DYNAMIC TESTING OF PILE FOUNDATIONS DURING CONSTRUCTION

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Abstract

Piles are slender deep foundation elements used to carry structural loads in conditions where shallow foundations do not provide adequate support. Commonly, pile driving hammers are used to force long prefabricated piles into the ground. Visual observations during pile driving provides a crude evaluation with generally insufficient and often erroneous information. Static load testing to evaluate pile load capacity is time consuming, expensive and in many cases impractical.

Dynamic pile testing constitutes a comprehensive and economical means to quantitatively evaluate the hammer-pile-soil system based on the measurement of pile force and velocity records under hammer impacts. Measurements, data processing and analysis are performed in real time in the field by a state-of-the-art dedicated system called the Pile Driving Analyzer® (PDA). Testing results include driving system performance, dynamic pile driving stresses and structural integrity, and estimation of pile load capacity. This paper presents discussions on dynamic pile testing equipment, analytical methods, and applications with illustrative examples.

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Introduction

Structural requirements and subsurface conditions along with economic considerations generally dictate the foundation used. Deep foundations are required where shallow foundations do not provide adequate support. Piles are long slender structural elements used as deep foundations and are generally classified by their material and/or by method of installation. Preformed piles are of timber, concrete, steel or a combination thereof. Precast concrete piles are typically square in cross section while steel piles may be pipes or H sections. Commonly, piles range in size from 250 to 600 mm in diameter and between 10 and 30 m in length; although much larger sizes are also utilized. An impact pile driving hammer generally consists of a heavy piece of steel called the ram and a mechanism to raise the ram so it falls (under gravity or with assistance) and impacts the pile in rapid succession to force the pile into the ground.

In general terms, the engineer must consider the following aspects of a pile foundation given information on structural requirements and specifications:

I. assessment of subsurface conditions.

II. selection of appropriate pile type and dimensions, selection of suitable driving equipment and determination of proper installation criteria.

III. evaluation of foundation behavior regarding load carrying capacity, and settlement under working conditions.

Under imposed loads, the performance of a pile foundation is a function of individual pile's structural strength and integrity, soil strength and deformation properties, and pile-soil interaction characteristics. Piles must have sufficient cross-sectional area and adequate strength to carry service loads and also to withstand handling and driving stresses during installation. They must have sufficient length to reach soil layers with adequate resistance to support imposed loads without undue settlements. The driving system must be capable of delivering sufficient force and energy to the pile for an effective and efficient installation.

Field observations during pile driving are an important and integral part of the foundation construction process. Visual observations of the hammer operation and pile driving resistance (i.e., blows per meter) are often recorded during installations. These so called "measurements", however, provide only a crude evaluation with generally insufficient and often erroneous information and results of the adequacy of the pile as a foundation element.

Due to the inherit uncertainties in conventional static analysis methods and the inadequacy of visual observations, selected test piles are often subjected to static loading. This conventional testing verifies initial design assumptions and preliminary installation procedures. Static pile testing is, however, expensive, time consuming and in some cases impractical, which greatly limits its application. For small projects with relatively few piles, static testing is often avoided due to the considerable testing cost compared to the overall foundation cost. Static load testing of more than one percent of piles on large projects is generally prohibitively time consuming and expensive. In situations such as near shore or offshore construction in deep waters, static pile load testing is practically impossible.

During recent decades, rational pile analysis methods based on the WAVE EQUATION approach (Smith 1960) has gained widespread acceptance. This approach utilizes modern numerical analysis and personal computers to model the total system. The accuracy of results from this computational approach, however, is dependant on the accuracy of the input assumptions (Hussein et al. 1988).

Dynamic pile testing with electronic field equipment is a viable technique to accurately and comprehensively monitor and analyze the hammer-pile-soil system during installation. Testing results are produced in the field immediately following each hammer blow which is essential for purposes of quality control.

