DEVELOPMENT OF GUIDELINES FOR CONSTRUCTION CONTROL OF PILE DRIVING AND ESTIMATION OF PILE CAPACITY

(PHASE I)

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ABSTRACT

A literature review covering the use of dynamic pile driving equations, wave equation methods, pile analyzers, and current practices by State Transportation Departments is presented. The literature review shows that no one dynamic pile driving formula can be considered superior to all others. However, the Hiley, Janbu, and Gates equations appear to be consistently among the best in published comparisons of formula predictions versus pile load test results. The Engineering News formula and its modified versions are found, with one exception, to be among the worst predictors of pile capacity in these studies. When wave equation methods are included in comparisons of predicted to measured capacity, the wave equation prediction is consistently equal to or better than the best formula. Pile analyzer results can be excellent; however, the ability of the operations is a crucial factor in its successful use.

The majority of the 34 states responding to a survey indicated that they use the Engineering News formula in its original or modified form. No other dynamic equation was mentioned. Several states indicated a switch in recent years from the Engineering News formula to wave equation analyses with a resulting increase in accuracy. Only two states make regular use of a pile analyzer, but they are very satisfied with it.

Recommendations are made for the improvement of current Washington State Department of Transportation procedures for construction control of pile driving and estimation of pile capacity. Recommendations for additional research is also included.

SUMMARY

Three general methods are presently available for construction control of pile driving and estimation of pile load capacity: dynamic formulas, wave equation analyses, and pile analyzers. Many hundreds of dynamic formulas are available; some of these are empirical, others are based on some form of Newton's laws of motion. However, only a handful of the available formulas are used with any regularity. Wave equation analysis is a more recent addition, although the theory was developed over a century ago. It took the development of numerical analysis and the general availability of computers to make this method practical. The latest method, pile analyzers, is actually an extension of the wave equation method. It incorporates data gathered by instrumenting the pile into a wave equation solution to back-calculate static pile capacity.

In a survey of state transportation departments in which 34 responses were obtained, it was found that dynamic formulas are used most often in their pile driving work, with wave equation analyses the next most popular, and pile analyzer use very limited, except for a few states. Of the states using formulas, all apparently use either the Engineering News or some modified version of the Engineering News formula. No other formula was mentioned in the responses. Very few states have conducted any type of investigation to compare the results from different methods and/or formulas.

Several states have abandoned the use of the Engineering News formula because of its inaccuracy and have gone to wave equation analyses. Those that have done so have indicated that they are now obtaining better correlation between predicted capacity and pile load test results, and are happy with the change.

Several studies can be found in the literature in which the accuracy of different pile driving formulas is compared. These studies show that no one equation is best, although the Hiley, Janbu, Pacific Coast Uniform Building Codes, Rabe, and Gates formulas appear to be somewhat better than the other major formulas. The Engineering News and Modified Engineering News formula are consistently among the worst in these comparisons, with the exception of one study which concentrated on data from Alabama and surrounding states. In that study the Engineering News equation was found to give the best correlation with pile load test results of the formulas used.

In studies which included wave equation analyses, this method consistently was shown to be equal to or better than the best formulas. All investigators who included a wave equation analysis in their study suggested its use by practicing engineers. Significant advancements have been made in wave equation analysis computer codes since some of these comparisons were conducted; therefore, it is apparent that this method represents a significant improvement over dynamic formulas. Although it will always take more training and some additional time to use wave equation methods, its complexity has been reduced significantly by the appearance of wave equation software for use with microcomputers.

A pile analyzer can produce very accurate estimations of pile capacity. However, a pile analyzer is relatively expensive to purchase and maintain and requires highly trained individuals to interpret the data it collects. Unless there is enough pile driving activity to keep a pile analyzer crew busy during much of the year, it may be preferable to hire outside contractors to perform pile analyzer work when necessary.

CONCLUSIONS

A review of literature has shown that only a few of the hundreds of pile driving formulas which have been developed over the past 150 years are actually used today. Among the few that are in use, no one formula is clearly superior to all the others. Studies of wave equation analysis methods, including pile analyzers, are more consistent. There is little doubt that these methods are superior to all formulas.

