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High-Strain Dynamic Testing of Drilled and Cast-In-Place Piles

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HIGH-STRAIN DYNAMIC TESTING OF DRILLED SHAFTS AND CAST-IN-PLACE PILES

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Abstract

High-strain dynamic testing of drilled shafts and cast-in-place piles has become routine procedure in many parts of the world today. Field testing is performed by measuring strain and acceleration records under impact of a falling mass. Wave equation analysis is utilized to design the weight, drop height and cushion of the hammer apparatus to assure a successful test. The Pile Driving Analyzer® (PDA) and CAPWAP® methods are used for data acquisition and analysis. Testing results yield information regarding pile static bearing capacity, structural integrity, and pile-soil load transfer and pile load-movement relationships. This paper discusses application of high-strain dynamic testing to cast-in-place shafts with emphasis on aspects unique to this type of pile. Suggestions regarding minimum requirements for good quality tests are offered. Five case histories reported in the literature are summarized and a sample specification is also included.

Introduction

Dynamic pile testing and analysis are well established methods in foundation engineering practices around the world (Goble 1994). Wave Equation analysis of pile driving is valuable in evaluating pile drivability and bearing capacity. Field testing is routinely performed with a Pile Driving Analyzer® (PDA) for comprehensive evaluation of the hammer-pile-soil system during pile driving, or restrike of driven piles. Analysis of dynamic data according to the CAPWAP® Method yields further information regarding pile load-movement and pile-soil load transfer relationships.

Cast-in-place piles are produced by forming holes in the ground and filling them with concrete. In most cases, a steel reinforcing cage is used. Two common techniques for constructing this type of pile are: (a) the continuous-flight-auger (CFA) where grout is introduced under pressure through the bottom of the hollow stem auger during auger withdrawal, and (b) the bored pile where a cylindrical hole is formed by drilling before placement of concrete. Cast-in-place piles (also called bored piles, drilled shafts, etc.) are constructed in sizes reaching 3000 mm in diameter and 75 m in length. Commonly used sizes range between 500 and 1500 mm in diameter and 5 to 30 m in length. They are used to support a wide range of structures and the larger shafts are designed to carry very large loads.

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Since deep foundations are often used to support structures where subsurface conditions are difficult, it is the very nature of these conditions that sometimes evokes questions regarding the structural condition and load carrying capability of cast-in-place piles. Structural integrity is dependent on subsurface conditions, grout/concrete quality and method of placement, workmanship, and design and construction practices. Load bearing capacity is a function of the pile's structural strength and integrity, strength and deformation properties of the supporting soil (or rock), pile-soil interaction characteristics and nature of applied loads.

Unlike pile driving where dynamic measurements during installation are possible to quantify hammer-pile-soil behavior (Hussein and Likins 1995), methods for evaluating capacity of cast-in-place piles require extra effort. A few days after installation, cast-in-place piles' structural integrity can be evaluated with low-strain dynamic testing methods (Rausche et al. 1994). During the past decade, application of high-strain dynamic testing methods has been expanded to include testing of drilled and cast-in-place piles. Experience from many countries show that high-strain dynamic testing of cast-in-place piles has economically produced reliable and accurate results.

High-Strain Dynamic Pile Testing Equipment and Analytical Methods

High-strain dynamic pile testing is based on the measurement of pile strain and acceleration under impacts of a relatively large weight. Pile strains are measured with preferably four strain transducers. Sensors are mounted around the pile circumference, ideally at a location approximately two pile diameters below its head. Figure 1 shows pile instrumentation. Data analysis is based on field measured dynamic records, sophisticated modeling and numerical techniques, and one-dimensional elastic wave propagation principles. Field testing is done according to the Case Method procedures as applied with a Pile Driving Analyzer (PDA). The PDA is a user friendly field data acquisition system and computer (see Figure 2) that provides power supply, signal conditioning, processing and evaluation of the measured dynamic data. Generally, testing results obtained in the field, in real time between hammer impacts, include results for evaluating hammer/driving system performance, dynamic pile stresses, pile structural integrity, and pile resistance and static bearing capacity (Rausche and Goble, 1979; Rausche et al., 1985; and Likins and Rausche, 1988). High-strain dynamic pile testing is part of many standards and specifications, such as ASTM D 4945 (Standard Test Method for High-Strain Dynamic Testing of Piles).