Dynamic Pile Testing

Background

In 1964, a research program (sponsored by several State Highway Departments and The Federal Highway Administration) was initiated at Case Institute of Technology (now Case Western Reserve University) in Cleveland, Ohio. The research objective was an economical and practical method to estimate static pile bearing capacity. The successful research resulted in modern dynamic pile testing and evaluation methods. Application of the method was later expanded to analyze the complete hammer-pile-soil system. Today, these procedures based on wave propagation theory are collectively called the Case Method and are conveniently applied in the field by dedicated electronic equipment called the Pile Driving Analyzer (PDA) system. The measured data is subjected to rigorous dynamic analysis using computer programs such as the CAse Pile Wave Analysis Program (CAPWAP®).

Testing Purposes

Dynamic pile monitoring for construction quality control and verification testing are routinely performed on thousands of project sites annually in the United States and around the world. Main objectives of dynamic pile testing include obtaining information on the following:

A) Hammer and driving system performance for productively and construction control.

B) Dynamic pile stresses during installation. To reduce the possibility of pile damage, stresses must be kept within certain bounds.

C) Pile integrity during and after installation.

D) Static pile bearing capacity at the time of testing. For the evaluation of long term capacity, piles are generally tested during restrike some time after installation.

Dynamic pile testing is performed under hammer impacts during driving (or restrike) and is significantly faster and less expensive than conventional static test methods. Many piles may be tested on a given project in a short period of time at modest cost. Additionally, more information is available from a dynamic test than would be obtained from a static test. Dynamic pile testing can be performed on any type pile, including cast-in-place drilled shafts (Townsend et al., 1991).

Instrumentation

The Case Method requires measurement of pile top force and velocity records, obtained with reusable bolt-on accelerometers (piezoelectric or piezoresistive) and strain transducers. Figure 1 shows an accelerometer and a strain transducer attached to the side of a precast concrete pile. Typically, one each accelerometer and strain transducer are attached to two opposite sides of the pile head to monitor, and account for (by averaging) effects of eccentric hammer impacts. The PDA (Figure 2) is a state-of-the-art user friendly data acquisition system and field computer that provides signal conditioning and numerical processing of the measured signals. For each blow, pile strains are converted to forces and accelerations to velocities as a function of time and evaluated according to the Case Method closed form solutions by the PDA in real time in the field. More than 30 dynamic variables can be computed for each blow. Figure 3 presents plots of pile force, velocity, displacement, and energy

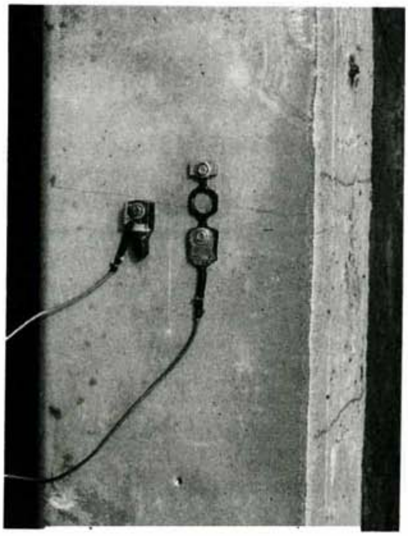


Figure 1: Pile Instrumentation, Accelerometer (left) and Strain Transducer (right)

