

Deep Foundations Quality Control and Quality Assurance Testing Methods

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Structural loading and allowable settlement requirements, subsurface geologic and geotechnical conditions, specific site and project considerations, local construction expertise and practices, economic factors, and the designer's experience and preference typically dictate the type of foundation system. Deep foundations designed to resist compression, uplift, lateral, and torsion forces support a wide variety of structures such as buildings, bridges, towers, causeways, piers, and platforms for land, near-shore, and offshore installations. They are generally categorized as either driven piles or cast-in-place shafts, with sizes typically ranging between 10 to 60 inches in diameter and 20 to 120 feet in length. In a number of cases, the piles used in Florida reached record numbers; e.g., driven piles over 400 feet in length and drilled shafts 120 inches in diameter. Driven piles may be wood, steel (pipe or H-shape), or concrete, and are installed with a pile-driving hammer. Cast-in-place shafts are constructed by drilling holes in the ground which are then filled with steel-reinforced concrete or grout; depending on their method of construction and size, they are known by different names (e.g., continuous-flight-auger (CFA) piles, auger-cast piles, displacement auger-cast piles, drilled shafts, bored piles, caissons, etc.).

The performance of a deep foundation is dependent on its structural strength and integrity, geotechnical strength and deformation properties of the supporting soil or rock, pile-soil/rock interaction characteristics, and magnitude and nature of applied loads. Each phase of the design, installation, inspection, and quality assurance testing process is critical to the success of a deep foundation in performing its intended purpose. Since the constructed deep foundation is underground, it cannot be conveniently reached for in-service assessment, as is the case for super-structure components. Commonly used testing methods employed in Florida for evaluations of structural integrity and load bearing capacity of deep foundations that are standardized by an ASTM standard are discussed; they include: low-strain integrity testing (*ASTM D-5882*), cross-hole sonic logging (*ASTM D-6760*), and dynamic load testing (*ASTM D-4945*).

LOW-STRAIN INTEGRITY TESTING

The performance of any deep foundation element under applied load is a function of its structural strength and integrity. The constructed profile and structural integrity of a cast-in-place pile or drilled shaft are functions of subsurface conditions, grout or

concrete quality and method of placement, construction method, and workmanship. Under the impacts of the pile driving hammer, piles are subjected to high driving stresses, which if excessive may cause pile structural damage. Assessment of structural integrity for cast-in-place piles, concrete piles, concrete filled steel pipe piles, and sometimes timber and steel piles can be conveniently and economically performed utilizing the non-destructive testing (NDT) dynamic low-strain pulse-echo method; commonly known as the Pile Integrity Test (PIT).

Testing is performed by impacting the pile or shaft top with a small hand-held hammer and measuring the response with an accelerometer. The impact causes a low-strain compression wave to travel down the pile; wave reflections are created by changes in pile "impedance" (related to cross-sectional area, material elastic modulus, and density), pile toe, and soil/rock resistance effects. Reductions in impedance (i.e., defects) cause reflected tension waves and bulges produce reflected compression waves. Soil resistance effects are minimized by selected data enhancements and filtering techniques. The test record is typically presented as the pile top velocity which includes the incident impact and resulting wave reflections. Data analysis is typically done by visual inspection of the test record, or by computer analysis utilizing numerical methods and simulation techniques. Figure 1 shows a field test with a Pile Integrity Tester (PIT) system. Figure 2 presents a PIT test result performed on an 18-inch diameter, 42 ft long, auger-cast pile with no structural integrity problems (i.e., no tension wave reflections along the pile length; note the compression wave reflection indicating bulging effect at a location approximately 25 ft below the pile top), and includes a clear pile toe wave reflection confirming shaft continuity. Figure 3 presents a test record (obtained on a similar nearby pile) with a strong tension wave reflection originating from approximately three feet below the pile top indicating a severe structural integrity problem at that location. The pile was excavated and the serious necking defect is shown in the photograph in Figure 3.



