STATIC PILE CAPACITY BY DYNAMIC METHODS

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ABSTRACT

Determination of static pile capacity is of prime interest to geotechnical and structural engineers, as well as those responsible for the pile installation. Dynamic evaluation methods for determining axial static bearing capacity are becoming standard practice in foundation engineering and construction. These methods range from purely analytical to field monitoring, and are based on one dimensional wave propagation principles. Wave equation computer programs are instrumental in assessing the drivability of a pile before construction, or in investigating its static bearing capacity during, or after installation. The Case Method requires the measurement of pile force and velocity histories during a hammer blow, and computes pile static capacity and other important installation parameters. The Pile Driving Analyzer is a special purpose field computer utilized for data acquisition and real time Case Method computations. Techniques are also available (CAPWAP) that take advantage of field dynamic measurements and wave equation type analysis for directly determining static pile capacity and soil resistance distribution, both along the shaft and under the pile toe. This paper discusses the principles, applications, limitations, and the performance of these dynamic methods in predicting static pile capacity. Case histories are presented for comparisons of results with values determined from full-scale static loading tests.

1. INTRODUCTION

Pile driving is one of the oldest construction activities, and perhaps one that has changed the least through the ages. Dynamics of bodies in motion were utilized by early pile drivers centuries before their principles were recognized or understood. It is logical that if more effort is required to advance a pile into the ground, then the pile should also support more load. It was not until the end of the 19th century, however, that quantitative assessments of pile load bearing capability were seriously attempted. In 1893, A.M. Wellington published an article in the Engineering News Record (ENR) magazine proposing a formula for computing pile capacity based on Newtonian physics of rigid body impacts and certain energy considerations (1). Since then, the original ENR formula has had many modifications and other researchers have proposed other formulae, resulting now in hundreds of different formulae to evaluate capacity. In

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reality, if any of these dynamic formulae consistently provided a reliable solution then only a single formula would be sufficient; this multiplicity of equations is therefore a stirring condemnation of the basic approach. Actually, Newton himself had warned against the application of his theory of impact to the problem of pile driving (2). The causes of the shortcomings in this approach are rooted in its simplicity: incomplete, crude, and oversimplified modeling of all components involved. Studies show that such formulae yield actual safety factors as low as 0.5 and as high as 16 or more when compared to actual static loading tests (3). This unpredictable performance is unacceptable causing most engineers to disregard these simple dynamic formulae and employ modern methods of capacity verification.

Early in this century, it was recognized that pile driving was better modeled by wave propagation than by idealized rigid body impacts. Mathematical closed form solutions for special cases were developed, but general purpose solutions were not easily obtained due to the complexity of the problem. In the 1950s, the availability of digital computers made a discrete solution of elastic one dimensional wave propagation possible and computer programs were written (4). This solution to pile driving analysis became known as the "wave equation." The method realistically models the hammer, pile, and soil with a high degree of accuracy; however, the results are basically applied in the same manner as the earlier energy formula result.

2. WAVE EQUATION ANALYSIS

As it relates to deep foundations, the term "wave equation" is a name applied to a numerical procedure by which impact pile driving is simulated and analyzed according to one dimensional wave propagation theories. Each component of the pile driving system that generates, transmits, or dissipates energy is modeled as a mass, spring, and/or dashpot. In the 1950s, E.A.L. Smith developed an algorithm and later a computer program code (believed to be the first non-military application of electronic computation in engineering) that made this approach of pile driving analysis practical (4). Smith's contribution included: a pile model that incorporates its geometry and mechanical properties, a soil model including a static elasto-plastic and a dynamic viscous component, a model for relatively simple hammers, a computational procedure which yielded a relationship between both pile static capacity and driving stresses and pile set per hammer blow, and recommendations for all model parameters. A typical wave equation representation of a pile driving system is shown in Figure 1. Detailed discussions on component modeling may be found in the literature (5). After Smith, several researchers compared bearing capacity predictions with static loading test results and confirmed the validity of the basic approach. Later work resulted in more refinement to the basic model to include thermodynamics of diesel hammers, residual stress analysis, and comparisons with actual field dynamic measurements. Starting in 1974, the United States

