



Standard Test Method for High-Strain Dynamic Testing of Piles¹

This standard is issued under the fixed designation D 4945; 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 covers the procedure for testing vertical or batter piles individually to determine the force and velocity response of the pile to an impact force applied axially by a pile driving hammer or similar device that will cause a large strain impact to the top of the pile. This test method is applicable to deep foundation units that function in a manner similar to foundation piles, regardless of their method of installation provided that they are receptive to high strain impact testing.

1.2 *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 5.

NOTE 1—High-strain dynamic testing requires a strain at impact which is representative of a force in the pile having the same order of magnitude, or greater, than the ultimate capacity of the pile.

NOTE 2—This standard method may be applied for high-strain dynamic testing of piles with the use of only force or strain transducers and/or acceleration, velocity or displacement transducers as long as the test results clearly state how the testing deviates from the standard.

NOTE 3—A suitable follower may be required for testing cast-in-place concrete piles. This follower should have an impedance between 80 and 150 % of that of the pile. However, additional caution and analysis may be required if the impedance is not within 10 %. 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.

2. Referenced Documents

2.1 ASTM Standards:

- C 469 Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression²
- D 198 Methods of Static Tests of Timbers in Structural Sizes³
- D 653 Terminology Relating to Soil, Rock, and Contained Fluids⁴

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² Annual Book of ASTM Standards, Vol 04.02.

³ Annual Book of ASTM Standards, Vol 04.10.

⁴ Annual Book of ASTM Standards, Vol 04.08.

D 1143 Test Method for Piles Under Static Axial Compressive Load⁴

3. Terminology

3.1 Except as defined in 3.2, the terminology used in this test method conforms with Terminology D 653.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *capblock*—the material inserted between the hammer striker plate and the drive cap on top of the pile (also called hammer cushion).

3.2.2 *cushion*—the material inserted between the drive cap on top of the pile and the pile (also called pile cushion).

3.2.3 *impact event*—the period of time during which the pile is moving in a positive and/or negative direction of penetration due to the impact force application. See Fig. 1.

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

3.2.5 *pile impedance*—indicates the resistance a pile has to a sudden impact change in velocity.

3.2.5.1 *Discussion*—It can be calculated by multiplying the cross-sectional area by Young's Modulus of Elasticity and dividing the product by the strain wave speed. Alternatively, the impedance can be calculated by multiplying the unit specific density by the wave speed and cross-sectional area.

$$Z = AE/c = \rho CA \quad (1)$$

where:

Z = Impedance,

A = Cross-sectional area,

E = Young's Modulus of Elasticity,

C = Wave speed of pile, and

ρ = Unit specific density.

3.2.6 *strain wave speed (or wave speed)*—the speed with which a strain wave propagates through a pile; it is a property of the pile composition.

3.2.7 *particle velocity*—the instantaneous velocity of a particle in the pile as a strain wave passes by.

3.2.8 *restriking*—the redriving of a previously driven pile after a waiting period of from 15 min to 30 days or more.

3.2.8.1 *Discussion*—The length of the waiting period is dependent upon the type of pile and the soil conditions along the shaft and at the toe of the pile.

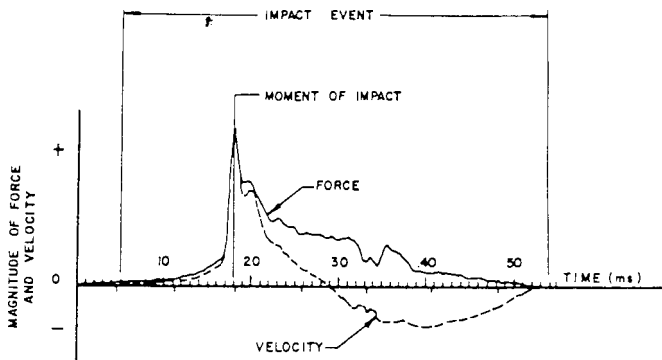


FIG. 1 Typical Force and Velocity Traces Generated by the Apparatus for Obtaining Dynamic Measurements

4. Significance and Use

4.1 This test method is used to provide data on strain or force and acceleration, velocity or displacement of a pile under impact force. The data are used to estimate the bearing capacity and the integrity of the pile, as well as hammer performance, pile stresses, and soil dynamics characteristics, such as soil damping coefficients and quake values. This test method is not intended to replace Test Method D 1143.

