Hardware Solutions for Quality Control of Deep Foundations - Overview

Garland Likins,[1] Frank Rausche,[2] Members ASCE, David Peterman[3]

Abstract

Deep foundation construction equipment and installation methods have undergone dramatic improvement in recent years. Larger equipment and higher design loads are often specified to reduce the number of piles and project cost. Therefore, performance of each foundation element is more critical, requiring additional quality assurance for every element of a project. Fortunately, modern electronics allow routine implementation of electronic tests by civil engineers to monitor the installation and/or assess the quality of cast-in-situ foundation installations. This paper presents an overview of currently available electronic monitoring techniques for quality control of deep foundations. Benefits include reduced liability, better accuracy, more information with less labor, and often a reduced cost.

Introduction

Obviously, quality (or lack thereof) is involved in the success (or failure) of any project. Projects built on deep foundations require that this support system be properly installed; failure of any component could result in failure of the entire project regardless of how carefully the above ground structure is built. Since visual inspection of driven or cast-in-situ piles is practically impossible after installation, good quality control during installation is of paramount importance. Most construction codes thus specify proper recording of installation observations. Many companies require Total Quality Management for risk management to reduce liability.

---

[1]President, Pile Dynamics, Inc., 4535 Emery Industrial Parkway, Cleveland, OH 44128.

[2]President, Goble Rausche Likins and Associates, Inc., 4535 Emery Industrial Parkway, Cleveland, OH 44128.

[3]Partner, Pile Dynamics, Inc., 4535 Emery Industrial Parkway, Cleveland, OH 44128.

In the past, manual visual observations of blow count or drilling progress, followed by static testing of a small sample of piles, were often the only available construction control. However, manually recorded observations were only as reliable as the observer. Errors were common. For example, counting blows during pile driving is monotonous, and lack of concentration or interference with the inspector can result in inadvertent errors in counting (***e.g.*** ...77, 78, **79, 70**, 71..). The field records were often transcribed for legibility, potentially compounding errors, particularly when the original field records were difficult to read. Obviously, such a process is labor intensive and therefore expensive. A manual recording system is also more subject to abuse; records can be easily altered. This is perhaps why both contractor and owner's representative each produced their own manual records, adding further to the effort and cost of the entire project.

The accuracy of both blow count and/or pile penetration frequently was very poor when reference marks were inaccurately drawn on the pile. The blow count for pile driving was often recorded for relatively large increments (blows per 250 mm, or blows per foot), and the pile driven farther than necessary to assure consistent blow count. If the **equivalent** blow count over a smaller interval (or several successive smaller intervals to assess consistency) could be **reliably** taken, then the accuracy and economy of the project could both be significantly improved.

Static loading tests are performed on a small number of piles (typically one percent or less) to twice the design load (proof load) to prove the foundation design. Because of the high cost of failure, test piles are often overdriven and proof tests usually pass easily, with actual safety factors then being higher than necessary. Production piles then use the same very conservative criteria, resulting in higher than necessary costs. In numerous cases the static tests are avoided due to high cost, unwanted construction delays, or because they are practically impossible for piles in deep water. Extra care is generally given in driving a test pile. Unfortunately, production piles are often installed with less care, and thus may not achieve the same quality.

Electronic monitoring systems are now available and easily applied to the installation of every pile. As a consequence, more care would typically be applied during production. In addition, the automatic installation documentation with electronics can faithfully record the entire installation process, eliminating virtually all human errors. Finally dynamic pile testing, already routinely applied worldwide, could be conducted on a random sample or fixed percentage of all piles as quality inspection perhaps causing more care to be exercised during installation.

In the design of any electronic monitoring or test system, the first consideration must be to isolate the problem to be solved, or what test is to be performed. Another question is what level of skill is required to operate the device; is an engineer required, or a technician, or a member of the pile crew? Is the device to be used for **monitoring** every pile, or just for **testing** selected piles? Will the test require selection, or extra preparation, of the test pile prior to installation? Should the installation of all piles be monitored? Can the test method be applied to selected or even every pile at any time during or after installation is completed?

A variety of sensors are available, each with a particular function, range of application and accuracy. All equipment and sensors must operate in extreme environmental conditions and give reliable information. If the sensors fail to give correct information, the device should alert the operator. Alternately, the operator must review the results after each test (rather than once per day or once per week); most errors will be quickly spotted and corrected before proceeding to the next pile. The components must be field worthy and include a reliable power supply. Use of line power is generally discouraged due to lack of availability. Thus, the device should be equipped to use rechargeable batteries or the battery of the crane or test vehicle where higher power is demanded. The basic results would be stored in non-volatile memory, and then printed or output.