Figure 2: The Pile Driving Analyzer

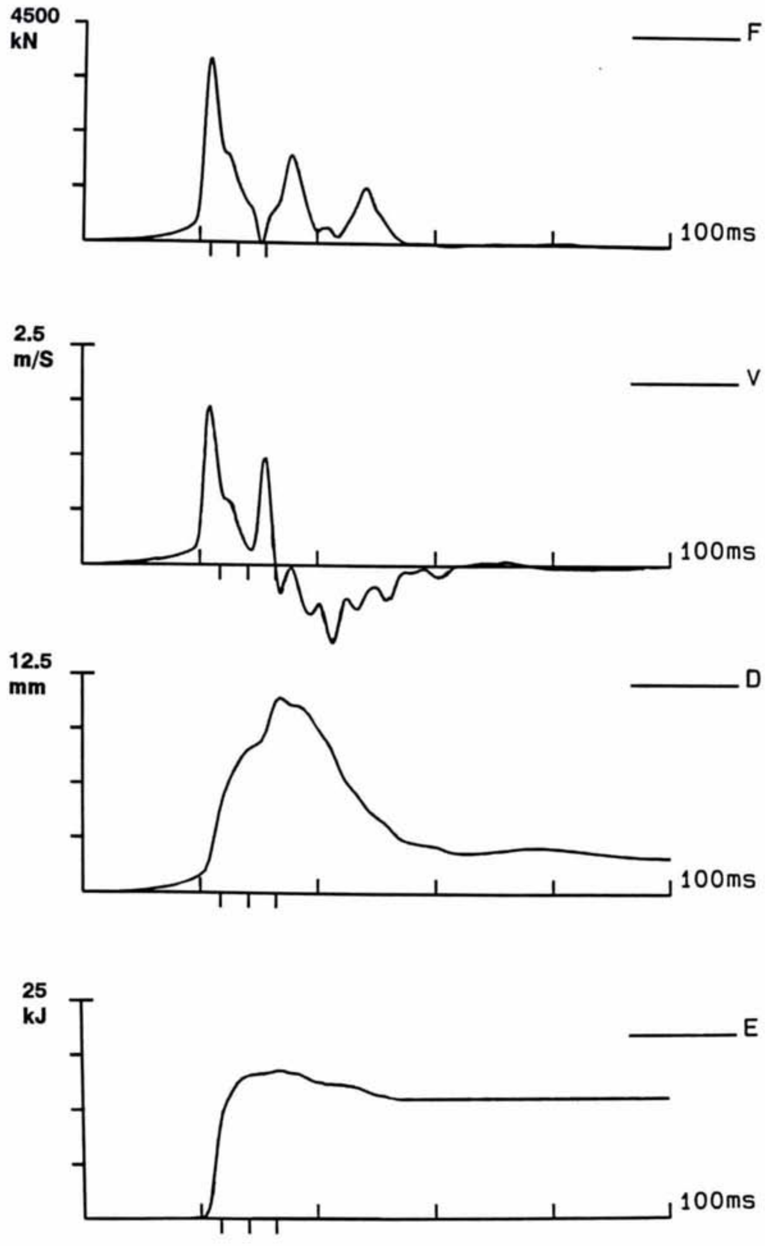


Figure 3: Records of Pile Force, Velocity, Displacement and Energy During a hammer Blow

records for an open end diesel hammer driving a 457 mm square 20 m long prestressed concrete pile.

Testing Applications

The installation process has a definite effect on the performance of a pile foundation. Dynamic pile testing during installation provides valuable information on the behavior of the hammer/driving system, pile and soil for a comprehensive assessment of the installation. The results are available immediately after each hammer blow. If sometimes is noted as less than ideal remedial action can be immediately suggested; correcting "problem situations" as early as possible provides the most benefit to the project. The following presents typical applications of dynamic pile testing.

Hammer/Driving System Performance

Impact pile driving hammers are specialized construction equipment used to install prefabricated piles. They may be operated by internal combustion (i.e., diesel cycle inside the hammer assembly) or external combustion (i.e., air, steam or hydraulic pressure supplied by an outside source); either type may be single or double acting. Single acting hammers rely on gravity alone for the ram down-stroke, while assistance is provided during the downwards ram travel of double acting hammers. For common land projects, hammers with ram weights between 20 and 100 kN and strokes between one and three meters are typically used. Between the hammer and the pile top there are typically the hammer cushion, the helmet or pile cap, and pile top cushion (for concrete piles); other elements (e.g., follower, adaptor, etc.) may also be present. Hammer cushions are generally synthetic materials while pile top cushions are typically sheets of plywood.

To the contractor, hammers are primarily production installation machines, but to the engineer they are "measuring devices". The contractor may want to increase production rate by improving the hammer efficiency. The engineer uses the pile driving resistance (often expressed in number of hammer blows per unit pile penetration) for assessment of pile adequacy; implicitly assuming proper hammer/driving system performance. Thus the hammer has a dual function (i.e., to drive the pile and be the inspection tool for pile acceptance).

