DYNAMIC EVALUATION TECHNIQUES FOR OFFSHORE PILE FOUNDATIONS

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INTRODUCTION

Fixed offshore jacket-type platforms are installed around the world for a variety of purposes including petroleum and gas production, navigational aids, and weather monitoring stations. Because of their location, offshore structures are designed and constructed to withstand the severe environmental conditions of open deep waters in order to provide a safe and stable area for both workers and machines. The majority of structures of this type are supported by driven pile foundations. Although construction time required is not a major factor in design, rapidity of installation is essential since in many locations the ability for large floating cranes to perform is limited by sea and weather conditions. Timeliness and economic feasibility of installation may, therefore, be directly dependent on the careful planning and flawless pile driving activity.

Foundations for offshore jacket-type structures consist of high load-carrying capacity driven steel tubular elements. Having to drive piles with 300 meters (1,000 feet) length to carry 45,500 kN (10,000 kips) utilizing hammers with rated energy of 2,500 kJ (1,800,000 ft-lb) into soils with unfamiliar properties is not an uncommon occurance. In many cases, there exist knowledge limitations and uncertainties at the planning, desing, and excution stages which require "the extrapolation of knowledge far beyond available experience" (Tomlison, 1977) Conventional means (Hussein et al., 1988) available to assess land-based piles are either unapplicable, or phisically impossible to facilitate in evaluating offshore piles. The ability of the hammer-driving system to advance the pile to the required depth, or the pile to withstand impact driving forces, and of the soil to follow desing theories and assumptions often leave the engineer with and added belief in luck.

Significant progress has been made in the past two decades in transforming the art of pile installation into a science based on advancements in mechanics of materials theories and computer science fields. Indeed, it would have not been possible to arrive at the present state of offshore construction without the utilization of these advancements. Dynamic evaluation and testing techniques represent the only rational approach to evalute offshore pile foundations. These include analytical computer programs that predict the behavior of the various components involved during pile driving; and field electronic equipment that monitor actual field conditions. The following presents an overview of the state-of-the-art in dynamic evaluation techniques.

WAVE EQUATION ANALYSIS OF PILE DRIVING

As it relates to pile foundations, the term "wave equation" is a name applied to a number of computer programs that simulate and analyse impact pile driving according to one dimensional elastic wave propagation theories. The first solution to the one dimensional wave propagation problem in elastic rods was given by St. Venant (Timoshenko and Goodier, 1951) who also suggested its applicablity to pile driving. In the late 1950s, E.A.L. Smith developed an algorithm and later a computer program code (Smith, 1960) for pile driving analysis based on the wave propagation theory. It may be that this program was the first application of electronic digital computers in non-military engineering work. All computer programs that follow Smith's concept are known as WAVE EQUATION. Researchers and practioners have been continually evaluating, improving, and refining wave equation computer programs. One of, the most comprehensive and widely accepted of these programs in known as GRLWEAP (Goble Raushe Likins and Associates, Inc. Wave Equation Analysis of Piles).

GRLWEAP is a wave equation program that utilizes personal computers to analyse impact pile driving. It is based on the original WEAP program which was developed in 1974 by the same authors under United States Federal Highway Administration sponsorship. GRLWEAP is integrated with a pre-processing input program (GRLINP) that simplifies data entry, and an output graphics program (GRLGRF) that reduces and presents results both in tabulated and plotted forms. The minimum hardware requirements for the personal computer (PC) is a 640 k byte memory and at least one disk drive. However, it is suggested that a coprocessor, printer, and plotter be used; the availability of screen graphics would also take advantage of the program's manu outpur features.

In practice, wave equation analysis may be employed to deal with one, or both of the following questions:

A: Given a complete description of hammer, cushions, pile, and soil; can the pile be safely driven to the required bearing capacity?
B: What is the static bearing capacity of the pile given pile driving or restriking blow count?

