7.1 Observe the penetrometer testing in progress for a preparatory sequences of blows prior to energy measurement. Determine and record information including drill rig type and serial number, hammer type and serial number, (cathead: number of turns, drop height, rope over or under the cathead, rope condition, crown sheave arrangement, for safety hammers note guide rod size and if hollow or solid) (automatic: trip system, drop height, blow rate). Note any significant hammer operating conditions such as weather, verticality, or changes in lubrication. Record drill rod dimensions, including outside and inside diameters, section lengths, and type of connectors. Do not combine drill rods of varying sizes (for example, AW with NW).

NOTE 4—The number, size, and condition of pulley sheaves affects the energy transfer. Energy is consumed in the friction and rotation of the sheave and thus they should be inspected and their number and condition noted. Verticality may affect the drop system; align the penetrometer system as close to vertical as possible. Because some automatic hammers are rate dependent, determine the hammer manufacturer's proper operating rate. If the rate is different, recommend hammer maintenance. Weather conditions can affect rope and cathead operations.

NOTE 5—Preparatory sequences of blows have the objective of bringing the equipment and operator to their normal functioning condition. The initial blows can be used to re-polish the cathead, dry a wet or damp rope, provide fresh lubrication for mechanical parts, identify any mechanical or human problems, and provide re-familiarization practice for all personnel.

7.2 Enter the test information including the project name, the boring name and location, operating crew names, reference elevations, the depth of the penetrometer, and any other descriptive information deemed useful. Record any unusual conditions or requirements that may affect the test results.

7.3 Enter the information describing the instrumented subassembly and drill rod including the instrumented subassembly type (for example, AW, NW-heavy, etc.), cross-sectional area, and length from the transducers to the bottom of the drill rod string.

NOTE 6—Energy evaluation of the hammer system is more reliable when the length L is 9 to 12 m or more.

7.4 Connect the instrumented subassembly for measuring force and acceleration to the top of the drill rod string. All drill rods in the drill rod string including the instrumented subassembly section should be steel and have the same diameter, and nominal area. The rod joints should be tight.

7.5 Connect each sensor electronically by a signal transmission cable system to the apparatus for recording, processing, and displaying data.

7.6 Follow the manufacturer's procedures to ensure the transducers and the apparatus for recording, processing, and displaying data are operating properly.

7.7 Operate the hammer and record the data using the apparatus for recording, processing, and displaying data.

7.8 During testing, the quality of the measurements shall be checked by the operator of the testing equipment.

7.8.1 When the instrumented subassembly and drill rods have nominally identical areas, the force and velocity measurements should be generally proportional to the rod impedance during the first $2L/c$ time after impact. Minor variations in proportionality occur due to connectors. Loose connections and significant changes in rod area from section to section can cause substantial variations in proportionality.

7.8.2 Successive force and velocity records shall be generally similar.

7.8.3 Force and velocity records shall return to near zero at the end of the record.

7.8.4 If the force becomes temporarily negative prior to $2L/c$ after onset of impact, then the drill rod joints should be tightened. Loose joints reduce the energy transfer and if observed should be noted to the penetrometer crew who should be instructed to carefully tighten all joints.

7.8.5 Individual pairs of force or velocity signals versus time shall be very similar for good quality data. This is the prime method to assess data quality and the reliability of the measured signals. Fig. 1 shows good data with proportionality of force with velocity in general agreement, and both force signals (F1 and F2) in agreement, and both velocity signals (V1 and V2) in agreement.

7.9 Perform measurements for at least 3 depths of quality data with 5 depths preferred, while using the SPT system in as nearly a routine manner as practical. It is preferable to make as many measurements as possible, and to average the energy results. Record the number of blows, or N-value, and penetration depth of the sampler for each test.

