ASTM INTERNATIONAL

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

This standard is issued under the fixed designation D4633; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

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 D1586 and Practice D6066. This procedure may also be applicable to other dynamic penetrometer tests.

1.3 The values stated in SI units are to be regarded as standard. The inch-pound units given in parentheses are mathematical conversions which are provided for information purposes only and are not considered standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method.

1.3.1 The converted inch-pound units use the gravitational system of units. In this system, the pound (lbf) represents a unit of force (weight), while the unit for mass is slugs. The converted slug unit is not given, unless dynamic (F = ma) calculations are involved.

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

1.5 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

1.5.1 The procedures used to specify how data are collected/recorded or calculated, in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analytical methods for engineering design.

1.6 The text of this standard references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.

1.7 *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]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D1586 Test Method for Penetration Test (SPT) and Split-Barrel Sampling of Soils

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D6026 Practice for Using Significant Digits in Geotechnical Data

D6066 Practice for Determining the Normalized Penetration Resistance of Sands for Evaluation of Liquefaction Potential

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms used in this standard, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

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

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

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*A Summary of Changes section appears at the end of this standard

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

3.2.4 *impedance (of the drill rod), n*—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.

3.2.5 *instrumented subassembly, n*—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.

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

3.3 *Symbols:*

3.3.1 *EFV*—the energy transmitted to the drill rod from the hammer during the impact event (see 8.1).

3.3.2 *ETR—(EFV / PE)* – ratio of the measured energy transferred to the drill rods to the theoretical potential energy.

3.3.3 *L*—length between the location of transducers on the instrumented subassembly and the bottom of the penetrometer.

3.3.4 *2L/c*—the time required for the stress wave (traveling at a known wave speed, *c*, in steel of 5123 m/s (16 810 ft/s)) to travel from the measurement location to the bottom of the penetrometer and return to the measurement location.

3.3.5 N_{60}—standard penetration resistance adjusted to a 60 % drill rod energy transfer ratio.

3.3.6 *N-value*—the number of hammer blows required to advance the sampler the last 0.305 m (1.00 ft) of the 0.457 m (1.5 ft) driven during an SPT test.

3.3.7 *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 10 and 50 (Ref (7)).

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

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 D6066.

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 D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors: Practice D3740 provides a means of evaluating some of those factors.

5. Apparatus

5.1 *Apparatus for Measurement*—An instrumented subassembly defined in 3.2.5 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 of steel drill rod and shall be at least 0.60 m (2 ft) in length. The location of the strain gauges and accelerometers shall be at least 0.30 m (1 ft) below the top of the instrumented subassembly, and shall be at least three diameters away from any cross sectional area change.

NOTE 3—While having the same nominal area for the instrumented subassembly as the drill string is desirable, variations in area are unavoidable since (*a*) the drill rods wear, (*b*) drill rod manufacture tolerance of wall thickness is rather loose, (*c*) joints already impose significant cross section changes far larger than the variation of cross section changes found among common drill rod types (for example, AW, BW, NW or N3), and (*d*) many drillers have and therefore mix both heavy and light section rods, particularly of the NW type), making it practically impossible to measure with identical cross sections.

5.2 *Apparatus to Measure Force*—Force data shall be obtained by attaching foil strain gauges in a full bridge circuit to the instrumented subassembly. The gauges shall be arranged symmetrically such that all bending effects are canceled. The instrumented subassembly shall have a minimum of two such full bridge circuits. Transducer systems that insert 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 instrumented subassembly within 100 mm (4 in.) of the force measurement location. The accelerometers shall be aligned axially with the rod in their sensing 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

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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 4—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 five times the low-pass filter frequency to avoid signal aliasing. 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) (Ref (**8**)). To avoid aliasing, data acquisition sampling rate shall be at least ten times the low-pass filter frequency for single sampling of each data point, or at least five times the low-pass filter frequency for analog to digital convertors with oversampling if the oversampling rate is at least 256 times the retained sampling rate.

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 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 2*L/c* time and the calculated energy result (see 8.1).

6. Calibration

6.1 *Force Calibration*—The instrumented subassembly shall be calibrated both in force and strain, each to an accuracy within ±2 %. The instrumented 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 $A_c = (F/E\varepsilon)$ where F is the applied measured force, E is the modulus of steel of 206 000 MPa (29 900 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 (33 ft) 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 (10 and 20 ft) long.

6.3 *Frequency of Calibration*—Force calibration and acceleration calibration shall be performed 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. If maintenance is performed on the instrumented subassembly (for example, repair), the unit shall be recalibrated before it is used again.

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; when applicable, a description of the cathead system (for example, number of rope 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; when applicable, a description of automatic-trip system, drop height, and 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.

NOTE 5—Ideally, do not combine drill rods of varying sizes (for example, AW with NW) in the drill string below the instrumented subassembly. Energy is calculated as per 8.1 using the properties of the instrumented subassembly.

NOTE 6—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 7—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 sub-assembly and drill rod including the instrumented subassembly type (for example, AW, NW-heavy, etc.), cross-sectional area, the length from the hammer impact surface to the transducers, and length from the transducers to the bottom of the drill rod string.

NOTE 8—Energy evaluation of the hammer system is more reliable when the length L is 9 to 12 m (30 to 39 ft) or more.

7.4 Connect the instrumented subassembly to the top of the drill rod string. The rod joints should be tight.

7.5 Connect each sensor 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 three 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 *Rig Calibration Interval*—Calibrate each hammer 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, whichever is less.

NOTE 9—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.

7.11 To ensure that the electronics are properly calibrated, the energy measurement system shall be checked with a built-in or external signal generator with known calibrated signals. The result of this known signal shall be compared with the expected result to confirm calibration of the signal conditioning.

8. Calculations

8.1 Calculate and record the energy transferred to the drill rods (*EFV*) to three significant digits 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.

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

8.1.1 The calculated energy *EFV* can be compared with the theoretical maximum potential energy (*PE*), and the ratio is known as the Energy Transfer Ratio (*ETR*). Calculate the energy transfer ratio (*ETR*) to the nearest whole percentage point.

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

9. Report: Test Data Sheet(s)/Form(s)

9.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in 1.5.

9.2 Record as a minimum the following general information:

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

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

9.2.3 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).

9.2.3.1 *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.

9.2.3.2 *Automatic Hammers*—Describe drop system, recommended blow rate by the manufacturer, actual blow rate while testing, estimated drop height, lubrication condition, anvil(s) dimension. Some hammers are rate dependent.