PDA Testing: 2008 State of the art

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ABSTRACT: At the first Stress-Wave Conference in 1980, the State of the Art of High Strain Dynamic testing involved equipment that tested the tester as much as the pile. The software was also difficult to use and experience with different piles, hammers, geotechnical design and construction conditions was limited. Through the intervening years, measurement and computational equipment has greatly advanced, many papers have been written, codes have changed, incorporating the new testing methods, and worldwide a dynamic pile testing industry has evolved. It is therefore time to review the current state of the art and review the progress that has been made.

This paper shows that while the basic methods have changed relatively little since 1980, today's field equipment and analysis software have greatly advanced and is now much more user friendly. Furthermore improved computer technology and refined software have made it easier and more reliable to calculate a variety of results, and has become much more automated to speed reporting of results to the end user. Worldwide standards and codes are reviewed, particularly those which take advantage of the improved knowledge from frequent testing. This paper shows how modern equipment can be used to perform testing with minimal interruptions on constructions sites and thus at vastly reduced cost. It also outlines the many newly developed additional applications, extending beyond the original dynamic load testing of impact driven piles, which are based on the basic high strain testing principles and which are now in routine use.

1 INTRODUCTION

A complete history of the development and implementation of stress wave theory to piles is given by Hussein and Goble (2004). Although there were sporadic measurements on piles in the mid 20th century, the activity that really gave rise to the birth of modern dynamic pile testing began in 1964 at Case Institute of Technology in Cleveland Ohio under the sponsorship of the Ohio Department of Transportation and the Federal Highway Administration (Goble, 1975). Study of the application of wave propagation led to the requirement to measure velocity and force near the pile top as the most practical solution to the problem. To obtain the velocity, accelerometers were used because they have their own gravitational reference system. To measure "force", initially foil strain gages were glued directly to the steel piles, but for savings of time and money, both pile top force transducers and strain transducers were soon developed and their adequacy proven. Force transducers, consisting of foil strain gages attached to a short pipe with a diameter matched to the pile size, were calibrated in a universal testing machine and temporarily for the duration of the test inserted between the hammer and the pile top. However, piles of different sizes required force transducers of different diameters. Their relatively large mass made their transport impractical. On the other hand, strain transducers which had the advantage of being adaptable to any pile type and size, could be easily transported to remote site locations. Measurements became "routine" and were successfully made on steel pipe piles, steel H piles, concrete piles, and timber piles.

Following that successful research program, which ran consecutively for 12 years, electronics had been designed for making the measurements and analysis methods developed for analyzing the measurements. Strain was converted to force using the pile area and material modulus of elasticity. The acceleration was integrated to velocity by analog integrators. These analog signals were stored on magnetic tape recorders, and viewed in the field on storage oscilloscopes. Analog computers (initially called "Pile Capacity Computer" but renamed "Pile Driving Analyzer®" or simply PDA in 1974) did the real time field computations according to the closed form solutions called the "Case Method", named after the University, to obtain capacity, maximum measured force, and energy transferred into the pile. The entire system could be contained in three transit cases with total mass approaching 100 kg. Because of the relatively high power needs of electronics, tape recorder and oscilloscope, AC generators were needed. Considerable expertise was required by specialists to operate the electronics and give meaningful opinions on site.

Following the return to the office during the Case research project, the analog signals from the tape recorder were played into an analog to digital converter (A/D) controlled by a small digital computer (8 K of vacuum tubes) which could duplicate the field computer computations. These digital computations included capacity searched over time for the maximum value (e.g. RMX methods), pile integrity by the Beta method (Rausche, 1979), maximum compression stress at the pile top and maximum tension stress along the shaft, and energy transferred into the pile. The digitized record was then further processed on a main frame computer using the CAse Pile Wave Analysis Program (CAPWAP®). This "signal matching" program input the velocity, assumed a soil model, and calculated the force required to keep the system in dynamic equilibrium; the soil model was iteratively adjusted to produce the best match between computed and measured force (Rausche, 1972). Because of this more intensive numerical analysis in CAPWAP, the correlation of predicted capacity to measured static load test results was better than the simple Case Method result from the PDA, and became standard practice for a well performed dynamic test. CAPWAP was at that time a lumped mass numerical analysis model and usually ran automatically (for the common relatively short land piles tested). By mid 1970s the program was converted to a mini computer and the process was manually interactive with the highly trained and specialized engineer. Until the late 1970s, this office processing was so complicated and labor intensive that most field testing results were submitted only to very few practioners for further analysis, and the resulting turn around period for reporting results was measured in days.

