Guidelines for successful High Strain Dynamic Load Tests & Low Strain Integrity Tests for Bored Piles

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ABSTRACT

High Strain Dynamic Pile Testing with the Pile Driving Analyzer® (PDA) was first offered by Pile Dynamics in 1972 following a decade of pioneering research at Case Western Reserve University. Later low strain integrity testing using Pile Integrity Tester, Cross Hole Sonic Logging, and Thermal Integrity Profiling was also popularized by PDI worldwide. Today, these methods are used across six continents and in more than 90 countries. Several countries have their own codes and specifications that define the test methods and its use.

It should be appreciated that these methods require a sound understanding of wave mechanics, soil mechanics, and the method of foundation installation etc. to ensure a good interpretation of the test results. In several regions, abuse of these methods has been reported which is primarily due to testing engineers not properly understanding the checks and balances that are required for proper testing and analysis. Engineering representatives of the end user can review the submitted testing reports for certain minimum requirements to assure the reliability and understand the interpretation and output obtained from PDA and CAPWAP® results.

This paper specifies the minimum guidelines required for high strain dynamic pile testing, particularly for bored piles (drilled shafts). It explains the importance and input of several parameters during the testing process like Match Quality, skin friction distribution, input of area, elastic modulus etc. Similarly for integrity testing, the paper describes the importance of Magnification Delay, Magnification, etc. for proper interpretation. The paper thus provides the information about how to perform good/ethical tests (which comprises of data collection and analysis) and the minimum required checks for the reviewer of the data and report.

1. Introduction

In deep foundation industry HSDPT, PIT, CSL etc. are now known terminologies for High Strain Dynamic Pile Testing, Pile Integrity Testing and Crosshole Sonic Logging, respectively. The original research on dynamic pile testing began at Case Western Reserve University more than 55 years ago (Eiber, 1958). The Ohio Department of Transportation (ODOT) and Federal Highway Administration (FHWA) subsequently funded a project starting in 1964 for further development of the technology (FHWA Ref. Manual – Vol. 2, 2006). High Strain Dynamic Pile Testing (HSDPT) with the Pile Driving Analyzer (PDA) was first offered by Pile Dynamics Inc. (PDI) in 1972 following this pioneering research. Similarly Low-Strain Integrity Testing (LSIT) and Cross-hole Sonic Logging (CSL) technology has also evolved over the years. A detailed historical development of these technologies has been documented by Hussein (2004).

Reliability of HSDPT has been rigorously investigated and its correlation with static load testing have been summarized by Likins (2004). Likins (2000) also highlighted the recent advances and proper use of PIT for integrity evaluation of piles. These methods are also standardized as per various codes worldwide.

Beim (2008) has reviewed the world wide acceptance of these techniques. Major standards and codes for HSDPT, PIT and CSL are summarized in that paper. These test methods are now part of various international codes and standards from USA, UK, Australia, China, Brazil, Germany, Canada, France etc. but yet to become part of India's code.

High Strain Dynamic Pile Testing was introduced to India in the later part of eighties (Vaidya, 2004) and the first author has been active from 1998 onwards. The main advantages of this test as compared to conventional static load test are time and cost savings. The current practice in India is to correlate the results of HSDPT with a static load test for one or more initial piles and then perform HSDPT on routine piles so that the required quantity for quality assurance as per contract or code specifications is satisfied.

The HSDPT method has several inputs and output parameters which need to be understood before interpretation of the resulting measurements; this is particularly true for bored piles. Any intentional or unintentional error can lead to a changed end result which in some cases can be significant; in many cases, data distortion or manipulation leads to loss of trust in a well developed technology. To correctly administer the HSDPT method, the tester must be well aware of the data collection requirements and proper interpretation. It is recommended that the client or consultant who reviews the project is also reasonably aware of the minimum checks that should be done before the analysis and report is accepted.

2. Basic Knowledge needs

It is desirable that the engineer who interprets the results is well trained in wave mechanics, has some knowledge of the pile installation method, has reviewed the installation records, is reasonably aware of the soil and its behavior, and has good personal integrity. It is recommended the site tester is formally trained to collect proper data, although data collection is practically automatic. For this it is best recommended that the user is trained in the operations either by the manufacturer (PDI) or one of their approved training instructors, and that he undergoes a qualifying exam to check his understanding of critical aspects of data quality, application and data interpretations. Currently, the PDCA Proficiency Test is routinely available in USA and also worldwide (www.PDAProficiencyTest.com). However, this exam covers mostly topics of driven piles and does not include bored piles, although many principles are in common.