7.10 Calculate the energy transferred to the drill rods (*EFV*) from the following formula using the time-varying functions of measured force *F(t)* and velocity *v(t)*. The integration is carried to the end of the record and the maximum energy transferred at any time during the record is determined.

$$EFV = max\left[\int F(t)\,v(t)\,dt\right] \qquad (1)$$

7.10.1 The calculated energy *EFV* can be compared to the theoretical maximum potential energy (*PE*), and the ratio is known as the Energy Transfer Ratio (*ETR*).

$$ETR = (EFV/PE) \qquad (2)$$

7.11 *Rig Calibration Interval*—Calibrate each hammer at a regular time period (at least yearly), or based on frequency of use as specified in the owner's quality assurance plan, or based on the client's quality assurance requirements. For frequently used hammers subject to wear, the required interval might be shorter. For infrequently used hammer systems, it is advisable to calibrate on first use. Rope and cathead operated hammers are operator dependent and may require more frequent calibration as operators change. It is desirable to calibrate prior to starting major critical projects.

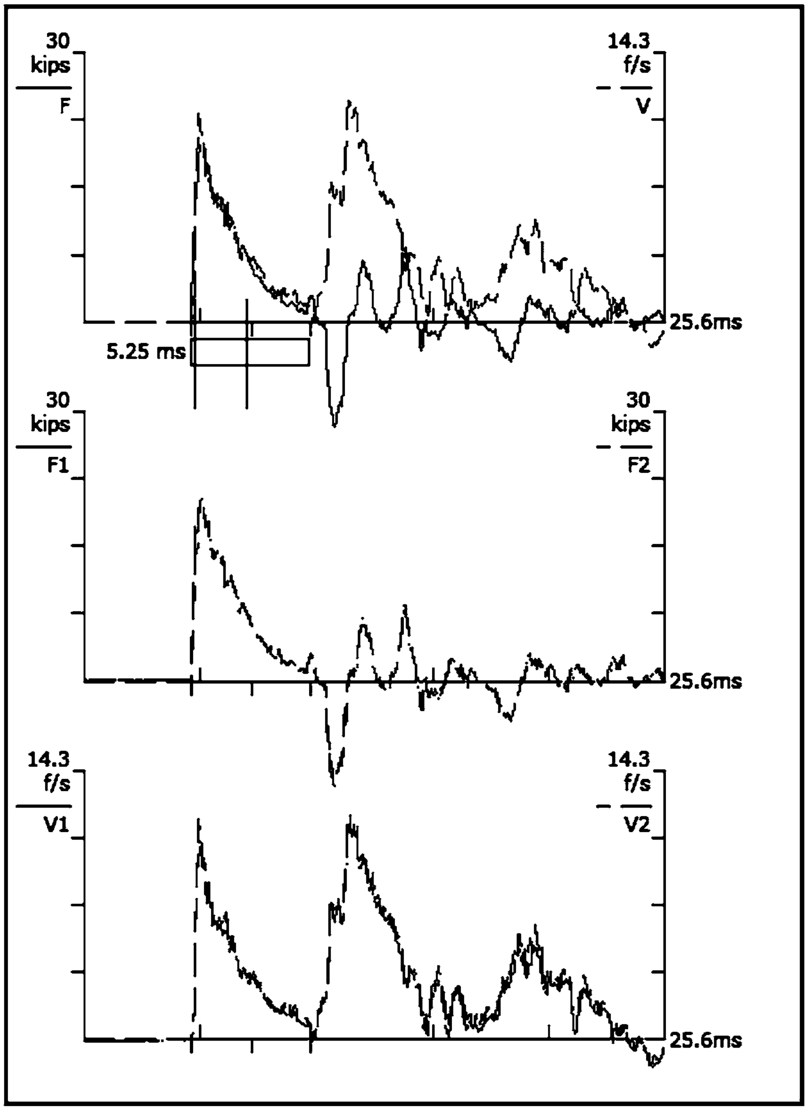

FIG. 1 Example Force- and Velocity-Time Measurement for SPT

7.12 To assure that the electronics are properly calibrated, the energy measurement system should be checked with a built-in or external signal generator with known calibrated signals. This known signal can be compared with the expected result to confirm calibration of the signal conditioning.

