ON THE APPLICATION OF PDA DYNAMIC PILE TESTING

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Introduction

The Pile Driving Analyzer (PDA) is a powerful tool to assess pile driving, which may supplement or replace static testing. Static testing is often physically or financially impossible, over water for example, or at very high loads. Statically testing only one percent of the piles is no longer adequate, particularly as design loads increase. With the PDA, it is possible to test five to ten percent of all piles on a site, and do it easily and economically. PDA testing makes it possible to solve problems encountered during pile driving based on facts rather than assumptions. Construction quality is improved through increased testing. This results in cost savings (sometimes tremendous savings) and reduced construction claims. PDA testing in now sufficiently accepted and standardized that several standards and specifications defining proper procedures have been written and accepted such as ASTM D4945, AASHTO T298, and several from other countries.

The PDA is seeing increasing usage in the testing of the various types of cast-in-place piles. In some parts of the world, this type of testing is the most common use for the PDA. This solution is particularly attractive for very large, high capacity piles where the large capacity makes a static test extremely costly. A large drop hammer can be mobilized and several tests can be performed quickly and cost effectively.

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Method Application

Dynamic testing should not be done merely to fulfill the requirements of a specification. It was probably required for a certain purpose and it is essential to respond to this test purpose. The purpose will vary from project to project, and the specification for one site may not be applicable to another. For example, specifications for production pile monitoring may be quite different from those for a test pile program which is primarily concerned with establishing a driving criteria. Tests for hammer performance evaluation require different procedures from tests where pile bearing capacity is at issue, or where information on driving stresses or potential pile damage is sought. Finally, tests on cast-in-piles, where a ram is mobilized for the specific purpose of pile capacity determination, will be very different from those tests conducted on driven pile projects. However, while there is a primary purpose, the engineer must always evaluate all available results to avoid any issue which could cause a major concern at a later stage of the project. A review of dynamic testing methods is found in Hannigan (1990).

If the primary testing purpose is for establishing driving stresses or inspecting hammer performance, then the tests must be performed during the installation process. The highest stresses at the pile top or the pile bottom are generally either at or near the end of driving, when penetrating a very hard soil layer, or when the hammer performance is highest for those hammers whose stroke can be increased. If tension stresses for concrete piles are of concern, the test must be started early in the driving process, perhaps at the very beginning of driving, to monitor the early, easy driving portion of the installation.

If the testing purpose is pile integrity or damage investigation, tests can be made either during driving or restrike. However, as shaft soil resistances increase, damage detection becomes more difficult. Furthermore, damage is often the result of either poor pile material quality, wide manufacturing tolerances, inadequate splices, or overstressing of the pile during driving. For the latter two categories, it is beneficial to observe the pile during installation to find out why the pile broke, and to establish a better installation procedure to reduce damage on subsequent piles. It is unlikely that all piles all piles on a site will suffer damage. Tests are generally made on several piles to determine the presence or absence of pile defects. Piles with apparent longer lengths than neighboring piles or with lower blow counts or unusual driving records should be investigated for potential damage; there is little economic merit of splicing a pile suspected of being damaged before first applying a PDA test.

Frequently, the test purpose is to determine pile bearing capacity. Increases and decreases in the pile capacity with time typically occur after a pile is driven (soil setup/relaxation). Therefore, **dynamic testing during restrike usually yields a better indication of long term pile capacity than a test at the end of pile driving.** The pile capacity during driving is usually less than the long term pile capacity particularly for piles driven in fine grained soils (clays, silts and even fine sands.) Excess positive pore pressures are generated during driving which reduce effective stresses in the soil and, thereby, reduce the pile capacity. As pore pressures dissipate, the soil resistance acting on the pile increases as does the axial pile capacity. This phenomena is usually called soil setup. Capacity may also be reduced during driving by lateral pile motions creating an oversize hole; the full capacity is restored by the natural overburden and time. The wait period between initial installation and restrike is important. A restrike after only 15 minutes for a pile installed in clay is not sufficient to predict long term capacity. Longer wait times of seven days or more are often necessary for piles in fine grained soils. Dynamic capacity should be evaluated by CAPWAP (Rausche, 1972, 1994).