3. Guidelines for Proper HSDPT Testing

A) Date

The date of the test is always included in the HSDPT output and should match the date the testing occurred.

B) Pile Diameter

The actual pile diameter for bored piles maybe different than that mentioned in drawings as the diameter depends on the diameter of chisel or the cutting tool. Therefore, it is generally recommended that the tester should calculate the actual diameter from the measured circumference of the pile at site and input the same into the program. Following is the sample part of CAPWAP output where for a 600mm diameter pile, incorrect area along the shaft is used (correct area is 2827 cm^2). However toe area is correct. Also perimeter at top is incorrect (1.884 m is correct).

PILE PROFILE AND PILE MODEL				
Depth m	Area cm^2	E-Modulus MPa	Spec. Weight kN/m^3	Perim. m
0.00	1296.77	33224.7	23.563	1.884
19.20	1296.77	33224.7	23.563	1.884

Toe Area 0.283 m^2

Top Segment Length 1.01 m, Top Impedance 1158.64 kN/m/s

Figure 1 Incorrect area and perimeter input

C) Wave Speed

The input of wave speed is critical to obtain a proper CASE Method result. It not only affects the time of reflection from the pile toe, but also affects the measured force if the data is taken with strain transducers. (Another method to measure force at pile top is through a "top transducer" and results in better certainty of the force measurement. However, that system is not yet widely used outside United States). The wave speed can either be obtained from a low strain integrity test (when a clear response from the pile toe is visible and the pile length is known) or it can be initially assumed and later corrected after a few blows onto the pile during field testing. Note that the RMX (maximum CASE Method resistance) or RSU (maximum Case Method resistance with correction for unloading) values will change for all the blows whenever the wave speed is corrected during the testing program. Alternatively, the wave speed can also be changed after the field testing and during the CAPWAP analysis (which is mandatory for all bored piles).

D) Soil Damping Jc

The Case Method soil damping constant shall generally follow the guidelines in the manual which are mentioned here for the sake of clarity. It affects the computed RMX. An experienced tester may select the damping factor based on his past experience of testing in similar soil conditions. A Jc = 0.5 is often a good starting solution. The damping factor is later correctly calculated from the CAPWAP analysis. PDI suggests following typical values for Jc:

- 0.40 to 0.50 for clean sands
- 0.50 to 0.70 for silty sands
- 0.60 to 0.80 for silts
- 0.70 to 0.90 for silty clays
- 0.90 or higher for clays

E) Pile Length and Penetration:

The pile length from sensor level to the bottom of the pile and the penetration of the pile into the soil should be correctly input into the system. An incorrect pile length can result in an incorrect wave speed and cause errors in capacity computation.

4. Data Quality Checks

A) Equipment Calibrations:

The first check before starting a test is to ensure that the internal calibration of the equipment is within acceptable limits as defined by the manufacturer. This ensures that all the components of the PDA including the cables and sensors are in proper working condition and capable of collecting data. An independent external PDA calibration box can check the system in the office.

The calibration certificates of the strain and acceleration sensors should be submitted with each testing report and can be reviewed and compared with the manufacturer's calibrations. The soon to be available 2014 CAPWAP program's output will list the calibrations, making it easy then to verify. Improper calibrations will alter the test results.

B) Force-Velocity Curves:

Once the data collection is started, the tester shall review the data collected from individual sensors to ascertain data quality. Typically, since data will be collected from a minimum of two strain sensors and two accelerometers, PDA presents data from a minimum four sensors. The curves from both the accelerometers, presented as velocity, shall closely match each other and should dampen to zero about the x-axis after the relatively short impact is completed. Refer to Figure: 2 for good V1and V2 velocity data. Figure 3 shows unacceptable V2 data.