Largest hydraulic hammer in the United States employed for dynamic testing of bridge pier foundations in Florida.

Advantages of PIT integrity testing include: minimal pile preparation is needed so random spot checking is possible; testing is simple and inexpensive so on many projects all piles can be tested to confirm integrity; and it identifies major defects (severity and vertical location). There are some disadvantages to this type of testing, including: data interpretation requires experience and expertise, length limitation of approximately 25 to 50 diameters (depending on various factors), multiple defects or those below a major impedance change cannot be discerned, small defects are often not detected, does not locate the horizontal position of a defect in the cross-section, the accuracy of the defect location along shaft length depends on an assumed stress-wave speed, and limitations in testing steel piles (H-piles, sheet-wall, pipe piles not filled with concrete, etc).

An innovative PIT application is the evaluation of unknown length of deep foundations supporting existing structures (e.g., bridges, telecommunication towers, buildings, etc.). Although success in assessing in-service deep foundation elements depends on the particular details of the foundation and structure in each case, its simplicity of application and low-cost are compelling reasons for its trial before more involved and expensive means are employed.

Extensions to the basic PIT method include the Transient Response Method (TRM) which requires an instrumented hammer to measure pile top force in addition to motion with evaluation in the frequency domain, and Two Accelerometer Method (TAM) which requires two simultaneous motion measurements at different locations on the pile to help separate wave input/reflections in the test records.

CROSS-HOLE SONIC LOGGING

Large diameter cast-in-place shafts are often utilized as deep foundations in difficult subsurface conditions to carry large structural loads. It is the very nature of these challenging construction considerations and loading conditions, and often minimal redundancy, that demand diligence in implementing a quality assurance and quality control testing program for each shaft. A common test for checking the structural integrity of drilled shafts, and larger diameter auger-cast piles, is the Cross-hole Sonic Logging (CSL) method, commonly applied with specialty systems such as the Cross Hole Analyzer (CHA). The purpose of the test is to assess the homogeneity and integrity of concrete between access tubes in a deep foundation.

CSL testing requires small access tubes (typically PVC or steel pipes 1½ to 2 inches in diameter) installed full-length in the shaft at the time of its construction. Normally, the number of tubes required is equal to the shaft diameter in feet (i.e., a 6 ft diameter shaft requires 6 tubes), with a minimum of 4 tubes. The tubes are attached to the steel reinforcement cage, and are filled with water immediately following the concreting of the shaft. Test equipment includes an ultrasonic transmitter and a matched receiver, and a data acquisition system. The transmitter and receiver are inserted into the bottom of two tubes, raising (and possibly lowering) them simultaneously while the transmitter continuously emits and the receiver acquires the ultrasonic signals. The records of signal travel time (and relative strength) yield an assessment of the concrete quality and continuity between the two tubes. The process is repeated by utilizing various combinations of access tubes to check around the shaft circumference and through its center.

Data interpretation consists of visual inspection of the test signals (“nested” in a “waterfall” diagram), and checking the signal’s First Arrival Time (FAT) and relative signal energy. Advances in computing technology and numerical techniques allow for application of tomography to CSL data. Tomography requires at least six scans per pile, which allows for a comprehensive assessment by quadrant and 3-dimensional presentation of the shaft quality as evaluated by the material wavespeed. Figure 4 presents test results obtained between three pairs of tubes (i.e., tubes 4-5, 5-6, and 1-6) for a 72-inch diameter, 64 ft long shaft, showing a defect at a location 42 to 47 feet below the shaft top. Figure 5 presents tomography results in 3-D for a 60-inch diameter, 40 ft long shaft.