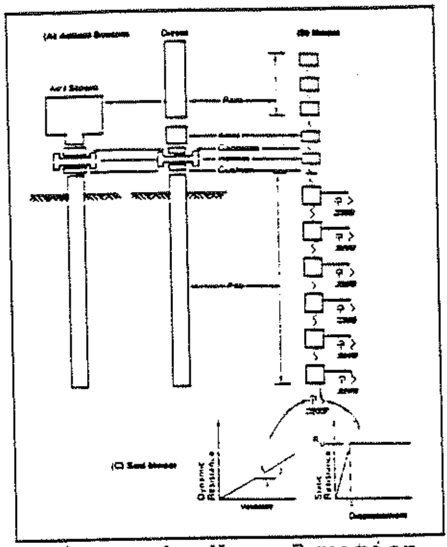


Figure 1: Wave Equation Analysis Model

Federal Highway Administration (FHwA) sponsored the development of practical wave equation computer programs that incorporate these research findings. Today, the most widely used program GRLWEAP (the most recent version of the FHwA sponsored program WEAP - Wave Equation Analysis of Piles) is executed on personal computers. The accuracy of WEAP computed results including pile static capacity and driving stresses as a function of driving resistance had been reported to be within 20% of actual field measured values (6) for normally functioning hammers.

The following is a general summary of the different parameters needed for the execution of a wave equation analysis, with emphasis on WEAP:

HAMMER:	model and efficiency
CUSHIONS:	(HAMMER AND PILE) area, thickness, elastic modulus, and coefficient of restitution
PILE CAP:	weight
PILE:	area, elastic modulus, and density (all as a function of pile length)
SOIL:	static capacity, percent skin friction and its distribution, quakes and dampings both along the shaft and at the toe

Modern programs such as GRLWEAP include files containing numerous hammer models and other input parameters which simplify data input, allowing the engineer to concentrate on data interpretation rather than making numerous calculations which could lead to mathematical error.

In practice, wave equation analysis may be instrumental in dealing with the following situations: (a) given a description of the hammer, pile, and soil; can the pile be safely driven to the required capacity? (b) What is the static capacity of a pile given pile driving or restriking blow count? An analysis to answer the first question is known as a drivability study in which pile driving stresses and blow counts are computed. Calculated stresses in the pile should remain safely below compressive and tensile strength of the pile material. The blow count calculated for the required pile capacity should be reasonable to be economical. In the second situation, wave equation analysis is used as a method to evaluate the static bearing capacity of the pile given the field observed driving resistance. This aspect of wave equation analysis usage is further illustrated in Example 1 below.

A precast prestressed concrete pile 60x60 cm square (area = 3600 cm^2), 9.5 m in length was driven with a Delmag D46-02 open ended diesel hammer, through silty clayey sand into soft limerock to a final penetration of 9.4 m and a driving resistance of 9 blows per 25 mm (355 bl/m). One week after installation, the pile was restruck with the same hammer, but with a higher fuel pump setting (i.e., 27% higher hammer energy), and the restrike blow count was 6 blows per 25 mm (240 bl/m). A wave equation analysis simulating restrike conditions was performed to evaluate the pile's static capacity. The summary of input parameters and analysis results presented in Figure 2 (in a so-called "bearing graph" relating pile stresses and static capacity to driving resistance) shows that at the observed blow count of 240 bl/m, the computed pile capacity is 2600 kN. By comparison, a static loading test performed within two days of the restrike indicated a pile capacity of 2400 kN. Similar correlations for other case histories have been reported in the literature.

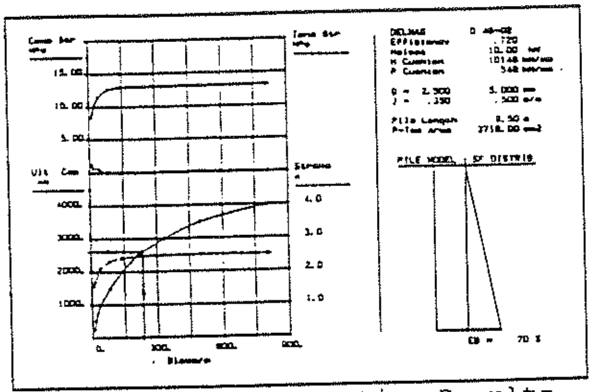


Figure 2: Wave Equation Results
Example 1

It is no surprise that the validity of the results is highly dependent on the accuracy of assumed input parameters which are not easily deduced from simple visual field inspection procedures. Field dynamic measurements utilizing modern electronics to confirm actual hammer performance and data analysis of the pile and soil response to impact transformed the analysis of pile driving from an art to a science. Today, these methods enjoy widespread acceptance and have become routine practice for many private consultants, contractors, and governmental agencies (e.g., federal and state highway departments, corps of engineers, etc.) and hence standards have been developed by several specifying agencies (e.g., ASTM, ICE, etc.) in many countries.

