Designation: D 4945 – 08

Standard Test Method for High-Strain Dynamic Testing of Deep Foundations[1]

1. Scope*

1.1 This dynamic test method covers the procedure for applying an axial impact force with a pile driving hammer or a large drop weight that will cause a relatively high strain at the top of an individual vertical or inclined deep foundation unit, and for measuring the subsequent force and velocity response of that deep foundation unit. High-strain dynamic testing applies to any deep foundation unit, also referred to herein as a "pile," which functions in a manner similar to a driven pile or a cast-in-place pile regardless of the method of installation, and which conforms with the requirements of this test method.

1.2 This standard provides minimum requirements for dynamic testing of deep foundations. Plans, specifications, or provisions (or combinations thereof) prepared by a qualified engineer may provide additional requirements and procedures as needed to satisfy the objectives of a particular test program. The engineer in responsible charge of the foundation design, referred to herein as the "Engineer", shall approve any deviations, deletions, or additions to the requirements of this standard.

1.3 The proper conduct and evaluation of high-strain dynamic tests requires special knowledge and experience. A qualified engineer should directly supervise the acquisition of field data and the interpretation of the test results so as to predict the actual performance and adequacy of deep foundations used in the constructed foundation. A qualified engineer shall approve the apparatus used for applying the impact force, driving appurtenances, test rigging, hoist equipment, support frames, templates, and test procedures.

1.4 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. The word "shall" indicates a mandatory provision, and the word "should" indicates a recommended or advisory provision. Imperative sentences indicate mandatory provisions.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

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

1.7 The method used to specify how data are collected, calculated, or recorded in this standard is not directly related to the accuracy to which the data can be applied in design or other uses, or both. How one applies the results obtained using this standard is beyond its scope.

1.8 *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.* For a specific precautionary statement, see Note 4.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C 469 Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
D 198 Test Methods of Static Tests of Lumber in Structural Sizes
D 653 Terminology Relating to Soil, Rock, and Contained Fluids
D 1143/D 1143M Test Methods for Deep Foundations Under Static Axial Compressive Load
D 3689 Test Methods for Deep Foundations Under Static Axial Tensile Load
D 3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
D 6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions*—For common definitions of terms used in this standard, see Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *cast in-place pile, n*—a deep foundation unit made of cement grout or concrete and constructed in its final 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 D18.11 on Deep Foundations.

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[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.

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

for example, drilled shafts, bored piles, caissons, auger cast piles, pressure-injected footings, etc.

3.2.2 *deep foundation*, *n*—a relatively slender structural element that transmits some or all of the load it supports to the soil or rock well below the ground surface, that is, a driven pile, a cast-in-place pile, or an alternate structural element having a similar function.

3.2.3 *deep foundation cushion*, *n*—the material inserted between the helmet on top of the deep foundation and the deep foundation (usually plywood).

3.2.4 *deep foundation impedance*, *n*—a measure of the deep foundation's resistance to motion when subjected to an impact event. Deep foundation impedance can be calculated by multiplying the cross-sectional area by the dynamic modulus of elasticity and dividing the product by the wave speed. Alternatively, the impedance can be calculated by multiplying the mass density by the wave speed and cross-sectional area.

$$Z = (EA / c) = \rho c A \tag{1}$$

where:

Z = impedance,
E = dynamic modulus of elasticity,
A = cross-sectional area,
c = wave speed, and
ρ = mass density.

3.2.5 *driven pile*, *n*—a deep foundation unit made of preformed material with a predetermined shape and size and typically installed by impact hammering, vibrating, or pushing.

3.2.6 *follower*, *n*—a structural section placed between the impact device and the deep foundation during installation or testing.

3.2.7 *hammer cushion*, *n*—the material inserted between the hammer striker plate and the helmet on top of the deep foundation.

3.2.8 *impact event*, *n*—the period of time during which the deep foundation is moving due to the impact force application. See Fig. 1.

3.2.9 *impact force*, *n*—*in the case of strain transducers*, the impact force is obtained by multiplying the measured strain (ε) with the cross-sectional area (A) and the dynamic modulus of elasticity (E).

3.2.10 *mandrel*, *n*—a stiff structural member placed inside a thin shell to allow impact installation of the thin section shell.

3.2.11 *moment of impact*, *n*—the first time after the start of the impact event when the acceleration is zero. See Fig. 1.

3.2.12 *particle velocity*, *n*—the instantaneous velocity of a particle in the deep foundation as a strain wave passes by.

3.2.13 *restrike, n or v*—the redriving of a previously driven pile, typically after a waiting period of 15 min to 30 days or more, to assess changes in ultimate axial compressive static capacity during the time elapsed after the initial installation.

3.2.14 *wave speed*, *n*—the speed with which a strain wave propagates through a deep foundation. It is a property of the deep foundation composition and for one-dimensional wave propagation is equal to the square root of the quotient of the Modulus of Elasticity divided by mass density: $c = (E/\rho)^{1/2}$.

4. Significance and Use

4.1 Based on the measurements from strain or force, and acceleration, velocity, or displacement transducers, this test method obtains the force and velocity induced in a pile during an axial impact event (see Figs. 1 and 2). The Engineer may analyze the acquired data using engineering principles and judgment to evaluate the integrity of the pile, the performance of the impact system, and the maximum compressive and tensile stresses occurring in the pile.