Impact pile driving hammers are commonly rated by the manufacturer based on their potential energy (PE) per blow (or equivalent potential energy in the case of double acting hammers), which in the simplest case is taken as the product of ram weight (W) and stroke (H). During the ram drop, potential energy is transformed into kinetic energy (KE). At the instant of impact, this energy is theoretically, $KE = 0.5(mv_i^2)$, where m is the ram mass and v_i the ram velocity at impact. However, due to many factors (e.g., diesel gas pressures, valve timing, mechanical friction, etc.) the energy at impact typically ranges between only 50 and 70% of the potential energy. Other energy losses occur in inelastic collisions, through driving system components, and in non axial displacement. The energy actually reaching the pile head is termed transferred energy. The maximum transferred energy is computed by the PDA from measured force and velocity records ($EMX = \int F(t)V(t)dt$) and is equivalent to the work done on the pile. Figure 4 demonstrates the hammer, driving system and pile with energy transfer concepts. Transferred energy is one of the most important parameters in pile evaluation. Figure 5 presents a summary of results from more than 750 actual field sites relating transferred energy at end of driving to manufacturer's rated hammer potential energy. The mean transfer ratio (ie., EMX/PE) is 35% with a wide dispersion which is a function the hammer efficiency, cushion behavior, soil resistance, and both hammer and pile sizes and types.

Dynamic pile testing provides valuable information regarding the overall hammer/driving system performance which is useful to the contractor to improve production efficiency and to the engineer in accurately assessing actual hammer performance. If blow count alone is used in evaluating pile capacity without accounting for actual transfer energy, results can be grossly in error (Hussein et al., 1993) as suggested by Figure 5. In addition to the PDA there are a number of other electronic devices to evaluate hammer performance (Likins and Rausche, 1988).

Pile Driving Stresses and Structural Integrity

Codes of practice often specify limiting pile stress levels under working loads. Under impact of the pile driving hammer during installation, however, a pile is subjected to a complex combination of compressive, tensile, and flexural forces that may produce much higher stresses than those experienced under service conditions. It may take hundreds or even thousands of hammer blows to drive a pile to the required depth. Unless carefully monitored and controlled, driving stresses in the pile may exceed the pile's material strength and cause structural damage. Dynamic pile monitoring with the PDA provides during installation computed maximum pile compressive and tensile stresses from the measured data for each hammer impact (Goble et al., 1980). It also provides evaluation of pile structural integrity (location and extent of damage) after each hammer blow (Rausche and Goble, 1978).