5. Apparatus

5.1 Apparatus for Applying Impact Force:

5.1.1 *Impact Force Application*—Any conventional pile driving hammer or similar device is acceptable for applying the impact force provided it is capable of generating a net measurable pile penetration, or an estimated mobilized static resistance in the bearing strata which, for a minimum period of 3 ms, exceeds to a sufficient degree the working load assigned to the pile, as judged by the engineer in charge. The device shall be positioned so that the impact is applied axially to the head of the pile and concentric with the pile.

5.2 *Apparatus for Obtaining Dynamic Measurements*—The apparatus shall include transducers, which are capable of independently measuring strain and acceleration versus time at a specific location along the pile axis during the impact event. A minimum of two of each of these devices, one of each on opposing sides of the pile, shall be securely attached so that they do not slip. Bolt-on, glue-on, or weld-on transducers are acceptable.

5.2.1 *Force or Strain Transducers*—The strain transducers shall have a linear output over the entire range of possible strains. When attached to the pile, their natural frequency shall be in excess of 2000 Hz. The measured strain shall be converted to force using the pile cross-section area and dynamic modulus of elasticity at the measured location. The dynamic modulus of elasticity may be assumed to be 200 to 207×10^6 kPa (29 to 30×10^6 psi) for steel. The dynamic modulus of elasticity for concrete and wood piles may be estimated by measurement during the compression test in accordance with Test Method C 469 and Methods D 198. Alternatively, the modulus of elasticity for concrete, wood, and steel piles can be calculated from the square of the wave speed (determined as indicated in 6.2) times the specific unit density ($E = \rho c^2$).

5.2.1.1 Force measurements also are made by force trans-

ducers placed between the pile head and the driving hammer, although it should be recognized that such a transducer is capable of altering the dynamic characteristics of the driving system. Force transducers shall have an impedance between 50 % and 200 % of the pile impedance. The output signal must be linearly proportional to the axial force, even under eccentric load application. The connection between the force transducers and the pile shall have the smallest possible mass and least possible cushion necessary to prevent damage.

5.2.2 *Acceleration, Velocity or Displacement Transducers*—Velocity data shall be obtained with accelerometers, provided the signal is capable of being processed by integration in the apparatus for reducing data. A minimum of two accelerometers with a resonant frequency above 2500 Hz shall be at equal radial distances on diametrically opposite sides of the pile. The accelerometers shall be linear to at least 1000 g and 1000 Hz for satisfactory results on concrete piles. For steel piles, it is advisable to use accelerometers that are linear to at least 2000 g and 2000 Hz. Either ac or dc accelerometers can be used. If AC devices are used, the resonant frequency shall be above 30 000 Hz and the time constant shall be at least 1.0 s. If DC devices are used, then they should be damped with low pass filters having a minimum frequency of 1500 Hz (−3dB). Alternatively, velocity or displacement transducers may be used to obtain velocity data, provided they are equivalent in performance to the specified accelerometers.

5.2.3 *Placement of Transducers*—The transducers shall be placed, diametrically opposed and on equal radial distances, at the same axial distance from the bottom of the pile so that the measurements compensate for bending of the pile. When near the upper end, they shall be attached at least one and one-half pile diameters from the pile head. This is illustrated in Figs. 2-7. Care shall be taken to ensure that the apparatus is securely attached to the pile so that slippage is prevented. The transducers shall have been calibrated to an accuracy of 3 % throughout the applicable measurement range. If damage is suspected during use, the transducers shall be re-calibrated (or replaced).

5.3 *Signal Transmission*—The signals from the transducers shall be transmitted to the apparatus for recording, reducing, and displaying the data (see 5.4) by means of a cable or equivalent. This cable shall be shielded to limit electronic or other interferences. The signals arriving at the apparatus shall be linearly proportional to the measurements at the pile over the frequency range of the equipment.