Relaxation (capacity reduction with time) has been observed for piles driven into weathered shale, and may take several days to fully develop. Pile capacity estimates based on initial driving or short term restrike tests can significantly overpredict long term pile capacity. Therefore, piles driven into shale should be tested after a minimum one week wait either statically or dynamically (with particular emphasis on the first few restrike blows). Relaxation has also been observed for displacement piles driven into dense saturated silts or fine sands due to negative pore pressure effects at the pile toe. Again, restrike tests should be used, with primary emphasis on the early hammer blows.

Capacity testing of cast-in-place piles requires that a hammer be mobilized to perform the test. Usually a drop hammer is used, in many cases constructed for the specific purpose of testing these piles. Some cast-in-place piles are very large in both diameter and capacity making a static test very costly and a dynamic test can result in large cost savings. Capacities as high as 4500 tonnes have been proven with dynamic tests (although with larger drop hammer, larger capacity shafts may be tested successfully). As a rule of thumb the ram should have a weight of one to one and one half percent of the capacity to be proven. Thus, to prove a capacity of 2000 tonnes a 20 tonne ram might be used. The testing effectiveness for a particular case can be checked with a wave equation analysis (Hussein et al. 1996). Some large diameter piles require a large displacement to mobilize their ultimate capacity and in these cases a larger ram is required than, for example, in testing a rock-socketed pier. However, it is not necessary to mobilize the total ultimate capacity if the particular pile being tested has a capacity that is much greater than required since the mobilized capacity determined by the test will be a lower bound on the ultimate capacity.

It should also be noted that the dynamic testing capacity estimates indicate the **mobilized pile capacity at the time of testing.** At very high blow counts (low set per blow), dynamic test methods tend to produce lower bound capacity estimates as not all resistance (particularly at and near the toe) is fully activated. It is, therefore, important that the hammer energy be high enough to cause a sufficient set per blow if the full ultimate capacity is to be determined.

Data Acquisition

It is absolutely imperative to obtain good quality measurements, since erroneous data produces results that are then meaningless or wrong. Good data requires good sensors that are properly calibrated. The criteria that should be used in examining the quality of the data is PROPORTIONALITY, CONSISTENCY, and WITHOUT DEFECTS. Generally good data will show good PROPORTIONALITY between force and velocity at and prior to the first peak (for uniform piles, without defects), and will also be CONSISTENT (data shapes and results) from blow to blow. Data should also be WITHOUT DEFECT (no electronic noise, final velocity near zero, and the displacement at the end of the record similar to that observed from the blow count).

Poor quality data can be due to bad sensors, improper attachment of sensors to the pile, damaged cables, excessive pile bending, nonuniform impact, or pile damage. The first three problems come from physical error sources associated with the testing. The PDA operator can check sensor attachment, or change sensors and cables and this usually fixes the problem. The last three problems come from hammer-pile misalignment, poor pile quality or excessive driving stresses and can be detected by the PDA or the PDA operator observing the measurements.

The PDA operator should be able to immediately recognize if the data is valid or contains serious flaws. Although the PDA automatically makes numerous checks on data quality (Likins 1992), it is generally recommended that data be acquired by an engineer with a good understanding of both wave propagation theory and pile driving. Improperly prepared or poorly trained personnel may not always understand when data quality is poor.

Data Interpretation

Even if the method is properly applied and the data quality is excellent, the test data must be properly interpreted and results communicated in a timely manner. Driving stress, integrity, and hammer performance evaluations are all relatively straight-forward. Capacity should be evaluated by CAPWAP and must consider a variety of inputs concerning the pile and recognize the influence of soil type and soil behavior. Two conditions must be present if the long term capacity is to be reliable evaluated. First, the test must be a restrike after a reasonable wait time, and an early restrike blow must be selected for analysis. Second, the set per blow must be sufficiently large to assure that the soil has failed and the full ultimate capacity has been achieved, or else the dynamic test will give only a lower bound estimate.