An analysis to answer the first question in known as a "driveability study". Actually, several analysis may be performed by varying inputs representing different components (hammer, cushions, or soil parameters) by which a family of solutions are generated to assess the sensitivity of results to variations in input values.

In the second case, analysis are performed and results are interpreted according to field observed quatities (blows per set, for example) to assess the static capacity of the pile.

A typical wave equation representation of a pile driving problem is shown in Figure 1. All the components that generate, transmit, or dissipate driving energy are represented by a series of concentrated masses, elastic springs, or viscous dashpots. The stocky ram is usually modeled as a single mass, the hammer assembly (cylinder, columns) by two masses and springs. In the case of diesel hammers, the thermodynamic cycle is also included in the model. As part of GRLINP, the models of over 200 hammers are stored in memory and the program user has only to specify the particular model by inputing an identification number for GRLWEAP excution. Results of a research study (Rausche at al., 1985) on hammer performance are also incorporated into the program as effeciency values for variuos conditions.

Hammer cushions are inserted between the ram point and pile cap to soften impacts and protect both the hammer and pile from damaging stresses. It is represented by a spring and a coeffecient of restitution to account for its elasticity and energy dissipation, respectively. The pile cap is a very compact element and is represented as a single mass. Hammer manufacturer's suggested cushions and pile cap sizes are tabulated as part of GRLINP for most hammer models and pile sizes.

Any pile configuration can be modeled by a series of masses and springs representing pile segments of 1.5 meters (5 ft) lenght. The mass and spring stiffness are computed from the material density and modulus of elasticity, segment area and length. Piles with up to 299 segments may be analysed by GRLWEAP.

Soil resistance to pile penetration is represented by both displacement and velocity dependent parts. Each pile segment below ground level is assigned a soil model to account for

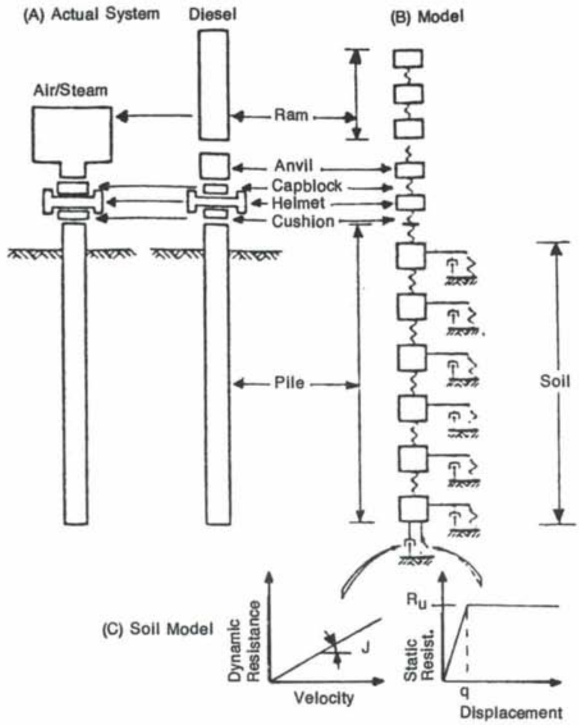

Figure 1: Typical wave equation model representation.