This "state of the art" was summarized by Goble (1980) at the time of the first Stress-Wave Conference, which was organized in Sweden by local practitioners there who had assessed the potential of dynamic testing and implemented it into their practice. Through the efforts of the Swedes, who packaged this testing with their other endeavors of piles and hammers in their "Balken Piling System", this technology spread into Asia and Australia. Although still a relatively novel idea, dynamic testing was common in many parts of the USA prior to then.

After the basics of the method were established and testing was common, the years following produced continuous improvements to make the system more user-friendly.

2 PDA SYSTEM IMPROVEMENTS TO CURRENT STATUS

The PDA changed to a digital computation device in 1982 (Likins, 1984) and to a DOS based PC system in 1990. The PC allowed the PDA to display the signals on the LCD screen and store the data on hard disk thereby eliminating oscilloscope and tape recorder. In 1992, the ability to simultaneously measure up to four accelerations and four strain signals was added. This allowed capability to measure signals at the pile top and simultaneously at other locations along the length with one instrument. When testing drilled piles, four strains also proved valuable in assessing data quality and reliability (Robinson, 2002). Further improvements included battery operation, touch screen data input, USB, and Ethernet ports.

Through the mid 1990s, all PDA testing was accomplished with the engineer on site. While this gave the engineer valuable insight into site conditions, it was labor intensive, travel expenses were costly, and scheduling was sometimes difficult. The Swedish testers first requested a system that could use the then new cell phone technology to transmit data from the site to the office. The pile crew would attach the sensors to the pile. With PDA units on several sites, one engineer could simultaneously monitor different tests from the office. A major advantage of this approach was a significant reduction in the turnaround of answers to the client. This procedure permitted for better scheduling for the contractor, and confirmation of the driving criteria at a much earlier time, both speeding production piling installation. A "remote" PDA system to implement these features was developed in 1997 and patented, and has seen extensive use in several countries (Likins, 2004b). Further improvement was achieved in 2007 with an upgrade of the wireless phone link to broadband internet connection which allows for data transmission of all records from up to 60 hammer blows per minute.

The "blow count" (e.g. the number of blows per unit penetration) or its inverse, the permanent penetration (set) per blow is an important observation, required in many specifications as an important quality control detail. In the USA, "blows per foot" during installation is generally recorded for the full length of the pile by a visual inspector who records all information in a "driving log". Software and hardware are included in the PDA to automate this practice. For restrikes where a number of limited blows causes a limited net penetration, which can change blow to blow, an overall average was generally sufficient (e.g. blows per inch, recorded for each inch of penetration) or penetration for ten hammer blows. Specifications in some countries may require manually recorded "set-rebound" graphs, particularly for capacity calculations by the Hiley formula. However, this practice poses a risk to the person making the measurement and is, therefore, discouraged. Although costly, a camera or electronic theodolite, should instead be used and since 2007 their signal can be captured by the PDA system. Since it is a displacement measurement, a stable reference surface is required for placing the camera.

The current 2007 PDA system uses a high resolution delta-sigma A/D to digitize the acceleration, providing for a more accurate digital integration of the data. It also includes either a cabled or a wireless data transmission from the pile to the PDA optionally with "smart sensors" which transmit their identification number and calibration value to the PDA. While cables have been used successfully for decades, eliminating the connecting cables is often helpful.

3 FORCE/STRAIN SENSORS

Sensors for making the basic force and velocity measurements were also improved. By modifying the original 1970 designs, the basic configuration for the strain transducer in common use today was developed in 1980. Further refinements to reduce its mass were made from time to time. A waterproof version was produced for underwater pile driving in the oil fields in 1989. A permanent built-in enclosure to better protect the sensing core was added in 1992, eliminating jigs for attachment and speeding installation.

Force has also been measured by one or more accelerometers on the ram and the helmet and the PDA multiplying them with the associated masses (Robinson, 2002), i.e. taking advantage of Newton's Second Law ($F = ma$). It removes the uncertainty of concrete modulus, and reduces excavation depths for drilled shafts and augered piles. It should be noted that the cushion underneath the ram does not affect the force at the pile top. However, any mass such as a heavy plate between ram and pile top should and can be accounted for by the PDA software. Force top transducers are another current option.

