Design and Testing of Pile Foundations

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Introduction

Piles are frequently required as the primary foundation support for a wide range of buildings, bridges, towers, dams and other massive structures. A variety of pile types installed by driving equipment of different designs in all types and even layered soils presents the designing engineer with great difficulties in establishing a safe but economical installation.

Traditionally, static analysis, probe piles, dynamic formulae and static testing were used to verify pile foundations. With the emergence of powerful computers and modern electronic measurements, improved techniques for analysis and construction control are now available to assist the engineer in obtaining a safe but lower cost solution. The differences between, and proper relationship to modern pile installation practices of wave equation analysis, dynamic monitoring equipment including the Pile Driving Analyzer and other hammer performance monitoring devices, and further analysis of these measurements by CAPWAP are all reviewed.

Foundation Design

Based upon structural loading and local experience, a pile type is generally selected when piles are required. The ultimate capacity is limited by either the structural strength of the pile shaft or the capacity of the supporting soil. The capacity (and long term settlement) of the pile-soil system may be estimated from static soil analysis based on soil mechanics and static or dynamic penetration tests of a relatively small probe to estimate required pile lengths for bidding purposes. Since most pile foundations consist of a number of piles acting as a unit, consideration must also be given to the capacity of a single pile compared to that of the whole group.

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Unfortunately, these capacity estimations are subject to a fair degree of data interpretation. Different soil testing methods and their evaluation can produce quite different solutions. Most building sites also have considerable variation in the soil conditions across the site. As a result, static analyses, while a necessary part of any foundation, are rarely used as the only means of capacity evaluation. Due to the high uncertainties, the required factor of safety would be too high to be economically viable.

Static Testing

Traditionally, "pile testing" meant a static loading test. In practice, static testing either proves that a pile can safely hold the service load without excessive settlement (proof test), or establishes an allowable load based on the ultimate capacity. Unfortunately, proof testing is more prevalent, resulting in higher actual capacity and greater foundation costs. However, it also serves to develop a criterion for installing the production piles. The criterion must be modified if the site soils are variable or if the driving system, pile type or construction technique is changed.

Static testing involves the application of static loads and the measurement of pile movements. Calibrated load cells should be used to determine the load applied and the displacement must be measured relative to a nonmoving reference. This implies that pile driving be restricted in the vicinity, and temperature effects must be minimized on the reference beams which must be supported far from the tested pile. In general, at some load the movement of the pile becomes unacceptable. The ultimate capacity or failure definition, however, is the subject of considerable discussion (Fellenius, 1980).

Many soils exhibit a continued increase in capacity even after several months. Therefore, after the test pile is installed, a waiting period is usually required before the pile can be tested to allow the soil to remold and the excess pore water pressure caused by pile driving to dissipate.

Because of the costs involved and the time required to perform static tests, only a small percentage of piles are actually tested. In some cases, such as offshore installations, the large loads and physical restrictions practically prohibit this approach. For very small projects, the testing expense can exceed the installation expense. Therefore, an installation criterion often must be established by other methods.

Dynamic Formulae

For centuries, engineers have relied upon the number of hammer blows per unit penetration to estimate the capacity of the driven pile. Engineers equated the hammer energy to the work done advancing the pile against the soil resistance. These equations are known as Dynamic or Energy Formulae. Their popularity is due primarily to their simplicity rather than accuracy.

Reliance on such formulae may lead to incorrect conclusions. The inaccuracies of the dynamic formulae are rooted in their simplicity of oversimplified modeling of hammer, driving system, pile, and soil. In fact, most foundation engineers agree that dynamic formulae are dangerously unreliable and their use is today generally discouraged.

Wave Equation Analysis

Over a century ago it was recognized that pile driving was modeled better by wave propagation theories. Solutions to the partial differential equation for wave propagation were developed specifically representing pile driving (Timoshinko and Goodier, 1981). Difficulties in representing the hammer-pile-soil system limited the application of these early efforts. Later, the solution of wave propagation was obtained graphically (DeJuhasz, 1949).

In the 1950's, a discrete solution of wave propagation was developed by Smith (1960) for digital computers. Computer programs of this numerical solution became known as the WAVE EQUATION. Smith's concept was evaluated and some improvements added (Goble and Rausche, 1986). Wave equation analyses, in contrast to dynamic formulae, can realistically consider practically all parts of the hammer-cushion-pile-soil system.

