Pile foundation

Dynamic stress wave analysis for design and construction

BY DAVID E. BECK, P.E.

For thousands of years, mankind has built on marginal sites by transferring loads to stronger, underlying soils or rock formations. Using bearing piles is one of the most efficient means of permitting large foundation loads when unstable site conditions prevent the use of shallow foundations.

Deep foundation design has been evolving for centuries, and a wide variety of piling types and design methods have been presented. Despite their considerable variations, most pile foundations are constructed through one of two basic procedures. One method is the use of "driven" piles, which are structural elements forcefully placed (driven) into the soil. The most common alternative involves removing soil to permit insertion of columnar structural materials. These are often referred to as "drilled," "cast-in-place," "augured," or other descriptive names.

The quantity of piles and installation depths required for a given foundation application depend greatly upon underlying soil properties, since the piling and adjacent soils must work together to develop the required bearing capacities. Figure 1 illustrates how deep pilings support compression loads by bearing directly on rock or other incompressible material, or by using the pile surface/soil friction relationship.

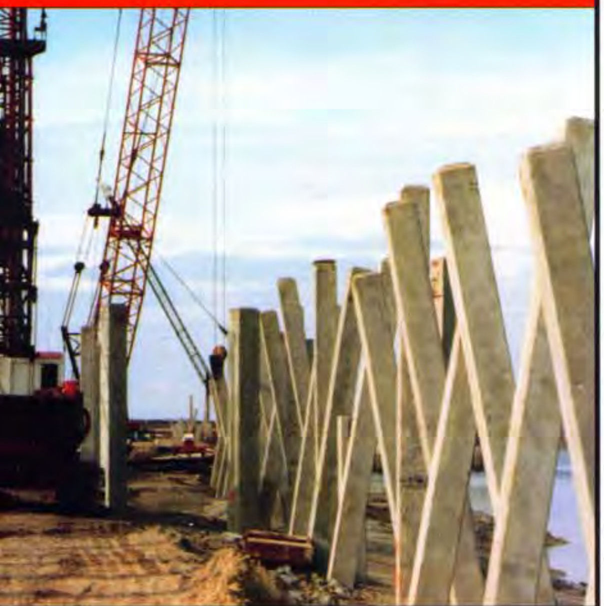
Usually, driven piles are made from steel pipe; steel structural shapes; pre-cast, prestressed, or regularly reinforced concrete; timber poles; or combinations of these materials, as illustrated in Figure 2. For drilled piles, vertical shafts are bored into soil laterally supported by either steel casings or bentonite suspension. Then concrete and reinforcement are placed into the open shafts. Although all pile types serve the same basic functions, the design and installation of driven piles and those types generally categorized as drilled or cast-in-place piles differ in almost every way.

This article is about driven piles and the relatively recent developments for design and testing that impart greater accuracy and quality assurance. First, a brief review of the evolution of driven pile design should help you gain a greater appreciation of the newer technologies.

Stress wave analysis has improved designs, thus lowering material usage and costs.

Soil properties and driving equipment

Deep foundation design should always involve thorough subsurface exploration, from which a competent engineer can recognize the depths and characteristics of the various strata and determine the most suitable types and sizes of piles for the intended project. If a well-defined layer does not exist to support the required end bearing capacity, vertical load resistance mostly results from side friction along the embedded pile surface area. The amount of load transfer from the pile column to adjacent soils via skin



friction depends upon such factors as the soil's internal friction properties, lateral earth pressures, the pile roughness, soil moisture content, and cohesiveness.

The soil disturbance resulting from pile driving may change some of these properties temporarily. When soil side friction is a component, optimum pile bearing capacity may be achieved only after soil re-consolidation occurs.

The simplest pile driving apparatus consists of a manually- or winch-raised falling weight that impacts the pile top, driving it into the soil. A "pile cap" and cushioning materials help ensure that driving energy from the hammer is distributed uniformly to the pile section. Today, most pile driving hammers for large-scale operations are powered partially or completely by steam, compressed air, hydraulic fluid, or diesel fuel. One type of pile driver, called a single-acting hammer, has a driving ram that is lifted by auxiliary power and then dropped on the pile. Double-acting pile driving hammers have driving rams that are propelled both upward and downward by the auxiliary power.