While PDA operation is relatively simple, each job presents unique challenges, particularly if recommendations or data interpretations are required on site. Many unforeseen problems with the hammer system, pile, or soil should be detected on site by the PDA engineer. Early detection and problem situation correction are required for maximum testing benefit. This is particularly true for special test programs or for the first dynamic test piles driven on a site to support and verify the preliminary driving criteria. Decisions made at this crucial time often can influence the overall foundation cost. If problems are not spotted as they occur, but only detected later during data review in the office by the supervising engineer, what is to be done with all the piles driven in the intervening period?

Assigning testing to a person with insufficient technical training, or an engineer with limited experience in dynamic pile testing, is not good practice as they often miss critical problems, creating difficulties easily avoided by having a qualified engineer on site. Final result interpretation should be by a professional engineer who understands wave propagation theory, pile design, and pile driving. A geotechnical engineer should review results for uplift, settlement, downdrag, scour, lateral loads, effective stress changes due to changes in the groundwater table or placing of surcharge, etc. Other items such as out of tolerance installation, pile material strength, and corrosion are not evaluated by the dynamic pile testing, but can also adversely affect the final performance of the pile and need review by the structural engineer.

Who Will Do the Testing?

When PDA testing first appeared contractors, geotechnical engineers, construction managers and other firms hired a specialty testing firm if a dynamic test was required by the construction specification. Testing is also called for if a specific problem develops for which dynamic testing may provide answers or assist in finding a solution. As the value of dynamic testing was realized, the demand for and use of the test increased, and the firm contracting the specialty service sometimes acquired the equipment and performed the tests with their own personnel. In this way, they expanded their scope of services. Today PDA testing is performed by public and private engineering organizations, specialty testing firms, engineering design organizations, and contractors. In general, it is best if the organization that specifies the testing be contractually responsible for hiring the specialty testing firm or acquiring the data and its analyses since this speeds transmission of all results into the hands of those who need them.

Whether to use a consultant or perform the testing in-house must be addressed. Do you have enough work to economically justify the PDA and PDA engineer? Does your firm have an engineer with the capability and desire to learn all about dynamic testing? "Desire" is really a key issue. It has been well said that

> "The successful implementation of any new technology is dependent on an in-house 'champion' to promote and develop a plan which complements the firm's organization and procedures. The champion must fully understand the technology... Simply stated an implementation plan must be developed... The firm must have in-house personnel who are either familiar with, or willing to learn the new technology. In addition, they must have the ability to define the specific scope of work for projects, to interpret results, and to provide guidance to other design and construction personnel." (DiMaggio, 1992).

Areas of Concern for a Proper Test

As usage increases, it is necessary to assure that the method is applied properly and correctly and that the results are reliable. Without reliable measurements, any analysis will be meaningless. And finally, without proper interpretation and communication of results testing will be a useless exercise and a waste of time and money. Engineering judgement is necessary so that the test will be conducted on piles which represent typical site conditions, e.g. to determine the driving criteria, or to unusual piles (with different blow counts or different penetrations) to determine (and correct) any potential problems. A statistically meaningful selection of test piles may improve the quality control.

A serious problem faced in the expansion of PDA testing is the maintenance of high standards for test engineers. They should be thoroughly trained both in the theoretical background necessary to perform the test and in the field experience required to understand the practical aspects of pile driving so that the results of the measurements can be understood. The equipment and the test requires a background that is different than most other field testing. A thorough understanding of wave mechanics is absolutely necessary and is usually not available from the educational background of the civil engineer. As the PDA has become easier to use, it has sometimes been assumed that this background is no longer required. Serious problems can result when untrained, or inadequately trained personnel are used to do PDA testing.