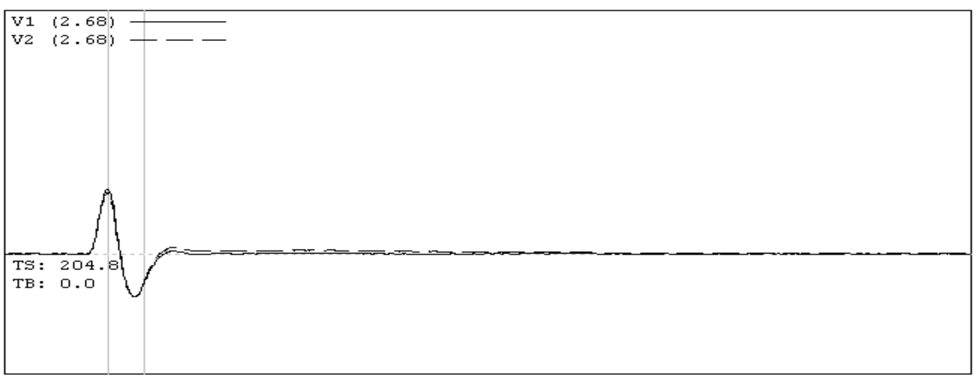

Figure 2 Good accelerometer data

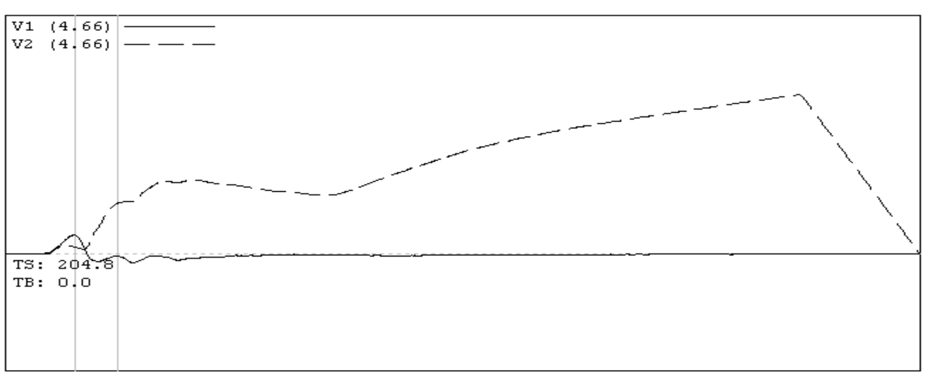

Figure 3 Bad accelerometer data

However, in case of strain sensors, separation of two force curves (obtained from measured strain multipled by area and modulus) is possible and acceptable to some extent due to small bending during hammer impact. Flat contact surfaces at pile top and ram weight bottom, cushioned by a modest amount of plywood, and good alignment of the drop weight with the pile, results in only small amounts of bending. Generally two, or preferably four, strains are measured with opposite locations to cancel these bending effects. One or three measurements are not acceptable. Any force curve should not be above (or significantly below) the x-axis at the end of the record as this may be due either to improper attachment of sensors or alternately to cracking of pile top concrete etc. Figure 4 shows the F1 curve is lifted above the x-axis, indicating in all likelihood a damaged or cracked pile top concrete. Figure 5 shows typical good quality data with both the F1 and F2 curves linear with x-axis and with no bending.