The CAse Pile Wave Analysis Program (CAPWAP) is a rigorous numerical method for a comprehensive analysis of pile and soil behavior under hammer impacts and also under static loading conditions (Rausche et al. 1994). The analysis is done in an interactive environment using measured force and acceleration in a wave equation type analysis employing signal matching techniques. Figure 3 presents the CAPWAP Method soil model. The hammer model is replaced by the measurements. Soil constants are assumed and the response calculated and compared with the measurements. Soil constants are iteratively changed to improve the

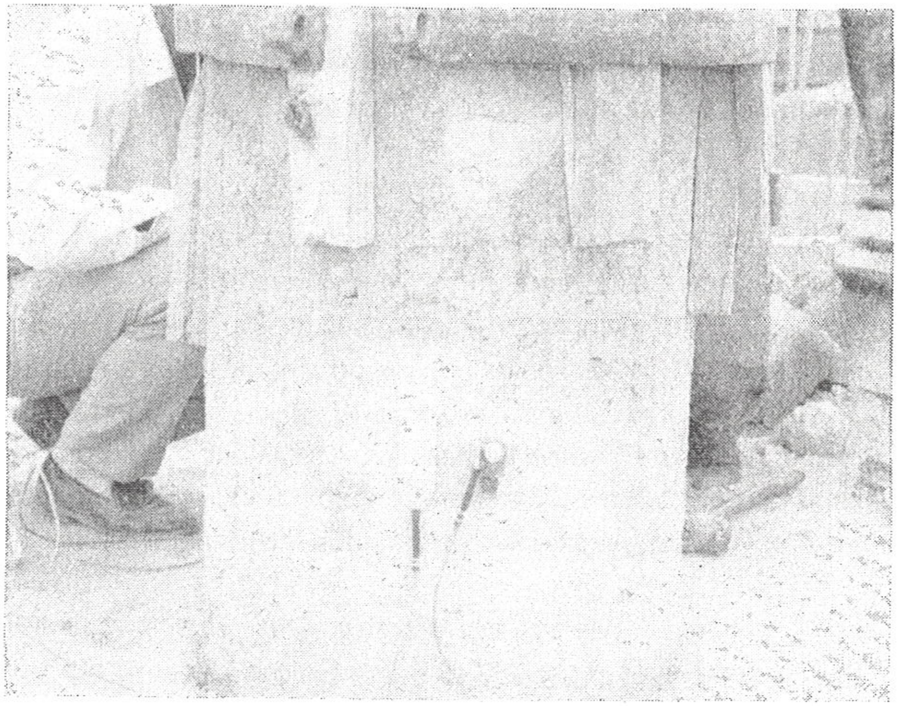

Figure 1: Pile instrumentation, strain transducer (left) and accelerometer (right)

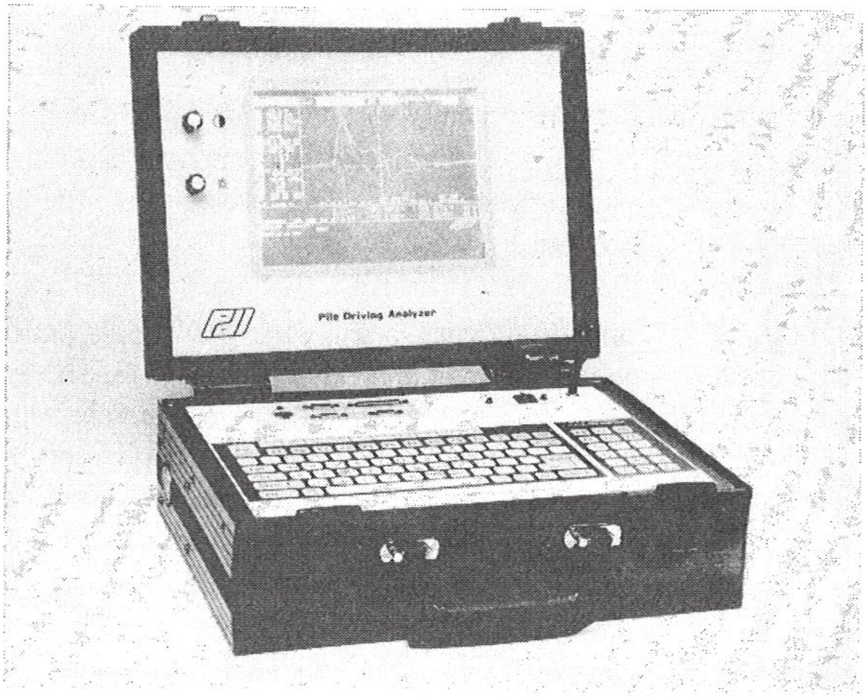

Figure 2: The Pile Driving Analyzer® (PDA)

computed versus measured response. Analysis results include: static pile capacity, soil resistance distribution, dynamic soil parameters, and a simulated static loading test. Figure 4 presents PDA measurements and CAPWAP analysis results for a bored pile 1500 mm in diameter, 53 m long under impact of a 20 tonne weight with a drop height of 2.5 m, resulting in a pile top set of 2.5 mm.