Monitoring Considerations

The inclination of a pile (often called "batter" or "rake") traditionally has been measured with a carpenter's level. This requires a careful eye and cooperation between the piling foreman and crane operator to position the leads and pile to the proper inclination. Angle measurements and adjustment are alternated in two perpendicular directions before the hammer is started. After several blows, the hammer is stopped and alignment verified, a process often repeated several times with a great productivity loss. Actually, the inclination angle can be measured in the two perpendicular directions using electronic tilt sensors attached to the piling leads. With the readout device located in the crane cabin, the operator can adjust the alignment even during installation thus greatly improving productivity.

All driven or auger cast pile projects require recording of blow count or grout take, respectively, as a function of depth. Such a system must be continuously active during the entire length of every pile installed, and would replace the manual observations taken on all piles on all projects.

The sound of impact pile driving has been used in the Saximeter (Likins 1988) to detect and count hammer blows, relieving the observer from the monotonous counting task. The time between blows can be converted to an equivalent blows per minute to evaluate all hammers, or compute the stroke of single acting diesel hammers. If an observer presses a single key for each penetration increment, a blow count log can be automatically generated and saved in memory (to reduce errors) with user comments or observations, for transfer at the end of the day to a computer. The blow count logs can then be professionally printed, without copy errors.

If a position detection device is combined with the Saximeter, the penetration increments can be automatically detected and the blow count log generated without human observer. Encoding wheels, linear position sensors, ultrasonic or laser technology, or proximity sensors can measure displacements with good accuracy over a large range consistent with typical pile lengths. This has been done in the Pile Installation Recorder (PIR). The PIR also accommodates information from additional sensors on a "network" system which identifies both the type and location of the sensor and its reading. For example, the distance measuring technology can also be used to record ram stroke. The angle of inclination data is also easily measured. Adding an accelerometer, quickly attached to the pile at the end of driving, can yield the final displacement and temporary compression (TC) of the pile. A typical system is shown schematically in Figure 1. Given the flexibility of the equipment, the PIR is easily adapted to drilled or auger cast (CFA) piles by placing torque, pressure and concrete/grout volume sensors on the network.

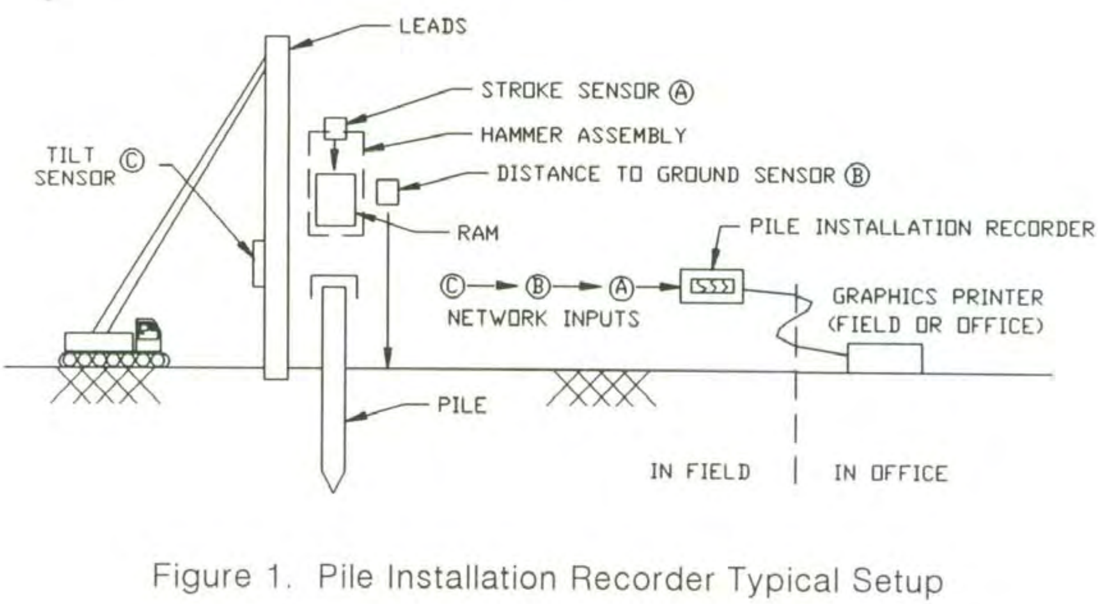

Figure 1. Pile Installation Recorder Typical Setup

Modern electronic devices have an internal clock which can record a "time stamp" for the beginning and end of installation so that the installation time and thus efficiency of installation can be determined for each pile. This feature is particularly helpful for the Pile Installation Recorder and Saximeter. The complete output should be clear, concise, and complete. Ideally, it would be highly automated with minimal user input (***e.g.*** "what is the pile name") and a very user friendly interface. All measurements (time, depth, count, pressure, torque, stroke, pile inclination,...) would be automatically converted to digital form, processed, and stored by a microprocessor. A responsible piling crew member can easily learn to operate this system. Output would be either directly printed or plotted at the end of each pile or saved in memory and downloaded to a personal computer at the end of each day. A typical result is shown in graphical form in Figure 2; of course, results could be printed in tabular form.