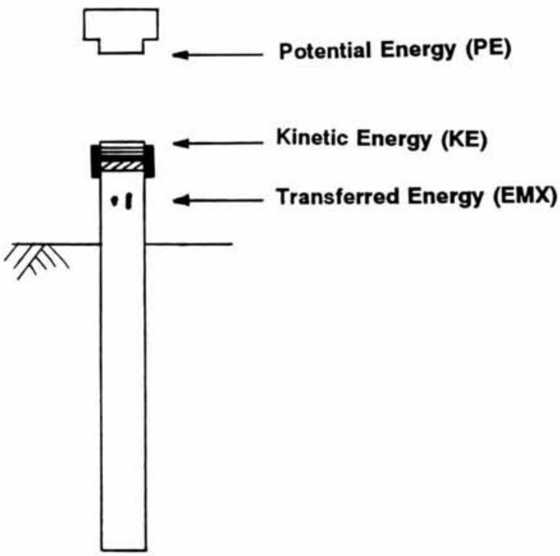


Figure 4: Energy Transfer from Hammer to Pile

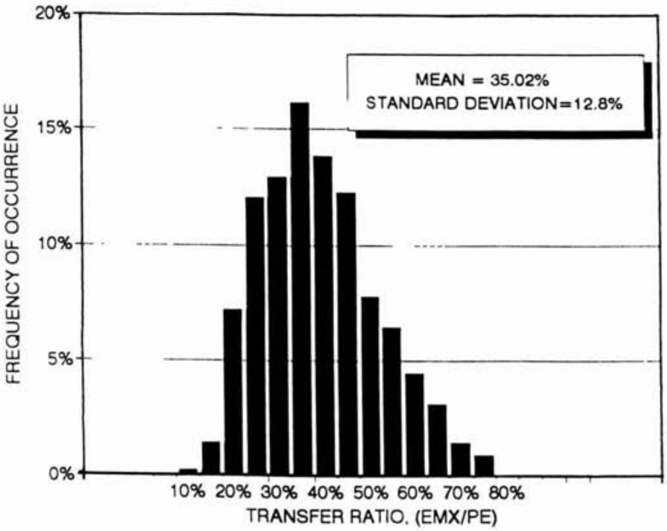


Figure 5: Hammer/Driving System Performance

Figure 6: Damaged Steel H-Pile

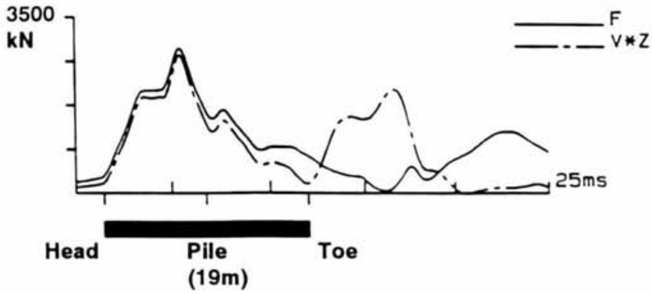
Figure 7: Damaged Prestressed Concrete Pile

After hammer impact, an axial compressive stress wave travels down a steel pile shaft at a speed of 5120 m/s (approximately 4000 m/s in concrete). Additional stresses are generated in the pile due to wave reflections. During easy driving (i.e, at low soil resistance), the incident compression wave is reflected at the pile toe as a tension wave that travels up the pile shaft (a potentially critical situation for concrete piles). There are also special cases where significant tension waves are generated in the pile shaft even under refusal driving conditions (Likins, 1983). In the case of a pile with high end bearing resistance, a compression wave reflection is generated at the pile toe which when superimposed on the incident compression wave can potentially double the compression stress at the toe. Piles are damaged whenever stresses (caused by hammer impact and/or wave reflection combinations and/or local contact stresses) exceed the material's strength. Piles may be damaged at their tops, toes, and/or along their shafts. Figure 6 shows a steel H-pile and Figure 7 a prestressed concrete pile, both damaged during installation. Figure 8 presents dynamic pile top PDA measurements of a prestressed concrete pile (356 mm square) before and after pile damage. Records presented in the top plot include a clear reflection from the pile toe which represents the full pile length (19 m); reflection in the data included in the bottom plot comes earlier than the pile toe indicating a reduced pile length (14 m).

Pile Capacity and Soil Resistance

The driving resistance encountered during installation and the long term service load capacity of the pile are of great interest to both the contractor and engineer. The behavior of the pile dictated by soil resistance under hammer impact loading is characteristically different than that under working loads. The soil resists pile penetration under hammer impacts with dynamic and static forces which are mainly functions of soil type and condition. Under service conditions, the pile's capacity to carry load is derived from static soil frictional resistance forces along the shaft (i.e., skin friction) and under the toe (i.e., end bearing). After installation, the pile's capacity to carry load may change with time due to dissipation of excess pore water pressure developed during pile driving, soil remolding and other factors.

Dynamic pile monitoring during installation provide immediate information on the static pile capacity at the time of driving. It may increase (called setup) or decrease (termed relaxation) depending on the nature of the soil or rock providing resistance. Changes of pile capacity with time can be conveniently evaluated by dynamic pile testing during restrike some time after pile installation.