Testing of driven piles is conveniently done utilizing the pile driving hammer blows. For testing cast-in-place piles, it is preferred to have a drop weight available for impacts. The weight needed is approximately 1.5% of the anticipated pile static resistance and the drop height used is generally between 1 and 3 m. A few sheets of plywood are placed as a cushion between the hammer and pile top to control pile dynamic stresses and reduce local contact non-uniformities. For a given application, GRLWEAP™ wave equation analysis is often performed to "design" the test system (weight, drop height and cushion of the hammer apparatus) to assure a successful dynamic test. An example of such analysis is illustrated in this paper.

Due to the complex nature of pile-soil interaction in the case of cast-in-place shafts, modifications to the conventional soil model commonly used in dynamic analysis are needed for a realistic representation. The CAPWAP soil model for analysis of cast-in-place piles incorporates radiation damping to account for soil motion associated with pile movement (Rausche et al., 1992, 1994).

Case Histories

During the past decade, high-strain dynamic testing of cast-in-place piles has enjoyed widespread acceptance around the world. The literature contains a large number of related technical papers and case histories of dynamic testing on drilled shafts. The following are brief summaries of five representative cases.

Jianren and Shihong (1992) reported on dynamic and static test results performed on drilled piles for a 257 m high tower span-over crossing the Yangtze River in Tai-Sheng-Quan Nanking, China. Test shafts consisted of two each 800 and 1500 mm diameter with corresponding lengths of 30 and 60 m. Subsurface conditions at the site consisted of clay, sand and gravel layers over highly weathered sandstone. Project specifications required that comparisons between dynamic and static load test results be made in a Class A prediction manner. The hammer used for dynamic testing had a weight of 12 tonnes with drop heights up to 1 and 2.5 m for the 800 and 1500 mm diameter shafts, respectively. Cushions consisted of two pieces of rubber plate 20 mm thick with two 15 mm steel sheets in between. Testing objectives included an appraisal of the reliability of dynamic testing to predict static bearing capacity of such large and long drilled shafts. Comparison of dynamic and static testing results performed within the same time frame indicated that the two methods produced capacity valuest hat were within 2.6% relative toe ach other. Based on the results of the test program, the use of dynamic e sting in evaluating the bearing capacity and structural integrity of the production shafts was

