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High strain dynamic pile testing, equipment and practice

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ABSTRACT: High strain PDA testing has become common for verification of capacity of both driven and bored piles. It also investigates other aspects of the installation of driven piles such as hammer efficiency and driving stresses. The high benefit of dynamic test results for the relatively low costs of the tests has resulted in widespread use. An overview of typical practice in the United States is given including a review of codes which guides the practical applications. The equipment hardware and software required to meet the current needs and the vision of the future is detailed, and the expertise required is discussed.

1 INTRODUCTION

As technology changes, the construction industry adapts. Construction of increasingly larger structures requires increased ultimate loads. Piles therefore become larger and longer. To install these piles, the pile driving equipment has changed dramatically from simple drop hammers to air, diesel or hydraulically powered hammers with greatly increased energy rating. Increased complexity and increasing loads, coupled with a need to maintain economy, requires better quality control and/or lower safety factors.

A century ago, dynamic formula, now widely considered as unreliable, was the only available means of assessing the pile capacity from a "measurement" of set per blow. Test piles were subjected to static tests for final proof. In the 1950's, the wave equation method of analysis using digital computers was developed and gave more dependable results since it was based on more accurate hammer and pile models, although the soil model was empirically developed. Personal computers have made wave equation analysis a readily available tool for estimating capacity and driveability.

Wave equation analysis requires assumptions about hammer system performance and soil behavior models. Unfortunately, these unknowns can cause considerable variation in results when for example the hammer efficiency from a poorly maintained hammer is greatly different than assumed. Fortunately, we can now simply measure the hammer performance and driving stresses as a result of research beginning in 1964 at Case Western Reserve University in Cleveland Ohio under the direction of Dr. G.G. Goble (Goble et al. 1975, Goble et al. 1980). The initial goal of the Case research project was to measure the pile capacity using the pile hammer as the loading device. Capacity was evaluated by both closed form solutions and discrete numerical analysis and correlated with hundreds of static tests to refine the procedures and establish databases to assure the necessary reliability. In addition to estimating capacity, the equipment developed over many years into a complete inspection of hammer performance, driving stresses and pile integrity and is known today as a "Pile Driving Analyzer®", or simply the "PDA".

2 CURRENT PROCEDURES FOR MEASUREMENT

The Case research project resulted in both closed form "Case Method" solutions (for capacity, energy transfer, driving stresses and pile integrity) and rigorous numerical modeling CAPWAP® software. Both required measurement of force and velocity of the pile. These parameters are routinely obtained by measuring strain and acceleration with the PDA using reusable bolt-on sensors for both strain and

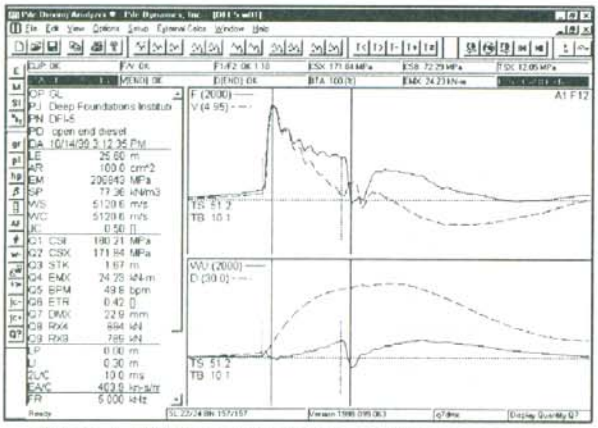

Figure 1. Windows PDA processing program.

acceleration quickly attached to any pile size and pile type in any weather condition. Sensors for underwater pile testing applications have proven reliable (Harnar et al. 1996). Recent advances include "smart sensors" which remember their calibration information and transmit it to the PDA. As an alternative to measuring strain and converting to force, top transducers used in the early research project which were sized to the pile dimensions and placed between the hammer and pile to transmit and measure force are now being seriously considered again. The signals are processed and data acquired by a PDA. Modern PDA systems are PC based with large mass digital storage and high resolution graphic screens. Data is acquired and analyzed by the user friendly Windows PDA-W program as shown in Figure 1.