Typical Test

A properly executed test should be preceded in the office by a wave equation analysis. This will alert engineers to any potential difficulties for the chosen pile and selected hammer. This information should be communicated to the PDA test engineer along with copies of the appropriate soil borings for the test site. If it is not already known, the purpose and scope of the test should be clearly communicated. Any unusual observation on piles driven to date should also be discussed. Actually this information exchange may have already been accomplished prior to arrival on site by the PDA engineer, but a brief meeting with the site engineer, contractor, and PDA engineer to discuss site specifics should be required.

The piles to be tested must be physically located and prepared to accept the test sensors. This involves drilling a few holes in steel piles (1/4 inch or 6 mm) and for concrete piles the installation of threaded anchors. A normal drill is used for steel pipes, H piles, or timber piles while an impact drill is needed for concrete piles. The contractor's help may be required to assist the test engineer in pile preparation if many piles are to be tested that day by working ahead of the engineer to prepare the next pile even as the PDA engineer is conducting a test on another pile. The process is relatively simple and with brief instructions pile preparation can often be accomplished by contractor personnel the day before the PDA engineer arrives on site. For displacement piles, the tops must be accessible from both sides, so in some cases testing of piles not yet driven may require moving the piles. Actual drilling of the piles takes about 5 to 10 minutes per pile. Pipe piles must also have the holes tapped which requires a few more minutes for each pile. This work must be done prior to lifting the pile into the leads since drilling while in the air is a safety hazard; it is better to simply test the next pile (prepared on ground) instead.

Sensors can be bolted to the webs of H piles (where they are protected) prior to lifting the pile, and the testing begun from the very first hammer blow. Protective pads have been used successfully on square concrete piles to attach sensors to the pile prior to lifting the pile. Otherwise, since the sensors are quite sensitive they should only be attached after the pile is lifted into the leads since they (or the cables) can be damaged as the pile bumps the leads while placing it under the hammer. A trained member of the pile crew usually attaches the sensors to the pile; a couple minutes instruction is generally sufficient. Usually, the early part of driving of a pile is not of much interest. Waiting until the pile is mostly driven before attaching the sensors saves considerable time in climbing leads. The one frequent exception is when tension driving stresses in concrete piles are an issue and in this case testing during early driving is required, although it may not be required for every pile tested.

The sensors are attached to the PDA by a single main cable. The PDA is generally powered by the car battery; if testing from a barge, then an alternate battery source or generator can be used. The test proceeds as the pile is driven with no interruption to the normal driving process. As the pile is driven, results are monitored for each hammer blow.

In the case of either driving or restrike, the PDA engineer must enter some information into the PDA for each pile. Most piles on a site have identical cross sections and, therefore, the cross sectional area is the same. In fact, the pile name and pile length are the most frequently changed information. For timber piles, a density measurement should be made on a sample that has been cut off the end of the pile. For both concrete and timber piles the wave speed is first assumed and then, if necessary, adjusted; this is generally accomplished by applying a few blows, making a brief stop of probably less than one minute to adjust the wave speed and compute the elastic modulus, and then testing is continued without interruption. Even if the wave speed changes during driving, (*e.g.*, because of development of micro cracks) the pile top properties will not change and a new elastic modulus is not required. The PDA engineer may have to occasionally adjust the overall pile wave speed.

Depending upon the goals of the test, the pile may be driven without interruption as if no test is in progress. However, in many cases the site engineer may have directed the PDA engineer to inform him when certain conditions are present, such as if predefined driving stress limits are exceeded or the desired ultimate capacity is reached. If these conditions are present and reported, the contractor may be directed to change his hammer performance, such as change the stroke, or change the pile cushion. This would require interrupting the driving. At any time if the PDA engineer observes damage to the pile shaft, he may alert the contractor to stop driving the pile and discuss the situation.

At the end of driving each pile, the sensors are removed; since the sensors are then at or near ground level it only takes a minute or two to remove them before instrumenting and testing the next pile.