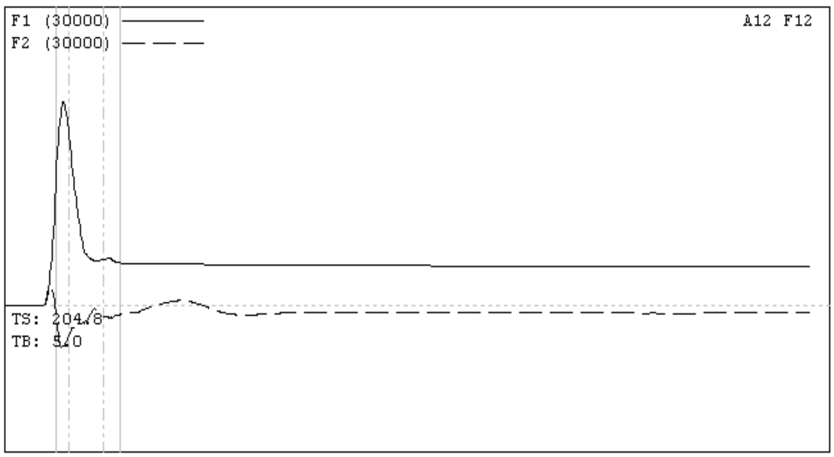

Figure 4 - Bad F1 strain data force is well positive at end – Cracked Pile Top

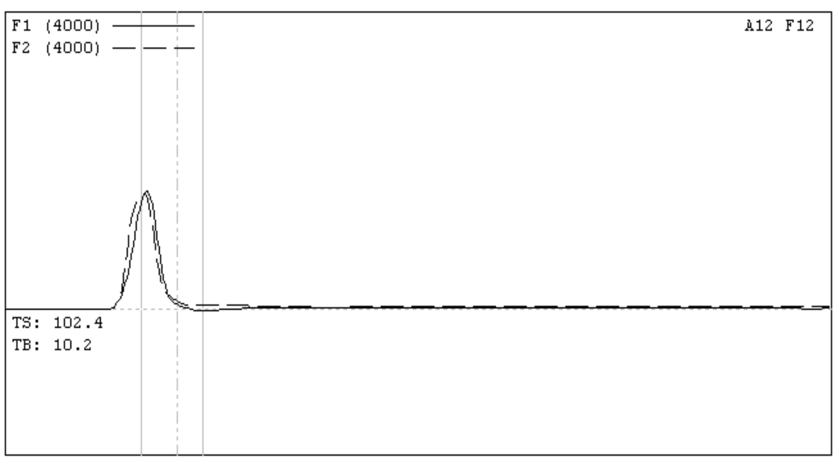

Figure 5 Good strain sensor data

C) Data Proportionality

Ensure that force is proportional to velocity (times the pile impedance constant) when there is minimal soil resistance in the upper soils. In general, the force and velocity at the first peaks should match each other. Non- proportionality to small extent can be explained due to small corrections to the elastic modulus or wave speed that maybe required. In some cases, non proportionality may also be due to crushing of concrete at the sensor location as the extended pile head or the pile concrete at top maybe of poor quality, as shown in Figure 4. If the pile shaft is not uniform, perfect proportionality will not be observed. If the cross section increases shortly below the sensors the force will be higher than the velocity at the first peak; if the section decreases, the velocity will be higher than the force. Figure 6 shows good quality data with nice proportionality between force and velocity curves.

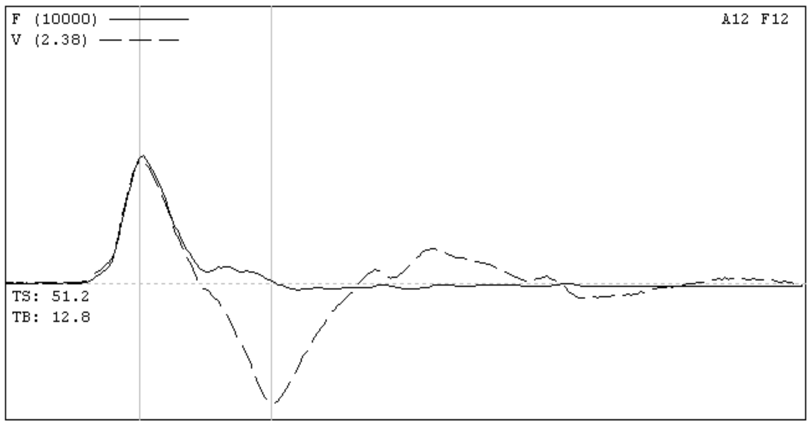

Figure 6 Good proportionality - Acceptable

5. Hammer Weight & Drop Height

It is important that a sufficient hammer weight is used for testing of bored piles. Typically the hammer weight shall be at least 1% of the required test load for bored piles with rock sockets or piles installed in clay soils where end bearing is not considered; for piles installed in soils where end bearing will be required, the hammer weight shall be a minimum of 2% of the test load. Higher test weights are always acceptable. The weight also shall be at least 7% of the dead weight of the pile. The hammer weight must be sufficient to activate the test load for working piles or ensure that the pile reaches the ultimate capacity for initial piles; activation is generally confirmed by a permanent set per impact of at least 2 mm. Note that a heavier hammer with a lesser drop is preferred compared to a lighter hammer with a large drop. Most drop weight systems allow a drop height upto 3m. The selection of hammer drop height also depends on the type of fall mechanism used (free fall, single line of crane etc), soil type etc.