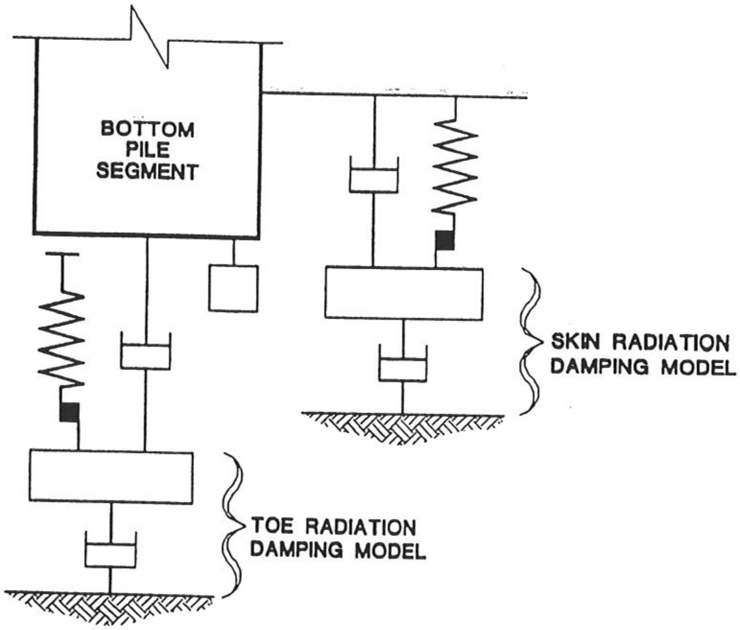

Figure 3: The CAPWAP® Method soil model

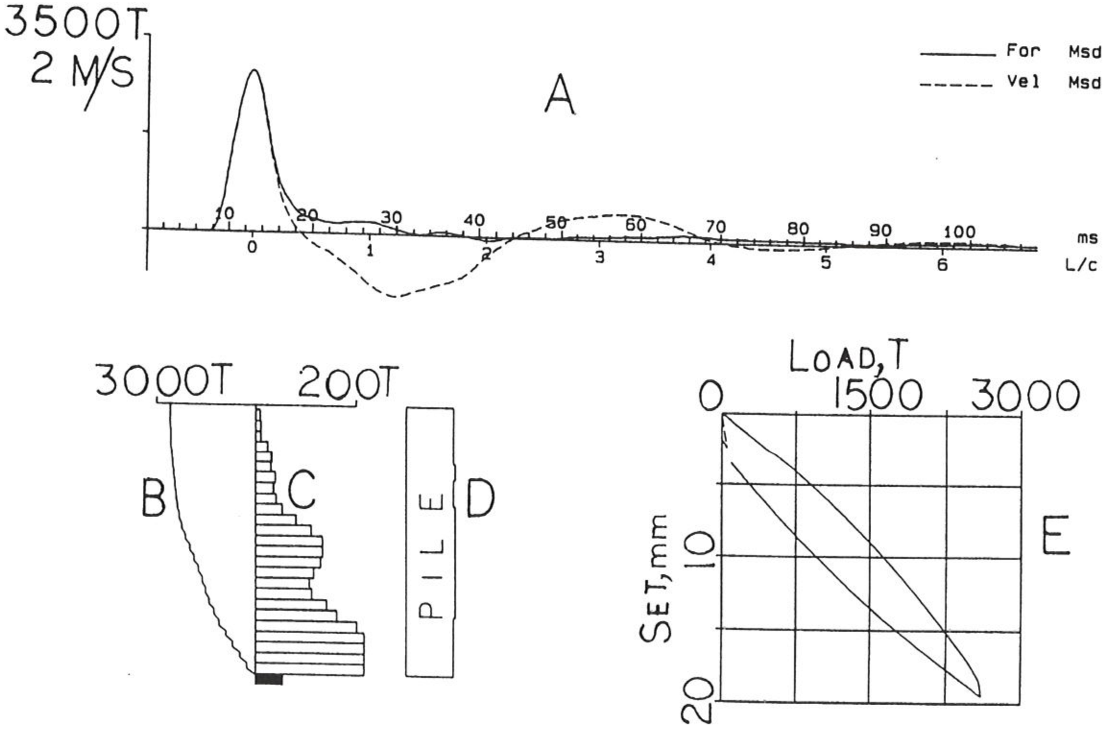

Figure 4: Dynamic test results of a bored pile
Pile: 1500 mm diameter, 53 m long; Hammer: 20 tonnes, 2.5 m drop, 2.5 mm set
(A) Measured pile force (solid) and velocity (dotted) records
CAPWAP results: (B) pile forces at ultimate resistance, (c) soil resistance distribution, (D) pile impedance profile, and (E) pile top and toe load movement relationships

approved and all further static testing eliminated. Findings of the testing program were also used to finalize the size of the 150 production shafts (1350 mm diameter, 58 m length) for additional savings in foundation cost. Random dynamic testing of production piles revealed two structurally defective shafts. This was confirmed with core drilling.

Townsend et al. (1991) reported findings of sponsored research performed by the University of Florida. The project consisted of designing and constructing a fully instrumented drilled shaft and two reaction shafts, performing high-strain and low-strain dynamic testing, and comparing the high strain dynamic test results with a static loading test. The soil profile at the site consisted of 9 m of sand and 2 m of clay over soft limestone. The test shaft was constructed by driving a 6 m long, 711 mm diameter steel casing and then augering with a 610 mm diameter auger to a depth of 13.7 m. Dynamic testing consisted of four drops ranging in height between 0.9 and 2.4 m of a 9 tonne hammer. Pile top cushion was 203 mm of plywood. Subsequent to presentation of the dynamic test results, a static loading test was independently performed by the University of Florida. The static pile capacity of 290 tonnes determined from dynamic testing was within 6% of the static loading test and the total shaft friction resistance agreed within 10 percent. Field dynamic testing was completed in a few hours, whereas the total time required for the static loading test was five days.