A survey of state transportation departments show a heavy reliance on the Engineering News formula in both its original and modified forms. However, there appears to be a trend away from Engineering News toward wave equation methods and the pile analyzer.

With regard to the practice of the Washington State Department of Transportation, the following conclusions are made:

1. The Engineering News Formula in both its original and modified versions is very inaccurate and its use should be discontinued.
2. It is likely that a substitute formula can be found which will provide greater accuracy. The formulas which appear to be best suited for WSDOT are the Hiley, Gates, Janbu, and Pacific Coast Uniform Building Code.
3. It is not possible, without additional research, to determine which of the suggested formulas will prove best for Washington State conditions.
4. A wave equation analysis is clearly superior to formula use and its expanded use by WSDOT is strongly encouraged.
5. Pile analyzers can provide useful information on large projects, but may not be well suited to routine use by WSDOT.

RECOMMENDATIONS FOR FUTURE RESEARCH

The results of this investigation indicate that current WSDOT procedures can be improved. The Engineering News formula should be replaced by a more accurate formula to be used on small pile driving jobs. Increased use of wave equation analyses is strongly recommended, and for the largest jobs a pile analyzer should be used. To fully implement these recommendations, additional research will be required as discussed below.

1. In order to pick the pile driving formula which is best suited for Washington State, data from old pile load tests should be examined. Whenever possible, calculations of predicted failure load based on various formulas should be compared to actual test results.[1] WSDOT files and those of local consultants and municipalities should be examined to build a sufficiently large data base to perform statistical analyses. It is probable that modifications of an existing formula to better fit the data (c.f. 19) could be accomplished.
2. Studies should be conducted on new projects in which capacity predicted by various formulas, a wave equation analysis, and pile analyzer predictions are compared to pile load test results. This will help to evaluate the practical aspects of the use of each of these methods and provides a better test of their accuracy.
3. Successful application of wave equation methods requires correct modelling of soil conditions, such as the selection of the side and tip damping constants. Studies are required to determine

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[1] Recommended formulas are: Hiley, Janbu, Gates, and Pacific Coast Uniform Building Code.

appropriate values for typical soil conditions throughout the State of Washington.

INTRODUCTION

Pile foundations frequently are used to support bridges and other transportation structures. In order to provide a safe, yet economical pile foundation, it is necessary to use design methods which can predict with reasonable accuracy the necessary depth of penetration and the resultant capacity of a given pile. Because soil conditions often vary significantly over a construction site, methods are needed which allow verification of the design penetration during pile driving and, if necessary, adjustment of the design value. Also, an in-situ method of determining actual pile capacity, as driven, is needed. Many methods have been developed during the past 100 years to accomplish each of these tasks. Currently there is no one method which generally is accepted as the best for any of the three. Differences, even between two widely used and accepted methods, can be very large.

In order to determine if significant improvements can be made in their methods of construction control of pile driving and estimation of pile capacity, the Washington State Department of Transportation (WSDOT) has funded the first phase of a three-phase project entitled "Development of Guidelines for Construction Control of Pile Driving and Estimation of Pile Capacity." This report presents the results of Phase I.

The objective of Phase I is to provide a state-of-the-art report which includes the following:

1. A description of the formulas and analysis techniques currently available to determine pile cut-off criteria and static pile capacity.
2. A description of the strengths and weaknesses of the most promising methods described in (1), in light of WSDOT needs.

3. A determination of whether or not current WSDOT methods can be significantly improved.

4. If significant improvement is deemed possible, a recommendation of whether or not additional research is necessary before new criteria can be established.

To accomplish these tasks, a survey of other state transportation departments was conducted to determine methods currently in use. Also, a review of the technical literature concerning dynamic formulas, wave equation methods, and pile analyzers was conducted with the help of the WSDOT library. Approximately 200 references were received and reviewed. Based on this literature, a discussion of dynamic methods of estimating static pile capacity (equations, wave analysis, and analyzers) is presented in the following section. Included in this section is an evaluation of the strengths and weaknesses of each of the methods described. In the next section, the current practices of other state transportation departments are described and compared to current WSDOT procedures.

The next section reviews published comparisons between actual pile load test results and pile capacity predicted by various formulas, wave equation methods, and pile analyzers. This information, along with the information provided by the various state transportation departments, provide the bulk of the data used to formulate the conclusions and recommendations of this report.