Advantages of CSL testing include: no limitation on shaft length for test applicability, provides location of defects along shaft length and in cross-section, can detect multiple defects, is not sensitive to soil type, and in most cases data interpretation is relatively simple. Disadvantages include: shafts require placing access tubes prior to concreting, not possible to test entire shaft length if the reinforcement cage is not full-length, checks the concrete only between the tubes and not the cover outside the steel cage, and interpretation of complex data (especially using tomography) requires experience and expertise.

A related technique is the Single Hole

Sonic Logging (SHSL) method which requires only a single access tube be installed in the pile. Testing is performed by lowering the transmitter and receiver on top of each other (about two feet apart) in series (instead of being in parallel as in the CSL case) to the bottom of the tube, and then scanning the pile as the two are retrieved. This method is typically used with small-diameter auger-cast piles.

HIGH-STRAIN DYNAMIC MONITORING AND LOAD TESTING

Visual observations of pile driving blow counts (e.g., blows/foot) under hammer impacts have long been an integral part of the installation process. However, this simple “measurement” provides only a

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Figure 1: PIT field testing.

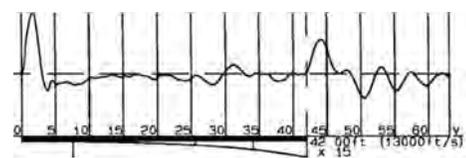


Figure 2: PIT test results showing a good pile.

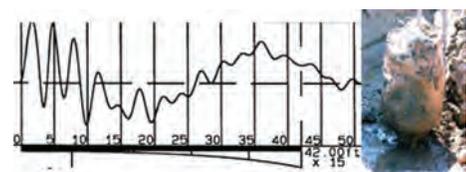


Figure 3: PIT test result and photograph showing a pile having a neck at 3 feet below pile top.

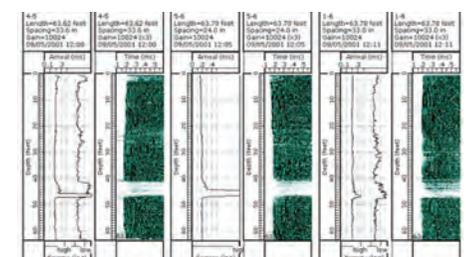


Figure 4: Cross-hole sonic logging test results.

Deep Foundations Quality Control and Quality Assurance Testing Methods Continued

crude evaluation regarding the pile bearing capacity and integrity, especially if analysis is based on antiquated theories and oversimplified methods. Starting in 1964, an extensive pile research program sponsored by the Federal Highway Administration (FHWA), Ohio DOT, FDOT, and others was undertaken at Case Western Reserve University in Cleveland, Ohio with the objective of developing electronic equipment and analytical methods to quickly, economically, and accurately evaluate static pile bearing capacity from dynamic measurements. This successful research provided the basis for modern high-strain dynamic testing and analysis methods, which today are a vital and routine part of deep foundations (driven piles, cast-in-place piles, and drilled shafts) worldwide.

High Strain Testing measures pile force and motion (with reusable strain transducers and accelerometers bolted to the pile/shaft top) under hammer impacts. For driven piles, the driving hammer itself is used for testing. For cast-in-place shafts a drop weight (weighing about 1.5% of the ultimate test capacity) is needed. Data acquisition and real-time field analysis require a specialty computer system – such as the Pile Driving Analyzer® (PDA). The testing results available immediately following each hammer blow are used for: pile driving hammer performance evaluation for productivity and construction control, dynamic pile driving stresses to reduce the risk of pile damage during installation, assessment of pile or shaft structural integrity, and soil resistance distribution and total static bearing capacity. Further analysis of the field recorded data can be performed with a “signal matching” computer program

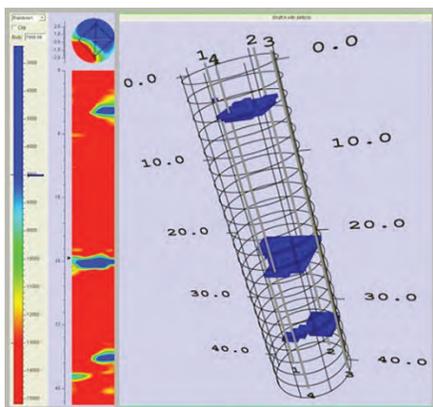


Figure 5: Cross-hole sonic logging tomographic results.