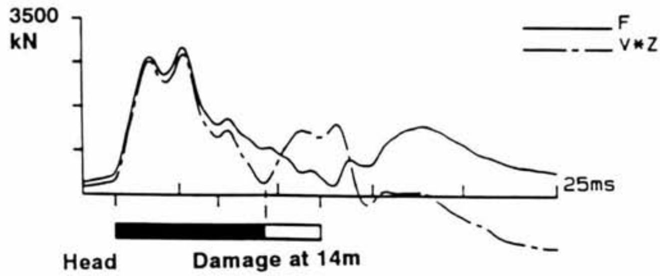
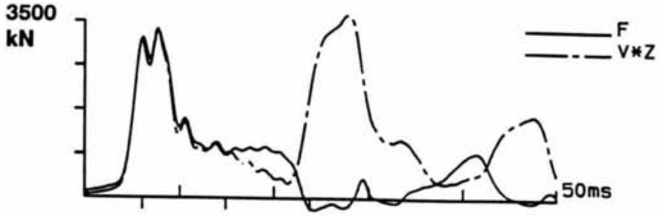
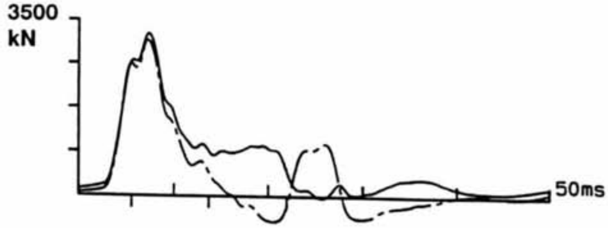


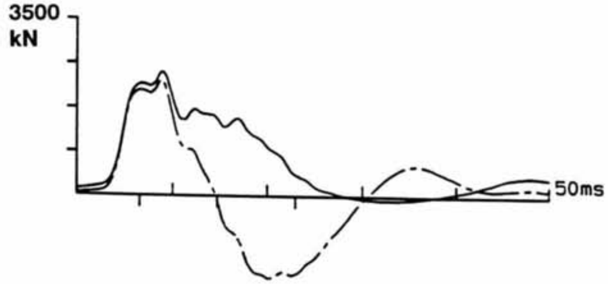
Figure 8: Pile Top Dynamic Records Before Pile Damage (top plot) and After (bottom plot)



End of Initial Driving
Blow Count: 6 blows per foot (50 mm/blow)
Pile Capacity: 580 kN



Restrike After One Day
Blow Count: 34 blows per foot (8.8 mm/blow)
Pile Capacity: 1340 kN



Restrike After 75 Days
Blow Count: 240 blows per foot (1.25 mm/blow)
Pile Capacity: 2670 kN

Figure 9: Pile Top Dynamic Records and Case Method Compute Pile Capacities

Comparisons between PDA predicted static pile capacities from restrike tests and those determined from full scale static loading tests with comparable wait times show excellent agreement (Hussein and Rausche, 1991). Figure 9 presents dynamic pile testing results performed on a prestressed concrete pile (457 mm square, 32 m long) driven into clayey sand with an open ended diesel hammer (rated energy 98 kN-m). Testing results indicate a substantial pile capacity increase with time.

Dynamic pile records obtained by the PDA may be analyzed by the rigorous numeric analysis CAPWAP for a more comprehensive understanding of the soil and pile behavior under hammer impacts and also under static loading conditions (Rausche et al., 1994). The analysis is done in an interactive environment using measured dynamic pile data and wave equation type analysis as a system identification process employing signal matching techniques. Analyses results include: static pile capacity, soil resistance distribution along pile shaft and under toe, soil damping and quake (maximum elastic deformation) values, forces along pile length at ultimate load, and pile head and toe load-movement relationship (i.e., simulated static loading test). Figure 10 presents typical CAPWAP analysis results. For this example, analysis was performed with data from the end of driving of a prestressed concrete pile (457 mm square, 30 m long) driven with a single acting air hammer (rated energy 57 kN-m) into mostly sandy soils.