DESCRIPTION OF AVAILABLE METHODS

Dynamic Pile Driving Formulas

Dynamic pile-driving formulas have been available for over 160 years to predict the static bearing capacity of piles. Smith (25) states that in the early 1960s the editors of Engineering News-Record had 450 dynamic pile formulas on file. All these formulas are based on the assumption that the ultimate capacity of the pile under static loading is directly related to the driving resistance of the pile in its last stages of embedment.

The stress-strain relationship in a pile during driving is extremely complicated, making an exact theoretical treatment impractical. A small percentage of the available pile-driving formulas are empirical in their entirety; however, most formulas are based on Newton's law of impact and conservation of energy principles and are modified to account for energy losses during impact and during the propagation of stresses. An inherent discrepancy involved in using impact laws in pile-driving formulas is that Newton himself (6) said that the impact theory should not be used for "bodies . . . which suffer some such extension as occurs under the strokes of a hammer." It is evident, therefore, that Newton did not intend for the impact theory to be used on pile driving type problems, making one wonder how the use of impact laws affects the accuracy of pile driving formulas.

In 1859, Redtenbacher proposed the following formula that Jumikis (14) terms the "pure, classical, complete dynamic pile-driving formula":

$$\underset{1}{e_h E_h} = \underset{2}{R_u s} + \underset{3}{e_h E_h \left[\frac{w(1 - n^2)}{W + w}\right]} + \left[\underset{4}{\frac{R_u^2 L'}{2A'E'}} + \underset{5}{\frac{R_u^2 L}{2AE}} + \underset{6}{KR_u}\right] \qquad (1)$$

where

1 = total applied energy

2 = useful work, i.e., energy used to move pile a distance s

3 = loss in impact

4 = loss in cap due to elastic compression

5 = loss in pile due to elastic compression

6 = loss in soil due to elastic compression plus other losses.

The definition of individual terms is given in Table 1.

Equation (1) can be solved for the ultimate bearing capacity, R, and then the safe bearing capacity of the pile, R_f, can be determined by dividing R by a factor of safety, F.

Except for those formulas based entirely on empirical results, all other dynamic pile-driving equations are simplifications of Redtenbacher's complete formula produced by introducing different assumptions on the energy loss terms. An example is a formula commonly known as Redtenbacher's formula, in which a completely inelastic impact is assumed (n=0). This formula is given in Table 1. Also shown in Table 1 are other commonly used dynamic pile driving formulas, several of which are discussed in detail below.

Engineering News-Record

This formula was published in 1888 by A.M. Wellington, editor of Engineering News, and originally was developed for use in measuring the bearing capacity of light-weight timber piles with fairly uniform penetration driven by drop hammers. The formula, as shown in Table 1, was modified for use with steam hammers. Wellington derived the equation by equating the applied energy to the energy obtained by graphically

Table 1. Commonly Used Dynamic Pile Driving Formulas

Formula Name	Equation	Reference Number	Year	Recommended Safety Factor
Eytelwein (Dutch)	$R_u = \frac{e_h E_h}{s\left(1 + \frac{w}{W}\right)}$ (drop hammers)	(15) (3)	1820	6
	$R_u = \frac{e_h E_h}{s+0.1 \frac{w}{W}}$ (steam hammers)			
Weisbach	$R_u = -\frac{sAE}{L} + \sqrt{\frac{2e_h E_h \; AE}{L} + \left(\frac{sAE}{L}\right)^2}$	(15)	1850	
Redtenbacher	$R_u = \frac{AE}{L}\left[-s + \sqrt{s^2 + e_h E_h \cdot \frac{W}{W+w} \cdot \frac{2L}{AE}}\right]$	(15) (2) (18)	1859	3
Engineering News-Record (ENR)	$R_u = \frac{e_h E_h}{s + z}$	(15) (3)	1888	6
Navy-McKay	$R_u = \frac{e_h E_h}{s\left(1 + 0.3 \frac{w}{W}\right)}$	(3) (15)		
Gates	$R_u = 27 \sqrt{e_h E_h}\,(1 - \log s)$ $e_h = 0.75$ for drop hammers $e_h = 0.85$ for all other hammers R_u (kips), s (in), E_h (ft-kips)	(3) (15)	1957	3