8. Report

8.1 All energy measurement reports shall include the following information, if applicable:

8.1.1 The name and affiliation of the person making the measurements.

8.1.2 Project and drill hole identification and the date and time.

8.1.3 Identification of the driller operating the hammer, the drill rig used (make, model, serial number), and a description of the hammer used (model and serial number if available).

8.1.3.1 *Rope and Cathead Operated Hammers*—Hammer dimensions, anvil(s) dimensions, rope size and condition, number of rope turns on cathead, rope over or under the cathead, diameter and condition of the cathead, number and condition of crown sheaves. For safety hammers, check for total stroke, drop mark, vents, lubrication condition and note size of guide rod and whether the guide rod is solid or hollow.

8.1.3.2 *Automatic Hammers*—Describe drop system, blow rate, estimated drop height, lubrication condition, anvil(s) dimension. Some hammers are rate dependent. Report the manufacturer's recommended operation rate and rate while testing.

8.1.3.3 Note any unusual hammer operating conditions that affect the hammer performance, or any changes in operating conditions. Examples include verticality, weather, or lubrication between trials.

8.1.4 The instrumented subassembly type, outside diameter, cross-sectional area and the drill rod type and diameter (recording section lengths and weights of each rod section may help assess uniformity), and cross sectional area between the hammer and the penetrometer at the bottom of the drill rods. Note and record locations of short drill rod sections.

8.1.5 The type and manufacturer of all energy measuring and processing equipment and information about the most recent calibrations of the energy measuring and processing instrument, including both force and acceleration transducers.

8.1.6 For each data set at which measurements are made, the penetration depth of the penetrometer below reference elevation, the total length between the instrumentation and the bottom of the sampler, and length from hammer impact surface to the instrumentation.

8.1.7 A record of all energy measurement results for each data set, with their average and standard deviation.

8.1.8 A representative plot of force and normalized velocity versus time for a typical blow from each data set to demonstrate the data quality.

8.1.9 The penetration resistance, or N-value, for each data set.

9. Precision and Bias

9.1 *Precision*—Test data on precision are not presented due to the nature of this test method. It is either not feasible or too costly at this time to have ten or more agencies participate in an in situ testing program at a given site.

9.1.1 The Subcommittee D18.02 is seeking any data from the users of this test method that might be used to make a limited statement on precision.

9.2 *Bias*—There is no accepted reference value for this test method, therefore, bias cannot be determined.

10. Keywords

10.1 energy; liquefaction; N-value; penetrometer; SPT; standard penetration test

APPENDIX

(Nonmandatory Information)

X1. Past History on SPT Energy Measurement

X1.1 The previous version of ASTM D 4633 was adopted in 1986 under the jurisdiction of subcommittee D18.02 on Sampling and Related Field testing for Soil Investigations following initial research by Schmertmann and Palacious (1977) (**4, 7**) to measure energy in the Standard Penetration Test (Test Method D 1586, Practice D 6066). The method was also adopted as an international reference test procedure by the International Society for Soil Mechanics and Foundation Engineering (**6**).

X1.2 In the earlier version, load cells or strain gages were used exclusively because accelerometers capable of measuring high acceleration were not reliable. The analysis method was called the "Force Squared" or EF2 method. The EF2 Method uses the theoretical proportionality of force and velocity to substitute force divided by impedance (*EA/c*) for the velocity. Provided there are no reflections from joints or changed cross sectional area, then EF2 energy can be calculated by integration of the square of the force as follows:

$$EF2 = \frac{c}{AE} \int_0^{'t'} [F(t)]^2 \, dt \qquad \text{(X1.1)}$$

where:

A = cross-sectional area of the drill rods above and below the force transducer,
c = stress wave speed in the drill rods (for example, 5120 m/s for steel),
E = modulus of elasticity of the drill rods,
$EF2$ = energy transmitted to the drill rod during the impact event,
$F(t)$ = dynamic force in the drill rod as a function of time, and
$'t'$ = time duration of the first compression pulse starting at $t = 0$ and ending at the time when the force first goes negative following the initial impact.