Lee et al. (1991) reported on an extensive testing program for the Suntec City Complex, one of the largest commercial developments in Singapore. The project included four 45-storey office towers, an 18-storey building, and an 8-storey convention center. Subsurface conditions at the site consisted of fill underlain by marine clay with sand layers over the Singapore Alluvium formation. The foundation consisted of 2600 bored piles. High-strain dynamic testing was performed on eighty (80) shafts ranging in size from 1000 to 1600 mm in diameter and 22 to 52 m in length. Wave equation analysis was used to design the drop weight system of ram weight of 25 tonnes, drop heights up to 4 m, and 175 mm of plywood cushion. Pile capacities in excess of 3000 tonnes were mobilized by the dynamic tests. Comparison between dynamic test pile results with the limited static testing showed good agreement. Dynamic testing was valuable in meeting the tight construction schedule of this fast track project. Conventional static pile testing would have caused significant delay and expense.

Prebaharan et al. (1990) reported results of dynamic and static tests performed on bored piles for the Marina Bay Station for the Singapore Rapid Transit System. The project comprised two 1100 m long tunnels and an underground station. Substructure consisted of 1600 bored piles with 1000 mm diameter and 25 to 50 m lengths founded in the Old Alluvium of Singapore Island. Initially, 51 production piles were selected for static loading tests. However, due to difficulties encountered in providing a reaction system for the static tests in the excavated site, 44 out of the 51 tests were replaced with high-strain dynamic tests. Agreement between dynamic and static test results permitted replacement of static loading tests for the project. The purpose of the dynamic tests was to evaluate the piles' static bearing capacity and structural integrity. A 7.7 tonne drop weight was used with drop heights between 2 and 5 m; plywood sheets with a total thickness of 100 mm were used for pile top cushion. Pile capacities of more than 2000 tonnes were measured with dynamic tests. Dynamic tests also detected a defect at a location 24 m below the head of one of the shafts. Examination of the installation record for this shaft revealed problems in concreting this pile at this depth.

Balthaus et al. (1985) reported on the practice of dynamic pile testing in Germany. Cast-in-place shafts up to 2000 mm diameter have been tested. Dynamic tests typically consist of two or three hammer blows with a drop height of up to 2.5 m. The paper includes high-strain dynamic test results on a 1500 mm diameter 13.2 m long shaft in non-cohesive soils. Also reported are test results of a 24 m long shaft with a mobilized capacity of 2000 tonnes. The authors conclude that high-strain dynamic testing has proven a valuable tool for estimating the bearing capacity of large bored piles in Germany.

Seidel and Rausche (1984) reported results of dynamic and static tests performed on drilled shafts for the West Gate Freeway in Melbourne, Australia. A static and dynamic test program was initiated after questions were raised regarding the shafts' bearing capacity and serviceability. Twelve shafts ranging in size between 1100 and 1500 mm in diameter and 35 to 64 m in length were dynamically tested. Nine shafts were socketed into mudstone and the remaining three into basalt. Six of the shafts socketed into the mudstone were also statically tested. A hammer with a weight of 20 tonnes and drop heights between 1.6 and 2.5 m was used for the dynamic tests. Dynamic and static tests were done totally independently and results were compared in a Class A prediction fashion. Dynamic activation of static pile resistance forces exceeded 3000 tonnes for some 1500 mm diameter shafts. Direct correlation of ultimate pile capacities was not possible since maximum values were not usually reached during the static tests. Skin friction predictions from dynamic tests and values obtained from instrumented shafts under static tests were remarkably similar. Pile head load-movement relationships obtained from both testing methods were comparable. Following this proof of concept, dynamic tests were used to replace over 60 additional planned static tests at savings of over US$ 2,500,000 and a time reduction of several months.

Wave Equation Analysis of Cast-in-Place Shafts

Wave equation analysis is commonly performed for evaluations of pile drivability during the design phase or pile static bearing capacity during the construction phase, and can be used to study the dynamics of cast-in-place shafts under high-strain impacts. The GRLWEAP program contains advanced features and options which make it particularly well suited for rationally analyzing cast-in-place piles, such as the constant-capacity variable-stroke option which is demonstrated here.

Wave equation analysis can be used to size the weight, drop height and cushion of the impact device needed for high-strain testing of cast-in-place piles. For a given situation, the hammer system should be appropriately designed to assure a successful dynamic pile test. Hammer impact should cause sufficient pile penetration to mobilize required pile resistance at reasonable dynamic pile stresses.