Testing Considerations

In contrast to monitoring during installation, testing is here defined as limited to the already installed deep foundation element. Usually testing every pile is neither necessary, nor appropriate, nor economical. Testing a small sample is often sufficient. For example, an existing foundation is to be reused or the design load raised. If original records are lost and soil information is available, it would be necessary to assess the pile lengths to estimate pile bearing capacity. The integrity of the existing piles might also be questioned. The pile length could be found with a so-called Parallel Seismic Test (sensitive probe lowered into a bore hole installed near the subject pile); however, additional tests require costly additional bore holes. Other systems to determine pile length include the Pile Integrity Tester™ (P.I.T.) (Rausche et.al. 1992) conceivably used on every pile at reasonable cost, and the Pile Driving Analyzer® (PDA) which is usually applied to selected piles only (Goble et. al. 1980). The PDA allows for the assessment of the pile bearing capacity, while both P.I.T. and PDA detect pile length as part of their pile integrity assessment. Both these tests are sometimes limited by pile length, or by the requirements that the pile be concrete for P.I.T., or be impacted by a large weight (***i.e.*** pile driving hammer) for the PDA. Thus, there is no single, universally correct, solution as different field conditions dictate a particular approach.

High Strain Testing Considerations

Static loading tests apply load to the test shaft while measuring the displacement of the shaft. Static testing is generally performed according to ASTM D1143; static loading specifications usually require that an