4.2 If sufficient axial movement occurs during the impact event, and after assessing the resulting dynamic soil response along the side and bottom of the pile, the Engineer may analyze

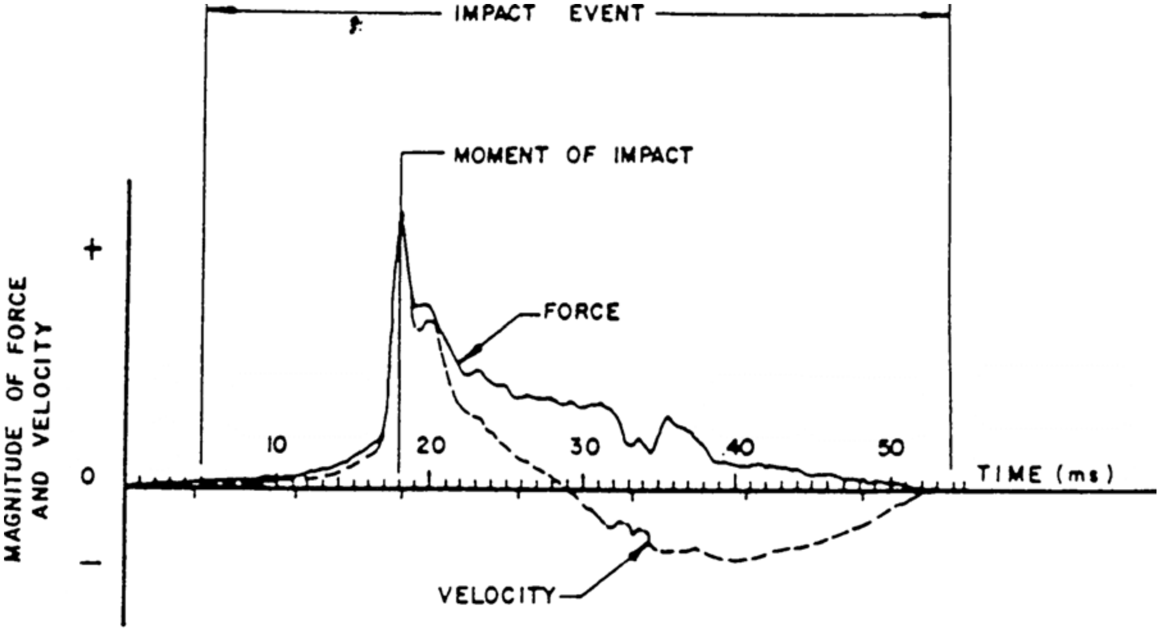


FIG. 1 Typical Force and Velocity Traces Generated by the Apparatus for Obtaining Dynamic Measurements

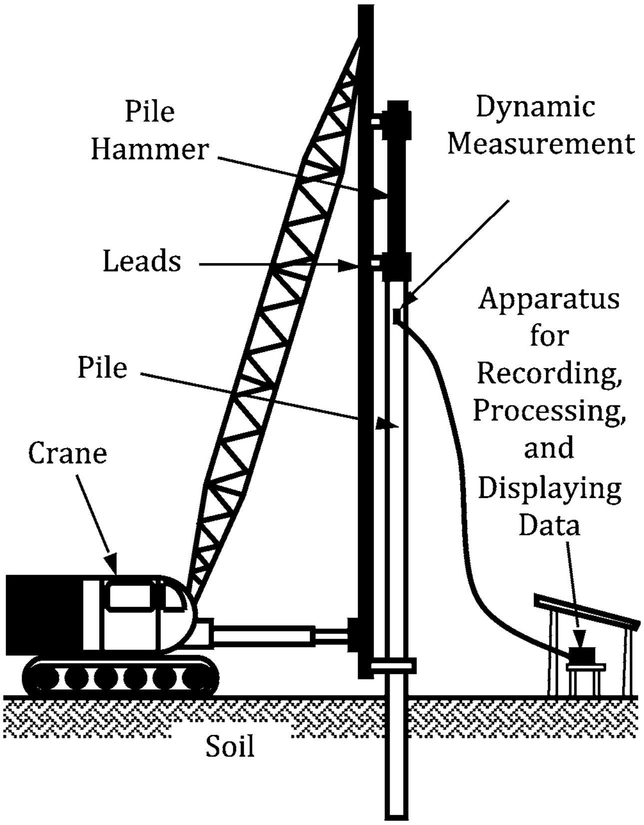


FIG. 2 Typical Arrangement for High-Strain Dynamic Testing of a Deep Foundation

the results of a high-strain dynamic test to estimate the ultimate axial static compression capacity (see Note 1). Factors that may affect the axial static capacity estimated from dynamic tests include, but are not limited to the: *(1)* pile installation equipment and procedures, *(2)* elapsed time since initial installation, *(3)* pile material properties and dimensions, *(4)* type, density, strength, stratification, and saturation of the soil, or rock, or both adjacent to and beneath the pile, *(5)* quality or type of dynamic test data, *(6)* foundation settlement, *(7)* analysis method, and *(8)* engineering judgment and experience. If the Engineer does not have adequate previous experience with these factors, and with the analysis of dynamic test data, then a static load test carried out according to Test Method D 1143 should be used to verify estimates of static capacity and its distribution along the pile length. Test Method D 1143 provides a direct and more reliable measurement of static capacity.

NOTE 1—The analysis of a dynamic test will under predict the ultimate axial static compression capacity if the pile movement during the impact event is too small. The Engineer should determine how the size and shape of the pile, and the properties of the soil or rock beneath and adjacent to the pile, affect the amount of movement required to fully mobilize the static capacity. A permanent net penetration of as little as 2 mm per impact may indicate that sufficient movement has occurred during the impact event to fully mobilize the capacity. However, high displacement driven piles may require greater movement to avoid under predicting the static capacity, and cast-in-place piles often require a larger cumulative permanent net penetration for a series of test blows to fully mobilize the capacity. Static capacity may also decrease or increase over time after the pile installation, and both static and dynamic tests represent the capacity at the time of the respective test. Correlations between measured ultimate axial static compression capacity and dynamic test estimates generally improve when using dynamic restrike tests that account for soil strength changes with time (see 6.8).