Double-acting hammers improve production rates by delivering blows more rapidly, although they are more complex to operate and maintain. The various single- and double-acting pile driving hammers have ram weights ranging from 1,000 pounds to 400,000 pounds. They can deliver 30 to 130 blows per minute and can impart 15,000 to over 1.5 million foot-pounds of energy per blow. Other, less widely used methods for installing piles involve such driving aids as vibratory equipment, water jetting, hydraulic jacking, and pre-boring.

Predicting pile capacities

Many mathematical procedures for predicting the load-carrying ability of driven piles have been devised over the past two centuries. Ranging between relatively simple and complex, these often are in the form of a single equation and are either static analyses based on soil mechanics or relate driving energies to load bearing capacities. Those formulas involving the principles of soil mechanics are termed "static." The alternative formulas involving driving energies and corresponding pile set (vertical movement) per blow are labeled "dynamic" formulas.

For foundation piles installed by driving hammers, predicting load capabilities using dynamic formulas was once considered the simplest and most reasonable approach. In most cases, these formulas relate energy expended during driving and pile penetration per hammer blow to calculate the optimum load bearing capacity. For simple drop hammers, driving energy was merely the product of ram weight multiplied by drop height. Driving resistance was determined by observing the number of hammer blows required for a selected amount of penetration, known as "blow count." The most popular dynamic formulas involved only these fundamental parameters.

A close-up of steel pipe pile and the cab of crane for pile driving equipment.

The outcome of a pile driving operation, however, is influenced by a substantial number of factors such as the condition of adjacent soils, pile material, type and condition of cushions, and hammer performance. Some early dynamic impact formulas included allowances for pile and soil elasticity, energy losses at cushions, and other circumstances that affect the conversion of driving energy to bearing capaci-

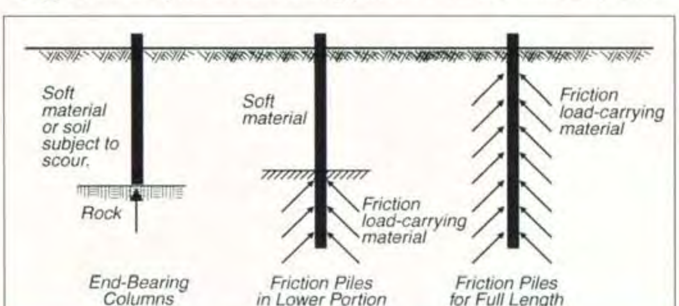


FIG. 1 **The load transfer functions of different types of bearing piles are shown above.**

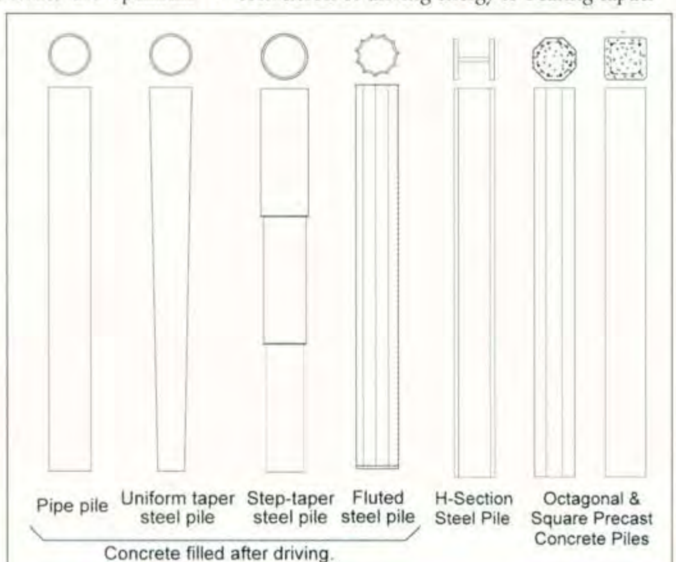


FIG. 2 **This figure illustrates various types of common bearing piles.**

ty. Many of the more inclusive, but relatively complex, formulas were used in other countries. However, engineers in the United States often preferred condensed versions that attempted to replace most variable units with a single, empirically derived numerical constant. The Engineering News formula is one such simplification; it has been used extensively in this country for many decades.