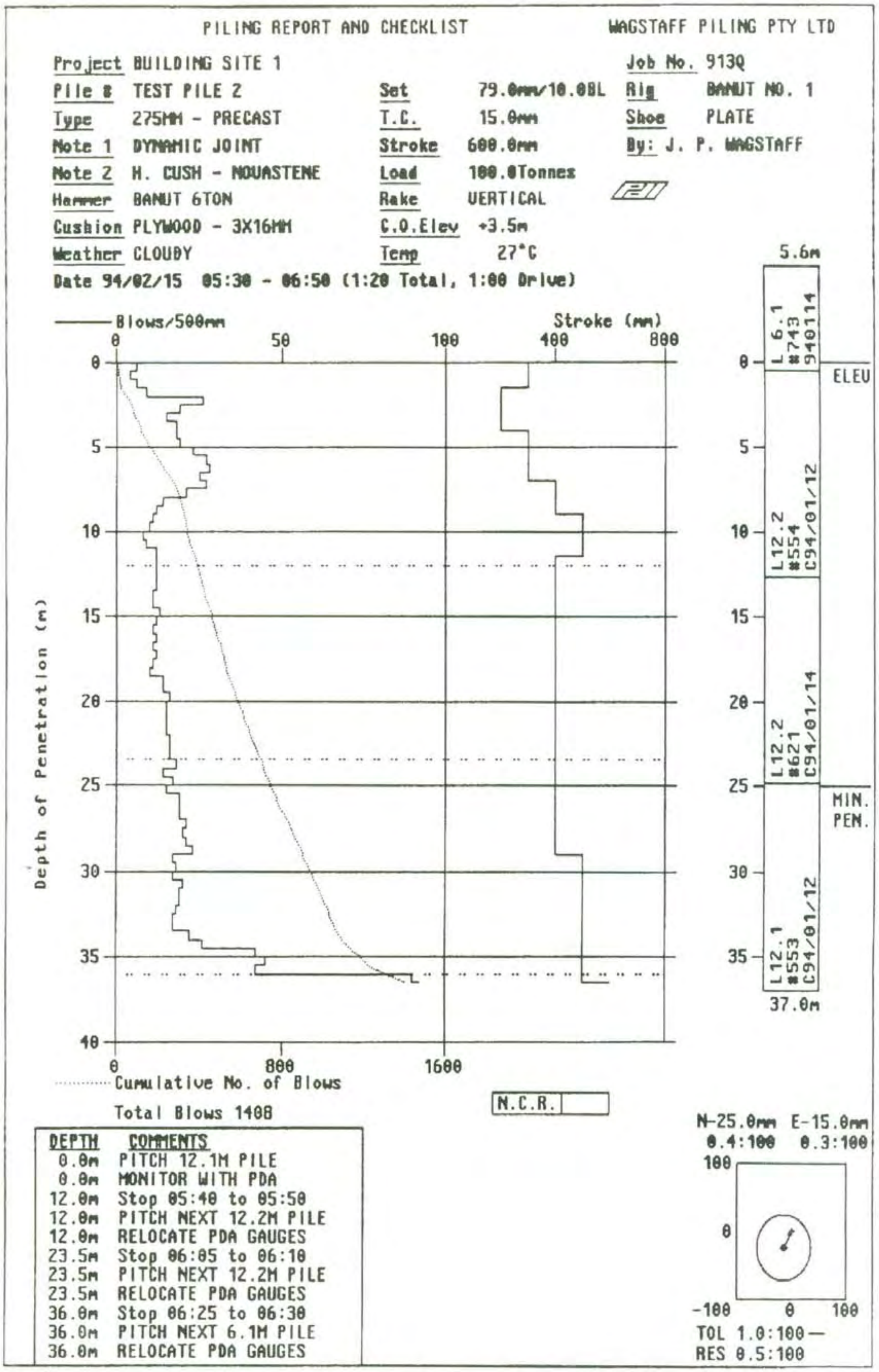

Figure 2. PIR Result

engineer be involved in the test and interpretation. While manual recording of measurements has been normal, this too can be automated, and with additional effort in the future the test could be preprogrammed through a personal computer (or microprocessor) to incrementally load and record the results. Well designed tests already require electronic load cells; digital displacement sensors are now available. Some tests have additional strain (using weldable gages or sister bars) or displacement (usually using telltales) sensors at various locations along the shaft, which in itself increases the need for automated data collection.

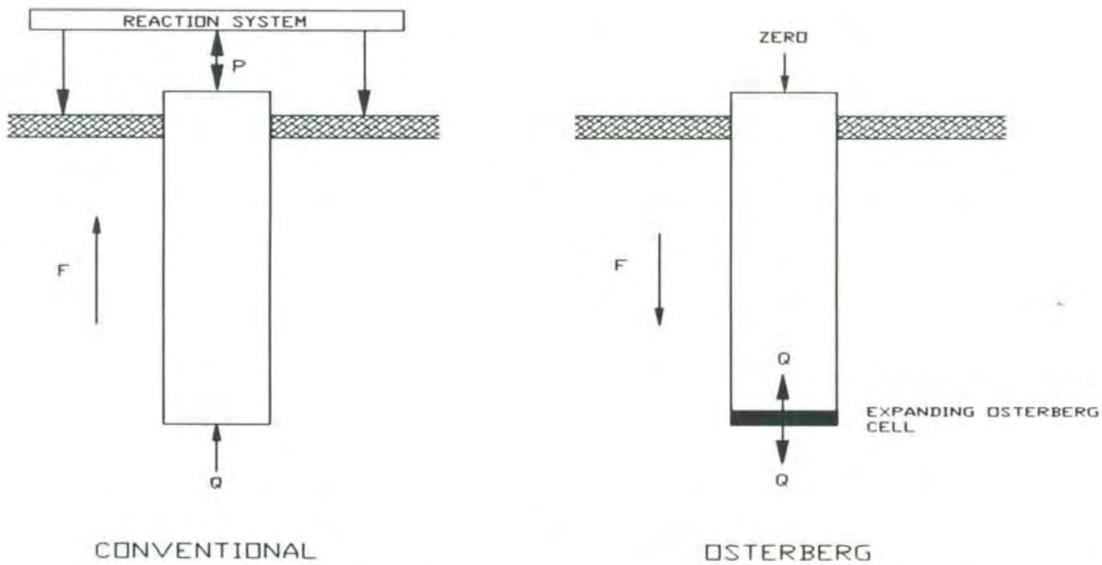

Figure 3. Schematic Comparison Between Osterberg Cell and Conventional Load Tests (after Schmertman 1993)

In some cases, the cost of a static test can be significantly reduced by using an Osterberg loadcell (Osterberg 1989). The savings are achieved primarily by using the soil system as the reaction load thus eliminating the conventional static reaction system as in Figure 3. The Osterberg loadcell is basically a hydraulic jack installed usually at the toe of a drilled shaft. Applying pressure to the loadcell tests the base in compression (as in a conventional static test), while simultaneously the top of the cell moves upward, testing upward shaft resistance (also in compression loading). The loadcell is pressurized and expanded until either a proof loading is achieved, either the shaft friction or end bearing failure load is reached, or until the maximum extension of the jack (typically 150 mm) is reached. The Osterberg loading rate is slow enough to be considered static.

An engineer must be involved in the planning, and the Osterberg device must be installed concurrent with the shaft or pile. The loadcell placement above or at the toe must consider the actual balance of soil resistance above and below the cell to achieve optimal performance. Otherwise, the solution will be only a lower bound proof load (twice the lesser of the friction or end bearing), since both friction and bearing usually do not fail simultaneously. For low shaft resistance cases, some additional loading (but less load and cost than a conventional static test) at the top may increase the ultimate capacity tested. In low end bearing situations, the loadcell may be placed above the shaft bottom, or the test performed in stages. The displacements are monitored with telltales both below and above the Osterberg loadcell. The load is determined by measuring the jack pressure. Additional instrumentation may include telltales at intermediate locations and/or sister bars for direct determination of strain. Data collection by automated methods becomes more important as the number of measurements increases.