The PDA is traditionally operated by a trained engineer who travels to the job site with the equipment, prepares the pile, and attaches the sensors to the pile. In recent times, pile preparation and especially sensor attachment are often done by the pile driving crew. The time required to drill the holes and attach the sensors is often only 5 to 15 minutes per pile tested (substantially less effort than a static load test).

The engineer first evaluates the data for quality. The PDA program checks for loose connections, unstable results, various ratios including the known theoretical proportionality between force and velocity at impact. If problems are detected, a warning is given, and corrective action can be taken. Once the data quality is satisfactory, the engineer interprets the data on-site using the PDA. He gives advice or opinions and answers questions that prompted the testing request. Following the on-site test, the engineer may further analyze the PDA data with CAPWAP, a signal matching computer algorithm which extracts the soil model from the measurements and provides a simulated static load test result.

Being on-site gives the engineer a feel for the project. He sees how the piles drive, the condition of the hammer, and the care that the crew gives to the installation process. However, this on-site process requires a considerable cost including hours of travel time and large travel expenses. The engineer usually arrives prior to the first test pile being driven. Unfortunately, this is often a time which is at best a guess due to weather, pile delivery, and assembly of the driving system. Further, the contractor's efforts to drive the first pile may be delayed due to a variety of reasons or equipment problems which are usually resolved during the test pile program and prior to production pile driving. In summary, during the test pile program considerable time is spent simply waiting. The active time for the PDA engineer on-site is often small.

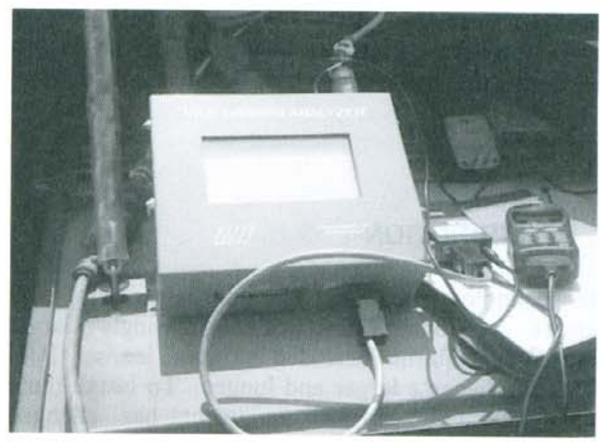

Figure 2. PAL on site (left) with cell phone (right).

3 NEW METHOD FOR DYNAMIC PILE TESTING

A new version Pile Driving Analyzer (PDA) called PAL has many powerful features to revolutionize dynamic pile testing. This smaller unit has a touchscreen for user friendly data entry and a self contained rechargeable battery sufficient for a full day's operation. Data is stored on a removable memory card. This PDA can be connected by the engineer on-site directly to a laptop running the Windows PDA program to provide full on-site PDA processing capability.

However, modern technology now allows for a more cost effective approach to dynamic pile testing. The PAL on-site can be remotely operated through cell phone technology by an engineer in the office, see Figure 2. The sensors are attached to the pile by the crew on-site or a trained technician. The pile sensors are connected to the PAL which dials the cell phone and connects to the office PDA engineer.

From this point on, the PDA engineer operating the PDA-W program on his office PC controls the remote PAL to collect the data and send it digitally to the office. The office engineer sees the data from the on-site remote PAL in real time as the test is in progress. Site observations are communicated with the office engineer with a cell phone or by the PAL's "message communicator" (which sends short messages either preprogrammed or user constructed). In turn the office engineer interprets the PAL data and communicates his advice to the site practically instantaneously.