Figure 5 contains the results of a GRLWEAP analysis performed for a 1000 mm diameter, 17 m long cast-in-place shaft under impact of a 16.5 tonne weight with ten drop heights ranging between 1.5 and 5 m, and 290 mm of plywood cushion. Analysis input information included a static pile capacity of 1100 tonnes (85% skin friction distributed uniformly over the bottom 80% of pile length), hammer efficiency of 75%, skin and toe soil quakes of 2.5 and 7.6 mm, respectively, and soil damping factors of 0.7 and 0.5 m/s for skin and toe resistance, respectively. The analysis results include computed pile permanent penetration, compression and tension dynamic stresses for each hammer drop height. For example, for a stoke of 3 m, expected pile set is 5 mm and maximum pile compression and tension stresses are 21.0 and 1.6 MPa, respectively. This exercise shows that for a hammer weight equal to 1.5% of pile capacity (i.e., 16.5 and 1100 tonnes, respectively), it is possible to achieve a pile set value of approximately 10 mm without causing concerns of pile damage.

Conclusions

High-strain dynamic testing of cast-in-place shafts is a proven, reliable, accurate and economical method for evaluating pile static bearing capacity and structural integrity. The equipment and analytical methods developed over the last three decades for testing driven piles can be, and have been, effectively applied to cast-in-place pile testing and analysis. Experiences from around the world show the applicability and usefulness of this type of pile testing. Advantages over other testing methods include: very low cost, speed of testing, minimal pile preparation, and the ability to randomly test piles after installation.

For successful testing, there are minimum standards that should be considered. A sample specification and guidelines for high-strain dynamic testing of cast-in-place shafts are included in the appendix to this paper.

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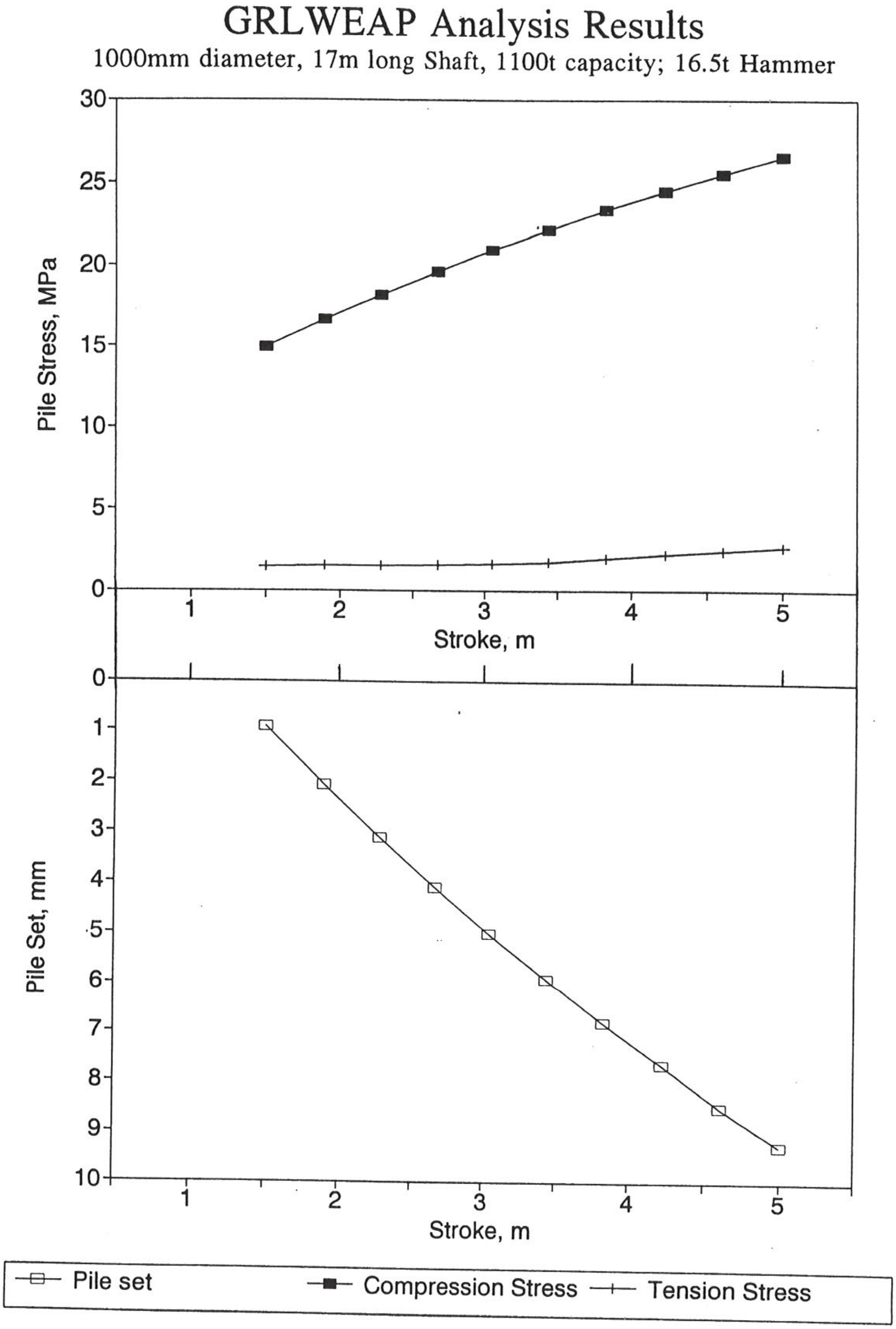