Dynamic testing involves attaching accelerometers and strain transducers to the pile shaft and testing under the impact of a large falling weight (ASTM D-4945, 1989) for high strain testing of piles as shown in Figure 4. The dynamic load can be provided by a pile driving hammer, or any large drop weight when testing drilled shafts. Stress wave measurements require knowledge of both acceleration and strain as a function of time during the blow; reusable transducers have been developed and have seen decades of routine use worldwide. The strain is generally converted to force from the modulus of elasticity and cross-sectional area of the pile. The acceleration is integrated to velocity, and, with good quality measurement, also to displacement. The energy transferred into a pile is computed from the integral over time of the product of force and velocity. Measurements are conditioned, processed and evaluated by a Pile Driving Analyzer (PDA) according to wave propagation theory using the Case Method (Goble 1980), or a special numerical analysis program (CAPWAP®) when further evaluation or a simulated static test is desired.

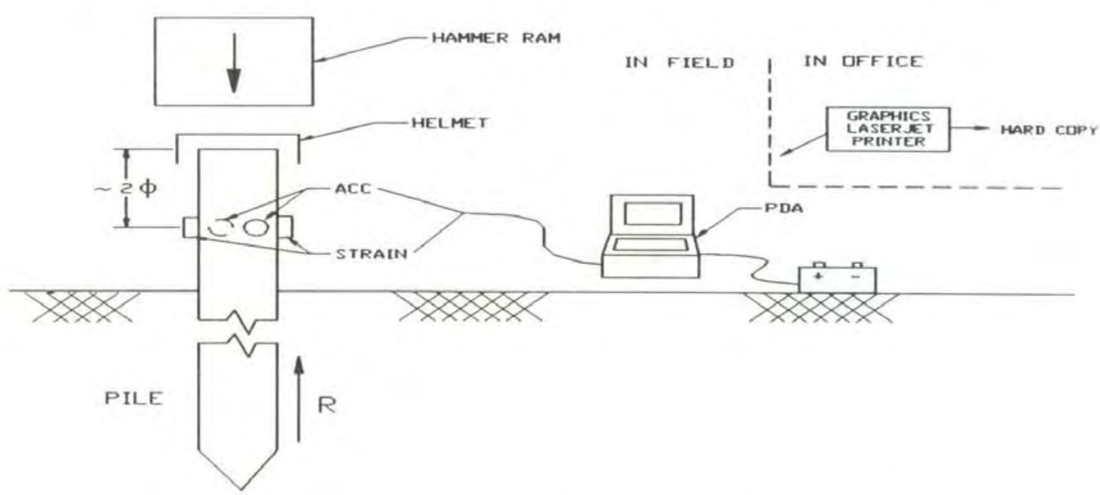

Figure 4. Typical High Strain PDA Setup

Capacity is calculated at the time of the test; tests during driving determine the remolded strength while restrike tests investigate the soil strength changes with time due to set-up or relaxation. Generally capacity results by this method are conservative often due to set-up, but also when the penetration resistance (set per blow; blow count) is high (analogous to a non-failing proof test with minimal net displacement). When replacing or supplementing static tests with dynamic tests, an experienced engineer should operate the PDA. In that case a variety of parameters need be reviewed such as soil strength time effects (set-up or relaxation), resistance distribution including negative friction and uplift, settlement concerns, and site variability. Of course, the PDA also provides a wealth of additional information on driving stresses, and hammer performance (poor hammer performance may cause low bearing capacity) which are not easily assessed in any other way. The potential of the PDA to test more piles for considerably less cost is highly attractive.

The same technology can be applied to measuring energy transferred into the drive rod of a Standard Penetration Test (SPT), and potentially to evaluate dynamic soil behavior. As an alternate assessment of energy efficiency, the Hammer Performance Analyzer (HPA; Likins 1988) uses radar technology to determine the velocity (and hence kinetic energy) of the SPT hammer or most pile driving hammers at impact. The main advantage of the HPA is that no sensor is attached and it can be easily included in the installation procedure of any or all piles/drill strings as shown in Figure 5. It should be noted that many modern hammers, primarily of the hydraulic type, have built in proximity switches for detecting the impact velocity; most of these hammers have energy readout and recording capability.