The entire driving system is modeled as a series of masses and springs. The mass of the individual elements and the stiffness of the springs reflect the mass and stiffness of various components of the real system. At each pile segment below grade, a soil resistance force is modeled by two components; one depends on pile displacement and the other on pile velocity. The displacement dependent resistance represents the static soil behavior and is assumed to increase linearly with pile displacement up to a limiting deformation commonly called the "quake". Thereafter, continued deformation requires no additional static force. Smith suggested a quake value of 0.1

inch (2.5 mm). However, others (Likins, 1983 and Authier and Fellenius, 1980) report toe quakes up to ten times higher than suggested by Smith with drastic effects on the tension stresses during driving and computed blow counts.

The velocity dependent resistance models the soil damping characteristics. The relationship between resistance and velocity is assumed to be linear by J, the damping factor. The soil's particle size is usually used as a guideline for choosing damping factors. Smith recommended damping constants based on the correlation of wave equation analysis comparisons of restrike blow counts with static test failure loads. High damping factors may limit the pile driveability. Unfortunately, these conditions of high damping or quake usually cannot be foreseen from the subsurface investigation alone.

In the beginning of the analysis, all pile, soil, and driving system components are initially assumed at rest in a zero stress condition (although WEAP86 has the capability to analyze multiple blows for residual stress analyses). The ram is assigned an initial velocity computed from the fall height and hammer efficiency. Without electronic measurements or the past performance of a particular hammer, efficiency is difficult to estimate.

During a small time increment, the ram moves a short distance, compressing the hammer cushion and exerting a force on the helmet mass. The hammer cushion force is computed from the stiffness and deformation of the springs. For diesel hammers, the gas forces from precompression, combustion and expansion can be modeled by the gas laws and included in the appropriate force equilibrium equations. By assuming the force under each mass from the previous time step, the helmet acceleration can be computed. Integration of this acceleration gives the change in velocity and displacement for the time step. Similar computations are made for each pile segment. Some pile segments have soil resistance computed from the current pile element velocity and displacement; this soil force is included in the force equilibrium equation for that pile segment. Once forces, accelerations, velocities, and displacements for all elements are calculated, the analysis repeats for the next time step with the updated motion parameters. After a sufficiently long time has been analyzed, the pile rebounds and the permanent set is calculated by subtracting the toe quake from the maximum computed toe displacement.

Wave equation analysis answers two questions. First, can the pile be safely driven to the required capacity given a complete description of pile, soil, hammer, and cushion properties? Second, what is the static capacity of the pile given observations recorded during pile driving? An analysis to answer the first question is a driveability study. The soil profile is studied, and a pile capacity is computed from soil strength parameters. Pile length, area, and material are selected. Hammer and pile cushions are selected; the analysis evaluates the ability of the hammer to efficiently drive the pile to the required capacity without imposing damaging stresses. In the second case, with the hammer, driving system, pile, and soil parameters all known or estimated, a wave equation analysis is performed for several static capacities. The resulting relationship of capacity to blow count is called a bearing graph. For any observed blow count, a capacity can then be determined. Soil strength changes as a function of time (setup or relaxation) should be considered. At every construction site some piles should be restruck for at least a few blows and the blow count observed.

Although the wave equation is an excellent tool for pile driving analysis, accurate results from any computer program requires correct data input and proper evaluation. Because the solution depends on assumptions (particularly hammer performance and soil parameters), additional feedback is necessary to either confirm, or provide the basis for change of input parameters. The only method to assure accurate results is the measurement of hammer and/or pile performance during pile driving or during restrike.

Observations and Electronic Measurements

Pile hammers are complex devices and may be classified as drop, air or steam, hydraulic, or diesel, depending on their power source, and may be either single or double acting. The operating principles of most pile hammers has been thoroughly documented (Rausche et al 1985, Rausche et al 1986). These extensive studies have established average efficiency values for different hammer types as follows: all diesel hammers 80%, other single acting hammers 67%, and other double acting hammers 50%; however, considerable scatter is also reported making additional measurements almost a necessity.