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

5.4.1 *General*—The signals from the transducers (see 5.2) during the impact event shall be transmitted to an apparatus for recording, reducing, and displaying data to allow determination of the force and velocity versus time. It may be desirable to also determine the acceleration and displacement of the pile head, and the energy transferred to the pile. The apparatus shall include an oscilloscope, oscillograph, or LCD graphics screen. For displaying the force and velocity traces, a tape recorder, digital disk or equivalent for obtaining a record for future analysis, and a means to reduce the data. The apparatus for

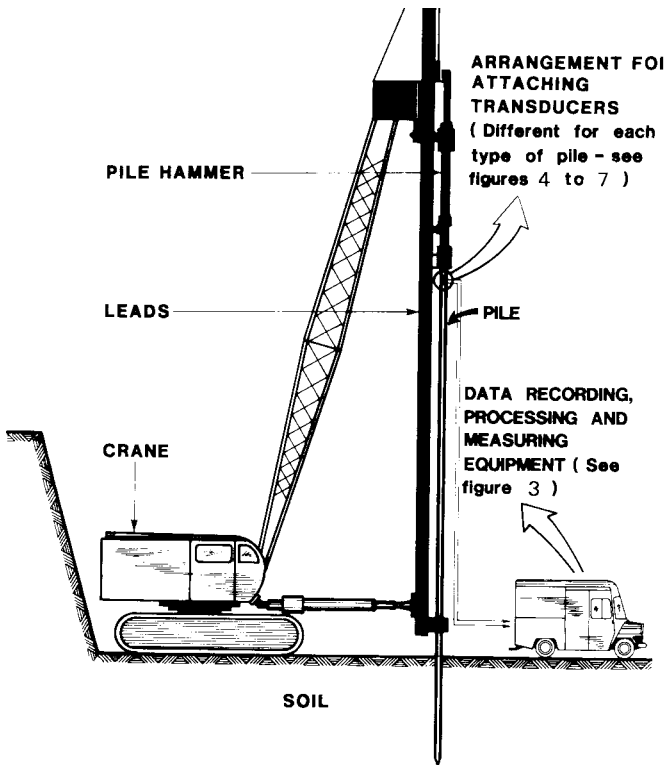


FIG. 2 Typical Arrangement for High Strain Dynamic Testing of Piles

recording, reducing, and displaying data shall have the capability of making an internal calibration check of strain, acceleration, and time scales. No error shall exceed 2 % of the maximum signal expected. A typical schematic arrangement for this apparatus is illustrated in Fig. 3.

5.4.2 *Recording Apparatus*—Signals from the transducers shall be recorded electronically in either analog or digital form so that frequency components have a low pass cut-off frequency of 1500 Hz (−3 dB). When digitizing, the sample frequency shall be at least 5000 Hz for each data channel.

5.4.3 *Apparatus for Reducing Data*—The apparatus for reducing signals from the transducers shall be an analog or digital computer capable of at least the following functions:

5.4.3.1 *Force Measurements*—The apparatus shall provide signal conditioning, amplification and calibration for the force measurement system. If strain transducers are used (see 5.2.1), the apparatus shall be able to compute the force. The force output shall be continuously balanced to zero except during the impact event.

5.4.3.2 *Velocity Data*—If accelerometers are used (see 5.2.2), 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.