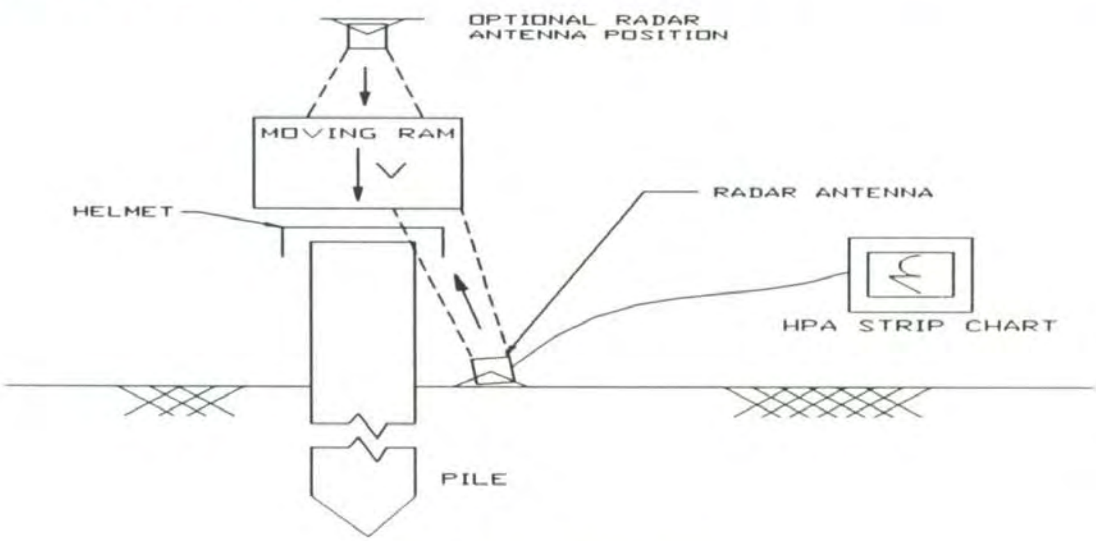

Figure 5. HPA Setup

Another proposed solution to determine capacity is a slow dynamic (some call it "quasi-static") test. The most common example is Statnamic (Janes 1991). A mass of typically two to three times the mass required for a dynamic test is placed on the pile top. A fuel charge (selected in advance to the desired force input) is then rapidly burned, propelling the mass upward and the shaft downward. The load is applied as a gradual ramp, but with a time duration of only about one tenth second (similar to a dynamic PDA test). If the force applied is low, the load will be a proof load only. If the force applied is larger than the pile capacity, the pile will achieve significant velocity (and large displacement), the imposed force must be balanced (Newton's second law) by both static and dynamic resistances, and the measured force and displacement curves cannot be directly interpreted. Unlike the true static loading of an Osterberg test, and in contrast to the sharp impact of a conventional dynamic test, the Statnamic gradual loading does not allow clear distinction between static and dynamic resistances and large overpredictions have been reported (Baker 1993, Janes 1994). The test uses a load cell to measure force and a remote sensor to monitor displacement; both are automatically recorded and results processed by a computer. A similar method has been devised in Europe with a large drop weight, but inserting massive springs between the weight and the pile top to extend the loading duration.

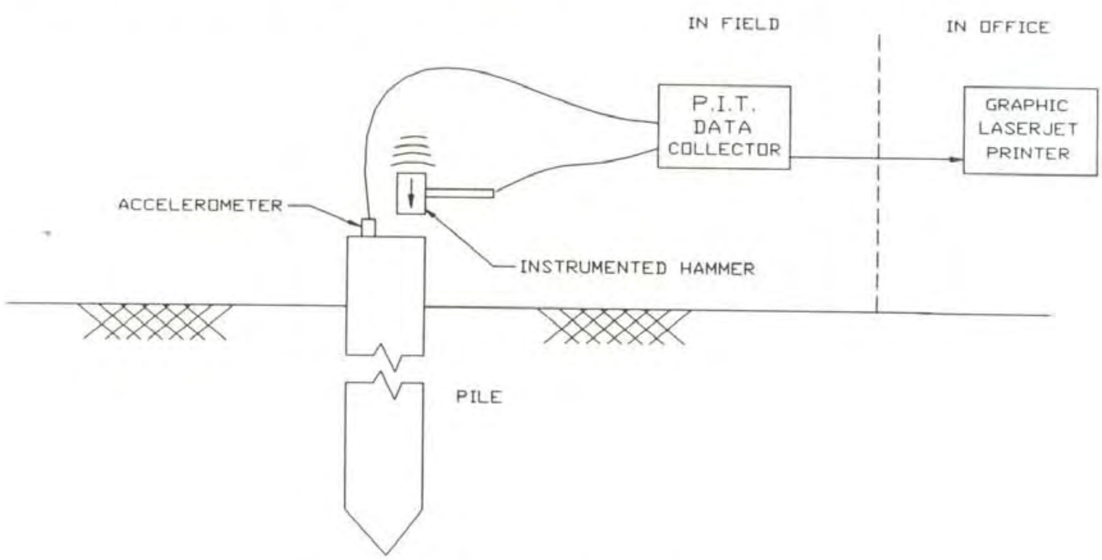

Figure 6. Low Strain P.I.T. Setup

Low Strain Testing Considerations

The signals generated by a small hand held hammer in a typical P.I.T. low strain integrity test are of a low intensity, requiring special instrumentation and processing equipment. The pile top is instrumented by attaching a sensitive accelerometer with a thin viscous material (often a wax) and then striking the pile top with a hand held hammer as in Figure 6. In this test, again the acceleration is usually integrated to velocity. This record contains both motion produced by the hammer input, and motion caused by reflected stress waves which are of particular interest. Due to both soil and pile damping effects on longer piles, reflections from cross section variations or the pile toe may require special amplification to be observable. The time from impact to observed reflection determines the location depth, and the reflection magnitude is related to the size of the cross section variation. An instrumented hammer may also measure input force. A system including two accelerometers can detect downward and upward travelling waves for piles embedded in the structure.