NOTE 2—Although interpretation of the dynamic test analysis may provide an estimate of the pile's tension (uplift) capacity, users of this standard are cautioned to interpret conservatively the side resistance estimated from analysis of a single dynamic measurement location, and to avoid tension capacity estimates altogether for piles with less than 10 m embedded length. (Additional transducers embedded near the pile toe may also help improve tension capacity estimates.) If the Engineer does not have adequate previous experience for the specific site and pile type with the analysis of dynamic test data for tension capacity, then a static load test carried out according to Test Method D 3689 should be used to verify tension capacity estimates. Test Method D 3689 provides a direct and more reliable measurement of static tension capacity.

NOTE 3—The quality of the result produced by this test method 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/sampling/inspection/etc. Users of this test method 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.

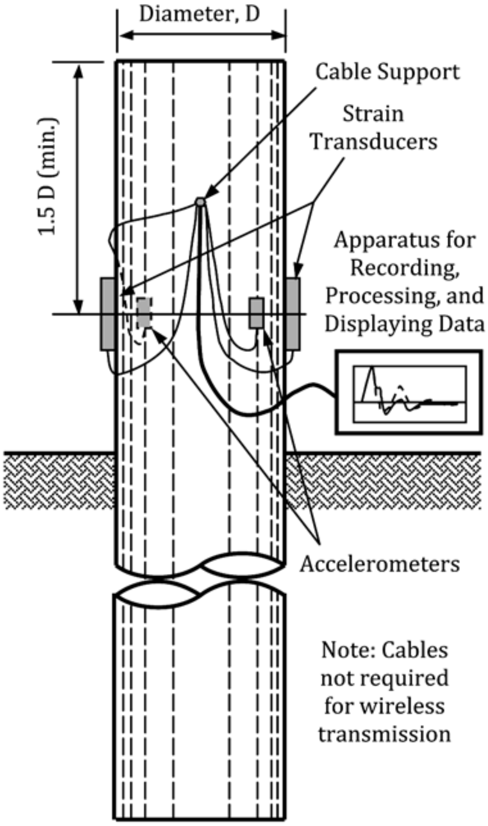
5. Apparatus

5.1 *Impact Device*—A high-strain dynamic test measures the pile response to an impact force applied at the pile head and in concentric alignment with its long axis (see Figs. 2 and 3). The device used to apply the impact force should provide sufficient energy to cause pile penetration during the impact event adequate to mobilize the desired capacity, generally producing a maximum impact force of the same order of magnitude, or greater than, the ultimate pile capacity (static plus dynamic). The Engineer may approve a conventional pile driving hammer, drop weight, or similar impact device based on predictive dynamic analysis, experience, or both. The impact shall not result in dynamic stresses that will damage the pile, typically less than the yield strength of the pile material after reduction for potential bending and non-uniform stresses (commonly 90 % of yield for steel and 85 % for concrete). The Engineer may require cushions, variable control of the impact energy (drop height, stroke, fuel settings, hydraulic pressure, etc.), or both to prevent excessive stress in the pile during all phases of pile testing.

5.2 *Dynamic Measurements*—The dynamic measurement apparatus shall include transducers mounted externally on the pile surface, or embedded within a concrete pile, that are capable of independently measuring strain and acceleration versus time during the impact event at a minimum of one specific location along the pile length as described in 5.2.7.

5.2.1 *External Transducers*—For externally mounted transducers, remove any unsound or deleterious material from the pile surface and firmly attach a minimum of two of each of type of transducer at a measurement location that will not penetrate the ground using bolts, screws, glue, solder, welds, or similar attachment.

5.2.2 *Embedded Transducers*—Position the embedded transducers at each measurement location prior to placing the pile concrete, firmly supported by the pile reinforcement or formwork to maintain the transducer location and orientation



NOTE—Strain transducer and accelerometer may be combined into one unit on each side of the deep foundation.

FIG. 3 Schematic Diagram of Apparatus for Dynamic Monitoring of Deep Foundations

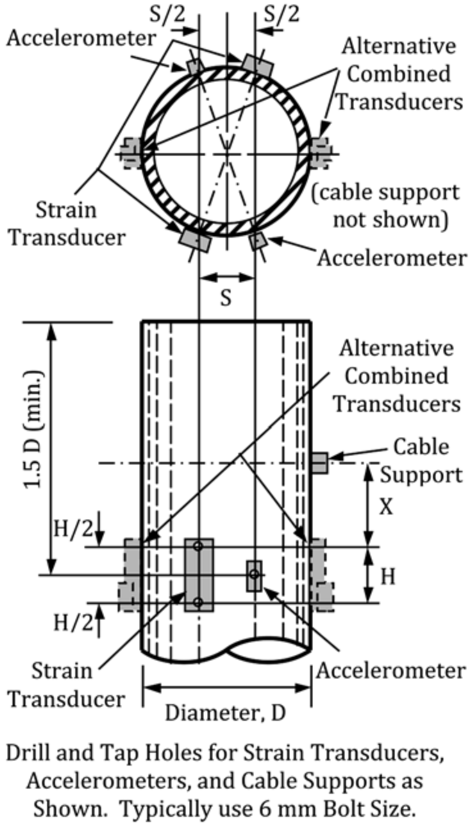
during the concrete placement. When located near the pile head, one of each type of embedded transducer located at the centroid of the pile cross-section should provide adequate measurement accuracy, which may be checked by proportionality (see 6.9). Embedded transducers installed along the pile length and near the pile toe help define the distribution of the dynamic load within the pile, but usually require data quality checks other than proportionality, such as redundant transducers (see 6.9). Embedded transducers shall provide firm anchorage to the pile concrete to obtain accurate measurements; the anchorage and sensors should not significantly change the pile impedance.