Figure 5: GRLWEAP wave equation analysis results

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APPENDIX

SPECIFICATIONS & INSTRUCTIONS FOR HIGH-STRAIN DYNAMIC TESTING OF DRILLED AND CAST-IN-PLACE SHAFTS

1.0 DESCRIPTION

High-strain dynamic testing is performed by obtaining and analyzing records of shaft force and velocity under drop weight impacts for evaluations of shaft load carrying capacity, structural integrity, and load-movement and shaft-soil load transfer relationships. Descriptions of this testing method are included in Section 455, Subsection 3.14 of the Florida Department of Transportation's specifications for structures foundations. Testing of drilled and cast-in-place shafts closely resembles testing of driven piles during restrike. The following are specifications and instructions for high-strain dynamic testing of drilled and cast-in-place foundation shafts.

This work shall consist of furnishing all materials, equipment and labor necessary for conducting high-strain dynamic tests on drilled and cast-in-place shafts (hereafter each noted as test shaft). The contractor will not be responsible for conducting the test, but will be required to supply material and labor as hereinafter specified and including prior to, during, and after the load test. High-strain dynamic testing is a non-destructive quick test and it is intended that the test shaft be left in a condition suitable for use in production. Testing procedures shall conform to the ASTM D 4945-89 specification unless as otherwise noted below. The shaft used for the test will be instrumented and tested by others, as approved by the Engineer, meeting requirements outlined in the ASTM D 4945-89 specification as well as those outlined below.

2.0 EQUIPMENT

The Contractor shall supply all materials and equipment required to prepare the test shaft, dynamically load the shaft, and return the shaft to a condition suitable for use in the finished structure. Equipment required to perform the test includes but is not limited to:

1) If a permanent casing is not used as a feature to construct the shaft, then a shaft top extension, consisting of a thin walled casing or equivalent, shall be used to extend the shaft by length equal to two pile diameters. This top length, defined as the "test area", must be exposed and readily accessible by the testing Engineer at the time of the test. If the shaft top is below grade, then the Contractor must have equipment available to remove surrounding soil (creating a safe working environment) so as to completely expose a test area of the shaft as described above. Windows on possibly four opposite sides of the shaft may have to be cut-off in the steel casing to reach the concrete.

2) Means to insure flat, level (axial to shaft) and solid concrete shaft top. Concrete should be level with, or above the casing.

3) A drop weight in the range of one to two percent (1 - 2%) of the anticipated pile capacity, or as determined by the Engineer.

4) A guide allowing variable drop heights typically between 3 and 7 ft (1 to 2 m), or as determined by the Engineer.

5) A shaft top cushion consisting of new sheets of plywood with total thickness between 2 to 6 inches (50 to 150 mm), or as determined by the Engineer.

6) A steel striker plate with a thickness of at least 2 inches (50 mm) and an area between 70 to 90% of shaft top area but not less than the area of the impacting surface of the drop weight to be paced on top of the plywood cushion.

7) If protruding reinforcing bars are present, the Contractor has the option to incorporate the reinforcing steel in the test area. Upon successful completion of the dynamic test, the surrounding concrete can then be removed as to make the pile suitable for use in the structure. If the Contractor selects not to incorporate the steel in such a manner as described above, then a steel beam or pipe (cross sectional area approximately 20% of the shaft cross sectional area) shall be supplied with sufficient length such that the ram impact will not interfere with the reinforcing bars. Steel striker plate and plywood cushion must also be sized so that they cover as much of the impact area as possible.