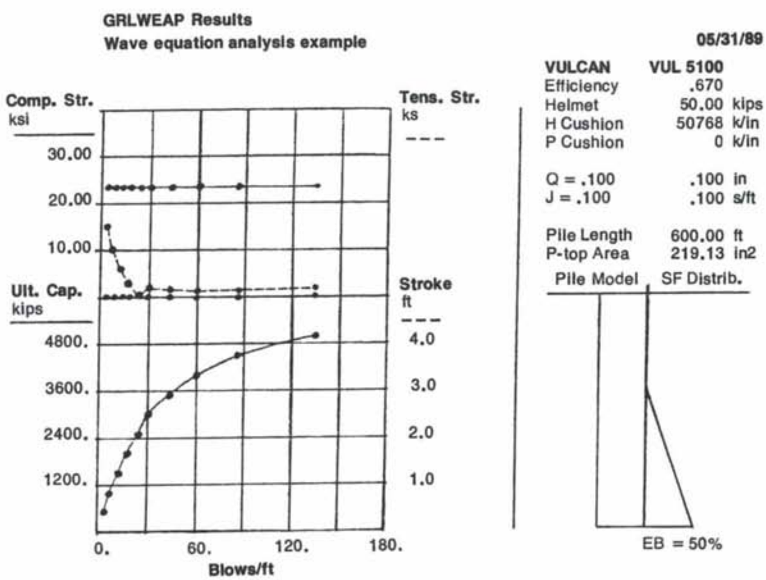

Figure 2: Typical wave equation plotter output results.

skin friction, the last element is assigned and added soil model to represent end bearing. The displacement component is defined by ultimate values for both elastic resistance and displacement (quake). The relationship between resistance and velocity of loading is defined by a damping factor. Normally, a series of static pile capacities is analysed. The program then requires the input of a percentage skin friction and its distribution. The user may input this distribution manually, or may choose one of 10 different profiles already stored as part of GRLINP.

GRLWEAP can analyse soil resistance capacities with constant end bearing, constant skin friction, or increases in both skin friction and end bearing. Furthermore, if unit skin friction and end bearing are input, the program then calculates pile stresses, transferred energies, and blow counts for up to 10 penetration points. The option for analyzing multiple blows for pile residual stresses is also available to the GRLWEAP user.

In summary, the inputs required for the execution of GRLWEAP are:
Hammer: model and efficiency.
Cushion: area, thickness, elastic modulus, and coefficient of restitution.
Pile Cap: Weight.
Pile: área, elastic modulus, and density as a function of length.
Soil: total static capacity, percent skin friction, quake and damping factors, both along the shaft and below the toe: alternatively, a soil analysis as a function of depth may be specified.

The following example is offered to illustrate how this computational tool relates to actual pile driving problems. This exercise involves the analysis of a 183 m (600 ft) long steel pipe pile 1,219 mm (48") O.D. and 38.1 mm (1.5") wall thickness) driven with a Vulcan V 5100 single acting steam hammer to a penetration of 110 m (360 ft) below mudline. Input quantities are summarized along with plotted output results in Figure 2. Manual suggested input values for driving-system and soil dynamic characteristics were selected. Pile capacities between 2,275 and 22,750 kN (500 and 5000 kips respectively) were analysed, assuming 50% skin friction distributed linearly along the botton 60% of pile lenght. Analysis results are plotted in the form of "bearing graph" relating pile capacity and driving stresses (both compressive and tensile) to blow counts. This bearing graph may be interpreted in one of two ways: (A) knowing the required pile capacity (say 20,500 kN, or 4,500 kips), the bearing graph shows that the blow count should be 282 blows per meter (86 blows per foot) and the expected pile compressive stress is 158.7 MPa (23 ksi), (B) if the blow count during driving is observed (say 200 blows per meter or 60 blows per foot), then the computed pile capacity and driving stress can be read from the bearing graph (18,200 kN and 158,7 MPa or 4,000 kips and 23 ksi), respectively. A three dimensional plot of forces at 13 piles sections at a capacity of 16,000 kN (3,500 kips) is shown in Figure 3, similar plots can be generated for pile stresses, velocities, and displacements for several capacities. All analysis results are also available numerically in tabulated forms.

Correlation studies confirm that wave equation analysis can predict pile driving stresses, hammer transferred energy, and pile bearing capacity within 20% of actual measured field values. There will be cases, however, where wave equation predictions do not agree well with actual performance. Differences may generally be attributed to inaccurate representation of hammer performance, cushion properties, or soil dynamic behavior assumptions.

Although the wave equation is an excelent tool for rational pile driving analysis, accurate results require correct data input and proper data evaluation. Because the solution depends on assumptions (particularly hammer performance and soil behavior), additional feedback is necessary to either confirm, or provide the basis for change of input parameters. The only way to assure realistic results is the measurement of field performance.