5.2.3 *Transducer Accuracy*—The transducers shall be calibrated prior to installation or mounting to an accuracy of 3 % throughout the applicable measurement range. If damaged or functioning improperly, the transducers shall be replaced, repaired and recalibrated, or rejected. The design of transducers, whether mounted or embedded as single units or as a combined unit, shall maintain the accuracy of, and prevent interference between, the individual measurements. In general, avoid mounting or embedding acceleration, velocity, or displacement transducers so that they bear directly on the force or strain transducers, and place all transducers so that they have immediate contact with the pile material.

5.2.4 *Strain Transducers*—The strain transducers shall include compensation for temperature effects, and shall have linear output over the full operating range (typically between –2000 and +2000 microstrain plus an additional allowance for possible strain induced by mounting on a rough surface). Attachment points shall be spaced (dimensions S and H in Figs. 4-7) no less than 50 mm and no more than 100 mm apart. When attached to the pile, their natural frequency shall be in excess of 2000 Hz.

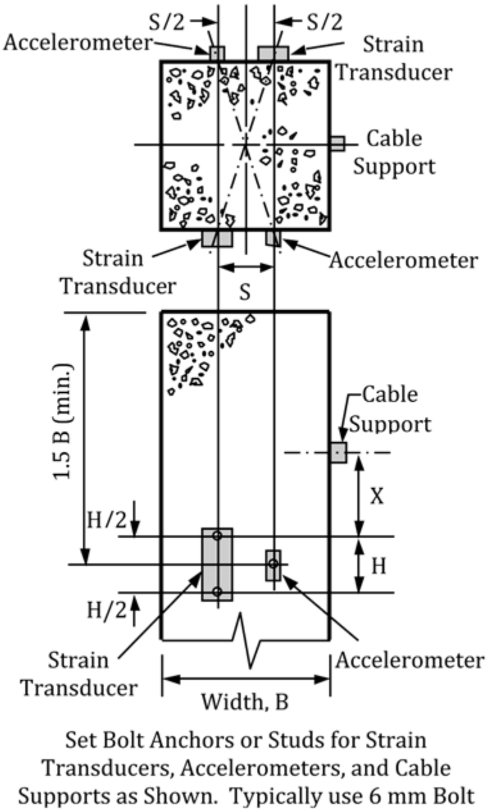
5.2.4.1 As an alternate to strain transducers, axial force measurements can be made by force transducers placed between the pile head and the impact device, or affixed in the pile cross-section, although such transducers may alter the dynamic characteristics of the driving system, the dynamic pile response, or both. Force transducers shall have impedance between 50 and 200 % of the pile impedance. The output signal shall be linearly proportional to the axial force, even under eccentric load application. The connection between the force transducers and the deep foundation shall have the smallest possible mass and least possible cushion necessary to prevent damage.

5.2.5 *Acceleration, Velocity, or Displacement Transducers*—Velocity data shall be obtained by using the dynamic measurement apparatus to integrate the acceleration signals from accelerometers. The accelerometers shall be directly attached to the pile surface, mounted to the pile with small rigid (solid, nearly cubic shape) metal blocks, or embedded in the pile. Do not use overhanging brackets or plastic



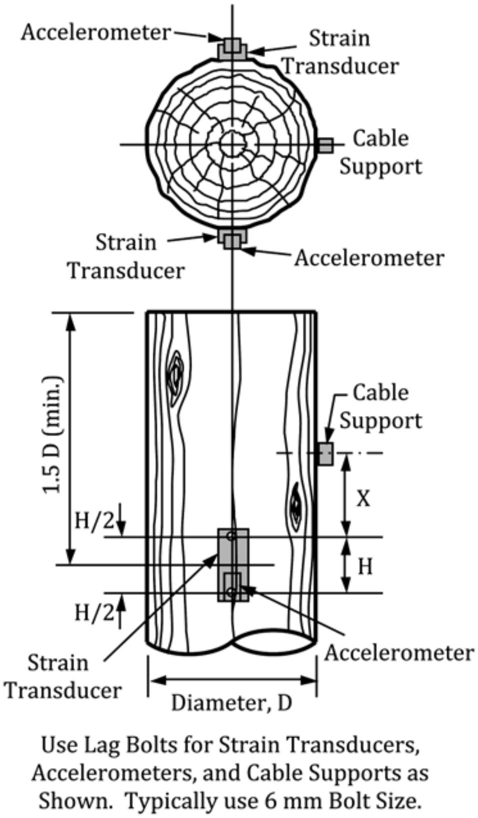
NOTE—Shown as separate transducers or alternative combined transducers.

FIG. 4 Typical Arrangement for Attaching Transducers to Pipe Piles



NOTE—Shown as separate transducers.

FIG. 5 Typical Arrangement for Attaching Transducers to Concrete Piles



NOTE—Shown as combined transducers.