The low strain integrity test signals are captured by a small battery powered data collection and processing device, P.I.T. Collector, which has data enhancement features (filtering, averaging, time amplification) and can output finished graphical results to plotters or laser printers. It can rapidly be taken from pile to pile to acquire integrity evaluation data (Likins 1993), making it possible to inspect every pile on site for major defects at a reasonable cost. Additional analysis can estimate the pile shape.

Additional Developments

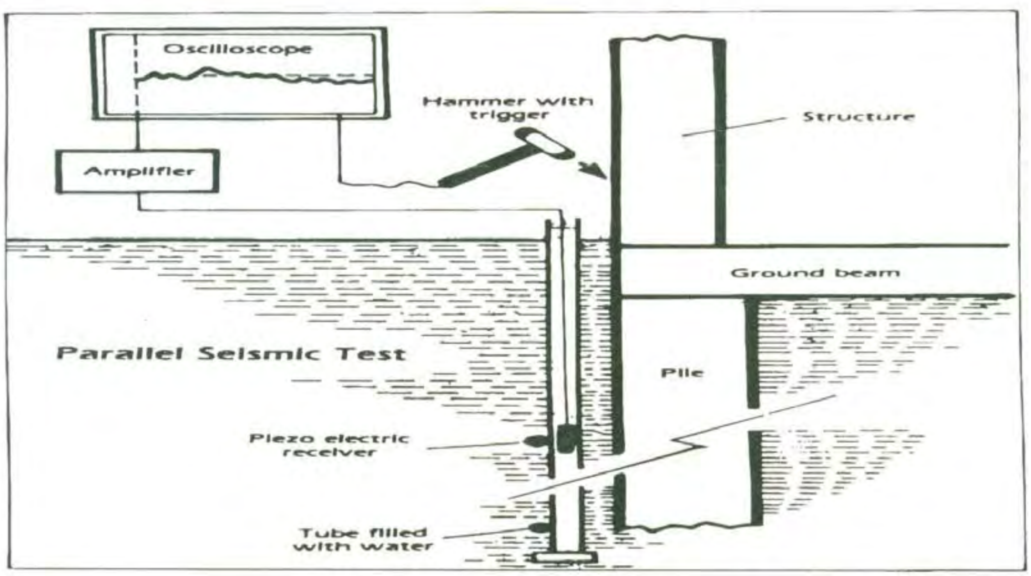

Figure 7. Parallel Seismic Test (after Stain 1982)

Other sensing devices finding increased use in the deep foundation industry include velocity measuring geophones and hydrophones for vibration or blast monitoring, and applications involving Parallel Seismic or Cross Hole sonic logging, with both methods relying on automated data acquisition and processing. For Parallel Seismic testing (Hertlein 1992), a small casing is installed adjacent to the pile in question, but to a deeper depth as shown in Figure 7. The pile is struck and the time from impact to signal pickup by a hydrophone at different depths in the casing is measured; since the rate of travel in the pile and the soil is different, the pile length is readily apparent from a series of measurements. Because of the needed borehole near the pile to be tested, this test is usually restricted to a few test shafts only. However, if the pile cannot be tested by P.I.T. or a PDA, then this test may be the best solution for length determination of some existing piles (*e.g.* piles embedded in an existing structure, steel sheet pile walls, H piles...).

Cross Hole Tests require at least two access tubes in a shaft (Levy 1970) into which a transmitter and a receiver are lowered as shown in Figure 8. The arrival time and magnitude of the signal provides further information on the integrity of the concrete between the two tubes; large shafts require several access tubes to investigate the full perimeter. The time required to perform the test is longer than for the low strain integrity test.