Table 1. Continued

Formula Name	Equation	Reference Number	Year	Recommended Safety Factor
Rankine	$R_u = \frac{2AEs}{L}\left[1 + \frac{e_h E_h L}{s^2 EA} - 1\right]$	(15)		
Hiley	$R_u = \frac{e_h E_h}{s + \frac{1}{2}(C_1+C_2+C_3)} \quad \frac{W + n^2 w}{W + w}$	(19)		3
Janbu	$R_u = \frac{e_h E_h}{K_u\ s}$ $\quad K_u = C_d\left(1 + \sqrt{1 + \frac{\lambda}{C_d}}\right)$ $C_d = 0.75 + 0.15\frac{w}{W}$ $\lambda = \frac{e_h E_h L}{AEs^2}$	(3)	1951	3-6
Pacific Coast Uniform Building Code (PCUBC)	$R_u = \frac{e_h E_h \cdot \frac{W + Kw}{W + w}}{s + \frac{R_u L}{AE}}$ $\quad K = 0.25$ for steel piles $= 0.10$ for all other piles	(3) (18)		4
Gow	$R_u = \frac{e_h E_h}{s + z \cdot \frac{w}{W}}$	(19)		

Table 1. Continued

Formula Name	Equation	Reference Number	Year	Recommended Safety Factor
Danish	$R_u = \dfrac{e_h E_h}{s + \sqrt{\dfrac{e_h E_h L}{2AE}}}$	(19)	1967	3-6
Rabe	$R_u = \dfrac{e_h E_h}{s + C} \cdot \dfrac{w}{w + \frac{W}{2}} \cdot B$	(15)	1946	2
Modified ENR*	$\dfrac{e_h E_h}{s + z} \quad \dfrac{W + n^2 w}{W + w}$	(18)	1965	6
Canadian National Building Code	$R_u = \dfrac{e_h E_h \cdot \dfrac{W + n^2(0.5w)}{W + w}}{s + \dfrac{R_u}{2A}\left(\dfrac{L}{E} + 0.0001\right)}$	(3) (5)		3

*There are several formulas that are modifications of the ENR formula and are known as Modified ENR. The Modified ENR presented here was proposed by the Michigan State Highway Commission in 1965.

NOTE: To be consistent, the net hammer energy is given in all equations as $e_h E_h$ even though many of the formulas were developed for drop hammers where the hammer energy is given by Wh. No units are given for any terms (except for empirical formulas) so that any consistent set of units can be used.

Table 1. Continued

A = cross-sectional area of pile

A' = cross-sectional area of cushion block

B = static supplement factor in Rabe's formula (see (27) for clarification)

C = temporary compression loss in the cap, pile, and soil; used in Rabe's formula (see (27) for clarification)

C_1, C_2, C_3 = coefficients for Hiley equation

e_h = efficiency of striking hammer (<1.0)

E = Young's modulus of elasticity of pile

E' = Young's modulus of elasticity of the cushion block

E_h = manufacturer's hammer energy rating

F = factor of safety

h = height of free fall of hammer

K = a coefficient to account for elastic compression plus other losses in Redtenbacher's classical formula

L = length of pile

L' = axial length of cushion block

n = coefficient of restitution

R_u = ultimate bearing capacity of pile in soil

R_F = safe bearing capacity of pile

s = pile penetration for last blow, also called "set"

w = weight of pile

W = weight of hammer

z = 0.1 for steam hammers; 1.0 for drop hammers integrating the area under typical load-settlement curves for timber piles driven by drop hammers, and all the losses are taken into account by a single factor, z. Usually e_h is assumed equal to 1 when using the ENR formula.

This formula probably is the most widely used dynamic pile-driving formula currently in use in the United States, mainly because of its simplicity and the fact that it is easy to use. However, several investigators have noted the extremely wide range of safety factors determined when using this formula (e.g., 1,5,19,27). This should not be surprising due to the simplicity of the formula and the way in which it was developed. Details of field studies which report comparisons between pile capacity predicted by the Engineering News formula (and other formulas) and pile load test results are presented in the section titled "Comparative Studies."