For static tests, instrumentation along the pile is required to determine the resistance distribution. Similarly, measurements along the pile during impact testing have been performed by various researchers (Goble 1970, Goble 1972, Gravare 1980, Niyama 1984), however, their results are of less value than for static tests because their evaluation is more difficult and fraught with more inaccuracies than the analysis of top measurements by signal matching. It was concluded that CAPWAP can compute the forces and motions at locations along the pile with about the same precision as could be measured. A case can be made for toe measurements giving an improved accuracy of toe resistance, particularly when both toe force and toe motion are measured so that a determination of the dynamic component of the toe resistance is possible. However, these measurements must be done with care if they are to be meaningful and of greater value than the CAPWAP result. The current PDA equipment with four strain and four acceleration channels is well suited to monitor this extra information. A recent example of PDA top and toe measurements obtained on a 450 mm prestressed concrete pile of 20.4 m length is shown in Fig. 1. The embedded sensors included standard strain transducers and piezoelectric accelerometers. In this case, it is easy to read the end bearing from the dynamic toe measurement. However, this is more difficult in cases of small penetrations where the unloading, i.e. the point of zero velocity, occurs at or shortly after the point of maximum force, a limitation common also to Statnamic.

4 MOTION SENSORS

Early piezoelectric accelerometers used a quartz crystal in compression. A patented plastic block mounting system was introduced in 1978 to filter out high frequency content. Unfortunately this block limited testing to cushioned hammers; steel-on-steel impacts, as has become common with certain hammer models, and SPT applications exceeded the frequency and/or acceleration range of these accelerometers. Fortunately, piezoelectric accelerometers with a quartz element in shear were introduced in about 1992. With improved data quality of these shear accelerometers, the mounting reverted to a rigid aluminum block system and steel-on-steel impact testing became possible.

In 1991, piezoresistive accelerometers were introduced, so the PDA system could be used with either piezoelectric or piezoresistive accelerometers, or both concurrently. There was no significant difference in data quality in the normal pile testing applications. In 2004, a new piezoresistive accelerometer was added that included a patented mechanical damper for improved data quality under extreme conditions.

5 CALIBRATION SYSTEMS

Calibration of the strain transducers involved a series of procedures. Early efforts generally measured force on a steel structural member in compression or tension and converted the force to strain from the known area and modulus. However, bending and end effects were troublesome. The best (and current) system measures directly the deformation of the transducer with sensitive linear electronics to determine the calibration. Accelerometer calibration systems have undergone similar improvements. Relying on calibrations from the manufacturers' low acceleration shaker tables proved inadequate. High acceleration shock calibrations to a level near 1000 g's were needed for more realism. Initial calibrations compared the measured acceleration of a known mass to the force applied in impact. Current state of