Why test in this remote mode? Simply stated, there are significant cost savings. In many cases, the cost to the owner of the engineer's travel time to site and the travel expenses approaches the cost of the test itself. Since the pile crew can attach the sensors to the pile, the PDA engineer could operate the PDA from his office and save this time and travel cost. With reduced costs, the project owner can perform more testing for the same total cost. The PDA engineer does not waste time waiting on-site for the test. But perhaps more importantly, the data analysis can begin immediately after data collection resulting in earlier availability of final results to speed up the construction and decision process. The report can be issued sooner. On large projects, the PDA engineer may still travel to the site for the initial test piles. However, subsequent production pile quality assurance testing can be performed remotely. This results in lower testing costs and easier scheduling of routine periodic tests. Thus, more tests can be performed at lower costs resulting in improved quality assurance for the project.

4 DYNAMIC TESTING USES AND GOALS

Obviously, whether testing on-site or remotely, the dynamic test must be performed with the correct goals to achieve the maximum benefit. Objectives of high strain dynamic pile monitoring during installation include evaluation of the energy transfer and driving stresses to assure the pile can be safely driven to the desired depth without damage. Capacity may be of interest during driving to establish the bearing layer or establish the driving criteria. However, for long term capacity evaluation, restrike data is usually required due to soil strength changes with time.

During driving, the PDA calculates energy transfer from the integral of the product of force times velocity. The energy transferred is then compared with the hammer's rated energy. When low hammer performance is indicated, the hammer can be serviced (cushion, compressor and hoses, air valves, fuel pumps, or piston rings inspected or corrected, etc.) or the cause of low performance determined and corrected so that hammer performance and thus pile installation productivity is improved. Maximum driving stresses are investigated to reduce the likelihood of pile damage. The PDA gives the direct compressive maximum at the sensor location. Since up to four strain sensors are attached to the pile and monitored separately, bending and local contact stresses can be assessed and hammer pile alignment improved. The maximum tension stress below the sensors for concrete piles is computed from the pile top measurements. If tension is excessive, a lower hammer stroke, or increased pile cushion thickness may be required. The maximum compression stress is estimated at the pile bottom for all piles driven to hard bearing layers. These stresses need little interpretation other than comparison with stress limits imposed by code or specification. The PDA can investigate the pile shaft for damage.

Evaluation of pile bearing capacity is more complicated because the soil strength is often altered by the installation process. The capacity during driving is often less than the long term pile capacity particularly for piles driven in fine grained soils (clays, silts and even fine sands) due to excess positive pore pressures generated during driving which reduce the effective stresses. As these pore pressures dissipate after driving ends, the pile shaft resistance increases. Capacity reduction during driving is also caused by lateral pile motions which create an oversized hole; with time, the overburden pressures reach equilibrium on the pile perimeter and increase shaft resistance. This phenomena of capacity gain with time is called soil setup. Therefore, dynamic testing during restrike tests after a sufficient wait period usually yield a better indication of long term pile capacity than a test at the end of pile driving. The wait time required is longer as the soil grains become finer.

Although less common, relaxation (capacity reduction with time) has been observed. Relaxation can be a serious problem for piles driven into weathered shale, and may take several days to fully develop. These losses can be caused by exposing the shale to water, due to fracturing of the rock or by heave from driving adjacent piles. Pile capacity estimates based upon initial driving can significantly over predict 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 blows). Relaxation has been observed for displacement piles driven into dense saturated silts or fine sands due to a negative pore pressure effect at the pile toe. Restrike tests after a few days are usually sufficient, with emphasis on early "high energy" blows. With sufficient experience on a site or in some limited geographical area, the engineer may eventually reduce the amount of restrike tests and just apply a reduction factor to the end of drive capacity to estimate the final resistance available.