Hiley

Olson and Flaate (19) reported that Hiley developed his formula in an attempt to eliminate some of the errors associated with the theoretical evaluation of energy absorption by a pile-soil system during driving. The factor 1/2 $(C_1+C_2+C_3)$ is analogous to the factor Z in the ENR formula. C_1 represents the peak temporary elastic compression in the pile head and cap. Chellis (5) has compiled values of C_1. The factor $C_2 + C_3$ represents the combined temporary compression of pile and supporting ground and is based on field measurements. The Hiley formula is used extensively in Great Britain and in Europe.

Eytelwein (Dutch)

The Eytelwein formula was developed at a time when steel and concrete piles were being used more frequently in place of timber piles, resulting in heavier piles and concomitant higher driving energies. Combinations of either a light hammer and a heavy pile or a heavy hammer and a light pile resulted in values of s that yielded widely varying results when the ENR formula was used. The ENR formula was modified in an attempt to account for this variation by adding an expression for the relative weights of pile and hammer. This modified form of the ENR is known as the Eytelwein formula.

A problem develops when this formula is used for piles driven by drop hammers where the pile set, s, is small. Note from the formula for drop hammers shown in Table 1 that as s approaches zero, Ru approaches infinity. This obviously is not possible, and indicates that the predicted ultimate capacity is too high for small values of s.

Janbu

This formula does not directly involve the law of impact. Janbu factored a series of variables that are difficult to evaluate out of the conservation of energy equation and combined them in his driving coefficient, C_d. The driving coefficient includes terms representing the difference between static and dynamic capacity, the rate of transferral of load into the soil with respect to depth, and hammer efficiency and is correlated with the ratio of the weight of the pile to the weight of the hammer. The overall factor, K_u modifies the driving coefficient by a term that includes λ, which incorporates the length and cross-sectional area of the pile, Young's modulus for the pile, the hammer energy, and the pile set.

Danish

Sorensen and Hansen (26) based the Danish formula on a study done using dimensional analysis, statistical analysis, and by simplifying some of the more complicated formulas. Their analysis was predicated on the following rationale taken directly from their report:

> Due to the fact that all the practical formulae are fundamentally wrong on several points, it cannot be assumed or even expected that the best formula is the one that considers the greatest numbers of energy losses or appears to be the most comprehensive. The only criterion by which any sound judgment can be made is the statistical analysis of the agreement between formula and load tests, and if simplicity can be combined with accuracy, so much the better.

Gates

The Gates formula is a strictly empirical relationship between hammer energy, final set, and test load results. It was developed by applying a statistical adjustment (based on approximately 100 load tests) to a significantly simplified form of existing equations. In his report, Gates (7) did not include the data on which his study was based and did not give an indication of the amount of scatter. It seems, however, that all soil types were included in the study.

Rankine

The Rankine formula is a special case of Redtenbacher's classical formula in which the impact is considered to be perfectly elastic (n=1) and the pile is considered to be supported entirely by friction. Therefore, Rankine's formula is the opposite limit expression from the Redtenbacher's formula shown in Table 1 in which the impact is considered to be perfectly inelastic (n=o).

Gow

Based on experience and intuition, the Gow equation was developed by adjusting the denominator of the ENR formula to represent the extra energy-absorbing characteristics of precast concrete piles.

Rabe

Rabe's formula is empirical, but is more complex than other empirical formulas. It is a combination static and dynamic formula that accounts for soil conditions as well as most of the other factors that influence pile capacity.

This formula can be cumbersome to use because to solve it requires extensive computation and several trial estimates of load. It is necessary to perform many of the computations prior to driving; otherwise, it becomes difficult to use in the field.

Modified Engineering News-Record (Michigan)

This is one of many so-called Modified ENR formulas. This version was proposed in 1965 by the Michigan State Highway Department (18) as the product of an extensive study to compare the efficacy of several dynamic formulas to predict bearing capacity of piles.

This version modifies the ENR formula by multiplying it by the factor

$$\frac{W+n^2w}{W+w}$$

which gives a ratio of combined ram-pile kinetic energy before and after impact. This factor, when multiplied by the initial energy, e_hE_h, defines the available energy after impact.