FIELD DYNAMIC MONITORING

The use of dynamic monitoring of piles was developed during the 1960s in a research project at Case Institute of Technology (now Case Western Reserve University) under the direction of professor G.G. Goble. By field measurements, unknowns in wave equation analysis discussed above can be eliminated; in addition, data is available to better understand the dynamics of pile driving. The Case project produced both equipment that can be used routinely and the numerical methods for processing the resulting measurements, both are known as the CASE METHOD. An extension of the Case project was the development of the CAPWAP method. The same researchers later developed a HAMMER PERFORMANCE ANALYZER which is used to assess hammer performance based on radar technology. The following presents discussions on these field testing methods.

Case Method and the Pile Driving Analyzer

The techniques most widely employed today for measurements and analysis of pile dynamics are collectively referred to as the Case Method. This name actually covers a wide range of equipment, equations, and procedures.

The Case Method of closed form solutions requires the measurement of force and velocity histories of the pile under a hammer blow. Using wave propagation theory and assuming an ideally plastic soil and an ideally elastic and uniform pile, Case Method analysis provides data sufficient for evaluating pile driving stresses, structural integrity (Rausche and Goble, 1978) and static bearing capacity (Rausche et al., 1985). The hammer system performance may also be determined (Likins, 1982) through the calculation of maximum energy delivered to the pile, ram impact velocity, and hammer cushion stiffness.

The Pile Driving Analyzer (PDA) and its associated transducers were developed to obtain data and perform Case Method analysis in the field. In addition to the PDA, the system includes two each strain transducers and accelerometers bolted near the pile top, an oscilloscope for signal quality monitoring, a seven channel FM instrumentation tape recorder for data storage, and optionally a plotter to obtain report quality records. A PDA system schematic is shown in Figure 4.

The strain transducers are reusable frames with four resistance foil gages attached in a full bridge. Pile velocity is obtained by integrating measured acceleration. Pile motion is measured wiht pioezoelectric accelerometers that are mounted on special blocks for electronic and mechanical isolation and for ease of attachement to the pile. Figure 5 presents plots of force and velocity histories measured near the top of a 40 m (460 ft) long pile during one hammer blow.

The Pile Driving Analyzer is a state-of-the-art, user friendly, field digital computer (shown in Figure 6). Basically, it computes some 40 different dynamic variables in real time between hammer blows after prodiving signal conditioning, amplification, filtering and calibration of the measured signals of strain and acceleration. Pile strains are converted to forces and accelerations to velocites as a function of time for each hammer blow. Force and velocity records are assessed for data quality and are evaluated according to Case Method equations. Analog to digital conversion of force and velocity inputs are each at 10,000 Hz with options allowing for up to 4 channels of A/D. Numerical computations are controlled by a 16 bit microprocessor. Results are available on a built-in printer.

The PDA can support a variety of standard peripheral equipment. Data is stored on either analog or digital records, viewed on an X-Y oscilloscope, and plotted on a strip chart or plotter. The RS 232 interface sends data from the PDA to any modern computer either directly or from remote field locations through telephone modem communications.

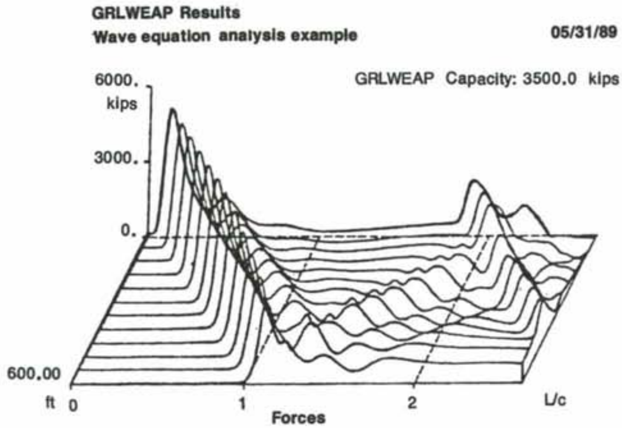

Figure 3: Wave equation generated force histories at 13 pile sections.