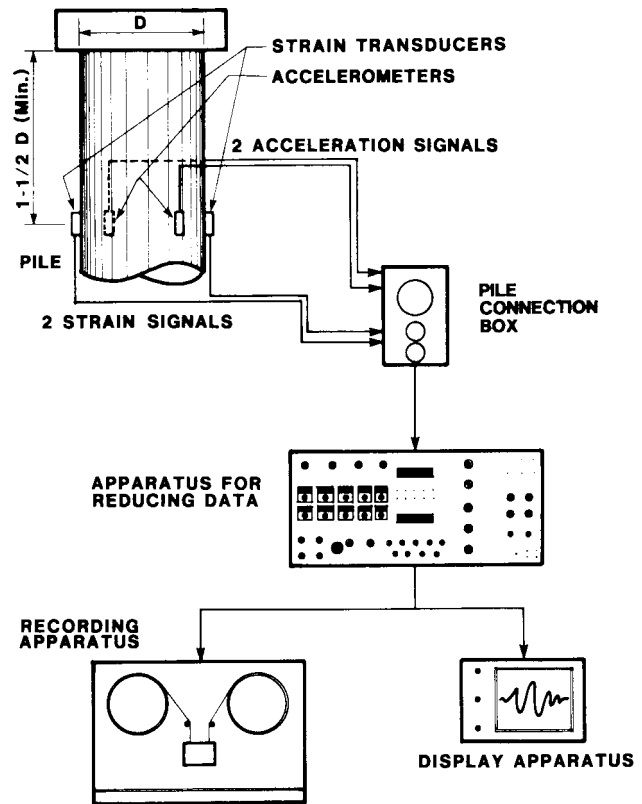


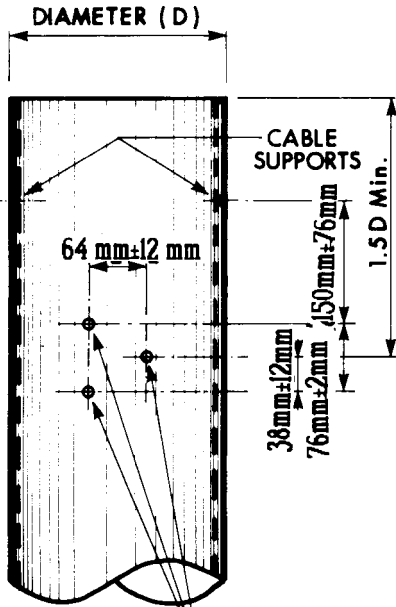
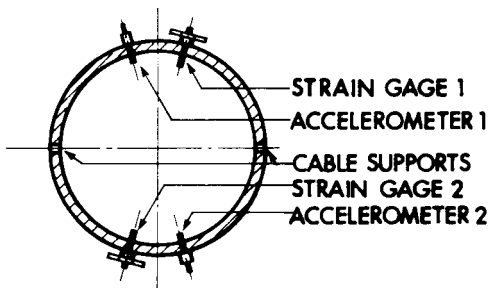
FIG. 3 Schematic Diagram for Apparatus for Dynamic Monitoring of Piles

5.4.4 *Display Apparatus*—Signals from the transducers specified in 4.2.1 and 4.2.2 shall be displayed by means of an apparatus, such as an oscilloscope, oscillograph, or LCD graphics screen on which the force and velocity versus time can be observed for each hammer blow. This apparatus may receive the signals from the transducers directly or after they have been processed by the apparatus for reducing the data. The apparatus shall be adjustable to reproduce a signal having a range of duration of between 5 and 160 ms. Both the force and velocity data can be reproduced for each blow and the apparatus shall be capable of holding and displaying the signal from each selected blow for a minimum period of 30 s.

6. Procedure

6.1 *General*—Record applicable project information (Section 7). Attach the transducers (see 5.2) to the pile, perform the internal calibration check, and take the dynamic measurements for the impacts during the interval to be monitored together with routine observations of penetration resistance. Determine properties 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 restriking. The force and velocity versus time signals shall be reduced by the apparatus for reducing data, computer, or manually to calculate the developed force, velocity, acceleration, displacement, and energy over the impact event.

6.2 *Determination of Strain Wave Speed for Concrete or Wood Piles*—The wave speed should be determined from the impact event if a tensile reflection wave from the pile toe is

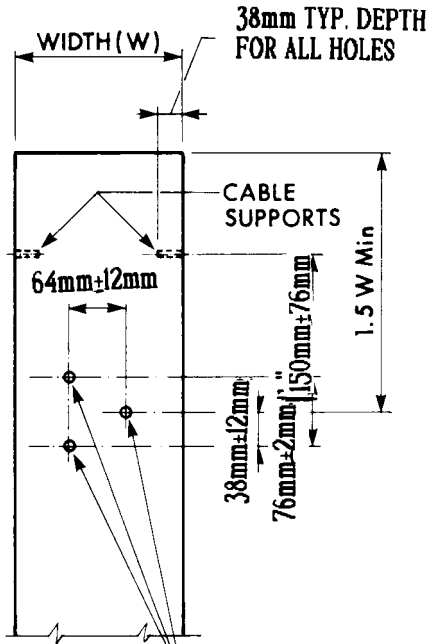
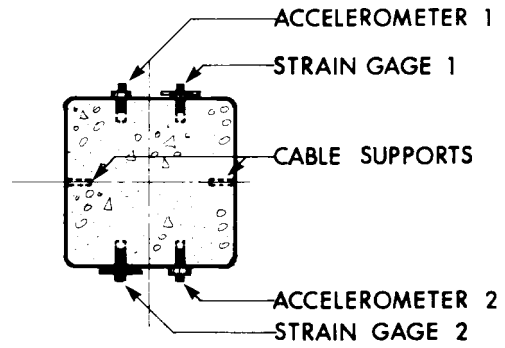