First introduced in 1888, the Engineering News formula evolved from studies of one type of drop hammer apparatus and the installation of timber piles. The equation has one numeric constant (1.0 for drop hammers) that was intended to represent all factors other than driving energy and pile set involved in the driving operation. Theoretically, it provided a safety of factor of six on ultimate bearing capacity. The formula's developer later modified the numeric constant for steam hammers (see Figure 3).

Dynamic formulas are reasonably accurate if the hammer and pile material are the same as those used when the formula was developed originally. But this method of analysis is less

ENGINEERING NEWS PILE DRIVING FORMULAS

For Drop Hammers	$R = \frac{2W_rH}{(s+1.0)}$
For Single and Double Acting Steam Hammers	$R = \frac{2W_rH}{(s+0.1)}$

In which:
R = Service load of driven pile (tons).
W_r = Striking weight of hammer (tons).
H = Fall height of striking part (feet).
s = Net displacement of pile upon impact (inches).

Fig. 3 **Estimating ultimate bearing capacity of driven piles.**

reliable when different soil conditions, driving equipment, and pile materials are used. Test loads conducted to compare predicted and actual pile bearing capacities for installations with conditions different than the original revealed that actual safety factors varied widely, representing an intolerable level of unpredictability.

Robert D. Chellis, a structural engineer with Stone & Webster Engineering Corporation, based in Weston, Mass., observed the errors with dynamic formulas. In his 1951 book, "Pile Foundations," he wrote: "Dynamic pile driving theories are based on assuming an instant propagation of force through the pile, whereas the force actually travels as a wave. The amount of side friction and the proportion of plastic to elastic yield in the soil have a great effect on these force waves [within the pile]."

A brief explanation of how driving operations produce force waves within a pile system follows:

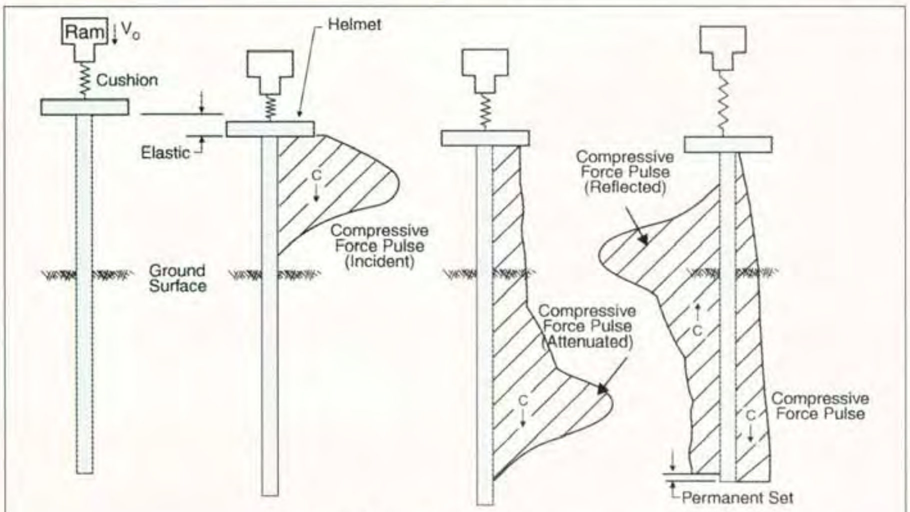
1) Ram impact instantaneously compresses the pile top, generating compressive forces within the upper portion of the pile.

2) The force is transmitted downward, progressively putting sections of the pile in motion and creating compressive stresses within the pile. The damping and frictional properties of the surrounding soil influence the rate and intensity of force propagation.

3) Upon reaching the bottom, the force wave is reflected upward within the pile system. Depending upon the magnitude of soil resistances along the pile shaft and bottom (toe), the reflected pulse generates tensile or compressive forces within sections of the pile.