Dynamic load testing indicates the activated or mobilized pile capacity at the time of testing. At very high blow counts (above about 10 blows per inch, or less than 2.5 mm 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. This can occur when piles are driven to refusal or in cases where setup increases are large and the hammer is then not capable of moving the pile during testing. Several solutions to overcome this under prediction dilemma for refusal conditions are available depending on the site conditions and availability of equipment. One solution is to apply a few blows at higher energy. The higher energy can be generated from a higher stroke, or a larger hammer or a big drop weight with more energy resulting in a smaller blow count (less than 10 blows per inch set; greater than 2.5 mm set per blow), and thus mobilize the full capacity. Another solution for closed end steel pipe piles at refusal is to fill the pile with concrete and then test as a composite section. The now stiffer pile will have a higher applied force and thus overcome more resistance. Another method is to add the end of drive end bearing to the restrike shaft resistance by superposition to estimate the service condition total load (Hussein 2000); this should only be done if the restrike is at refusal conditions and where no toe relaxation is possible. Alternately, if setup (and relaxation) can be estimated, the pile need not be driven to the full required ultimate capacity but rather only to a usually reduced "target" capacity or to refusal.

A CAPWAP analysis usually is made to confirm the PDA field capacity result. The soil is modeled similar to wave equation methods. The wave transmission is modeled by the method of characteristics (CAPWAP Manual 1999). The hammer model is replaced by the measured force and velocity as a boundary condition. Since these measurements are redundant, the soil model can be iteratively investigated. If the measured velocity is input into the CAPWAP analysis model, then the force required to hold the system in dynamic equilibrium can be computed and subsequently compared with the measured force (usually the wave down is input and the wave up is computed and compared). The soil model is adjusted either automatically by the program or by the engineer until the computed and measured forces (or wave up) are in agreement. The final soil model (distribution and dynamic and static parameters) then describes the soil behavior during the hammer impact. CAPWAP has been proven to have good agreement with static load test results (Likins et al. 1996). The CAPWAP pile and soil models can be subjected to a simulated static loading to produce a load movement curve comparable to static test. CAPWAP also provides resistance distribution results where negative friction (downdrag) may be a concern.

Numerous factors are usually considered in pile foundation design. Some of these considerations include additional pile loading from downdrag or negative skin friction, soil setup and relaxation effects, cyclic loading performance, lateral and uplift loading requirements, effective stress changes (due to changes in water table, excavations, fills or other changes in overburden), settlement from underlying weak layers and pile group effects. These factors merit consideration when considering the interpretation of dynamic testing results. The foundation engineer should determine if any of these considerations apply to his design.

5 USA PRACTICE

The USA is interesting since practically every possible pile-hammer-soil combination can be encountered. Most PDA testing in the USA has been on driven piles with the testing engineer on-site with the PDA. A considerable experience has been accumulated. Early tests from the research project at Case included extensive correlations with static load tests. Private consultants began in 1972 to apply the method in their own private sector projects, either testing themselves or specifying testing in project documents (often resulting in the contractor hiring a testing firm to provide the service). Based on favorable experience and the results of the research project, highway agencies specified dynamic testing. With time and the support of the Federal Highway Administration for this testing, more highway agencies have included dynamic testing in their practice, either by acquiring the equipment or by hiring outside consultants. As a result of this varied exposure, many contractors see a benefit and now hire testing firms to assist them when piling problems arise, or they often propose dynamic testing as an alternate when static testing is specified.

For small projects with only a few piles, a couple piles per structure are tested. Since the time to install all piles is relatively short, often the piles are tested during driving or with relative short wait times during restrike. For medium sized projects, the first production piles often serve as dynamic test piles and are distributed over the site to check site variability. Usually some restrikes are included in the test program. In a growing number of cases, longer wait times before restriking are being employed to take more advantage of the ususal strength gains with time. For larger projects, the amount of static testing is generally reduced after establishing a correlation of dynamically and statically tested piles, and then supplemented by additional dynamic tests to increase the total percentage of piles tested. This improves the overall quality assurance while reducing testing costs.

Because of the large amount of dynamic testing performed, various codes and specifications are now in place for USA application. In 1986, the D4945 consensus standard was adopted by ASTM (American Society of Testing and Materials) for "High Strain Dynamic Testing of Piles." Testing in the USA follows these guidelines (ASTM D4945-96 is most recent revision).