FIG. 6 Typical Arrangement for Attaching Transducers to Wood Piles

mounting blocks that can deform during impact. Accelerometers shall be linear to at least 1000 g and 1000 Hz for concrete piles. For steel piles, it is advisable to use accelerometers that are linear to at least 2000 g and 2000 Hz. For piezoelectric accelerometers using an AC coupled signal path, the resonant frequency shall be above 30 000 Hz when rigidly mounted, or above 10 000 Hz if the mounting is damped, and the time constant shall be at least 1.0 s to preserve the low frequency signal content. If piezoresistive accelerometers are used, then they should have a resonant frequency of at least 2500 Hz and a damped mounting. Alternatively, velocity or displacement transducers may be used to obtain velocity data, provided they are equivalent in performance to the specified accelerometers.

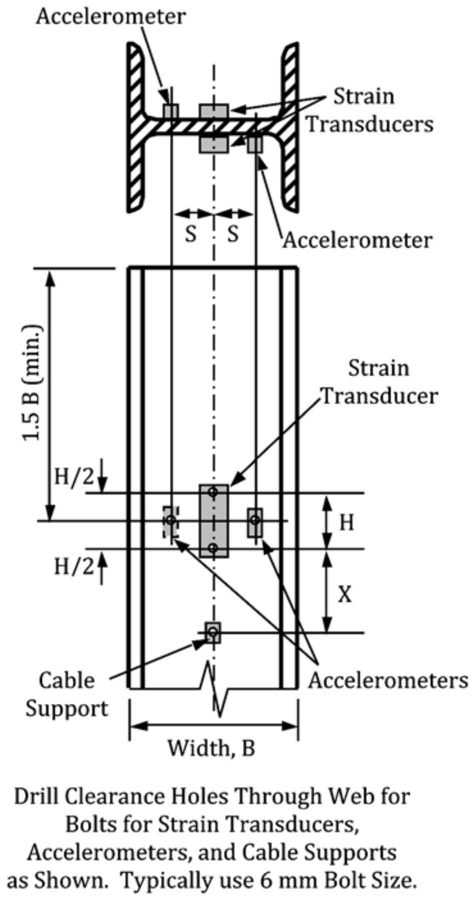
5.2.6 *Combined Transducers*—Force and velocity instrumentation may use individual transducers connected separately to the pile, or transducers connected together and attached to the pile as a combined unit.

5.2.7 *Placement of Transducers*—To avoid irregular stress concentrations at the ends of the pile, locate transducers a distance of at least 1.5 times the pile width from the top (or bottom) of pile as illustrated in Figs. 4-7. (These figures are typical, but not exclusionary.) Align transducers with their sensitive direction parallel to the long axis of the pile. Arrange strain transducers so that when averaged their measurements cancel axial bending stresses. Arrange accelerometers so that when averaged their measurements cancel movements due to bending. Unless located at the pile centroid, place similar types of transducer so that they are symmetrically opposed and equidistant from the pile centroid in a plane perpendicular to the pile axis. Verify the final position, firm connection, and alignment of all transducers, both external and embedded. Section 6.9 describes an important proportionality check required for both external and embedded transducers that helps verify measurement accuracy.

5.3 *Signal Transmission*—The signals from the transducers shall be transmitted to the apparatus for recording, processing, and displaying the data (see 5.4) by means of a cable or wireless equivalent. An intermediate apparatus may be used for initial signal processing prior to transmission of the signal data to the apparatus for recording, processing, and displaying the data if the processing functions it provides meet the requirements of 5.4. Cables shall be shielded to limit electronic and other transmission interference. If wireless transmission is used, the signals arriving at the apparatus shall accurately represent the continuity and magnitude of the transducer measurements over the frequency range of the dynamic measurement apparatus.

5.4 *Recording, Processing, and Displaying Data*:

5.4.1 *General*—The signals from the transducers (see 5.2) shall be transmitted during the impact event to an apparatus for recording, processing, and displaying the data. The apparatus shall include a visual graphics display of the force and velocity versus time, non-volatile memory for retaining data for future



NOTE—Shown as separate transducers.

FIG. 7 Typical Arrangement for Attaching Transducers to H-Piles

analysis, and a computational means to provide results consistent with Engineer's field testing objectives, for example, maximum stresses, maximum displacement, energy transferred to the pile, etc. The apparatus for recording, processing, and displaying data shall include compensation for temperature effects and provide a self-calibration check of the apparatus for recording, processing and displaying. No error shall exceed 2 % of the maximum signal expected. Fig. 3 shows a typical schematic arrangement for this apparatus.

5.4.2 *Recording Data*—The raw data from the transducers shall be recorded on site, electronically in digital form, with a minimum of 12 bit ADC resolution and including at most only the minimal processing required to obtain the force and velocity. Transducer data recorded after minimal processing shall also record the information required to recover the raw data signals for later reprocessing as needed, for example, calibrations, wave speed, mass density, pile area, etc. When determining velocity by analog integration of acceleration, or analog differentiation of displacement, use a minimum sample frequency for each data channel of 5000 Hz for concrete piles and 10 000 Hz for timber or steel piles. When determining velocity by digital integration of acceleration, or digital differentiation of displacement, use a minimum sample frequency for each data channel of 10 000 Hz for concrete piles and 40 000 Hz for timber or steel piles. Both analog and digital processing shall include signal conditioning that retains the frequency content appropriate to the sampling rate of the interpreted velocity signal. The minimum total time sampled for each impact event shall be the greater of 100 milliseconds or $3L/c$ (where L is the pile length and c is the pile material wave speed) with most of this time following the moment of impact as shown in Fig. 1.