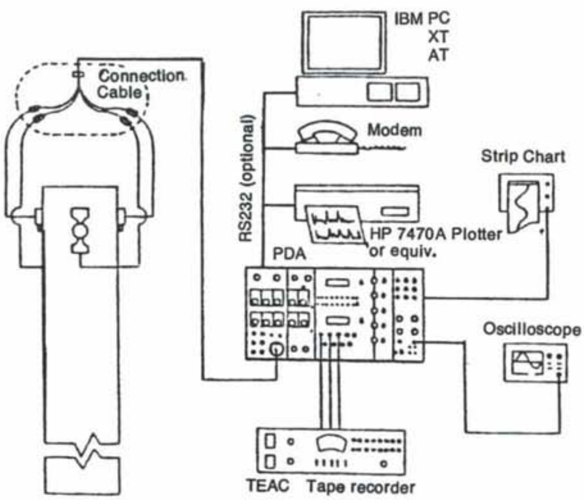

Figure 4: Pile driving analyzer system schematic.

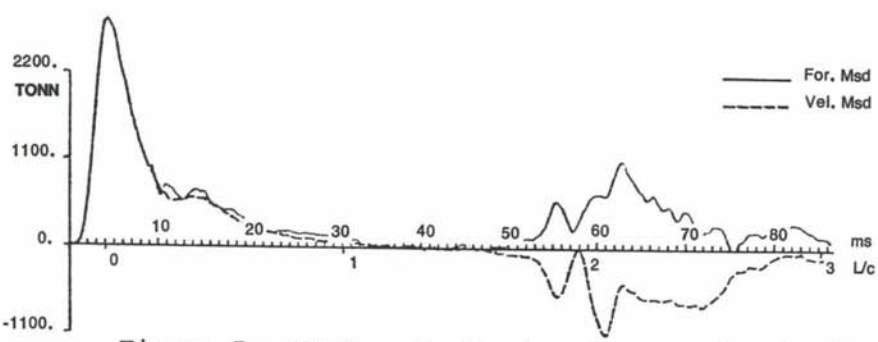

Figure 5: Plots of pile top force and velocity records during one hammer blow.

Figure 6: Pile driving analyzer.

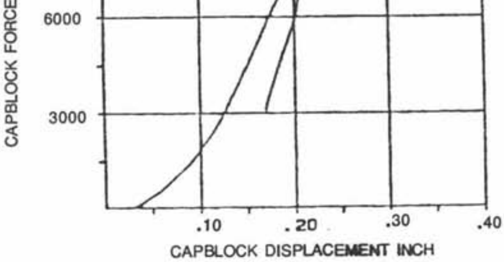

Figure 7: Force vs. displacement curve for hammer cushion.

As alredy mentioned, the PDA applies Case Method equations to field measured data to provide real time computations of data analysing the hammer, cushion, pile, and soil conditions under a hammer blow.

Given measured pile top force F (t) and velocity v (t), total soil resistance is computed from:

$$R(t) = 1/2\{\left[F(t) + F(t2)\right] + Z\left[v(t) - v(t2)\right]\} \quad (1)$$

Where

Z = pile impedance, EA/c

t2= time t + 2L/c

L = pile length below gages

c = sress wave speed

E = pile elastic modulus

A = pile cross sectional area

This total resistance consists of a dynamic and a static component. The static resistance component is, of course, the desired pile capacity. The dynamic component may be computed assuming a Case damping factor (J) from:

$$Rd(t) = J\left[F(t) + Zv(t) - R(t)\right] \quad (2)$$

Static pile capacity is then the result after subtracting the computed dynamic resistance Rd(t) from total resistance R(t). The factor J is dependent on the soil type and behavior under dynamic loading, empirical values are available for different soil conditions.