8) One (1) kW of 115 Volt AC power.

9) Surveyors' transit, laser light, or equivalent for measurements of pile set under each impact.

3.0 DYNAMIC TESTING FIRM

It is the _________________ responsibility to employ and compensate a specialized testing firm. Testing is to be performed by an independent testing specialist from a firm with a minimum of five (5) years experience in dynamic shaft load testing. The actual test shall conducted and/or supervised by a Licensed Professional Engineer with at least two (2) years of dynamic testing experience. Selection of the firm must be acceptable by the Engineer.

The independent dynamic testing firm must supply the following testing instrumentation in addition to that outlined in ASTM specification D 4945-89 Section 5:

1) Pile Driving Analyzer® (PDA) manufactured by Pile Dynamics, Inc., model GCPC or more recent.

2) Four calibrated strain transducers.

3) Four calibrated accelerometers.

Prior to performing the dynamic test, the testing Engineer must be provided with soil borings, shaft installation records, concrete properties (strength, *etc.*) and details regarding the anticipated dynamic loading equipment. The test Engineer is required to perform wave equation analyses (using GRLWEAP™ or equivalent) to determine the suitability of the proposed dynamic loading equipment and an acceptable range of ram drop heights so as not to cause damage in the shaft during the test.

4.0 PROCEDURE

4.1 1) The test shaft shall be constructed using the approved installation techniques.

2) If a permanent casing is not required, then the upper length equal to two shaft diameters, noted as the "test area", must be cased in a thin wall tube or equivalent as noted above. Casting of this test area must be made as a continuation of the construction of the shaft. There should not be soil contamination or non-uniformities in the concrete located within or below the test area. Shaft top shall be made level to the casing and smoothed.

3) Prior to testing time, the Contractor shall make the shaft test area length completely accessible to the testing Engineer.

4.2 1) Prior to the test four "windows" (approximate size of 6 by 6 inches (150 by 150 mm)) diametrically opposite of each other will be located and removed from the casing if appropriate.

2) In cases where casing is not present, the testing shall smooth (by grinding) areas around the pile circumference such that proper gage attachment can be accomplished.

3) Gages shall be attached by the testing Engineer to the exposed concrete or steel casing in a secure manner as to prevent slippage under impact.

4) Shaft top should be examined to insure concrete is flush with or above the casing.

5) Apply plywood cushion and then striker plate to the shaft top. If reinforcing protrudes from the shaft top, then the steel beam or pipe (used to transfer the impact to the shaft top) should be secured in such a manner as not to move under impact.

6) At least two (2) hammer impacts should be applied to the pile top. First drop height should be minimal to allow the testing Engineer to assess the testing equipment, the driving system and pile stresses. Subsequent impacts can then be applied by utilizing higher drop heights.

7) Upon completion of the test, it is the Contractors' responsibility to return the pile to acceptable production condition.

5.0 REPORTING OF RESULTS

It is the testing Engineers' responsibility to submit a timely report of the testing results. In addition to the field results, results from at least one (1) CAPWAP® analysis (CAse Pile Wave Analysis Program) must also be included. In addition to reporting applicable information outlined in ASTM specification D 4945-89 Section 7, the testing Engineer must also provide the following:

1) Wave Equation analysis results obtained prior to testing.
2) CAPWAP analysis results.
3) For each impact the maximum measured force, maximum calculated tension force, transferred energy to the gage location, corresponding stresses, and the Case Method bearing capacity.
4) Assessment of the test results both with respect to pile capacity and integrity.

6.0 METHOD OF PAYMENT

The high strain testing procedure shall be considered as any material, labor, equipment, etc. required above the requirements of drilled shaft/auger cast pile installation. This item should include everything necessary to perform the shaft test, under direction from the Engineer. All costs associated with the normal production of the test shaft are measured and paid for elsewhere in the contract documents.

7.0 BASIS OF PAYMENT

The complete and accepted "High Strain Dynamic Load Test" shall be paid for at the contract price bid for "High Strain Dynamic Load Test", each. This shall constitute full compensation for all costs incurred during the procurement, installation, conducting of test, and subsequent removal of test equipment.

Payments shall be made under:

Pay Item:	Pay Unit:
High Strain Dynamic Load Test	Each