3. CASE METHOD

Beginning in 1964, research conducted at Case Western Reserve University in Cleveland, Ohio developed a method to predict static pile bearing capacity from electronic measurements taken during pile driving, or restriking. The research project went through several stages of development along two lines: (a) improving the electronic equipment required for data acquisition, and (b) refining the theoretical basis of capacity prediction. The resulting procedures are referred to as the "Case Method". The Case Method closed form solutions require the measurement of force and velocity during a hammer blow by using a "Pile Driving Analyzer" (PDA) along with specially designed strain transducers and accelerometers. Using wave propagation theories and assuming a uniform elastic pile, the PDA applies the Case Method for determining some 40 dynamic variables in real time after each hammer blow. The most interesting of these quantities are: Case Method axial pile capacity, maximum energy delivered to the pile, maximum compressive and tensile pile driving stresses, and inspection for location and extent of pile damage. Further detailed discussions of each of these quantities are available in the literature (7).

For a uniform pile with impedance $Z=EA/c$ (where E is Young's modulus, A is cross-sectional area, and c is the stress wave speed which is dependent on E and mass density), the measured force $Fj(t)$ at time t and location j, and the measured velocity $vj(t)$ may be used to calculate upward traveling wave

$$Wuj(t) = [Fj(t) - Zvj(t)]/2 \qquad (1)$$

and the downward traveling wave

$$Wdj(t) = [Fj(t) + Zvj(t)]/2 \qquad (2)$$

If a passive soil resisting force, Rx, appears at time $t = x/c$ at some location, x, along pile shaft (caused by an impact at time $t = 0$ at the pile head), then two waves are created each having a magnitude half of Rx. To satisfy equilibrium and continuity conditions, the upward wave is in compression and will reach the pile head at time $t = 2x/c$; and the downward wave is in tension and will reach the pile toe at time $t = (L-x)/2$, where L is pile length, reflects upward in compression and reaches the pile head at time $t = L/c$. If a resistance force, Rb, is generated at the pile bottom at time $t = L/c$, then a compressive wave of magnitude, Rb, will travel up the pile reaching the pile head at time $t = 2L/c$. If all resistance forces are constant throughout the first pass of the impact wave, then at time $2L/c$ it can be shown (8) that the total resistance

$$R = (F1 + Zv1 + F2 - Zv2)/2 \qquad (3)$$

where 1 and 2 refer to times $t1$ and $t2$ $(= t1 + 2l/c)$.

R is the total resistance encountered during the passage of the wave during time period $2L/c$. Various considerations are necessary to obtain the pile static capacity Rs: (a) elimination of soil damping, (b) proper choice of time $t1$, (c) time dependent soil strength changes, and (d) the pile must have sufficient penetration under each impact to overcome the soil elastic deformation. Consideration (c) contains soil mechanics aspects and does not affect the Case Method computations. Since the capacity computed reflects the capacity at the time of testing, testing the pile during a restrike after an appropriate wait period allows pore pressures due to pile driving to dissipate and soil strength gains, commonly called "set-up", to be properly considered. Consideration (d) is needed to assure that the full ultimate resistance value is computed and not just a lower bound mobilized capacity.

Damping is associated with velocity. We can calculate pile bottom velocity from top measurements as:

$$vb(t) = (F1 + Zv1 - R)/Z. \tag{4}$$

By definition the Case Method damping force is $Rd = Z(Jc)vb$ where Jc is the dimensionless Case Damping constant. The total resistance is the sum of the static and damping forces

$$R(t) = [Rs(t) + Rd(t)] \tag{5}$$

thus the static resistance is

$$Rs = R - (Jc)(F1 + Zv1 - R) \tag{6}$$

or expanding into terms of only F and v

$$Rs = (1 - Jc)(F1 + Zv1)/2 + (1 + JC)(F2 - Zv2)/2 \tag{7}$$

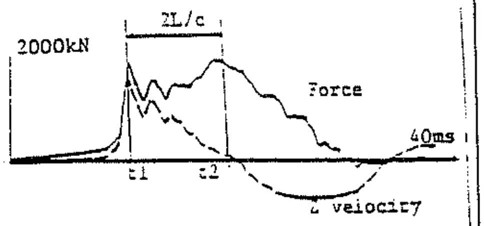
The damping appears to be related to the soil grain size and its behavior under dynamic loading and the damping constant JC may be computed if the ultimate static capacity from a static loading test is known. Alternatively, the following values were empirically compiled for various soil types: clean sands 0.10 to 0.15, silty sands 0.15 to 0.25, silts 0.25 to 0.40, silty clays 0.40 to 0.70, and 0.70 to 1.00 for clays.