5.4.3 *Processing Data*—As a minimum, the apparatus for processing signals from the transducers shall provide the following functions:

5.4.3.1 *Force Measurements*—The apparatus shall provide signal conditioning for the force measurement system. If strain transducers are used (see 5.2.4), the apparatus shall compute the net axial force on the cross-section of the pile. The force output shall be balanced to a reference level (for example, zero) prior to the impact event.

5.4.3.2 *Velocity Data*—If accelerometers are used (see 5.2.5), the apparatus shall integrate the acceleration over time to obtain velocity. If displacement transducers are used, the apparatus shall differentiate the displacement over time to obtain velocity. If required, the apparatus shall zero the velocity between impact events and shall adjust the velocity record to account for transducer zero drift during the impact event.

5.4.3.3 *Signal Conditioning*—The signal conditioning for force and velocity shall have equal frequency response curves to avoid relative phase shifts and relative amplitude differences and retain all frequency components in the data below at least 2000 Hz.

5.4.4 *Display of Data*—For each impact event, the raw or processed signals from the transducers specified in 5.2 shall be displayed during data acquisition or replay as a function of time, such as on a digital graphics display.

5.4.5 *Field Supervision*—A qualified engineer shall directly supervise all field testing and assess data quality and reliability for later detailed evaluation (see 6.9). Alternatively, field personnel may transmit the data concurrently as acquired to a qualified engineer supervising the testing from a remote location.

6. Procedure

6.1 *General*—Allow sufficient time for driven and cast-in-place deep foundations constructed of concrete to gain adequate structural strength prior to testing. Record applicable project information (Section 7). Attach the transducers (Section 5) to the deep foundation, perform any calibration checks recommended by the equipment manufacturer, and take the dynamic measurements for the impacts during the interval to be monitored together with routine observations of number of blows per unit penetration ("blow count") or set per blow. Determine the pile response to the high-strain dynamic test from a minimum of ten impact records during initial driving and, when used for soil resistance computations, normally from one or two representative blows at the beginning of a restrike.

NOTE 4—**Warning:** Never approach a deep foundation being tested while the hammer or large drop weight is operating as materials or appurtenances may break free and jeopardize the safety of persons in the vicinity. Preferably the contractor crew will attach the transducers to the pile.

6.2 *Determination of Wave Speed for Deep Foundations*—The wave speed of concrete or wood piles should preferably be determined from an early impact event if a tensile reflection from the pile toe is clearly identified. Divide two times the length of pile below transducers by the observed time between start of the impact (for example, initial sharp rise of the signal) and the start of the tensile reflection (for example, later relative velocity increase) to obtain the wave speed. For piles with instrumentation at both the head and near the toe, the wave speed can be calculated from dividing the distance between these locations by the time between impact arrivals at these locations. Alternatively, place the pile on supports or level ground free and clear from neighboring piles and obstructions. Then attach an accelerometer to the pile and strike the end of the pile with a sledge hammer of suitable weight. Take care not to damage or dent the pile. Record (see 5.4.2) and display (see 5.4.4) the accelerometer signal. Measure the total time between acceleration peaks for at least three cycles of reflection or $6L/c$ (where L is the pile length and c is the pile material wave speed). Divide the product of the number of cycles and twice the total pile length by this total time to determine the wave speed. The wave speed of structural steel piles can be assumed as 5123 m/s. Assumed wave speed values, and those determined during a low strain event, should be verified directly or indirectly if possible. The overall wave speed observed during a high-strain event as described above may differ (typically slower) from the local wave speed used to compute impedance because of variability in pile properties, degradation of pile material during repeated hammer blows, or splices in the pile length.

6.3 *Determination of Mass Density of Deep Foundations*—The density of each wood pile shall be determined from the total weight of the pile, or a sample of the pile, the corresponding volume, and the gravitational constant. The density of concrete or grout can be measured in a similar manner. Alternately, the density of concrete piles is often assumed to be 2450 kg/m^3 and the density of grout used for auger-cast or similar types of piles is often assumed to be 2150 kg/m^3. The mass density of structural steel piles can be assumed as 7850 kg/m^3. The mass density of composite deep foundations, such as concrete filled steel pipes, can be computed from a weighted average of the areas of the materials at each differing cross-section. Assumed and computed values of mass density should be verified directly if possible, or indirectly through their effect on impedance and proportionality (see 6.9).

6.4 *Determination of Dynamic Modulus of Elasticity of Deep Foundations*—The dynamic modulus of elasticity (E) for concrete, wood, steel, or composite piles can be computed as the product of the square of the wave speed (determined as indicated in 6.2) times the mass density ($E = \rho c^2$). The dynamic modulus of elasticity may be assumed as 207×10^6 kPa for structural steel. Assumed and computed values of the dynamic modulus of elasticity should be verified directly if possible, or indirectly through their effect on impedance and proportionality (see 6.9).

NOTE 5—Alternatively, the static modulus of elasticity for concrete piles and wood piles may be determined from measurements made during a compression test performed in accordance with Test Methods C 469 or D 198 respectively. The Engineer should then estimate the dynamic modulus (typically assumed 10 % greater) from this measurement.

6.5 *Preparation*—Mark the pile clearly at appropriate unit intervals to prepare for recording blow counts. Attach the transducers as described in Section 5. Determine the pile wave speed (see 6.2) and density (see 6.3). For concrete piles or concrete filled pipe piles, place a pile cushion made of plywood or other material with similar stiffness on top of the pile. For concrete filled pipe piles, the concrete must completely fill the pile top so that the impact is transferred through the pile cushion to the concrete. Position the impact device on the pile head to apply the impact force concentric with the long axis of the pile. Prepare the apparatus for recording, processing, and displaying data to receive the dynamic measurements and balance the strain (or force) and acceleration signals to their respective reference levels (for example, zero).