4) When continuous hammer blows produce insignificant additional movement at the pile toe because of soil resistance, usually a sufficient amount of load carrying capacity has been achieved.

When continuous hammering produces insignificant movement at the pile toe, the load carrying capacity has been achieved.



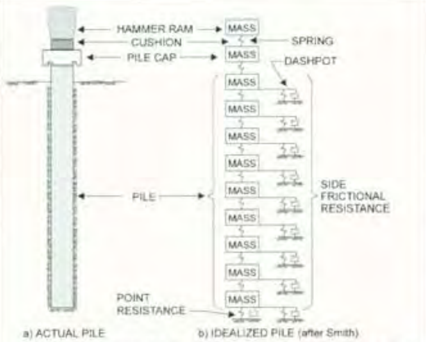
Source: FHWA Design and Construction of Driven Pile Foundations Manual

Fig. 4 **Wave propagation in a pile is shown.**

Designing with stress waves

Chellis was not the first to discuss pile driving in terms of stress waves. According to geotechnical consultant David Rempe, P.E., based in Champaign, Ill., "During the 1930s, investigators identified the role of wave action in foundation pile driving and developed mathematical models for simulating simplified combined pile-soil conditions, providing the basis of modern wave equation analysis. Unfortunately, their simplistic solutions were of limited practical value because they did not realistically simulate the elastic/plastic response of the soil, [the] dissipation of driving energies, and the relationship between driving forces and bearing capacity. More realistic solutions would have required massive calculations that, in the absence of high-speed computers, were not feasible. In short, at that time the concepts were in place but the computational tools were not."

Several major developments occurred in the mid-1950s to advance the application of this



From M.T. Davisson, "Pile Load Capacity", August 1975

Fig. 5 **Pile model diagram for wave equation showing mass, spring, and dashpot segments.**

relatively newfound knowledge. During this time, E.A.L. Smith of Raymond International, an engineering and construction services company based in Santa Fe Springs, Calif., devised an innovative numerical procedure simulating stress wave propagation in driven piles. The coincidental emergence of electronic computing power, which is capable of performing numerous calculations efficiently, provided the first opportunity to design and analyze driven pile foundations.

Frank Rausche, Ph.D., P.E., of GRL and Associates, Inc., a geotechnical consulting firm based in Cleveland, said: "Smith's efforts initiated the modern era of pile foundation design. His algorithms and analytical procedures, while initially developed to solve stress-related problems in non-uniform shaped piles, allowed accurate predictions of driving stresses within the pile and the pile set for each hammer blow. The resulting Wave Equation, which is actually a long series of equations, was quickly embraced by pile driving professionals because of its value for selecting equipment and driving procedures to optimize productivity, reduce pile damage during driving, and more accurately predict pile behavior. The Wave Equation has since become the predominant model and is one of several stress wave-based analytical tools used for pile design and installation."

Modeling with the wave equation

Wave Equation analysis is fundamentally a modeling technique that cleverly combines elements of soil engineering, physics, mechanics, and vibration analysis.

The driving hammer, helmet (or cap), and pile are considered separate segments connected by springs. Every pile segment is characterized by its mass and spring stiffness, the latter related to the modulus of elasticity of its material. The ram and other components, such as cushions, are characterized similarly and also include coefficients of restitution, which account for rebound and energy losses.

Soil resistance occurring along the embedded portion of the pile and at the pile toe is also elastically modeled, although additional considerations are needed because of its damping properties and plastic behavior (quake). Soil segments adjacent to the pile are simulated mathematically as combinations of spring (representing elasticity), friction blocks (representing plasticity), and dashpots (representing motion damping). Many of the values that identify the properties of the soil, pile, hammer, and cushions require user input.