Simple visual observations are instrumental in qualitatively assessing the performance of the hammer system. The penetration resistance has long been used as an indicator of the soil bearing capacity. So called "set-rebound graphs" can be made to measure the temporary pile compression: it is extremely dangerous, however, and most engineers find the risk not worth the reward. Additional observations of the ram during hammer operation (stroke, blows per minute, etc.) can be taken as a measure of the overall hammer performance. In recent years, however, advanced electronic measuring devices have transformed the evaluation of pile driving from an art to a science. By detecting the sound of hammer blows, the Saximeter can determine the time between hammer blows and can then calculate the effective blows per minute or, for single acting diesel hammers only, the ram stroke which then gives the actual potential energy. By employing radar technology, a Hammer Performance Analyzer can measure the ram velocity as a function of time; the maximum kinetic energy can then be calculated and compared with the actual potential or manufacturer's rated energy for a guide to hammer performance. Some modern hammers have electronic sensing devices for timing, velocity, pressure or other parameters; these measurements should be recorded.

The techniques most widely employed today for both measurement and analysis of pile dynamic events were developed under the direction of Professor G.G. Goble at Case Institute of Technology hence, collectively referred to as the Case Method (Goble et al 1980). The Case Method requires the measurement of pile force and velocity during a hammer blow. These data are sufficient for evaluating pile driving stresses, pile integrity, and pile capacity. The hammer system performance is also determined through the calculation of maximum energy delivered to the pile, ram impact velocity, and hammer or pile cushion stiffness. All these results are computed in a fraction of a second after each hammer blow by the Pile Driving Analyzer.

The Pile Driving Analyzer

The Pile Driving Analyzer (PDA) system can be easily employed on a routine basis in the field. Two pairs of strain transducers and accelerometers can be quickly attached to any pile type, drilled shaft or caisson under any weather condition. The PDA system also includes an oscilloscope to monitor the signals for each blow, an instrumentation tape recorder or digital storage device (lap top computer or special disk) for data storage, and optionally a plotter for report quality plots.

The PDA is a state-of-the-art, user-friendly computer for the rugged field environment (Pile Driving Analyzer Manual, 1987). It analyzes the hammer-cushion-pile and soil from pile force and velocity measurements in real time between hammer blows according to the Case Method. To achieve this function the PDA first provides signal conditioning. Analog to digital conversion of force and velocity occur each at up to 20,000 Hz for up to 4 channels of A/D for additional data inspection. The digital computations are controlled by a fast Motorola 68000 microprocessor. Results are output to a built-in printer which also documents all input and output selections.

The Case Method

Pile force (F) and acceleration (a) are measured and the velocity (v) is obtained by integrating the acceleration. Using wave propagation theory and assuming a uniform elastic pile, the total soil resistance R active during pile driving can be calculated from

$$R = [F(t1) + F(t2) + \{v(t1) - v(t2)\} Z]/2 \qquad (1)$$

where $t2 = t1 + 2L/c$ and t1 is a selected time during the hammer blow and Z is the pile impedance Mc/L (L is the pile length, M the pile mass, and c the wave transmission speed). This total resistance R is the sum of static S (displacement dependent) and dynamic D (velocity dependent) components. To extract the static resistance, the following must be considered: (A) elimination of the damping component; (B) proper selection of time t1; (C) correction for early skin friction unloading; (D) time dependent soil strength changes (i.e., set-up or relaxation); and (E) no permanent (or very small) pile set will mobilize only a portion of the total resistance.

For consideration (A), the static resistance is obtained by subtracting the damping force D calculated from the computed toe velocity from the total resistance R.

$$S = (1 - J_c)\ [(F(t1) + Z\ v(t1)]/2 + (1 + J_c)\ [(F(t_2) - Z\ v(t2)]/2 \qquad (2)$$

The damping factor, J_c, can be solved directly from the above equation if the failure load of a static load is substituted for S. In this way, the damping constant was found to be related to the soil grain size (from 0.1 for sand to 1.0 for clay) although recent studies have produced methods which automatically evaluate the capacity for piles with little or moderate shaft friction without requiring the damping factor J (PDA Manual, 1987).

For consideration (B), time t1 is usually defined as the first or second relative maximum velocity. In most cases, the displacement (obtained by integration of velocity) at the arrival of the velocity peak at any point along the pile is larger than the soil quake assuring that the full resistance is mobilized. In cases where a considerable compression of the soil is needed to overcome the quake, then time t1 is varied through the measured records so that a maximum static capacity is computed.