NOTE

For wall thicknesses less than 6mm, drill holes at 5mm

5.5mm DIA. HOLES TAPPED FOR 6MMX20 THREADS(TYP. OPPOSITE SIDE AND FOR CABLE SUPPORT HOLES)

FIG. 4 Typical Arrangement for Attaching Transducers to Pipe Piles



NOTE

9mm diameter hole can replace 6mm studs with 9mm threaded insert

6mm DIA. HOLES FOR EXPANDABLE 6mm DIA. ANCHOR STUDS (TYP. OPPOSITE SIDE AND FOR CABLE SUPPORT HOLES)

FIG. 5 Typical Arrangement for Attaching Transducers to Concrete Piles

clearly identified. Alternatively, place the pile on supports or level ground free and clear from neighboring piles and obstructions. Attach accelerometer to one end of the pile and strike the other 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 time between acceleration peaks for as many cycles of reflection as possible. Divide this time by the appropriate travel length of the strain waves during this interval to determine the wave speed.

6.3 Preparation—Mark the piles clearly at appropriate intervals. Attach the transducers securely to the piles by bolting, gluing, or welding. For pile materials other than steel, determine the wave speed (see 6.2). Position the apparatus for applying the impact force so that the force is applied axially and concentrically with the pile. Set up the apparatus for

recording, reducing, and displaying data so that it is operational and the force and velocity signals are zeroed.

6.4 Taking Measurements—Record the number of impacts for a specific penetration. For drop hammers and single acting diesel and air/steam/hydraulic hammers, record the drop of the ram or 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, record the kinetic energy from the hammer readout when available. Record the number of blows per minute delivered by the hammer. Take, record, and display a series of force and velocity measurements. Compare the force and the product of velocity and impedance (see 6.5) at the moment of impact.

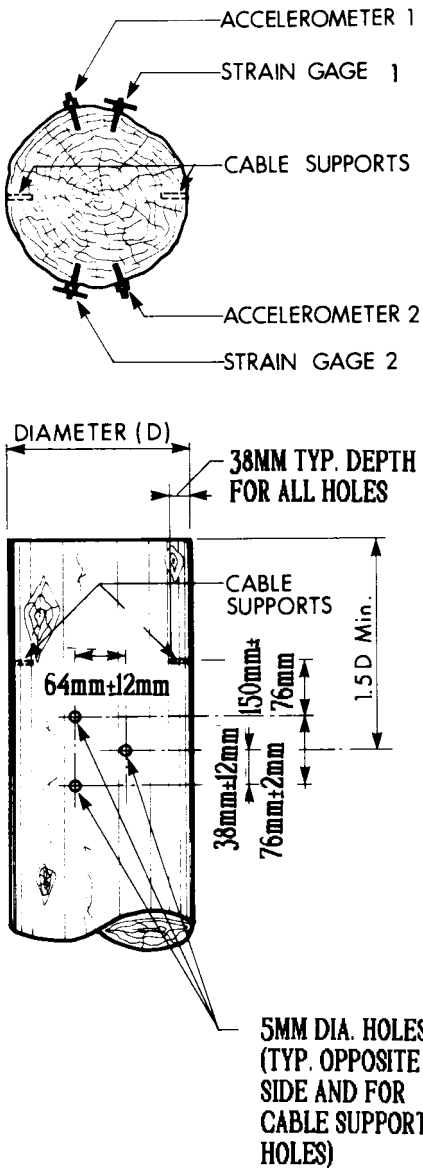
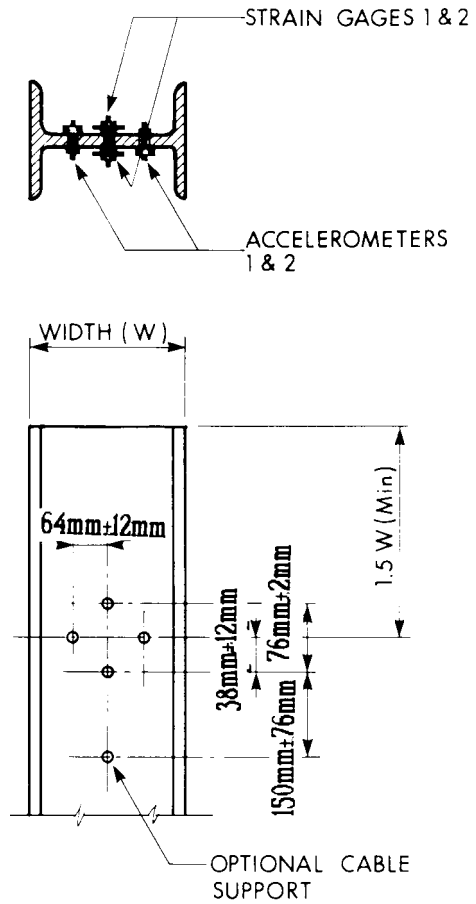