(CAPWAP®) with advanced numerical methods to verify field results and provide a simulated pile static load-movement graph.

Figure 6 presents the PDA testing results (between penetrations of 37 to 62 feet) of a 24-inch square, 100 feet long, prestressed concrete pile driven with a single-acting diesel hammer. Results shown include maximum dynamic compression and tension stresses (CSX and TSX), hammer ram stroke height (STK), maximum energy transferred to the pile (EMX), static pile load bearing capacity (RMX), and driving blow count in blows per foot (blows/foot) all presented as a function of pile penetration depth. Figure 7 presents the results of a full-scale static load test and CAPWAP simulation of pile-top load-movement graph for a 30-inch square (with an 18-inch circular void), 110 ft long prestressed concrete pile from a current construction project in Florida. The excellent agreement between the statically measured and dynamically predicted results demonstrates the reliability and effectiveness of high-strain dynamic pile testing and analysis methods.

Advantages of high-strain dynamic testing include: application to any type of driven pile material (wood, steel, concrete, and composite) and cast-in-place foundation method (auger-cast pile, drilled shaft, bored pile, etc.), little pile preparation is needed, piles and shafts can be randomly tested after installation, much more economical and significantly faster than conventional static load testing, site variability easily assessed by testing a higher percentage of piles on site, evaluates structural integrity in addition to load bearing capacity, testing can be conveniently performed at various times to assess time-dependent soil resistance and pile load bearing capacity (i.e., setup, relaxation effects), and axial capacity of inclined piles can be easily tested.

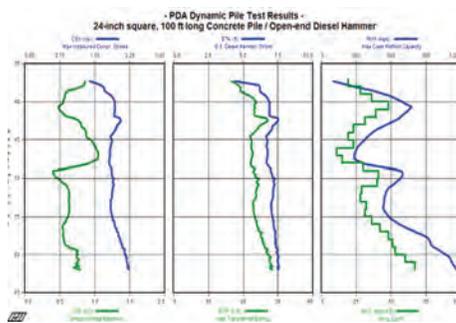


Figure 6: PDA testing results of a 24-inch square, 100 feet long, prestressed concrete pile driven with a single-acting diesel hammer.

Disadvantages include: an appropriate (large enough) drop hammer is required on site to test cast-in-place shafts, data interpretation and analysis require experience and expertise, and elements supporting existing structures cannot be tested in-service.

A related analytical method is the Wave Equation Analysis of Pile driving (WEAP). It simulates and analyzes the dynamics of a pile or shaft under hammer impacts according to one-dimensional elastic wave propagation theories utilizing discrete element modeling and numerical methods. The results are used to predict the dynamic compatibility of the hammer-pile-soil for evaluation of driveability of driven piles and load bearing capacity of driven piles and cast-in-place shafts. Thus it is useful to select equipment to potentially safely install the pile to the desired depth and capacity.

OTHER METHODS

In addition to the three common testing methods detailed in this article, there are other methods for construction monitoring, inspection, and testing of deep foundations. They include: the Pile Installation Recorder (PIR) system used for monitoring the installation of auger-cast piles (by measuring grout volume and other parameters versus auger-depth during installation) and driven piles (by monitoring blow count versus pile penetration during driving); the Saximeter for monitoring hammer and pile during driving (counts the number of blows/ft, stroke height of open-end diesel hammers, and hammer impact energy); Shaft Inspection Device (SID) and Downhole Camera System (DHC) for inspection of drilled shafts prior to concreting (by visually inspecting bottom and sidewall cleanliness and properties); Gamma-Gamma Logging (GGL) which utilizes a radioactive source for assessment