6.6 *Recording Hammer Information*—Record the mass of the hammer ram or drop weight. For drop hammers and single acting diesel and air/steam/hydraulic hammers, record the drop height of the ram or the ram travel length. For double acting diesel hammers, measure the bounce pressure, and for double acting steam or compressed air hammers, measure the steam or air pressure in the pressure line to the hammer. For hydraulic hammers or any of the previously listed hammer types, record the kinetic energy from the hammer readout when available. Record the number of impact blows per minute delivered by the hammer.

6.7 *Taking Measurements*—Take, record, and display force and velocity measurements for each impact event. Compare the force and the product of velocity and impedance at the moment of impact (see 6.9). Obtain the net permanent displacement per impact from the pile driving blow count record, or from marks placed on the pile prior to and after the test using the same reference, directly from the displacement transducers (if used), or by integration of the velocity versus time record (typically less reliable). Obtain the maximum energy transferred to the location of the transducers from the integral over time of force multiplied by velocity.

6.8 *Time of Testing*—Dynamic tests performed during the initial installation of a driven pile typically monitor the performance of the impact device, the driving stresses in the pile, the pile integrity, and relative changes in capacity. If the test results are used for static capacity computations, then dynamic measurements should (also) be performed during restrikes of the deep foundation, after waiting a period of time following the initial installation sufficient to allow pore water pressure and soil strength changes to occur. (See Note 1.)

6.9 *Data Quality Checks*—Confirm the accuracy of dynamic measurements obtained near the pile head by periodically checking that the average of the measured force signals and the product of the impedance and the average of the measured velocity signals agree proportionally at the moment of impact. Do not expect proportionality when reflections occur from pile impedance changes nearby and below the transducers or from soil resistance, such as for transducers near the pile bottom or, depending on the rise time to the initial force peak, transducers located between the pile head and the bottom. Reject non proportional data. Two velocity signals should generally agree well at a particular measurement location, even though the two force signals may indicate significant bending. Two embedded strain measurements made in close proximity to the pile axis at the same location, or at adjacent locations on the pile axis, can provide a consistency check of each other. For piles with a high percentage of end bearing, analysis of measurements made near the pile head may provide confirmation of measurements near the pile bottom. For an impact device delivering relatively similar impacts, the force and velocity versus time over a series of consecutive impact events should be relatively consistent. Consistent and proportional signals of (average) force versus (average) velocity times pile impedance are the result of the transducer systems performing properly and the apparatus for recording, processing, and displaying data being properly calibrated. If the signals are not consistent, or are not in proportionality agreement, investigate the cause and correct as necessary. If the cause is loose or misaligned instrumentation, then correct the problem prior to continuing the test. If the cause is determined to be a transducer malfunction, it must be repaired or recalibrated, or both, before further use. If the cause cannot be determined and rectified, then the test is to be rejected. Perform self-calibration checks of the apparatus used for recording, processing, and displaying data periodically during testing as recommended by the manufacturer, and recalibrate before further use if found to be out of manufacturer's tolerance.

NOTE 6—It is generally recommended that all components of the apparatus for obtaining dynamic measurements and the apparatus for recording, processing and displaying data be calibrated at least once every two years to the standards of the manufacturer.

6.10 *Followers and Mandrels*—If a follower is used for installing and testing cast-in-place concrete deep foundations, this follower should have an impedance between 80 and 150 % of that of the deep foundation. However, additional caution and analysis may be required if the impedance is not within 10 % of that of the deep foundation. For mandrel-driven piles, the mandrel may be instrumented in a similar way to a driven pile provided that the mandrel is constructed of a single member with no joints.

6.11 *Testing Cast-in-Place Deep Foundations*—For testing cast-in-place piles it is often advantageous to build up the top of the pile to encase protruding reinforcement, to strengthen it for the impact using a steel shell, or to eliminate excessive excavation (sensors must be mounted at least 1.5 diameters below the impact location). The pile top should be flat and square to the longitudinal pile axis, and should be protected with plywood cushions, or other cushion material of uniform thickness. A thick steel plate may also be placed on top of the plywood to distribute the impact. Preferably apply a series of single impact blows using a drop mass having a weight of at least 1 to 2 % of the desired ultimate test capacity, beginning with a low drop height to check transducer function and pile stresses and then progressing to greater drop heights to mobilize additional pile capacity. For externally mounted transducers, carefully select transducer locations having sound concrete, and grind or sand the pile as necessary to obtain a smooth, flat, clean surface on which to mount the transducers parallel to the pile axis. Because cast-in-place piles may have non uniform material properties and a variable, irregular cross-section, when using externally mounted transducers consider placing four strain transducers equally spaced around the perimeter and as described in 5.2.7. The average force determined from each diametrically opposed pair of transducers can then be compared together, and with the average velocity as in 6.9, to assess the data quality of all force measurements.

NOTE 7—The strength and dynamic modulus of elasticity for cast-in-place deep foundations depends on the quality and the age of concrete, and can vary considerably over the cross-section and along the length of the deep foundation. The dynamic modulus of elasticity as calculated from the wave speed (see 3.2) will therefore be an average value which may differ from the modulus at the transducer location. If the cast-in-place deep foundation is encased in a steel shell, then use a composite mass density and composite dynamic modulus of elasticity.

7. Report

7.1 The report of the load test shall include any information required by the Engineer plus the following information when applicable and as available.