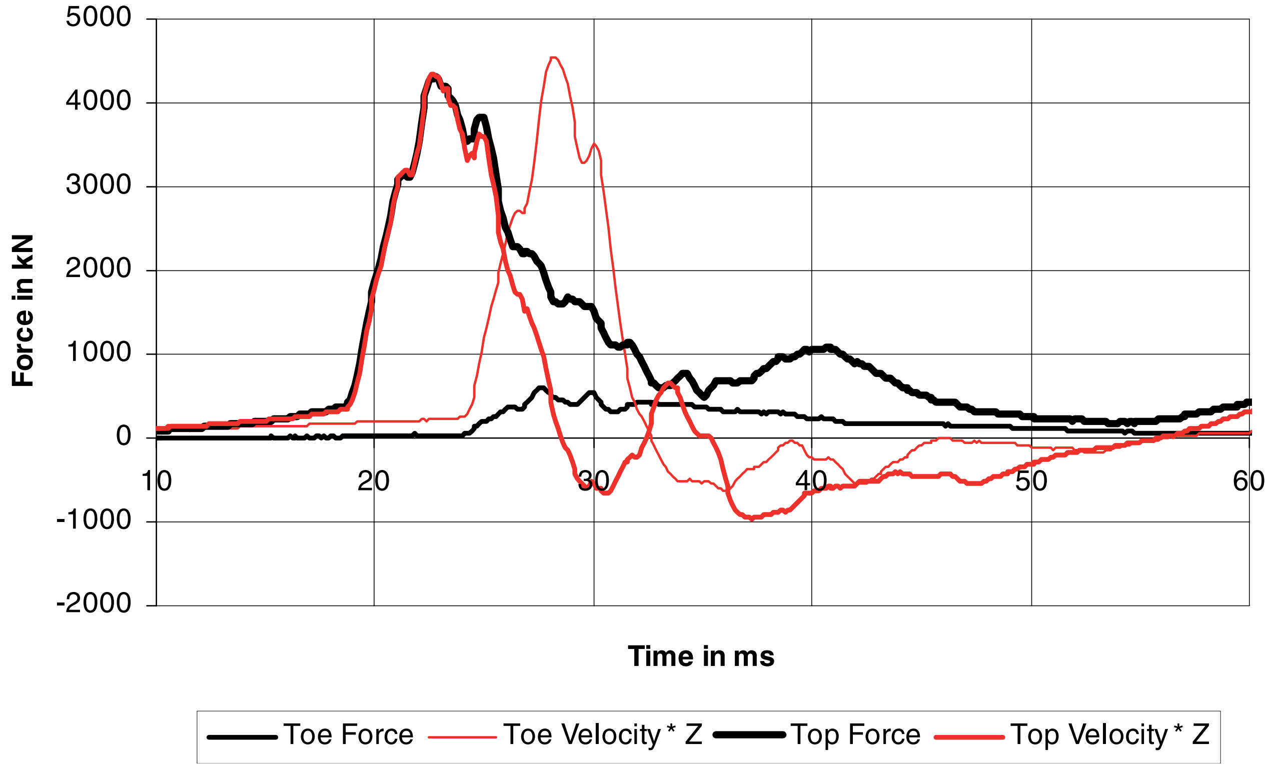

Figure 1. PDA top and toe measurements on a 450 mm square PSC pile.

the art calibration systems use a Hopkinson's Bar, and known stress wave theory of proportionality with strain, to obtain a known high acceleration input for calibration.

6 ANALYSIS AND REPORTING

PDA data acquisition and processing has seen considerable improvements. While the basics of computational methods have remained similar since the first Stress-Wave Conference (Goble, 1980), there have been improvements primarily due the improved speed of computation and memory capacity of the modern PDA. Thus while dynamic monitoring was initially limited to a basic Case Method bearing capacity, transferred energy and pile top force result, the range of possible PDA calculated outputs now includes (in addition to obvious results like maxima of acceleration, velocity, displacement, impulse, wave-up, wave-down):

- Stresses at the individual strain gages for bending evaluation;
- Maximum tension stresses both due to upward and downward traveling tension waves
- Compression stress at the pile bottom
- Blows per minute and/or hammer stroke of diesel hammers
- Maximum Case Method capacity
- Capacity based on measured transferred energy and displacement (Paikowsky 1992, Rausche 2004)
- Shaft resistance and end bearing components
- Pile integrity indicator (beta)
- Frequency spectra of measured quantities
- "Target" capacity during installation based on assumed setup and relaxation parameters.

Software was developed in the early 1990's to statistically summarize the results, calculated by the PDA for each monitored hammer impact, such as stress maxima, transferred energy, Case Method capacity to graphically summarize (see Fig. 2) the massive amounts of data commonly collected during pile monitoring for greater efficiency and clarity. Similarly, other software was added to plot not only force and velocity vs time, but many derived quantities aiding in the compliance with the ASTM D4945 reporting requirements.

With the advent of the PC in the early 1980's, CAPWAP was converted from a UNIX workstation to the PC environment and relatively cumbersome procedures (compared to previous operations) for transmitting data were simplified. At about the same time, the pile model was converted from discrete lumped mass/springs to a continuous model using the method of characteristics (De Juhasz, 1942). Although a few early systems were deployed using a DEC PDP-11 base, the advent of the IBM PC allowed a more widespread distribution of processing and analysis capability by the mid 1980s. Beginning in 1985, due to the increasing computational power of micro-computers, automated search routines, reflecting the authors' extensive experience, could be re-introduced in the signal matching software. Several extensions to the basic Smith soil model were implemented as experience was gained including:

- residual stress analysis,
- multiple blow analysis,

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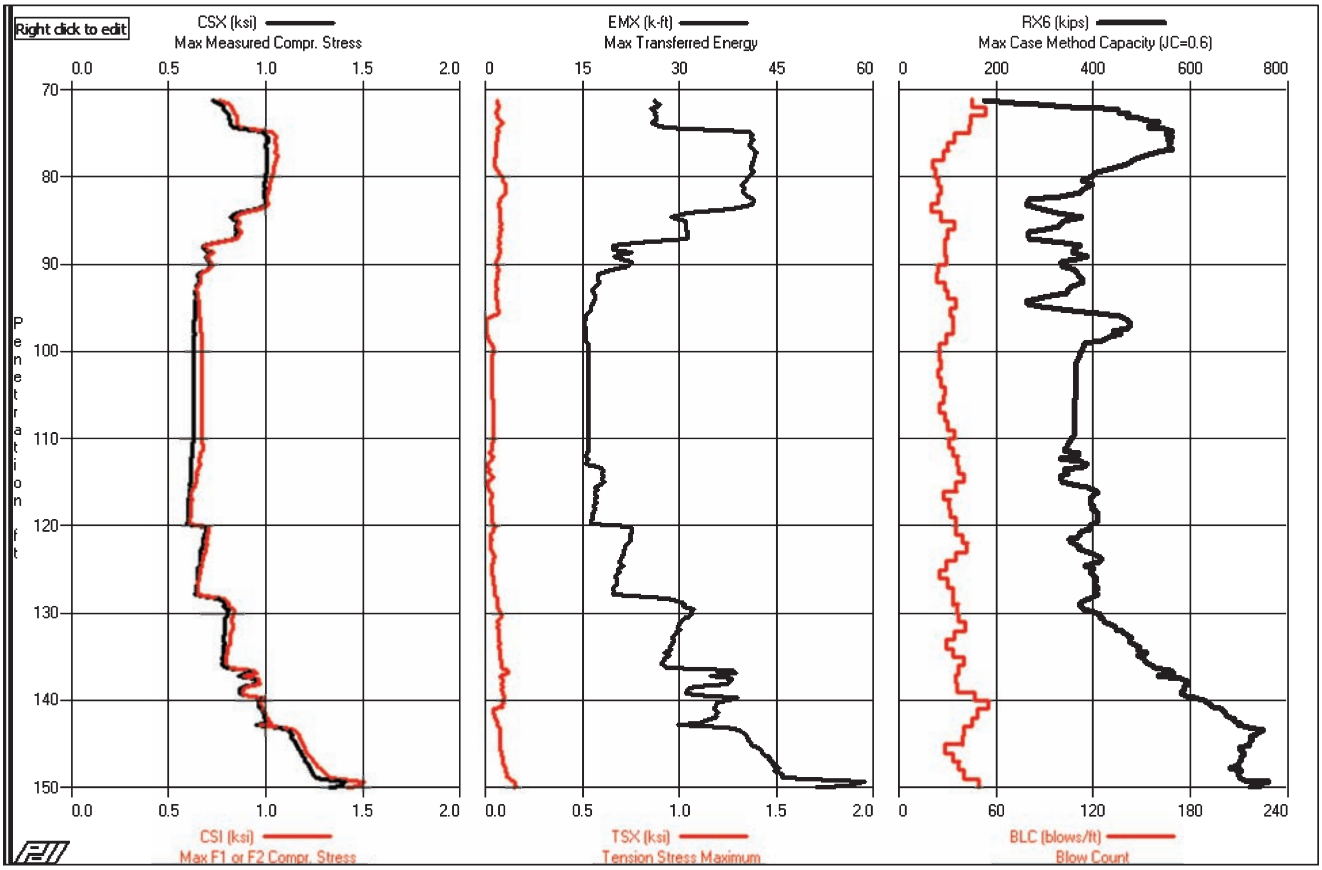

Figure 2. PDA graphical pile monitoring result summary.

- radiation damping,
- Smith/viscous/Seidel and non-uniform damping models,
- enhanced splice and slack models,
- multiple toe resistance forces for piles with multiple end bearing surfaces,
- toe gaps
- differing unloading stiffnesses
- variable unloading and reloading levels,
- toe and shaft soil mass effects

As a result of these and other enhancements, the ability to interface between various programs, with thanks to the increased computer speed and therefore the possibility for doing additional trial analyses in a short time, both the quantity and quality of the analyses in the search have been greatly improved. Today, it is generally required to perform signal matching for all dynamic load tests. It also has become more common to analyze several records in sequence and as a representation of the soil behaviour under larger penetrations than possible with a single impact loading. An example, Fig. 3 shows a CAPWAP calculated series of load set curves obtained from four test blows applied to a 1070 mm diameter bored pile in soft rock by an 18 MN ram.