Beginning in the 1980's, the Federal Highway Administration offered a demonstration project for dynamic pile testing. They currently provide workshops for State highway agencies which includes dynamic methods as an important part of their recommendations. Many State highway agencies have developed their own specifications for use. Florida DOT has probably the most extensive code and PDA is an integral part of their quality control procedures. AASHTO has general specification T298 (similar to but improved version of ASTM D4945). In additional they recognize dynamic testing with its own reliability and benefit when assigning safety factors to foundations in the "AASHTO Standard Specifications for Highway Bridges". In general, higher levels of testing result in a lower safety factor.

The US Army Corps of Engineers included dynamic testing in their 1993 manual on "Design of Pile Foundations". The American Society of Civil

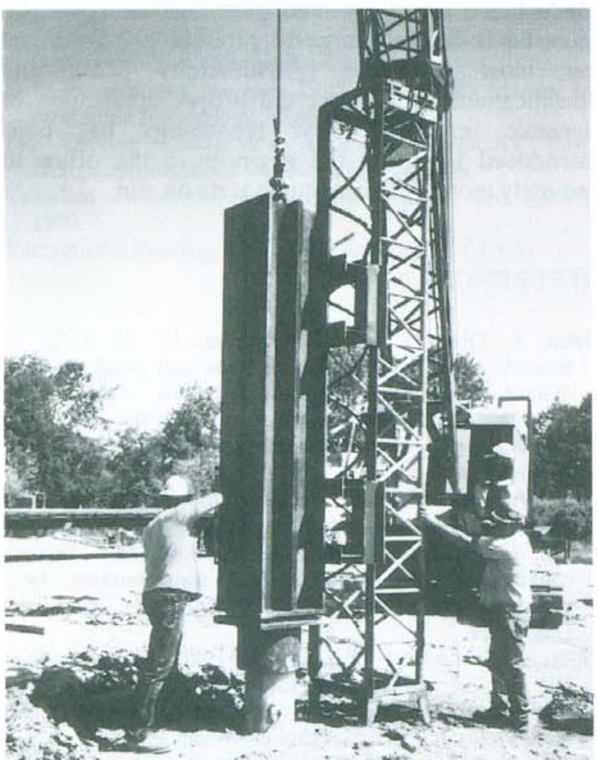

Figure 3. Drop weight test on augercast pile.

Engineers (ASCE) developed a consensus standard for pile testing entitled "Standard Guidelines for the Design and Installation of Pile Foundations"(ASCE 20-96) which includes dynamic pile testing. The private sector work generally has followed the local highway department practice and the three regional building codes. A recent joint effort of these three regional code authorities resulted in the International Building Code (IBC) with application in April 2000. IBC allows ASTM D4945 testing to evaluate static capacity. Before IBC adoption, many consultants employed dynamic testing on their private projects for either capacity evaluation or monitoring hammer performance and driving stresses

Two USA organizations (Deep Foundations Institute and Pile Driving Contractors Association) have endorsed PDA testing. DFI produced a consensus document "Inspector's Manual for Driven Pile Foundations (Second Edition 1997)" with positive comments on dynamic testing. PDCA has promoted a model code (dated 1999) in both working stress and LRFD versions which allows substitution of static tests by dynamic tests after a proven correlation with considerable reductions in safety factor and thus cost savings for increased percentages of piles tested.

It is conservatively estimated that every year several thousands of piling projects have dynamic pile testing on driven piles. While occasional PDA dynamic testing for drilled piles in North America has been made starting in 1974, this procedure is now routinely applied on drilled shafts and augercast piles in many countries in Asia, Europe and South America using drop weights (Rausche et al. 1985, Hussein et a., 1996). Figure 3 shows high strain acceleration and strain sensors attached to an augercast pile. The pile was extended above the ground surface with a thin liner. The lower section of the liner was then removed and the sensors attached to the resulting smooth concrete using anchors in the same manner they are attached to driven concrete piles. The pile top surface is usually flat and relatively smooth and only needs some minimal plywood cushion to distribute the impact over the entire top surface. A steel plate is then placed above the plywood as a striker plate for the impact weight. If reinforcement protrudes from the pile top, the pile can be built up above the reinforcement and then removed after the test.