FIG. 6 Typical Arrangement for Attaching Transducers to Wood Piles

NOTE 4—If the dynamic measurements are to be used for bearing capacity computations, take the dynamic measurements during restriking of the pile at time periods sufficiently long after the end of initial driving to allow pore water pressure and soil strength changes to occur. Further geotechnical conditions, such as underlying compressible layers, need always be considered, as they should be in any type of bearing capacity computation.

NOTE 5—**Warning:** Before approaching a pile being driven, check that no material or other appurtenances can break free and jeopardize the safety of persons in the vicinity.

6.5 *Data Quality Checks*—For confirmation of data quality, periodically compare the force and the product of the velocity and pile impedance at the moment of impact for proportionality agreement and the force and velocity versus time over a series of selected and generally consecutive impact events for consistency. Consistent and proportional signals from the force or strain transducers and the acceleration, velocity or displacement transducers are the result of the transducers systems



NOTE: All holes at 8mm diameter.

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

performing properly and the apparatus for recording, reducing and displaying data being properly calibrated. If the signals are not in proportionality agreement, investigate the cause and correct the situation if necessary. If the cause is determined to be a transducer, it must be repaired or recalibrated, or both, before further use. Perform internal calibration checks for the apparatus for recording, reducing, and displaying data at least once for each test day; if found to be out of manufacturer's tolerance, the apparatus for recording, reducing, and displaying must be recalibrated before further use.

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

6.6 *Analysis of Measurements:*

6.6.1 Obtain force and velocity from the readout of the apparatus for reducing data (see 5.4.3) or from the display apparatus (see 5.4.4). Record the impact force and velocity and the maximum and minimum forces for the selected representative blows. Obtain the maximum acceleration directly from the accelerometer signal or by differentiation of the velocity versus time record. Obtain the displacement from the pile driving record, and from the displacement transducer, if used in

accordance with 5.2.2 or by integration of the velocity versus time record. Obtain the maximum energy transferred to the location of the transducers.

6.6.2 The recorded data may be subjected to analysis in a computer. The results of the analysis may include an assessment of integrity of the pile, the driving system performance, and the maximum dynamic driving stresses. The results may also be used for evaluation of static soil resistance and its distribution on the pile at the time of the testing. Such further use of the data is a matter of proper engineering judgment.

NOTE 7—Normally, there is better correlation between mobilized resistance and bearing capacity where there is a measurable net penetration per impact of at least 3 mm.

NOTE 8—Evaluation of static soil resistance and its distribution can be based on a variety of analytical methods and is the subject of individual engineering judgment. The input into the analytical methods may or may not result in the dynamic evaluation matching static load test data. It is desirable and sometimes necessary to calibrate the result of the dynamic analysis with those of a static pile load test carried out according to Test Method D 1143.

7. Report

7.1 The testing report should include all information indicated below, as applicable to the type of pile being tested. Any required information that could not be obtained should be indicated in the testing report as being not available.