Pile capacity with penetration is readily available since a value is computed for each hammer blow. Time dependent soil strength changes may also be studied by testing piles at both end of initial drive and later during restrike.

Compressive stresses near pile top are directly computed from measured strains. Pile top measurements along with wave mechanics considerations, are used by the PDA to compute compressive forces at the pile toe and tensile forces along the pile shaft.

In a uniform pile, stress waves are reflected wherever the impedance (Z) changes. The reflected waves arrive at the pile top at a time that depends on the change location. The reflected waves are evident in both force and velocity pile top measurements; the magnitude relative change allows to determine the extent of the impedance change.For a uniform pile, this change is either a reduction in area (bad splice, for example), or strength (severe buckling, for example).

Energy transferred to the pile top is calculated from:

$$E(t) = \int F(t)v(t)dt \qquad (3)$$

The maximum of the E(t) curve is the most important information for an overall evaluation of the performance of the hammer-driving system. This is computed according to the Case Method and printed by the PDA as EMX. The transfer efficiency of the hammer system can easily be computed as the ratio of EMX to the hammer rated energy (usually reported as ram weight times stroke).

Solutions derived from measured dynamic pile top quantities and impulse-momentum considerations have been developed to solve for the maximum ram velocity prior to impact. This value (Vi) is computed from:

$$Vi = (1/mr) \int_{0}^{t_0} F(t)dt \qquad (4)$$

Where mr is the ram mass, and t_0 is the first time of zero pile velocity after impact. Knowing ram impact velocity enables the computation of ram kinetic energy at impact ($KE = 1/2\ mv^2$). The ratio of the kinetic energy to rated energy is an indication of hammer efficiency; the ratio of EMX to KE may be an indication of cushion efficiency, and as mentioned earlier, the ratio of EMX to the rated energy is an overall measure of hammer system performance.

Using free body force equilibrium considerations and the pile top force and velocity measurements, the force in the hammer cushion can be directly computed; using the same measurements and momentum considerations, the displacement in the cushion can also be obtained. By plotting the force versus the displacement for the hammer cushion, a complete loading history of the cushion can be obtained (as shown is Figure 7) and the stiffness can be directly determined for each hammer blow.

The real time availability of a complete automatic analysis of the hammer-cushion-pile-soil system under each hammer blow makes it possible to avoid, or resolve problems during the execution of pile installation.

CAPWAPC

The Case Pile Wave Analysis Program - Continuous version is an analytical method that combines field measured data with wave equation type procedures to compute pile static capacity and resistance distribution (Rausche, 1970).

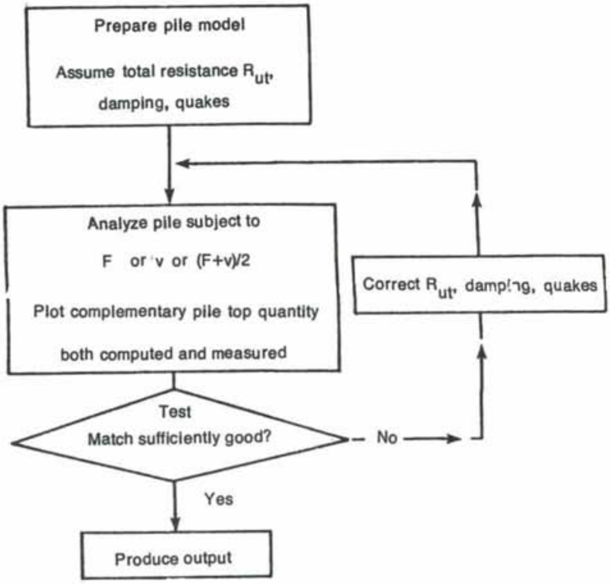

Figure 8: Flow chart of CAPWAPC procedure.