Time, t1, is normally chosen as the first relative velocity peak, it should be delayed to account for conditions of soils with low stiffness (i.e, large quake). This can be automatically investigated by varying t1 through the whole impact and searching for the maximum result. Early skin friction unloading on piles with longer lengths in high skin friction soils can be compensated by calculating the amount of unloading. For piles with very little or no skin friction, an exact solution for static resistance may be obtained which is independent of damping assumptions by finding the capacity at the time vb is zero. Recent advances also allow computation of capacity for piles with moderate friction which also do not require selection of a damping constant.

The PDA is a user friendly field computer and data acquisition system that provides power supply and signal conditioning for the transducers. It applies Case Method solutions to the measured data to calculate capacity, hammer performance, driving stresses, and integrity. Required PDA inputs include pile length, area, elastic modulus, and wave speed, in addition to specific calibration factors for two strain transducers and two accelerometers.

The following example illustrates the data provided by the PDA and its Case Method interpretation to compute pile static capacity, and a comparison with a full static loading test.

A steel H-pile (length of 23 m and area of 100 cm^2) was driven with an ICE 640 double acting diesel hammer to a depth of 22 m and a driving resistance of 8 blows per 25 mm (315 blows per m) and restruck a few days later encountering a resistance of 16 blows per mm (630 blows per m). Subsurface conditions at the site were described as loose to firm alluvial silts and residual soils overlaying partially weathered rock. Dynamic data of pile top force and velocity (times impedance) for a restrike blow are plotted in Figure 3. The computed Case Method static pile capacity was 2246 kN, assuming a Case damping factor Jc = 0.4. By comparison, the static loading test (see Figure 4) indicated an ultimate capacity of 2150 kN according to Davisson's failure criterion. Similar correlations have been reported in the literature (9).



F1=F(t1)=1800 kN
F2=F(t2)=F(t1+2L/c)=1867 kN
v1=Zv(t1)=1467 kN
v2=Zv(t2)=Zv(t1+2L/c)=58 kN
J=0.4
R,static=(1-J)(F1+v1)/2 + (1+J)(F2-v2)/2
=(1-0.4)(1800+1467)/2 +
(1+0.4)(1867-58)/2
=2246 kN