Wave Equation Analysis

The problems associated with using dynamic pile-driving formulas to predict static bearing capacity of a pile are numerous. Many difficulties stem from the fact that pile driving is not a simple problem that can be solved by the direct application of Newton's laws (6). With the exception of Rabe's formula, none of the other formulas listed in Table 1 even attempt to account for the soil types and soil conditions into which the pile is being driven. Other problems develop from the simplifying assumptions made in accounting for energy losses in the system. Empirical formulas only can be used in restricted applications because they generally are developed for specific pile types, driving equipment, soil types and conditions and are of limited general use. Evidence for this can be found in the "Comparative Studies" Section of this report where the results of studies comparing formula predictions of ultimate capacity to the results of pile load tests are presented. The ASCE Manual of Engineering Practice (2) gave the following words of caution in 1946 about the use of dynamic pile-driving formulas:

> Experience has shown that (dynamic pile-driving formulas) cannot be relied on when used indiscriminately but should be used with discretion, particularly in light of experience gained at the site. Because of the uncertainities involved, the misapplication or misuse of these formulas by those with insufficient experience, and the unreliable behavior even when they have been intelligently used, no pile formula is recommended in this manual.

An alternate method of predicting static bearing capacity of piles involves analyzing the longitudinal wave transmission in piles by the wave equation. A wave equation computer program allows the user to predict the driving stresses induced in a pile for any blow of the hammer, to determine the resulting motion of the pile during the impact, and to determine the resistance of soil at the time of driving. This information allows the engineer to determine the compatibility of the driving equipment with the pile type, size, and soil conditions. From a theoretical standpoint, the wave equation models the development of bearing capacity in a pile driven into soil much more accurately than Newton's impact laws, which form the basis of most dynamic pile-driving formulas. However, analytical solutions to the wave equation for piles are not available due to the complex nature of pile-driving problems. The only solutions to this problem currently available are based on numerical methods.

The first person to publish a discussion of the wave action that occurs during the driving of piles was Isaacs in 1931 (14). Glanville et al. (8) published a solution in 1938 of the wave equation applied to pile driving; however, the value of his solution was diminished by the number of simplifying assumptions necessitated by the unavailability of computers at that time. It was not until the early 1960s that the wave equation method first was put into practical form by Smith (25) in his classical paper. Further research and development by others has produced the many computer programs now available to analyze pile driving by wave equation methods.

Smith's solution (25) consists of using a finite-difference method to numerically model the wave equation, thereby calculating the pile set for a given ultimate load. A graphical representation of his idealized model is shown in Figure 1, wherein the ram, cap block, pile cap, pile, and soil resistance are idealized as discrete elements consisting of weights, springs, and dashpots.

Because they usually are short, heavy, rigid objects, the ram and the pile cap are represented as individual weights without elasticity. The ram and pile cap are shown in Figure 1 as W_1 and W_2, respectively. In contrast, the capblock is idealized as a spring (K_1) because it is a relatively short, light, springy item made of wood, plastic, or other similar material.

The pile, although heavy, generally is long and therefore somewhat compressible, making it subject to wave action when struck by the ram. The wave action is simulated mathematically by separating the pile into discrete units, where the mass of each unit is represented by an individual weight (W_3 to W_{12}) and the elasticity of each unit is represented as an individual spring (K_2 to K_{11}). The motion of each unit is determined as though it is a separate and distinct object. However, care must be taken to select a unit length significantly smaller than the wavelength of the impact wave produced in the pile; otherwise, this numerical method will break down.

Smith's soil model consists of a system of external springs and dashpots and is fairly complicated. Therefore, only a brief discussion will be presented here. Further details can be found in Smith (25). The soil resistance acting on a pile can be divided into two parts--the bearing resistance at the bottom of the pile and the frictional resistance along the sides of the pile. Smith's model analyzes both the point resistance and the side resistance in terms of three factors:

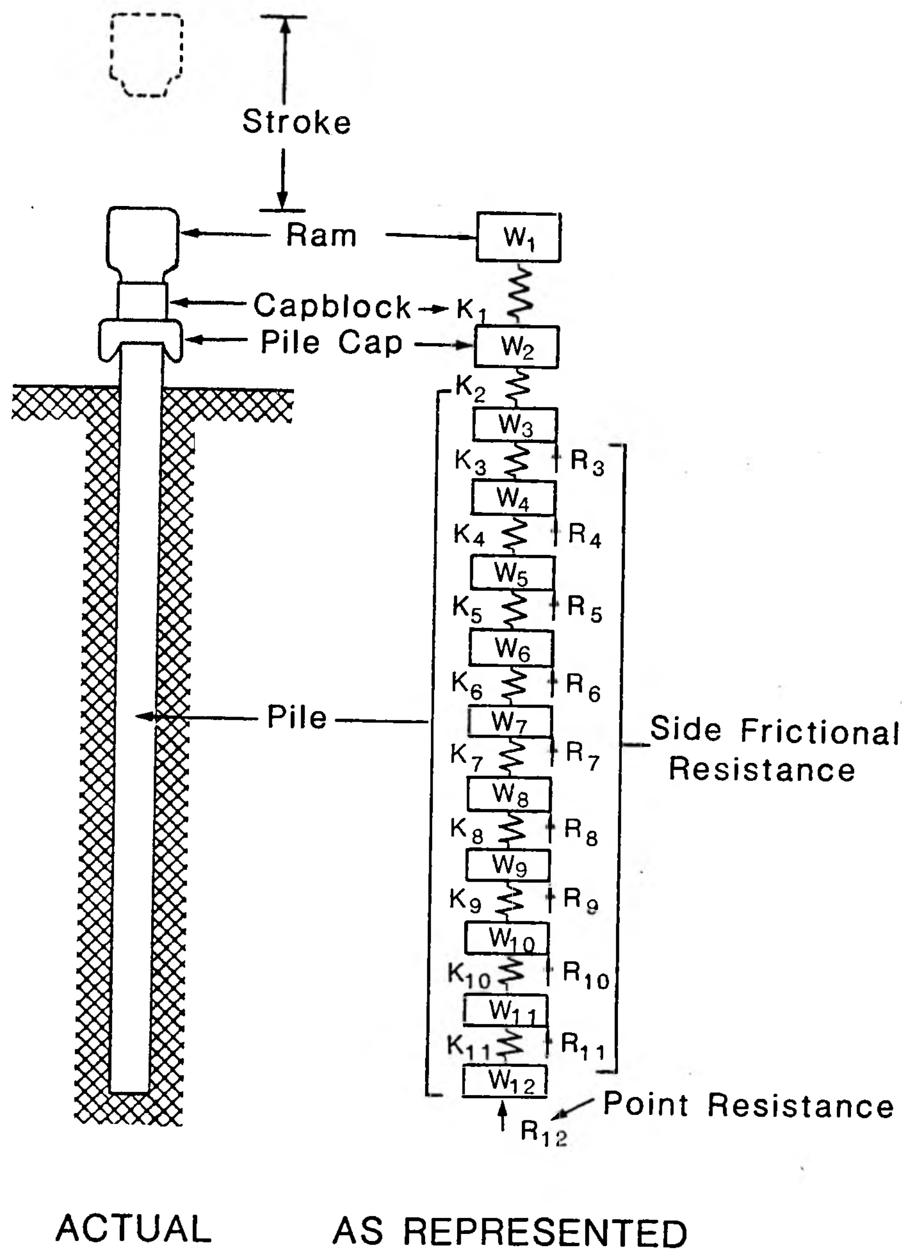

Figure 1. Smith's (25) Lumped Mass Pile Model.

1. Elastic ground compression (also called "quake").

2. Ultimate ground resistance.

3. Viscous damping based on a damping constant.

However, the analysis of the point resistance differs from the analysis of the side resistance in the value of the damping constant used, with the damping constant for the point resistance being larger than that for the side resistance. This difference accounts for the fact that as the pile is driven downward, the soil under the pile point is displaced rapidly, whereas the soil along the side is not. A useful and versatile facet of using a numerical wave equation solution is that the soil resistance can be distributed over the full length of the pile in any manner that best represents the soil conditions at a particular site.