7 DYNAMIC TESTING CODES, SPECIFICATIONS

While it was often more a matter of curiosity for owners or authorities to call for a dynamic test,

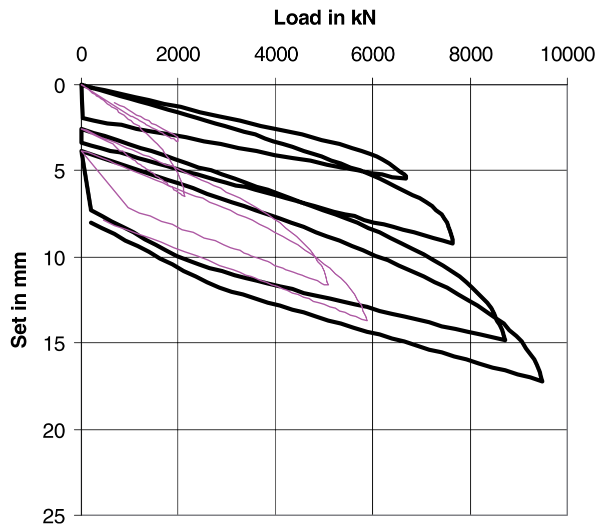

Figure 3. CAPWAP load-set curves for four consecutive impacts applied to a drilled shaft.

codes and specifications have been modified to allow for and take advantage of these tests for QA and QC. For example, for buildings in the USA, our national building code (IBC) calls for either static or dynamic load testing and the highway department model code (AASHTO) allows for either static or dynamic testing for quality control (Beim 2008).

With the growing emphasis on LRFD (load and resistance factor design), the reliability of the capacity evaluation method (e.g. static load test, dynamic load test with signal matching, wave equation, dynamic formula, or static analysis) then defines the resistance factor which reduces to a greater degree those results which are considered less reliable. In the USA an example for such a specification is the 2006 Interim Specification for highway bridges (AASHTO, 2006); examples in other countries include the Australian Code AS2159 (1995), and Eurocode EC7. Static or dynamic testing methods have higher resistance factors, typically 0.75 and 0.65, respectively, compared to dynamic formula factors of 0.4; however, these codes and specifications are complex and care must be exercised in their use. More reliable methods (static or dynamic testing) translates to more usable load per pile for any given ultimate pile capacity, and thus fewer piles required, or shorter piles, resulting in significant cost savings to the project.

8 PILE TESTING IN PRACTICE

PDA testing is very common in USA The state-of-the-art practice for dynamic load testing always includes signal matching analysis. Capacity evaluation may be based on testing during pile installation, but usually requires restrike testing after some wait period, between 15 minutes and several weeks, to take advantage of the usual increase with time, commonly called ''set-up'', or protect against an occasional capacity reduction called ''relaxation''. For smaller projects with fewer piles, usually the first production piles become the ''test piles'' to establish the driving criteria. For larger projects a special preconstruction test program may be required. Either way, if static load tests are also specified to establish capacity (to gain the highest LRFD resistance factors), dynamic tests are usually made to search for the best bearing layer, select the optimal pile type and pile length, and find an optimized installation procedure.

Dynamic pile testing is not limited to capacity evaluation. An important application is installation monitoring. On most concrete pile driving sites in USA, piles are tested throughout the installation to assess driving stresses (at pile top, bottom and tension along the length) and determine a cushion thickness, or stroke limitations to reduce the likelihood of damage. For all types of piles, including offshore, occasionally requested is an investigation of suspected pile damage and recommendation of an improved installation procedure. The hammer performance is judged from the measured energy transferred to the pile; this is often used as part of the qualification for hammers acceptance, or to establish the driving criteria, particularly when more than one hammer are employed on a job site.

While most PDA testing for driven piles is still performed with the engineer on site, growing interest in ''rapid construction'' procedures calls for taking advantage of the remote data transmission technology to reduce costs, improve efficiency, and speed of analysis and delivery of conclusions to the end user. Particularly Sweden, Australia, and the UK have already effectively made this transition to routine remote testing without the need for on-site engineers.