6. CAPWAP Analysis

A good CAPWAP analysis is mandatory after data collection for all bored piles. The analyst should consider the soil profile and the pile concreting logs to find a reasonable solution. Using the same soil and concreting information, the analysis results should be reviewed for reasonableness by the report reader. The Match Quality (MQ) parameter printed with the CAPWAP output is a very important parameter to assess if the analysis and the final output should be accepted. Generally, a MQ less than 5 is considered acceptable and is preferred. Match Quality is almost always below 5 for tests on driven piles, and often below 3. Lacking an adequate explanation, analyses with MQ greater than 7 are classified as unreliable.

7. Reliability Studies

It is normally difficult to check the knowledge of an engineer or the testing company. The Proficiency Test mentioned in Section 2 is then useful. Although the integrity of the pile can be verified, it is difficult to verify the integrity of the testing company. A lack of integrity and providing falsified results leads to loss of faith in the otherwise reliable technology. Thus reliability studies are useful to ensure that the testing company has adequate knowledge and experience of testing. It is not necessary that the results of static and high strain dynamic tests will match in all the cases unless adequate precautions were taken in selecting the pile for such correlation studies. It should also be appreciated that submitting the data and report to an independent third party knowledgeable in the method for a review will detect gross abuse (small differences in results, like within 10%, are still quite acceptable). It is generally observed that the practice of third party reviews has resulted in ensuring that those testing companies who are willing to learn and have good integrity will produce reliable test results.

8. Low Strain Integrity Testing

Low Strain integrity testing requires an expert technician or an engineer to collect proper data. Actually proper data collection constitutes a large part of good integrity testing report. However, the test has been abused sometimes which leads to loss of confidence. In some cases, trying to test hundreds of piles in one day also leads to shortcuts resulting in poor data quality and resulting in poor interpretation. Some of the minimum checks that can be enforced are listed for further understanding.

A) Magnification Delay (MD)

The MD defines the time when exponential magnification of the signal with time should be applied to the pile. The default value of 20% of the total pile length works well in most situations. This should only be modified when the free standing length of the pile is more than 20% of its total length. This situation might occur only for marine piles. The change in MD value beyond 20% of pile length is a most common abuse of data. Refer to Figure 7 which shows the data with proper magnification delay (blue arrow) and where a defect is apparent (red arrow) prior to the expected time of reflection from the pile toe (green arrow). However, for the same data, if a later magnification delay (blue arrow in Figure 8) is applied, then the defect diminishes and the defective pile incorrectly appears acceptable due to the inappropriate change in MD value.