X1.2.1 The EF2 method integrates the energy content of the first compression pulse traveling down the drill rods, and as such, only measures part of the energy delivered to the sampler. Several correction factors (K_1, K_2, and K_c) were recommended in the old standard. As experience was gained it was realized none of these factors applied to the EF2 method correctly.

X1.2.1.1 The correction for short rods of less than 30 ft, K_2, was based on theoretical wave mechanics under the assumption that the hammer energy input was terminated by the reflective tensile wave and the remaining energy could be predicted. The factors never agreed with actual field measurements. Subsequent research has shown that this factor is not correct and should not be used. Liquefaction evaluation methods such as NCEER 2001 (**8, 9**) that advocate short rod correction factors based on the theoretical calculation are not correct.

X1.2.1.2 The correction K_c compared the actual time of first negative with the theoretical wave travel time $2L/c$, and corrected the wave speed, c. Since the wave speed in steel is invariant, such correction is inherently wrong.

X1.3 There were numerous problems with measurement of EF2 energy in the old standard. The only instrumentation requirement in the standard stated in the apparatus section: "The engineer may use any suitable apparatus that measures E_i or ER_i with a required accuracy of ±2 %. Such an apparatus usually consists of a load cell, processing instrument, and digital timer." Numerous errors could be made because of these vague instrumentation requirements.

X1.3.1 Most of the experience with energy measurements in the U.S. during the 1980s were obtained using a Binary Instruments device developed by Hall (1988) (**10**). The device was an analog system that was connected to load cells inserted in the drill string. The device sensed zero force to terminate integration of the first compression pulse.

X1.3.2 One error associated with the Binary Instruments device was integrating beyond time $2L/c$ under hard driving conditions ($N > 50$). This error was identified by Kovacs (**5**) and modifications were made to D 4633 and the Binary instruments device; however, some erroneous data were published by Riggs et al (**11**) and possibly others. Sometimes values over 100 % of theoretical energy were obtained.

X1.3.3 Another EF2 method error was the use of incorrect cross sectional area of the drill rods. In the United States, only the outside diameter of drill rods is standardized while the inside diameter varies among manufacturers (**12**). Often the true cross sectional area was not known and some published EF2 data could be erroneous.

X1.3.4 The differences in behavior between the strain gage or piezoelectric load cells are not known. The piezoelectric load cell was suspected of poor performance and questionable high peak forces due to the effect of its own mass under high accelerations.

X1.3.5 Kovacs et al (**5**) compiled the most comprehensive report on EF2 energy measurements for safety and donut hammers as well a few automatic hammer systems.

X1.3.6 In 1983 after EF2 energy measurements in Japan on a liquefaction study by Kovacs et al (**13**), Seed et al (**14**) recommended that the SPT N value be normalized to 60 % drill rod energy (N_{60}). Since then, N_{60} has become standard practice for evaluation of liquefaction resistance as outlined in Practice D 6066.

X1.4 Since it is highly unlikely that true one-directional wave propagation exists in any dynamic penetrometer system, the Force Velocity (EFV) method is the only fundamentally correct method of measuring energy content (**2**). The EFV method, integrated over the complete wave event, measures the total energy content of the event. Correction factors are not necessary for the EFV method.

X1.5 EFV and EF2 data were compared by several practioners using instrumented sub-assemblies as outlined in this standard (**1, 3**). EF2 data were either higher or lower than EFV by as much as 10 to 15 %. A comparison between the same Binary Instruments Device using EF2 and the new systems in this standard with EFV would be useful.

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(10) Hall, J. R., "Drill Rod Energy as a Basis for Correlation of SPT Data," *Proceedings of the Second European Symposium on Penetration Testing*, Amsterdam, Balkema, 1982, pp. 57-60.

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