For consideration (C), on long piles with large shaft friction, the measured velocity may become negative (move upward) very early in the blow unloading the shaft friction along the upper portion of the pile, before the full resistance is mobilized. A correction to the maximum simultaneously occurring resistance is made by adding the shaft resistance that was unloaded.

For consideration (D), dynamic methods give capacities at the time of testing; end of driving testing gives the effective resistance to driving while testing after a waiting period allows pore pressures to dissipate and the soil to remold, thereby including the soil setup. It is always recommended that some piles be monitored during restrike after a waiting period to assess any soil strength changes. Consideration (E) means that the soil must fail so that its ultimate capacity may be measured. If the loading was only in the soil elastic range, then the ultimate capacity is only partially mobilized. In some cases, CAPWAPC analyses at both the end of driving (to obtain toe resistance) and on restrike (to obtain shaft friction) can be combined to project the full capacity of a pile.

In addition to capacity determination, the Case Method and PDA also assist in the evaluation of hammer performance, driving stresses and pile integrity. Unlike capacity calculations which require judgement and experience and may be affected by time dependent phenomena such as setup or relaxation, calculations of stresses, integrity and hammer performance are very straightforward and results are easily interpreted.

The CAPWAPC Method

CAPWAPC is an analytical method that combines field measured data with wave equation type procedures to calculate the pile capacity. The ultimate load from CAPWAPC can be used in place of the static failure load to calculate the Case Method constant J. It is often used to supplement or replace a static test. Results also indicate the distribution of the soil static resistance, quakes and damping factors required for a wave equation analysis; dynamic testing including the CAPWAPC analysis can therefore be used to confirm the input assumptions for the wave equation.

The current CAPWAPC pile model employs the continuous wave transmission model. The soil reaction forces are passive and are assumed to consist of static (elasto-plastic) and dynamic (linearly viscous) components, both along the shaft and below the pile toe and is for all practical purposes identical with the wave equation soil model. To start the analysis, a complete set of wave equation type soil constants is assumed and entered into the computer model. In this dynamic analysis, the hammer model is replaced by the measured velocity imposed at the top pile element. CAPWAPC then calculates the force necessary to induce the imposed velocity. If the computed and measured forces do not agree, the soil model is changed and the analysis repeated (Rausche et al 1972). This iterative process is repeated until no further improvement in the force match can be obtained. The CAPWAP soil model can then be used in a wave equation analysis or in CAPWEAP (a special provision of CAPWAP which replaces the hammer by the measurements) for varying capacity input to predict the capacity vs. observed penetration resistance.

After a CAPWAPC analysis has been performed, the pile and soil model may also be subjected to a static analysis, often referred to as a "simulated static test." In this analysis, the pile is incrementally loaded. The force and displacements at the pile head and along the shaft are then computed. A load displacement graph is produced.

Dynamic pile testing methods have become widely accepted within the last decade and benefit all parties associated with a pile project. Since dynamic testing with the PDA and CAPWAP is so flexible, engineers are creatively adapting this technique to their specific projects. The engineer is presented with much more information to assist in design and construction control. The contractor obtains information on the performance of his hammer system which can be used to reduce driving time and lower his costs. Knowledge of stresses and pile integrity, if a problem and generally bid as a contractor expense, can lead to procedures to reduce damage. The owner is assured of a higher quality foundation since more piles are tested. The faster dynamic testing reduces construction time and is less expensive than static tests. Testing indicator piles often verifies adequate capacity at smaller penetration depth for reduced time and cost of the foundation. If problems are detected, they can be corrected early in a project at comparatively modest cost and reduce legal problems or construction claims.

Application of Capacity Determination Methods

The methods of capacity evaluation each have a different function, accuracy and cost which preclude selecting of a single method for all installations. Figure 1 demonstrates the relationship of these methods such that the pile foundation can be as safe and economical as practically possible.