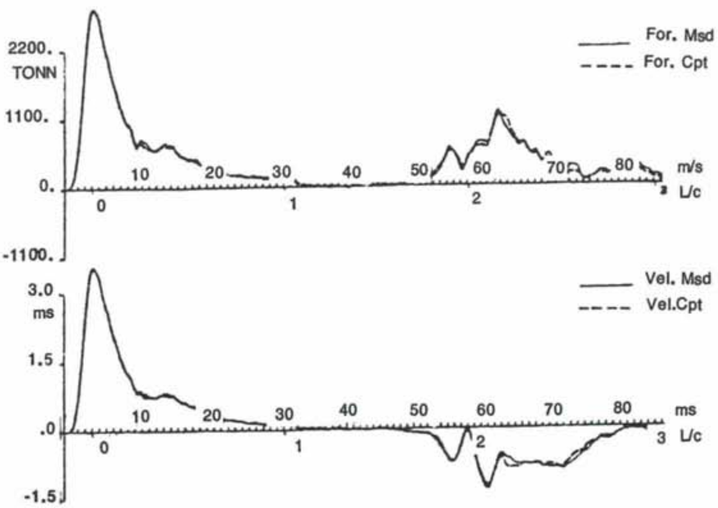

Figure 9: Plots of measured and CAPWAPC computed pile top force and velocity records.

In order to perform the CAPWAPC analysis, the pile below the point where the gages were attached is modeled in the form of a series of segments of equal stress wave travel time. The soil reaction forces are passive and are assumed to consist of a static (elasto-plastic) and a dynamic (linearly viscous) components, both along the shaft and below the pile toe. In this way the soil model has at each point three unknowns: elasticity, plasticity, and viscosity. To start the analysis, a complete set of wave equation type constants is assumed and entered into the program. Then in a dynamic analysis, the hammer model is replaced by the measured velocity imposed at the top pile element and CAPWAPC calculates the force necessary to induce the imposed velocity. The measured and calculated force records are both plotted, if they do not agree, the soil model is changed and the analysis repeated. This iterative procedure is repeated until no further improvements between measured and computed forces can be obtained. Alternatively, the force may be imposed as the boundary condition and the corresponding velocity computed. The CAPWAPC procedure is illustrated in Figure 8.

Results from a CAPWAPC analysis include comparisons of measured with the corresponding computed force/velocity curves, as illustrated in Figure 9. Numerically, for each segment of the pile, ultimate static resistance, soil quake and damping factors are tabulated. Also included in the results is a pile load-set curve from static test simulation.

Since they are calculated during the analysis, forces, velocities, displacements, and energies may be printed or plotted as a function of time for all pile segments.

The Hammer Performance Analyzer

One of the most troublesome assumptions in a wave equation analysis is the hammer efficiency. The Hammer Performance Analyzer (HPA) was developed to measure ram impact velocity for each hammer blow which can be used to compute kinetic energy for hammer performance determination.

The HPA utilizes radar technology together with special purpose electronics. As shown in Figure 10, the system consists of two basic components:

* The antenna, which contains a housing supported on an adjustable stand, and
* The signal conditioner and strip chart recorder unit, which powers the antenna, contains the frequency voltage conversion circuitry, and provides an analog hard copy of the ram motion on paper tape.

The antenna is placed so that the ram moves within the radar's active cone as illustrated in Figure 11. No connections to

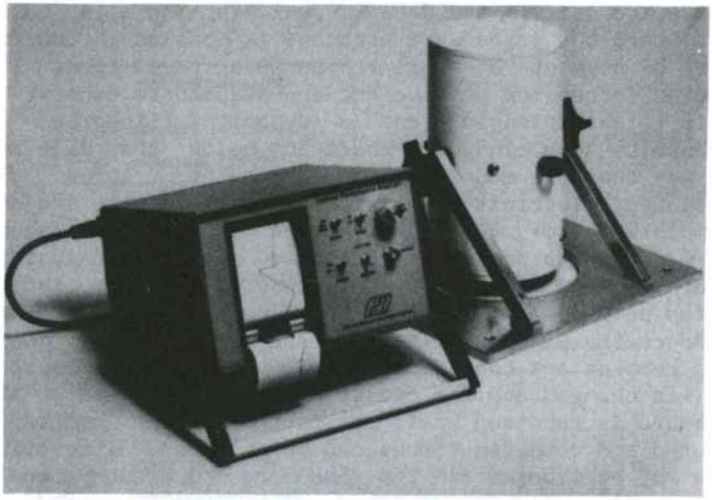

Figure 10: Hammer performance analyzer.