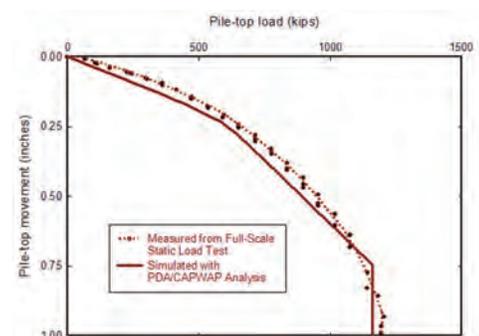


Figure 7: Full-scale static load test and CAPWAP simulation of pile-top load-movement graph from a current construction project in Florida.

of structural integrity of cast-in-place shafts; Parallel Seismic Testing (PST) which requires a small borehole for housing a hydrophone close to the deep foundation, Parallel Inductive Method (PIM) which utilizes metal detection technology to sense the proximity of steel piles, and Bending Wave Method (BWM) for assessment of unknown length of piles or shafts in-place under existing structures; Rapid Load Testing (such as Statnamic and PLT systems) and bottom-up static loading (Osterberg-Cell system) for evaluating the capacity of deep foundations; in addition to conventional full-scale static loading for testing deep foundations in compression, tension (uplift), and lateral load capacity.

Many codes, specifications, guidelines, and standards of practice in Florida, nationwide, and indeed in many countries worldwide have included references to quality control and quality assurance testing methods for deep foundations. These include: Florida Department of Transportation (FDOT) Standard Specifications for Road and Bridge Construction - Section 455 Structures Foundations; American Society of Civil Engineers (ASCE) Standard guidelines for the Design and Installation of Pile Foundations; AASHTO T-298; IBC Section 1807; and numerous ASTM Standards. Internationally, the Canadian Foundation Engineering Manual - Chapter 20; Australian Standard AS2159 piling Design and Installation; United Kingdom Institution of Civil Engineers (UK-ICE) Specification for Piling; German Society for Geotechniques section 2.1 - Recommendations for Static and Dynamic Pile Tests; in addition to China (CABR), France (Norme Francaise NFP94-160-10), and numerous other countries.

Perhaps more so than any other component of the structure, there is usually a very limited and short period of time available for testing a deep foundation before it is incorporated into the structure. Admittedly there is a cost to any testing. Some try to “cut costs” by minimizing or sadly even eliminating such testing all together. However, in perspective of the whole foundation cost (or even the total project budget), the costs for the three ASTM-standardized methods discussed here are extremely modest. Considering the cost and consequence of a foundation failure, every effort should be expended to assure success. In deep foundations work, testing is smart “insurance.” The price of adverse

publicity alone for a foundation failure is almost beyond measure and remediation costs often rival the original foundation cost. Since such testing is routine practice and part of most national and state foundation codes, a prudent amount of testing may help limit liability exposure and certainly reduce the risk of failures. Low strain testing and analysis NDT methods (PIT and CSL) can detect major structural flaws. High strain dynamic pile testing (PDA and CAPWAP) evaluates the load carrying capacity and can be used creatively to optimize the foundation design. A well planned and effectively implemented testing program often results in significant total foundation savings many times the cost of the testing. ■



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Mohamad H. Hussein, PE is Vice President of GRL Engineers, Inc (www.pile.com), a consulting engineering firm with offices nationwide specializing in dynamic testing and evaluations of deep foundations. Over the past 23 years, he has been involved in deep foundations projects in 35 states in the USA and 15 countries overseas. He is the Chairman of the Deep Foundations Committee of the American Society of Civil Engineers Geo-Institute, and a member of the Pile Foundations Committee of ASCE's Geotechnical & Construction Standards, in addition to technical committees of the DFI, PCI, and ASTM. Engineer Hussein is a regular presenter at FICE's GMEC conferences.



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