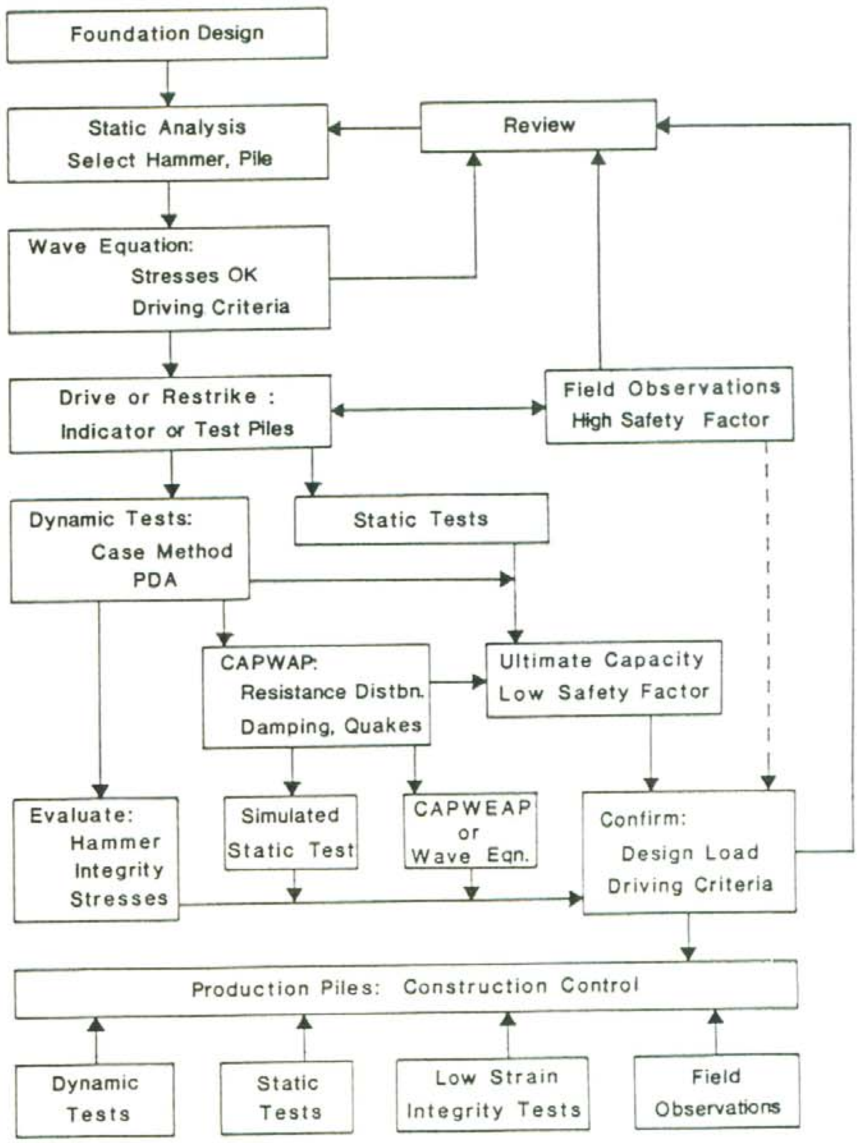

Figure 1: Pile Foundation Design and Testing

After reviewing the appropriate soils investigation and structure loads, the engineer will recommend a pile type and design load. After selection of the hammer system, a preliminary driving criterion is selected, preferably by a wave equation analysis which also verifies that the hammer/cushion combination will install the pile without causing harmful driving stresses. It should be noted that the same measurements and analysis which are made for pile driving can also be applied to SPT or dynamic penetrometers (Triggs and Liang, 1988) to improve the reliability of such data and to directly compute shaft friction, damping and quakes for more accurate wave equation input.

During the pile driving, electronic measurements of the ram velocity, observations of blow count, stroke, cushion descriptions, and penetration are made which can be compared with the original assumptions. As many soils exhibit strength changes with time due to either setup or relaxation, monitoring the pile during restrike after a waiting period is recommended to obtain more economical foundations for piles with setup (capacity increases) or to prevent major problems for piles with relaxation (capacity losses).

The pile capacity is confirmed by static and/or dynamic testing methods. While static testing is the best proof of capacity, typically fewer than one percent of all piles on site are actually tested. A waiting period for setup/relaxation considerations is generally specified prior to the test. To take full advantage, the test should be carried to failure to establish the ultimate capacity to increase design loads or reduce driving criteria for the production piles. Unfortunately, a large percentage of these load tests are carried only to a proof load and valuable information is therefore lost. Static testing is also very time consuming and costly.