A Wave Equation analysis predicts the compression or extension of each pile segment and determines stresses within individual segments resulting from hammer impacts and subsequent force waves. Simultaneously, it predicts the damping effect of soils along the embedded pile length. For individual pile segments,

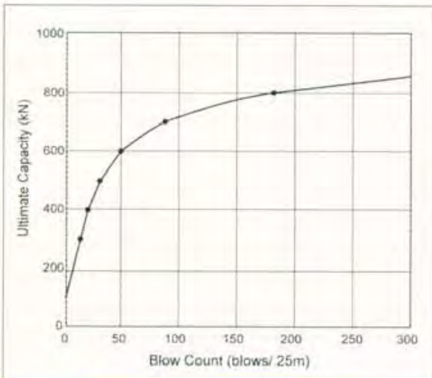
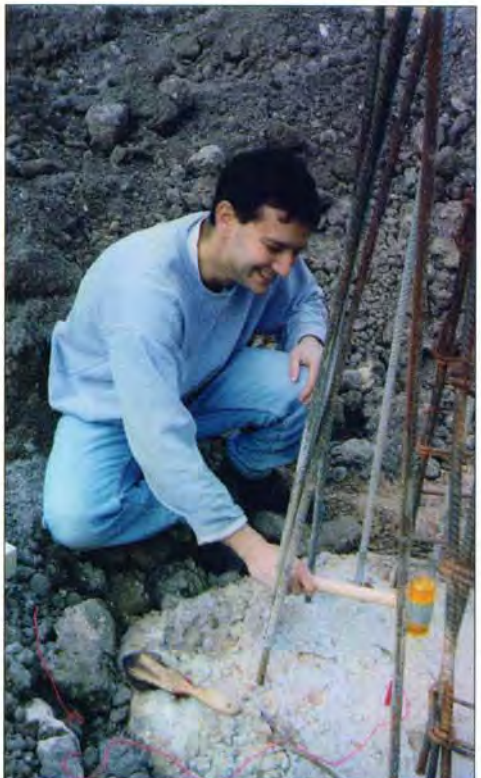


Fig. 6 **Typical graphical wave equation output showing bearing capacity versus blow count.**

the model also calculates accelerations, velocities, displacements, and driving resistance. By continuing the analysis over a range of bearing capacities, a "bearing graph" can be plotted showing different capacities and corresponding driving resistances (blow counts) for the system being analyzed (Figure 6). Other output information shows maximum compressive and tensile stresses as a function of blow count, thereby facilitating pile design to withstand driving forces.



A technician strikes the cast-in-place concrete pile with a light hammer (above). The data from the resulting incident and reflected force wave is recorded in the Pile Integrity Tester recorder (below).

Stress wave technologies for quality assurance

Development of the Wave Equation as an analytical tool opened the door to unprecedented advancements for designing and constructing deep pile foundations. Today, most people usually design pile foundation systems using stress wave-based systems and the numerical model developed by Smith, with speed and accuracy being the primary benefits.

A complete analysis to determine everything from the hammer performance to pile capacity can be completed in a matter of hours. In conjunction with static and dynamic quality control tests on driven piles, the application of stress wave analysis has resulted in lower allowable design safety factors — in the range of 2.0 to 3.0 — that result in more efficient material usage and improved economics.

These safety factor reductions require that quality control measurements be taken either during or after pile installation on either special test piles or on sample production piles. According to Rausche, the most commonly used dynamic pile testing methods include the following:

- dynamic pile monitoring during installation of impact driven piles,
- dynamic pile load testing for driven piles, as well as drilled shaft piles,
- pulse echo and transient response integrity tests, and
- cross-hole sonic logging for drilled shaft piles.

The importance of these procedures relates to the inherent uncertainties associated with all types of deep pile foundations. Even though not all of these technologies evaluate impact driven piles, they are described below because of their close relationship with stress wave methodologies.

Dynamic pile monitoring involves attaching accelerometers and strain transducers near the top of the pile being monitored. The sensors measure force and velocity as the pile is driven into the ground. Data is fed directly to an onsite computer, such as Pile Dynamic, Inc.'s Pile Driving Analyzer®.

The system's software measures soil resistance, calculates tensile and compressive stresses within the pile, and determines the hammer energy being transferred to the pile as well as blows per minute. The information is developed in real time between hammer blows for immediate comparison with predictions from wave equation analyses.