7.2 *General*:

7.2.1 Project identification and location, and

7.2.2 Log(s) of nearby or typical test boring(s).

7.3 *Deep Foundation Installation Equipment*:

7.3.1 For driven piles: description of driving methods and installation equipment used for driving piles, testing piles, or both as appropriate, for example, make, model, and type of hammer, size (ram weight and stroke), manufacturer's energy rating, capabilities, operating performance levels or pressures, fuel settings, hammer cushion and pile cushion descriptions with cushion exchange details, and description of lead type and any special installation equipment such as a follower, mandrel, punch, pre-drill or jet.

7.3.2 For cast-in-place concrete piles: description of construction methods, drilling or augering equipment, and concrete or grout placement, for example, type of drill rig, type and dimensions of drill tool(s), auger(s), and cleanout tool(s), tremie, concrete or grout pump, and casings.

7.4 *Test Pile(s)*:

7.4.1 Identification (name and designation) of test pile(s),

7.4.2 Required ultimate axial static compressive capacity,

7.4.3 Type and dimensions of deep foundation(s) including nominal or actual cross-sectional area, or both, length, wall thickness of pipe or casing, and diameter (as a function length for tapered or composite deep foundations),

7.4.4 For driven or cast-in-place concrete piles: date(s) test pile constructed or cast, design and measured concrete cylinder strengths and date of test(s), density, effective prestress, and description of internal and external reinforcement (type, grade, size, length, number and arrangement of prestress wire, longitudinal bars, lateral ties, and spiral stiffeners; casing or shell size and length),

7.4.5 For steel piles: steel designation, grade, minimum yield strength, and type of pile (for example, seamless or spiral weld pipe, H section designation),

7.4.6 For timber piles: length, straightness, preservative treatment, tip and butt dimensions (and area as a function of length), and measured density for each pile, 7.4.7 Description and location of splices, special pile tip protection, and any special coatings applied if applicable,

7.4.8 Inclination angle from vertical, design and installed, and

7.4.9 Observations of deep foundations including spalled areas, cracks, head surface of deep foundations.

7.5 *Deep Foundation Installation*:

7.5.1 For cast-in-place piles, include the volume of concrete or grout placed in deep foundation (volume versus depth, if available), and a description of installation procedures used, such as casing installation or extraction,

7.5.2 For driven piles, include date of installation, driving records with blow count, and hammer stroke or operating level for final unit penetration,

7.5.3 Elevations of the pile top, pile bottom, and ground surface referenced to a datum, and

7.5.4 Cause and duration of installation interruptions and notation of any unusual occurrences.

7.6 *Dynamic Testing*:

7.6.1 Description of the dynamic test apparatus, including make, model, analog or digital velocity integration, sampling rate, transducers, measurement location(s), etc.,

7.6.2 Date of test(s), sequence of testing (for example, "end of driving" or "beginning of restrike"), and elapsed time since end of initial driving for restrikes,

7.6.3 Density, wave speed, and dynamic modulus of elasticity of the test deep foundation,

7.6.4 Penetration resistance (blows per unit penetration, or set per blow) and embedment depth,

7.6.5 Graphical presentation of velocity and force measurements in the time domain for representative blows,

7.6.6 Analysis method(s) used to interpret or evaluate test measurements,

7.6.7 Interpretation of the test measurements, including measurements down the pile if applicable, to estimate as appropriate the overall magnitude of the dynamic and static axial compressive capacity mobilized at the time of testing, the distribution of the dynamic and static axial compressive capacity along the pile length, and the engineering properties of the pile and the soil or rock adjacent to the pile as used in the interpretation,

7.6.8 Comments on the performance of the impact device as measured by the energy transferred into the deep foundation with comparison to manufacturer's rating or ram weight and drop height,

7.6.9 Comments on the driving stresses within the deep foundation, and whether measured or estimated through analysis,

7.6.10 Comments on the integrity of the deep foundation, and

7.6.11 Numerical summary of measured and interpreted results, with statistical analysis as appropriate.

8. Precision and Bias

8.1 *Precision*—Test data on precision is 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. The inherent variability of the soil, or rock, or both surrounding the pile, the pile driving apparatus, and the pile itself adversely affect the determination of precision.

8.1.1 The Subcommittee D18.11 is seeking any data from the users of this test method that might be used to make a limited statement on precision.

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

9. Keywords

9.1 augered piles; deep foundations; drilled shafts; driven piles; driving stresses; dynamic testing; pile bearing capacity; pile driving hammer performance; pile integrity

SUMMARY OF CHANGES

Subcommittee D18.11 has identified the location of selected changes to this standard since the last issue (D 4945 – 00) that may impact the use of this standard (approved Oct. 1, 2008).

(*1*) Change title and text to include deep foundations that function similar to driven piles, specifically cast-in-place piles.

(*2*) Inclusion of current D18 caveats, D 6026, and D 3740.

(*3*) Require supervision by a qualified engineer during test planning and field work.

(*4*) Refer approval of testing variations to the "Engineer" in responsible charge of the foundation design.

(*5*) Added definitions in Terminology, especially "wave speed" and "particle velocity."

(*6*) Improve and clarify "Significance and Use."

(*7*) Addition of embedded and combined transducers.

(*8*) More specific and updated requirements for transducers and for processing, recording, displaying data.

(*9*) More complete Procedure, including determination of wave speed, density, and modulus, an improved description of data quality checks, and consideration of the time of testing effects.

(*10*) Updated and condensed reporting requirements.

(*11*) Updated figures to show more generic test equipment.

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