The delays and expenses of static testing are leading reasons why dynamic testing is often requested as a replacement for or supplement to static tests. Dynamic tests can be performed concurrently with installation and, as several piles are usually tested per day, they are cost effective. Dynamic testing also provides information on hammer performance, driving stresses, and pile integrity which is not available by static testing alone. On a small percentage of projects, dynamic testing may produce inconclusive capacity results if the CAPWAPC soil model is highly unusual. Refusal blow counts may also cause underprediction of the ultimate capacity (similar analogy to static proof tests with small net settlement versus a pile loaded to a definite plunging failure) as only part of the capacity may be mobilized;

further CAPWAPC analysis of both end of driving toe resistance and restrike shaft friction may in some cases be used to project the ultimate capacity.

After capacity evaluation, a safety factor is applied to confirm the allowable load and installation criterion. For the same reliability, this safety factor can be assigned a lower value after testing (Goble et al,1980, Jaeger and Bakht, 1983), thus adding an economic incentive for testing.

The procedures for selecting an installation criterion can be performed as either a preconstruction test if the project is sufficiently large, or as part of the first few production piles. In any case, the remaining piles should be installed subject to additional construction control. Although on some sites this may be only recording the blow count, all larger projects should have a well planned program of periodic dynamic monitoring and/or additional static tests as construction progresses to confirm consistent hammer performance and soil conditions across the site. As the trend in recent years has been to higher capacity piles to reduce foundation costs, a comprehensive control program is increasingly required (Thompson, 1987).

The largest source of problems on any piling site is the hammer system since in no other facet of construction is the installing equipment relied upon so heavily for construction control as in pile driving. When hammer problems occur, early detection is critical to the foundation quality. Cushion properties and pile length also influence the transferred energy and driving stresses. On many projects, the driving criterion is established with a single hammer; during production, additional hammers with similar energy rating are used often without consideration that their transferred energy can be substantially different (Rausche et al 1985, Thompson 1987, Chen et al 1979, Wu et al 1985). Dynamic testing is by far the best procedure for hammer performance monitoring and every construction control program should include dynamic tests at regularly scheduled intervals.

On many concrete pile projects, the pile shaft integrity is confirmed using Low Strain Testing which involves hitting the pile head with a small hand held hammer and electronically observing reflections from discontinuities or the pile toe (Rausche et al 1988). Although this method is simple and quick, the method only investigates shaft integrity and has serious limitations. The test should be applied to a large number of piles to establish typical records and minimize misinterpretation of single results.

The above discussion is intended as a general guide to a satisfactory pile installation. Unexpected results, difficulties, or capacities or penetrations significantly different than originally anticipated should be addressed by additional analysis or testing. The experienced engineer will need good judgement in developing or modifying a program to obtain the most benefit at realistic cost.

Sample Specification

The verification or testing procedure is generally included as part of the project plans. The following sample specification, based on Figure 1, should be modified to match the project requirements.

A. Perform initial wave equation analysis of soil conditions, pile type and capacity, and pile driving equipment utilized.

B. Drive test piles to driving criteria established by the wave equation, subject to change due to actual hammer performance and soil strength changes. Dynamic testing shall be performed during the final driving.

C. For fine grained soils, evaluate piles by dynamic testing after a sufficient waiting period by restriking the piles. Alternatively, other piles could be tested which have been previously installed to identical criteria or with varying penetrations. Restrike testing is essential for capacity determination including setup/relaxation since the PDA gives capacity at the time of testing.

D. Perform supplementary, rigorous wave analysis of the measured data using CAPWAPC on several piles tested to verify field results.

E. Based on testing results, review capacity, hammer performance, driving stresses and pile integrity to confirm the installation criteria.

F. Static testing is recommended on larger projects, especially if the dynamic testing is inconclusive or higher capacity is required than indicated by dynamic tests. For sites with sufficient dynamic testing, the amount of static testing may be significantly reduced.

G. Test additional piles at regular intervals throughout the project for construction control. Testing may involve static tests or dynamic tests during driving or restrike as conditions require, if the hammer system is replaced or modified, or if driving is unusual to determine if hammer, pile or soil changes exist.