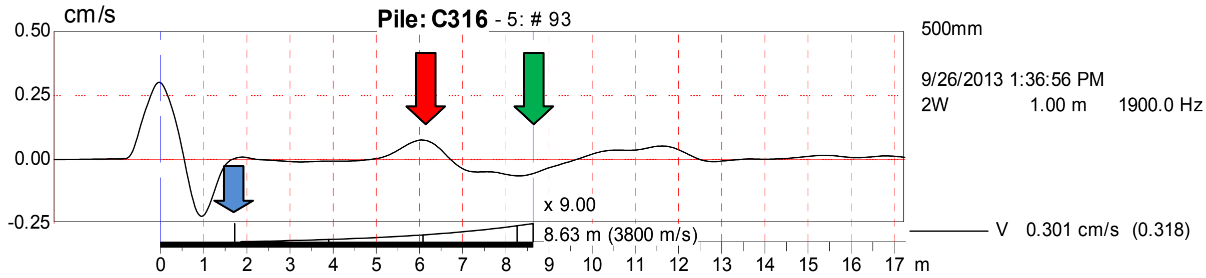

Figure 7 Appropriate MD – Defective Pile

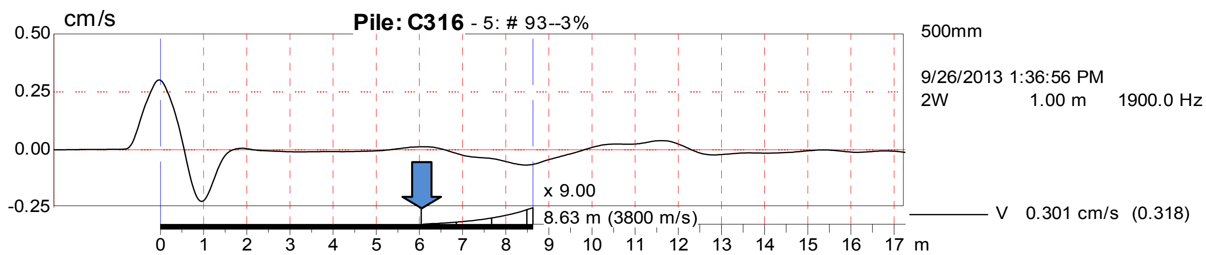

Figure 8 Inappropriate MD – Defective Pile appears OK

B) Magnification (MA)

A similar MA value should be used for similar length piles of similar diameter. An MA value equal to its pile length (in meters) is many times a good starting solution, although higher values may be needed for piles in strong soils. Using very low MA values may mask apparent defects for questionable piles. In general, if there is no apparent reflection from the pile toe, either the pile is defective (as in Figure: 7), or pile preparation has been inadequate, or the magnification value is too small, or the shaft is relatively long and of a sufficiently non-uniform character (e.g. generally with a relatively large bulge) and the data should be classified as "inconclusive".

C) Filters

The Hi Pass Filter (HI) is used to eliminate low frequency drifts in the data. HI is normally either zero (indicating no filter is used) or a value which is at least 20 times the input pulse width. Using a very low HI value between 1 to 30 distorts the data and the interpretation. Use of LO Pass filters is discouraged; Wavelet (of a value between 1 or 2) is recommended to remove the very high frequency content (generally caused by Raleigh surface waves or short protruding reinforcement). Long protruding reinforcement (certainly 3 m or more) often results in a low frequency noise of about the same frequency as the input pulse width (1 to 2 m) and makes the data unusable; such long reinforcement should be removed prior to testing.

D) Integrity Testing Report Formats

It has been observed that there are a variety of report formats. However, in general an integrity test report should clearly specify 1. Piles that are acceptable. 2. Piles that show major defects and are not acceptable 3. Piles that show minor defects and maybe acceptable after review of loads, additional tests etc. 4. Piles that are inconclusive due to bulges, high soil resistances etc.

9. Other NDT methods

CSL testing is relatively uncomplicated, but if results show an “anomaly” then the engineer must decide what course of action to take. Some CSL systems only present the processed results, and they can be subject to manipulation. If the raw data is presented as a “waterfall” diagram, as required by ASTM D 6760, then the reader of the report can assess the situation more fairly.

Thermal Integrity Profiling (TIP) measures the heat produced during early curing of the concrete to evaluate the shaft integrity. If there is a local cool spot, then there is likely a deficiency of cement content, representing a deficient concrete strength. The data is in an embedded format and cannot be altered.

In both CSL and TIP, the dates for the testing as shown in the report are fixed and cannot be changed in the PDI systems, and can be compared with the installation dates for the piles in question as a further check.

10. Summary

- Pile foundation testing with PDA, PIT and CSL is proven worldwide and has been widely accepted in India and worldwide. They are relatively inexpensive and provide significantly more information than traditional static load tests.
- However, even today in various countries including India, clients or consultants are not fully aware about data interpretation and analysis. This has sometimes led to malpractices/manipulation. In some cases, there are genuine mistakes by testers and at times there is less interest to provide good quality reports.
- It is in the interest of the technology developers, reputable testers, and end user clients to ensure ethical testing else there will be less trust in PDA and PIT which are extremely powerful and useful tools for foundation testing.
- It is observed that good testing is possible when all those concerned with testing are reasonably updated on various test methods, interpretations etc. This paper is an effort to provide some basic understanding about data collection and interpretation before a report is accepted. Recommendations of what to inspect in the reports have been made to help spot the most common mistakes or areas of concern.
- Third party reviews by knowledgeable experts should be included when the end client is not personally familiar with data interpretation.
- PDA / PIT exams that also include interpretation of bored piles is one option to assess the knowledge of the test engineer before he authenticates the report.

11. References

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