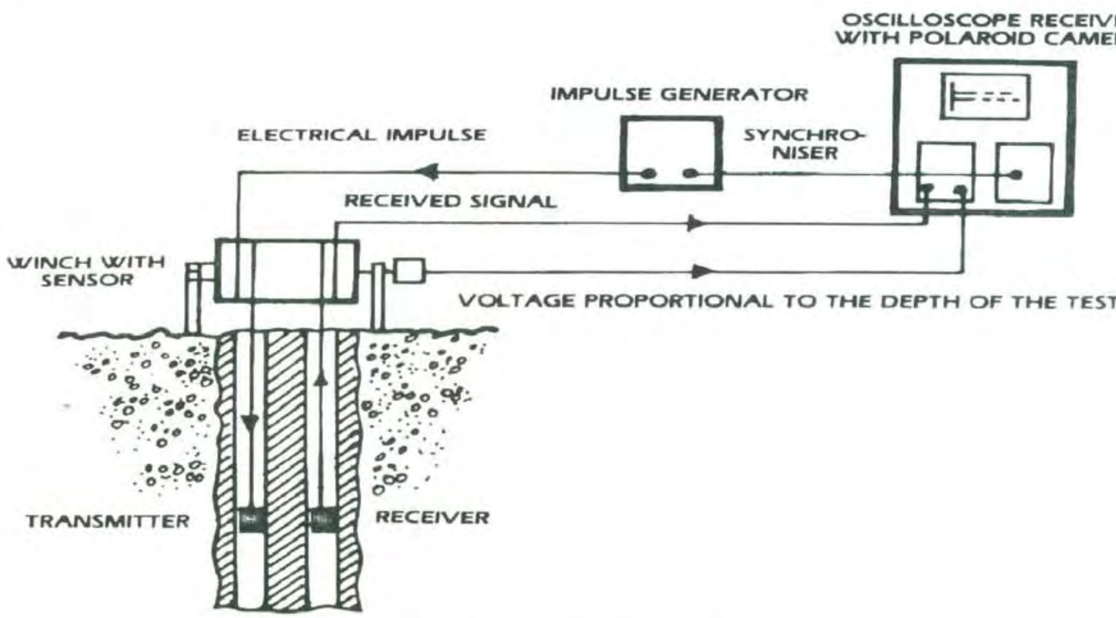

Figure 8. Cross Hole Tests (after Stain 1982)

<u>Conclusions: Advantages and Disadvantages</u>

Improved quality assurance is increasingly demanded for deep foundation installations, primarily from a liability perspective. Using electronic hardware solutions to automatically monitor the entire installation process, or dynamically test selected piles, also has economic advantages; the new monitoring methods being overall less expensive than manually collecting data, primarily because they are less labor intensive.

The automatic monitoring of pile installations can provide more information and with improved accuracy in the recording. Electronic devices are impartial and never bored by repetitive tasks. Well designed equipment is easy to use, yet powerful and measures during installation. Results are professionally presented in a standard format. The device frees up time for the crew, or replaces manual observers, and because there is no need to wait, the productivity rate of installation also improves.

Under favorable site conditions, Osterberg testing can be an attractive alternate to static testing. Dynamic testing methods such as the PDA are significantly faster and far less expensive than static loading tests, and provide information on capacity, hammer performance, driving stresses, and structural integrity. Piles selected for dynamic testing can be chosen at any time, even after installation has been completed, with restrike tests allowing for investigation of capacity changes as a function of time.

Low strain integrity testing, parallel seismic tests, or cross hole testing can only be used to evaluate integrity or length of suspect shafts. Low strain integrity testing can be economically applied to every pile if necessary and piles to be tested need not be designated in advance. Cross hole testing requires advance planning and installation of access tubes in the shaft, and requires more time to complete the test. The cost of test per pile is therefore higher than low strain integrity testing. Parallel seismic tests require an extra borehole adjacent to the pile tested; this extra effort and cost generally limits this testing to a few selected shafts.

Appendix - References

American Society for Testing and Materials (ASTM). (1989). "Standard test method for high-strain dynamic testing of piles." D4945-89.

Baker, C et al. (1993). "Drilled shafts for bridge foundations." Federal Highway Administration, DTFH-61-88Z-00040.

Goble, G.G., Rausche, F. and Likins, G.E. (1980). "The analysis of pile driving a state-of-the-art." ***Proc. International Seminar of Application of Stress Wave Theory on Piles***, Stockholm, Sweden, 131-161.

Hertlein, B. (1992). "Selecting an effective low-strain foundation test." ***ADSC Foundation Drilling***.

Janes, M., Bermingham, P. and Horvath, B. (1991). "Pile load test results using the statnamic method." ***4th International DFI Conference***, Rotterdam.

Janes, M., Sy, A. and Campanella, R.G. (1994). "A comparison of statnamic and static load tests on steel piles in the fraser delta." ***Proc. Deep Foundations, 8th Annual Symposium***, Vancouver Geotechnical Society, Vancouver, B.C.

Levy, J. (1970). "Sonic pulse method of testing cast-in-situ concrete piles." *Ground Engineering*.

Likins, G. and Rausche, F. (1988). "Hammer inspection tools." ***3rd Int'l Application of Stress-Wave Theory to Piles***, Ottawa, Canada.

Likins, G., Rausche, F., Miner, R. and Hussein, M. (1993). "Verification of deep foundations by NDT methods." ***ASCE Conference***, Dallas, TX.

Osterberg, J.O. (1989). "New load cell testing device." ***Proc. 14th Annual DFI Conference***, 17-28.

Rausche, F., Likins, G.E. and Shen, R.K. (1992). "Pile integrity testing and analysis." ***4th Int'l Conference on the Application of Stress Wave Theory to Piles***, The Hague, Netherlands, 613-618.

Schmertman, J. (1993). "The bottom-up, Osterberg cell method for static testing of shafts and piles." ***13th Central PA Geotechnical Seminar***, Hershey, PA.

Stain, R. (1982). "Integrity testing." ***Civil Engineering***.