Summary

Several methods for determining pile capacity have been summarized. Static testing, if performed to failure, is an ideal way to assess a pile's ultimate static bearing capacity. It is, however, very expensive, time consuming, and in certain instances, physically impossible to perform. These conditions limit the number of test piles to just a few. Wave Equation is an excellent tool for predicting the dynamics of pile driving if realistic inputs are assumed. It is not, however, possible to always accurately predict the performance of the hammer, cushion, soil, etc. Dynamic measurements and analysis of force and velocity during pile driving can be used to verify the wave equation assumptions. On site, the Case Method with a Pile Driving Analyzer can estimate pile capacity, monitor hammer performance and pile stresses, and investigate pile integrity. Because of their flexibility and low cost, dynamic testing methods may be applied to a relatively large percentage of the piles to cut costs and eliminate problems.

A well conceived and properly executed testing program will give engineers, contractors and owners the highest confidence in their foundation. Installation difficulties will be detected early in the project and corrected. Decisions and production driving will be kept on schedule, minimizing delays, unnecessary costs, and claims so the project will be completed on time to the satisfaction of the owner.

References

Authier, J., and Fellenius, B., 1980, Quake Values Determined from Dynamic Measurements, the 1st Seminar on the Application of Stress Wave Theory on Piles, Stockholm, Sweden, pp. 197-216.

Chen, D.S., Toto, J.V., and Wong, I.H., 1979, Field Evaluation of Hammer Efficiency and Pile Driving Criteria, Symposium on Deep Foundations, ASCE Convention, Atlanta.

DeJuhasz, K.J., 1942, Graphical Analysis of Impact of Elastic Bars, Journal of Applied Mechanics 9, p A122-A128.

Fellenius, B.H., 1980, The Analysis of Results From Routine Pile Load Tests, Ground Engineering, Vol. 13, No. 6, pp. 19-31.

Goble, G.G., Moses, F., and Snyder, R.E., 1980, Pile Design and Installation Specification Based on Load Factor Concept, Transportation Research Record #749, National Research Board, Washington D.C.

Goble, G.G., and Rausche, F., 1986, Wave Equation Analysis of Pile Foundations - WEAP86, FHWA contract DTFH61-84-C-00100.

Goble, G.G., Rausche, F., and Likins, G.E., 1980, The Analysis of Pile Driving A State-of-the-Art, The 1st Seminar on the Application of Stress Wave Theory on Piles, Stockholm, Sweden.

Jaeger, L. G., and Bakht, B., 1983, Number of Tests Versus Design Pile Capacity, ASCE, Geotechnical Journal, Vol 109-6.

Likins, G.E., 1983, Pile Installation Difficulties in Soils with Large Quakes, Symposium on Dynamic Measurements of Piles and Piers, ASCE Convention, Philadelphia.

Pile Driving Analyzer Manual, August 1987, Pile Dynamics, Inc., Cleveland, Ohio, August 1987.

Rausche, F., Goble, G.G., Likins, G.E., and Miner, R., 1985, The Performance of Pile Driving Systems, FHWA, Contract DTFH61-82-1-00059.

Rausche, F., Likins, G.E., Goble, G.G., and Hussein, M., 1986, The Performance of Pile Driving Systems: Inspection Manual, Federal Highway Administration, Contract DTFH61-82-C-0059.

Rausche, F., Likins, G. E., and Hussein, M., 1988, Pile Integrity Evaluation by Impact Methods, Third Seminar on the Application of Stress Wave Theory on Piles, Ottawa, Canada.

Rausche, F., Moses, F., and Goble, G.G., 1972 (September), Soil Resistance Predictions from Pile Dynamics, ASCE, Journal of Soil Mechanics and Foundations.

Smith, E.A.L., 1960, Pile Driving Analysis by the Wave Equation, ASCE Journal of Soil Mechanics and Foundations, SM, Vol. 86, pp. 36-61.

Thompson, C. D., 1987, High Capacity Piles in the Hamilton Bayfront Area, 12th Deep Foundation Institute Seminar, Hamilton, Ontario.

Timoshinko, S., and Goodier, J.N., 1981, Theory of Elasticity, McGraw-Hill Book Company, Inc., New York.

Triggs, J. F., and Liang, R. Y., 1988, Developement of and Experience From a Lightweight, Portable Penetrometer Able to Combine Dynamic and Static Cone Test, First International Symposium on Penetration Testing, Orlando, Florida.

Wu, M.J., Gurtowski, T.M., and Yamane, G.Y., 1985, Field Evaluation of Diesel Hammer Performance, Proceedings of International Conference on Soil Mechanics and Foundation Engineering, San Francisco.