Summary

Dynamic testing is routinely performed for comprehensive evaluation of hammer-pile-soil systems during pile installations. The Case Method is based on the measurement of pile force and velocity records under hammer impacts and the real time data processing and analysis with dedicated electronic equipment in the field. Testing results include hammer and driving system performance information needed to improve the contractor's production rate and the engineer's confidence in pile evaluation. Pile driving stresses are monitored for each hammer blow so corrective measures can be taken to avoid pile damage. Pile structural integrity is monitored during the whole installation process; in case of damage, information is available on the location and extent of damage along pile length. Static pile capacity is computed during installation; for evaluation of time dependent pile capacity changes, testing is done during pile restrike some time after initial driving. Dynamic pile testing can be conveniently applied to driven piles and other deep foundations. It is significantly faster, less expensive and yields more information than conventional pile static testing.

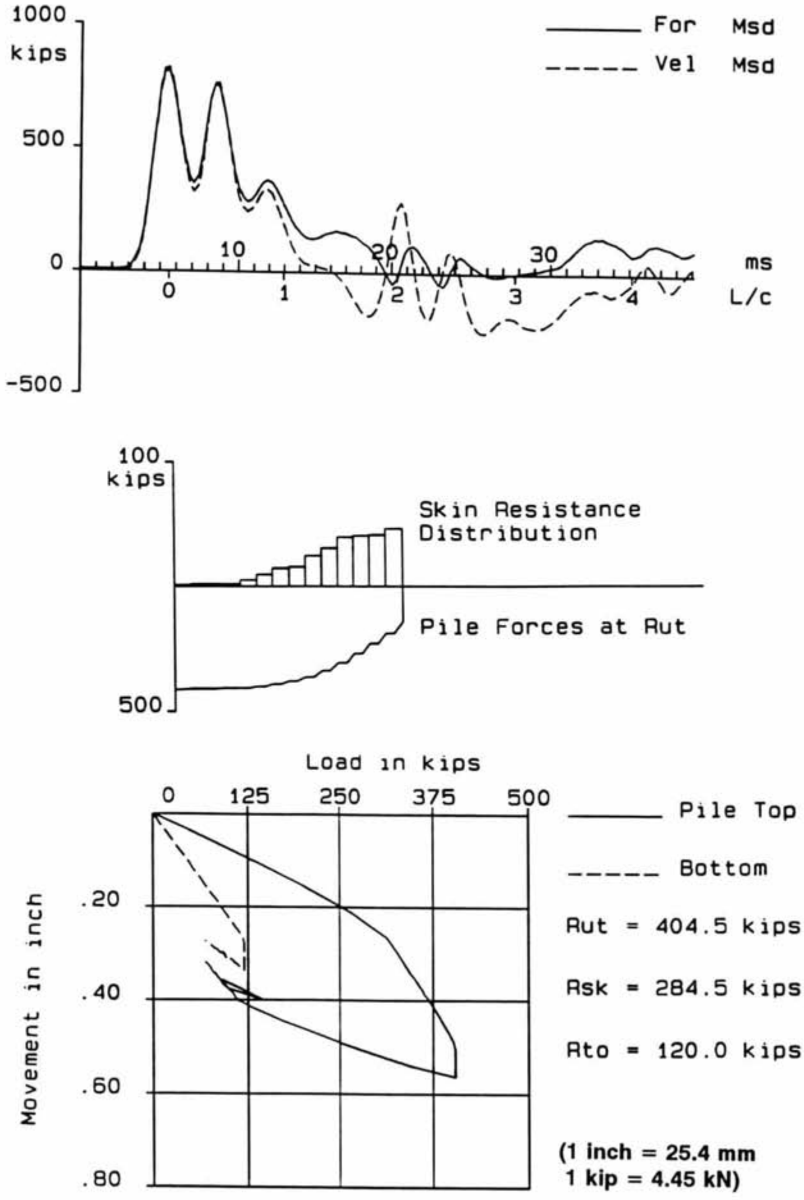


Figure 10: Typical CAPWAP Analysis Plotted Results

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