Figure 3: Case Method Computations; Example 2

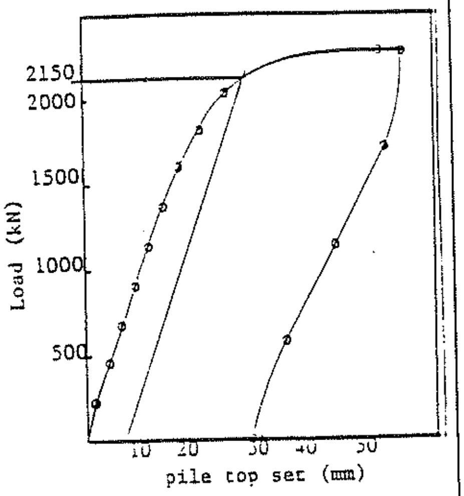


Figure 4: Static Load Test Results; Example 2

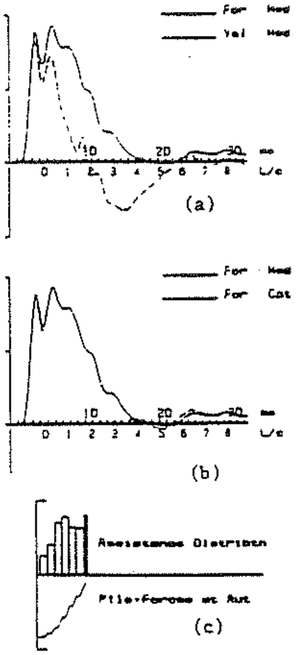
4. CAPWAP Method

The CAse Pile Wave Analysis Program (CAPWAP) is a rigorous analytical procedure (developed in the late 1960s by the same researchers at Case Western Reserve University) to compute soil resistance forces and their distribution, along with quake and damping parameters from measured pile top force and velocity histories during a hammer blow (10). The analysis is usually performed interactively by the engineer using a personal computer, although the program in its expert system mode can also obtain solutions "automatically". Early CAPWAP versions used spring-mass discrete elements and numerical procedures which were very similar to wave equation techniques. The current CAPWAPC version now models the pile by a continuous wave transmission model. The soil reaction forces are passive and are modeled as a function of pile motion (displacement, velocity, and acceleration). The soil reaction primarily consists of static (elasto-plastic) and dynamic (linear damping) components. In this way, the soil model has at each point three unknowns: elasticity, plasticity, and viscosity.

To perform the analysis, a complete set of wave equation type constants is assumed. Then in a dynamic analysis with the hammer model replaced by the measured pile top velocity, CAPWAPC calculates the force necessary to induce the imposed velocity. The measured and calculated forces are compared; if they do not agree, the soil model is adjusted and the analysis repeated. This iterative procedure is repeated until no further improvement between the measured and computed forces can be obtained. Plotted results from a CAPWAPC analysis include: measured pile top force and velocity records, comparisons of measured and calculated force match, soil resistance distribution as a function of pile length, and pile forces at ultimate capacity. Numerically, for each segment of the pile, ultimate static soil resistance (and unit friction and bearing values) soil quake and damping factors are tabulated. Because they are calculated during the analysis, forces, velocities, displacements, and energies may be printed or plotted for each pile segment.

After a CAPWAPC analysis has been performed, the complete pile and soil model is subjected to a static analysis by incrementally loading the pile and computing the resulting element penetrations and associated static resistance values. The final result of this analysis is the applied pile top and toe force and movement. This analysis is analogous to a static loading test and is therefore often referred to as a "simulated static loading test".

The following example presents a case history where a CAPWAPC analysis was performed on a pile that was also statically tested. A precast prestressed concrete pile (length 18.3 m and area of 930 cm^2) was driven with a Conmaco 65E5 single acting air hammer to a depth of 13.7 m and a blow count of 5 bl/in (196 bl/m), and was restruck three days later with a resistance of 10 bl/in (392 bl/m). The soil conditions were fine sandy silt. The CAPWAPC analysis for a restrike blow (Figure 5) shows measured pile top force and velocity, measured and computed pile top forces, and soil resistance distribution and pile forces at the computed ultimate capacity of 1890 kN (according to the Davisson failure criterion). The static loading test failed at an ultimate pile capacity of 1845 kN. A comparison between simulated and measured static pile top load-set curves in shown in Figure 6. Similar correlations has also been reported in the literature (11).



measured pile top force and proportional velocity dynamic records

measured and CAPWAPC computed pile top force records

resistance distribution and pile force at ultimate capacity from CAPWAPC

Figure 5: CAPWAPC Example 3

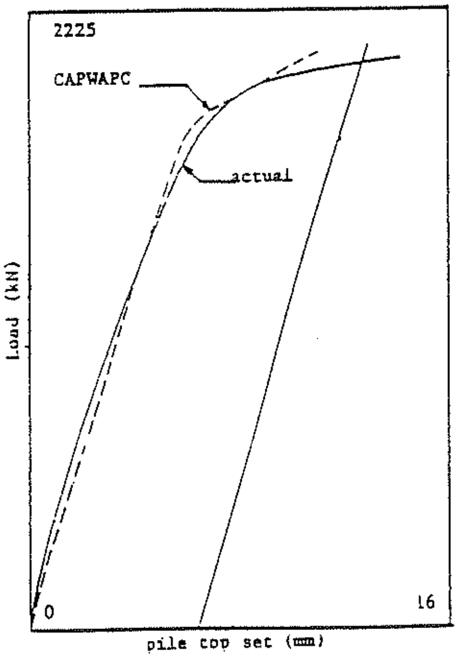


Figure 6: Actual and CAPWAPC Simulated Static Load-Set Plots; Example 3

5. CONCLUSION

Dynamic testing and analysis procedures offer the engineer and the constructor methods to evaluate the total hammer-cushion-pile-soil system during or after pile installation in a much shorter time, at significantly less cost, and with sufficient accuracy, compared with any other way of testing or analysis. This article presented background information, practical applications, and performance evaluation discussions of dynamic pile analysis and testing procedures using actual case histories.

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