7.1.1 General:

7.1.1.1 Project identification/location, and

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

7.1.2 Pile Installation Equipment:

7.1.2.1 Description of pile installation equipment used for either driving piles or drilling piles or the testing of these piles or combination thereof, as appropriate, including size (ram weight and stroke) and manufacturer's energy rating, capabilities, and type, operating performance levels or pressures, fuel settings, hammer cushion and pile cushion descriptions, and description of lead type and any special installation equipment such as for use of a follower or mandrel, predrifting or jetting.

7.1.3 Test Piles:

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

7.1.3.2 Working load and safety factor (or required ultimate capacity) of the pile(s),

7.1.3.3 Type and dimensions of pile(s) including nominal or actual cross sectional area, or both, length and diameter (as a function of pile length for timber or composite piles),

7.1.3.4 For concrete piles, cast-in-place pipe piles, or drilled shafts: date test piles made, cast, or installed, design concrete cylinder strength, density, effective prestress, or reinforcement details (size, length, of longitudinal bars), description of internal and external reinforcement used in test pile (size, length, number and arrangement of longitudinal bars; casing or shell size and length),

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

7.1.3.6 For timber piles: length, straightness, preservative treatment, tip and butt dimensions (and area as a function of length), and measured density for each pile,

7.1.3.7 Description and location of splices, if applicable,

7.1.3.8 Description of special pile tip protection, if applicable,

7.1.3.9 Description of any special coatings applied, if applicable,

7.1.3.10 Inclination angle from vertical of all test piles, and

7.1.3.11 Observations of piles including spalled areas, cracks, head surface of piles.

7.1.4 Pile Installation:

7.1.4.1 Date of installation and pile embedment below reference,

7.1.4.2 For drilled shafts, include the nominal size of the auger, volume of concrete or grout placed in pile (volume versus depth, if available), and a description of special installation procedures used, such as pile casing installation or extraction, or both,

7.1.4.3 For driven piles, include hammer cushion and pile cushion exchange information; include driving records, including blow count and hammer stroke or operating level for final unit penetration,

7.1.4.4 Cause and duration of interruptions in pile installation, if applicable and related to the investigation, and

7.1.4.5 Notation of any unusual occurrences during installation or excavation, or both, which may relate to the investigation.

7.1.5 Dynamic Testing:

7.1.5.1 Description of all components of the apparatus for obtaining dynamic measurements and apparatus for recording, reducing and displaying data, and of test procedure including description and location of the sensor attachment,

7.1.5.2 Date tested and sequence of test pile such as "end of driving" or "beginning of restrike" (restrikes referenced with time since end of driving) or embedment depth,

7.1.5.3 Test pile identification,

7.1.5.4 The length below sensors, cross sectional area, density, wave speed, and dynamic modulus of elasticity of the test pile,

7.1.5.5 Penetration resistance (number of blows per unit penetration) during the test,

7.1.5.6 Graphical presentation of velocity and force measurements in the time domain for representative blow of each pile tested,

7.1.5.7 Method(s) and one-dimensional wave propagation theory used (give reference) to evaluate data (particularly for the capacity evaluation, if applicable),

7.1.5.8 Comments on the capacity of the pile at the time of testing; mention shall be made as to if capacity is of remolded state as at end of driving or from a restrike with sufficient wait after driving. When applicable, summarize variables describing the soil model, including damping factors, quakes, and resistance distribution,

7.1.5.9 Comments on the hammer performance as measured by the energy transferred into the pile (with comparison to manufacturer's rating),

7.1.5.10 Comments on the driving stresses in the pile,

7.1.5.11 Comments on the integrity of the pile, and

7.1.5.12 Results of testing shall be summarized and presented numerically, with notation of time testing such as "end of driving" or "beginning of restrike" and noted by embedment

depth; also standard deviation and range where statistically significant.

8. Precision and Bias

8.1 *Precision*—The precision of this test method for direct measurement of strain and acceleration in a pile by means of high-strain dynamic testing has not been determined. The precision cannot be determined due to the variability of the

pile, pile driving hammer, and the soil surrounding the pile.

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

9. Keywords

9.1 dynamic testing; pile bearing capacities; pile foundations

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