Testing of piles during restrike is generally easier and faster since good access is available. The location of sensor attachment is not critical and can be done at any convenient location above ground level, except that it is desirable that they be at least 1.5 diameters below the top. The knowledgeable PDA and site engineers will almost always request some form of restrike if capacity is an issue. This may involve only a short 15 minute interruption, or it may be that the first pile tested during the day should be restruck at the end of the day (or the following day, or after a weekend interruption). Some specifications require a minimum period such as a 24 hour, 48 hour, or 7 day wait before the restrike.

Depending on the level of communication and cooperation present on site, there may be more of less communication between the three parties involved. Information may be reported freely and advice given to assist the project. If driving is as expected and no major problems detected, then the PDA engineer may simply acquire data and when finished with the test program leave the site and discuss the findings with his client as soon as possible afterward.

Conclusions

PDA dynamic pile testing has now been in routine use for more than 20 years. Standards such as ASTM D4945 prescribe how the test should be performed. With experience on thousands of sites, a practice has developed. The results of this experience can be summarized as follows:

1. The PDA operator must be well-trained in one dimensional wave mechanics, equipment operation, and pile driving practice if he is to take advantage of the full capabilities of this dynamic test.

2. Good data quality is essential for reliable results.

3. The purpose of the PDA testing should be clearly understood. The PDA operator should seek to address this concern, but also be alert to other potential problems detected by the test which could affect production pile installation.

4. The PDA can be useful in evaluating hammer operating characteristics, solving driving problems, and measuring driving stresses. It can also be very effective in pile damage detection.

5. Pile capacity determination is one of the most important tasks for the PDA. It has been found to give good results in capacity prediction and is often used to replace static tests. If calibrated with a static load test, the PDA can then extend the static test result over the job site in a very cost effective manner. The field PDA result is usually further investigated by CAPWAP. The result must be used with an understanding of soil behavior and how it can affect pile capacity. Changes in pile capacity can be evaluated with PDA tests at different wait times. This type of test makes it possible to take advantage of the capacity gained during setup and to avoid problems that arise from relaxation.

6. Capacity can also be determined for cast-in-place piles. It is necessary to mobilize a ram and usually a drop hammer is used. Wave Equation analysis will effectively evaluate proposed testing systems. Usually the ram weight must be one to one and one half percent of the capacity being proven. In some cases, due to the large displacements that must be mobilized, it is difficult to reach the ultimate capacity.

7. The capacity that is determined by the PDA with a CAPWAP analysis will be less than the ultimate capacity if the dynamic test penetration is small or zero. However, this capacity will constitute a lower bound and, thus, can be used to provide a proof load test result.

References

Standard Test Method for High-Strain Dynamic Testing of Piles, (1989), ASTM Designation: D4945, ASTM Committee D-18 & Subcommittee D-18.11, American Society for Testing and Materials.

Hannigan, P. J. (1990), "Dynamic Monitoring and Analysis of Pile Foundation Installation", Deep Foundations Institute Short Course Text.

Hussein, M., Likins, G., Rausche, F. (1996), "Selection of Hammer for High Strain Dynamic Testing of Cast-in-Place Shafts", Proceedings of 5th International Conference on Application of Stress Wave Theory to Piles, Orlando, Florida USA.

Likins, G. and Peterman, D. (1992), "Dynamic Pile Testing and Analysis using Expert System Methods," Proceeding of 4th International Conference on Application of Stress Wave Theory to Piles, Rotterdam, The Netherlands.

Rausche, F., Moses, F., and Goble, G. G. (1972), "Soil Resistance Predictions from Pile Dynamics", Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, September pp 917-937.

Rausche, F., Hussein, M., Likins, G., Thendean, G. (1994), "Static Pile Load-Movement from Dynamic Measurements, Proceedings of Settlement '94, Texas A & M University, ASCE, Geotechnical Special Publication No. 40.