A large hammer strikes a driven pile while conducting dynamic pile monitoring.

Pile foundations can be analyzed with dynamic pile load testing even when they are not being driven. Previously driven concrete-filled piles and concrete-filled drilled shaft pilings are typical examples. The dynamic load test involves electronic sensors attached to the pile and computer equipment similar to that described above. The finished pile is impacted with a large drop hammer and subsequent analysis of the incident and reflected force wave yields information about bearing capacity, load distribution, soil stiffness, and damping factors.

Pulse echo and transient response integrity tests are used to assess pile integrity and/or pile

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length, but not bearing capacities. Primarily applicable to concrete piles, either drilled or driven, these test methods are also suitable for timber piles.

These tests require only a small-impact hammer, sensitive accelerometer, specialized data recorder, and an output device. A hammer blow to the top of the installed pile creates impact waves whose velocity and length is recorded. Imperfections in the pile are revealed when the wave is reflected upward prematurely. The location and size of an imperfection can be estimated by the wave reflection.

Cross-hole sonic analysis is used to determine the quality of poured concrete piles, slurry walls, and other types of concrete foundations. As the pile is constructed, small tubes are placed to permit insertion of sonic transmission and reception sensors. As shown in Figure 7, a transmitter (T) lowered into one tube sends a signal that is sensed by a receiver (R) in another tube. As the sensors are lowered, the time required for the signal to travel from transmitter to receiver and the signal energy are measured. The data, when analyzed by specialized, onsite computer software, reveals the presence and extent of defects such as cracks, contamination, and voids.

Deep foundations of the future

The design and construction of deep foundations continues to be a growing segment of civil and geotechnical engineering. Developments have permitted engineers to design confidently for higher allowable loads than were acceptable only a few decades ago.

However, major international associations and organizations serving the deep foundation industry are continuing efforts to improve most areas of design, analysis, and onsite testing. The growing international scope of these efforts is especially noteworthy. Stress wave design and testing procedures have become the standard in several Asian and European countries, Australia, Brazil, and the United States.

These various analytical tools and procedures are being developed further for improved reliability and ease of use. For example, data from dynamic pile monitoring and load tests can now be transmitted in real time to engineering offices via wireless telephone for timely and more cost-efficient engineering review.

The ultimate goal of all these efforts is to achieve the most economical use of materials and labor while assuring long-term performance of driven pile foundations. ■

Figure 7: A schematic drawing of cross-hole sonic analysis.

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A letter to the author in the next issue of CE News

Predicting pile capacity

I read David Beck's article, "Pile foundations: Dynamic stress wave analysis for design and construction," (Page 42 of the October issue) with avid interest. While in Urbana, Ill.,

as a graduate student, I became familiar with the work of R.D. Chellis and his form of the Hiley equation.

Predicting the pile capacity by analyzing the pile-hammer-soil behavior during the deep foundation design stage is a necessity. However, I must agree with J.E. Bowles when he says: "The best means for predicting pile capacity by dynamic means consists on driving a pile, recording the driving history, and load testing the pile." It would be reasonable to assume that the other piles at the site with a similar driving history would develop the same load capacity.

Emilio M. D'Arce, P.E.
Cincinnati

Response from David E. Beck, P.E.:

Thanks for your comments. While I agree that a site-specific load test program has traditionally been the best way of checking actual versus theoretical (from dynamic formulas) load carrying capacities of driven piles, conducting the load test is time-consuming and creates an added expense. One long-term objective of stress wave analysis is to reduce the need for load tests. Skilled professionals indicate that this can be accomplished by using a pile driving analyzer to monitor reactions as the pile is being driven and comparing the results with predictions from the wave equation analysis. Additionally, stress wave analysis is the best predictor of material stresses in the pile itself resulting from driving forces and the corresponding soil reaction. Knowing this allows engineers and contractors to select the most cost-efficient pile material.

Stress wave analysis, with its several decades of history, is still somewhat in its development stages. However, a considerable amount of supporting data has been accumulated that indicates that this is a valuable design and construction tool when correctly applied.