To perform the high strain test, the drilled shaft or augercast pile is then subjected to an impact of an impacting weight. In most cases a simple drop weight is preferred. Figure 3 shows a two ton drop weight (four H piles welded together) being positioned to test an augercast pile. Other drop weight designs include solid steel cylinders, concrete filled steel pipes or heavily reinforced concrete blocks. As a general guide, the weight should be at least 1 to 1.5% of the desired ultimate capacity to be proven (Hussein, 1996) to assure load activation at reasonable stresses. Larger existing weights can be used provided the weight and shaft diameters remain about comparable. Regardless of size, shape or composition, the drop weight is generally guided to an axial impact by a short set of leads as in Figure 3, and is raised by cable and dropped by releasing the drum brake. An alternative and preferable drop method involves raising and securing the weight and then completely releasing it for a true free drop (e.g. releasing hydraulic jaws such as used for vibratory hammers used to grab steel piles, or by tripping a simple mechanical release).

The test for a drilled shaft usually consists of a few separate impacts. A low drop height is first applied to assess signal quality and alignment of the weight with the shaft. After each impact, the net permanent displacement or "set per blow" is carefully measured to evaluate full capacity activation. Compressive stresses are compared with the concrete strength. Alignment adjustments are made if necessary and a second higher drop height is applied. The test continues with increasing drop heights until either the set per blow exceeds a value sufficient to insure the full capacity activation, or until the indicated capacity is above the required ultimate capacity, or until the stresses become too large and the risk of pile damage is then too high. Most tests are completed in less than five impacts. If the pile top has been built up to accommodate the dynamic test, the extra top section is removed to facilitate completing the foundation.

The measured pile top strain and velocity data are analyzed by CAPWAP to independently check the total capacity mobilized for each blow. A CAPWAP analysis can be performed in a short time on site after each impact to determine if the set per blow is low so that the full capacity has not yet been activated and another larger impact is required. Upon completing the CAPWAP analysis, a simulated static load test is obtained.

6 WORLDWIDE PRACTICE

PDA use outside the USA revolves around established local practice. In many locations, testing drilled shafts as described above is the primary application. In some locations, testing of driven piles is predominate and follows procedures common in the USA. Many contractors drive precast segmental regularly reinforced concrete piles. Often these contractors obtain the equipment and perform the testing themselves. In many cases a "design-build" process is common and the contractor is then encouraged to find better foundation solutions and is fully responsible for the foundation installation; in such cases many have found great benefit in dynamic testing to assure quality and economy. In some countries the ultimate pile capacity has been greatly increased as a result of more dynamic testing; for example, in Sweden the allowable loads for the same identical piles have approximately doubled as a result of codes requiring higher percentages of piles to be tested by PDA. There are numerous country specific codes detailing application of dynamic PDA testing (Beim et al. 1998). Monitoring hammer performance for offshore oil platform installation is regularly specified by the oil companies; if driving is greatly different than expected, then capacity is further evaluated.

7 CONCLUSIONS

Dynamic pile testing with the PDA with subsequent CAPWAP analysis has become a routine practice for engineers and contractors worldwide. The methods have been applied to driven piles during driving to monitor the hammer and driving stresses. Because pile capacity is a function of time due to changes in soil strength due to effects of the driving process, long term capacity is usually evaluated during restrike several days after initial installation. In many parts of the world, dynamic pile testing methods have been successfully applied to drilled shafts and augercast piles by applying an impact of a large drop weight. To activate the full soil resistance (and thus correlate best with a static test failure load) for either driven or drilled piles, the energy input must be sufficiently large to produce a 2.5 mm set per blow or more. Numerous codes and specifications now direct the proper application of dynamic testing. New technology has been introduced to allow the engineer in the office to remotely monitor dynamic pile tests on site.

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