9 BORED PILE TESTING

Although the first tests on drilled shafts and augercast (CFA) piles were conducted as early as 1974 and 1977 respectively, the application of dynamic testing to these deep foundations in the USA basically became common only with the introduction of the APPLE (Robinson, 2002) in the last few years. Worldwide, dynamic testing using large drop weights has been common practice in many countries for decades following a series of correlation tests and almost 100 production tests in Australia (Seidel, 1984). Suggested practice has been documented by Hussein (1996). Typically, the drop weight needs to exceed 1% of the required ultimate capacity, and be well aligned with the pile top. The top of the tested element needs to be properly prepared and then protected from uneven impact surfaces by a few layers of plywood or other cushioning material. Four strain transducers are strongly suggested. This allows comparisons between the ''diagonally opposite pairs'' to assess data quality. Since the cross sectional area may vary with depth for uncased shafts, this becomes an additional variable to be extracted from the analysis, and soil borings and installation records are often helpful to finding a good solution.

10 TRAINING AND CONTINUED EDUCATION

The clear economic advantage of the dynamic pile test in an environment that values QC and QA with reduced factors of safety (or higher LRFD resistance factors), coupled with improved hardware and software systems, expanded use of dynamic testing from only a few testing houses worldwide in 1980 to hundreds at present. The number of test engineers has similarly increased and is today easily exceeds 1000. The need for a more rigorous and standardized training has led to regularly scheduled workshops in various parts of the world. A few universities include this technology in their deep foundations courses and a few better text books deal with this subject (e.g. Salgado, 2008).

The widespread distribution of more user friendly and affordable measurement and analysis systems also brings challenges in maintaining the quality of testing. The test engineers must be adequately trained to properly operate the equipment and obtain good quality measurements, and then understand the theory and correctly apply it during analysis and data interpretation. Resources and learning time must be granted to engineers newly entering this field of technology. Misapplication, through ignorance, has occasionally resulted in poor results, discouraging potential clients from specifying additional testing. For this reason, certification examinations for testing personnel (Seidel, 2000) are being offered and often required by many large end user client organizations to assure quality of test results. Furthermore, in countries where the independence of the testing house can be compromised by high pressure tactics or where extreme competition necessarily leads to inadequate quality or outright fraud, specifications must be explicit in assuring a direct line between the tester and the owner or authorizing agencies. As an additional protection, owners and/or authorities should train their own specialty engineer to be able to review the reports, or insist on a random review process using recognized independent experts.

11 OUTLOOK

Where will we be another two decades hence? Without doubt, measurement systems will become faster, smarter, more accurate, more powerful and more widely applied to all kinds of foundations (driven and drilled). There will be a greater variety of sensors and processors. These measurement systems will be remotely operated by the pile driving crews with no direct field involvement by the test engineer. They will include automatic rejection of data from faulty sensors, sensor attachment, and other reasons for low-quality measurements while backup systems will reduce interruption of the testing process due to measurement problems.

Analysis systems will be separated in two distinctly different systems:

(a) The expert's system which requires a detailed analysis, interactively performed by the very knowledgeable analysis engineer. This effort may occasionally be required where conditions involve difficult soils or soils where no experience exists, unusual or heavily non-uniform pile types and other situations where little prior experience exists.
(b) The standard system which provides for automatic signal matching analysis in a reliable simple and easily understood manner. All dynamic load tests will be analyzed with this system unless the conditions require review by the expert.

Because of concerns of the integrity or capability of testing houses, it can be expected that peer reviews of reports and analyses will be more frequently required. Certification of testers will be mandatory.

There will be more types of pile load tests and more systematically organized data banks providing correlations of results from these tests. The contents of these data banks will also be invaluable when back-up material is required to demonstrate the accuracy and precision of these methods. As methods improve, the reliability will increase and safety factors can be decreased (or LRFD resistance factors increased), and will vary as the quantity of testing changes, resulting in more testing with less risk and hence more economic foundations.

12 CONCLUSIONS

While both experimental and analytical approach of dynamic pile testing have seen little change, considerable progress has been made in the dynamic pile testing hardware and associated software since the first Stress-Wave Conference in 1980. Sensors have been modified for more reliability in difficult environments, and new technology has improved the quality of the acceleration measurements. Calibration of sensors has seen significant improvement in accuracy. Current systems of data acquisition use digital processing, resulting in more compact systems with greater accuracy. Remote testing with the equipment on site but the engineer in his office is becoming common. Processing and reporting of results have been reduced from days or even weeks to a matter of minutes. Applications have expanded from only tests on driven piles to common testing of augered and drilled foundation elements. Further developments for improved reliability and economy of testing and analysis are expected in the near future.

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