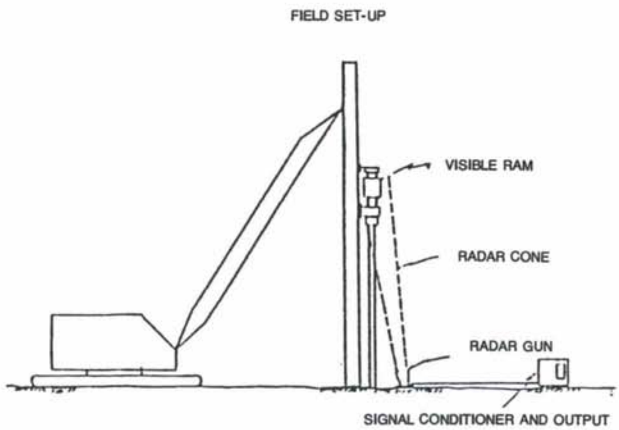

Figure 11: Operation of HPA with air/steam/hydraulic or drop hammer with visible ram.

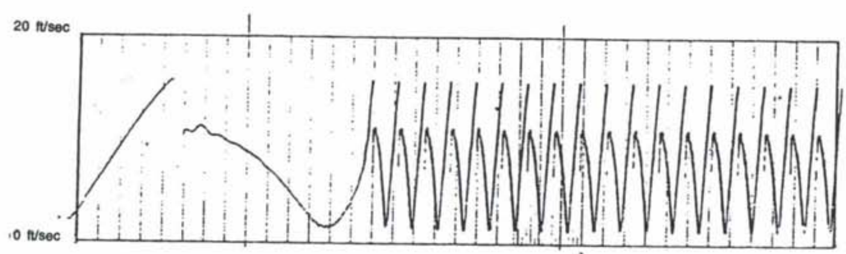

Figure 12: HPA sample output.

the pile or hammer are required. The fastest moving object within the beam is automatically locked in. From the Doppler shift, the antenna generates a signal which is proportional to the speed of the moving object. The ram impact speed can then be determined from the strip chart output. The plotted output may be compressed to investigate the peak ram velocity variations for a series of blows (Figure 12), or expanded to obtain detailed plots for a thorough performance analysis. The analog signals can also be tape-recorded for future reference.

Findings from HPA measurements are invaluable in determining hammer performance, and are easily incorporated into other analytical procedures such as wave equation.

CONCLUSION

Several dynamic techniques for analysis and measurements of pile installation have been summarized. Wave equation is an excellent tool for predicting the dynamics of pile driving and avoiding potentially costly mistakes. Results within 20% may be expected if realistic inputs are assumed. It is not, however, possible to always predict the performance of the various elements involved (hammer, cushion, soil, etc.). Dynamic testing with measurement of pile force and velocity can provide the basis for improving the accuracy of wave equation assumptions. The Case Method can be employed on site with a Pile Driving Analyzer to estimate pile capacity, monitor hammer and cushion performance, pile stresses, and to investigate pile integrity. The CAPWAPC program combines field measurements with wave equation type analysis to compute pile capacity and soil resistance distribution. Furtheremore, soil dynamic parameters (damping, quake) are extracted by the analysis. The Hammer Performance Analyzer provides a simple means to measure ram impact velocity. These data can be used to determine the efficiency of the pile driving hammer.

The availability of computers and automated numerical analysis should not be applied blindly, and do not relieve the engineer from making final decisions. All techniques discussed above should be added to the engineer's bag of tools that he has for dealing with pile driving evaluations.

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