Once the system is completely discretized (i.e., the pile is divided into segments with the appropriate spring constant and soil resistance), it can be analyzed in a series of separate time intervals. The ideal time interval would be that which would allow the stress wave to just travel from one element into the adjacent element. This is not possible, however, from a practical standpoint because the speed of the wave varies while the time interval remains constant. The best practical time interval to use is the largest that will result in a completely stable numerical solution. Unfortunately, there is no simple rule that governs all possible situations, but Smith (25) gives criteria to use as guidelines. It is important to note that the required time interval is related to the length of the pile element chosen--the smaller the pile unit length selected, the smaller the time interval must be.

Since the publication of Smith's paper in the early 1960s, a multitude of computer programs have been written that use a numerical model of the wave equation to analyze the pile driving problem. Some of these programs incorporate finite element methods rather than finite difference methods. Two programs are of special interest to this report and will be discussed hereinafter.

A wave equation was developed by Hirsch et al. (12) in the early to mid 1970s for determining the dynamic behavior of piles during driving. This program, commonly known as the TTI wave equation program, was developed by the Texas Transportation Institute, under the auspices of the Federal Highway Administration. The TTI program was intended for general practical use by highway departments and was meant to assist highway departments in the understanding, use, and practical application of pile driving analysis by the wave equation. For many years, the TTI program probably was the most widely used wave equation program in the United States.

In the late 1970s and early 1980s, a wave equation program known as WEAP (Wave Equation Analysis of Piles) was developed by Goble and Rausche (10) under contract to the Federal Highway Administration. The motivation for the development of the WEAP program came from problems the New York Department of Transportation (NYDOT) encountered when they attempted to incorporate the TTI wave equation program into their pile driving practice. NYDOT experienced serious problems when TTI was used for piles driven by diesel hammers, in that unrealistic values of driving stresses sometimes were obtained. The WEAP program improved upon the TTI program by analyzing piles driven by diesel hammers using a thorough model of both the thermodynamic and mechanical hammer operation. WEAP also improved and refined existing techniques for wave analysis of piles driven by air-steam hammers. Many highway departments and private contractors have switched from the TTI program to the WEAP program for wave equation analysis of piles.

Pile Analyzer

Two major shortcomings of most dynamic pile analyses are the uncertainty of the actual energy applied by the hammer to the pile during driving and the distribution of soil resistance along the pile. Research begun in 1964 at Case Western Reserve University under Goble initially concentrated on using electronic equipment to measure force and acceleration at the top of the pile for each blow of the hammer so that the actual applied energy could be determined. Using these data, they were able to relate their dynamic measurements to static bearing capacity using a single force-balance theory (11). Static bearing capacities predicted by the proposed theory were compared to model pile load tests, full scale load tests, and load test results conducted in Michigan (18), with the results indicating that the method showed promise as a means of predicting static bearing capacity of piles.

A later study extended the application of the force and acceleration methods to the calculation of the distribution of soil resistance along the pile (24). The prediction of the magnitude of dynamic soil resistance is an important factor in choosing efficient hammer characteristics. In addition, this work used two methods to predict static bearing capacity: (1) an improved version of the force-balance theory discussed above, and (2) a wave equation analysis method. The static capacities predicted by these two methods were compared to load test data, with the result that both methods yielded better correlation with the load test results than any of the energy formulas they used. The best predictions resulted from the wave equation analysis method due to the inclusion of both dynamic and static soil resistance.

A further development using force and acceleration measurements was published in 1979 by Rausche and Goble (23) that suggested a procedure for detecting discontinuities and reductions in cross section at points along the pile below the ground surface. The theory behind this method uses one-dimensional wave propagation considerations to predict the effect that stress waves produced by pile damage would have on the force and acceleration records. The actual force and acceleration records then are examined to see if evidence of pile damage exists.

A major drawback in the early use of this electronic measuring equipment was that personnel well trained in electronics were required to operate the equipment in order to achieve usable results (9). In order to make this method feasible for routine use in the field, special purpose computers were designed and constructed to perform all necessary computations in the field and display the results. This equipment has been changed and improved through the years and now is available to anyone who is interested from Pile Dynamics, Inc., a privately owned company. The proprietary name of this equipment is the Pile Driving Analyzer, but it is more commonly known as the pile analyzer or the "Goble" analyzer.

Discussion of Methods

The three general methods of construction control and estimation of pile capacity discussed above each have their own advantages and disadvantages. Driving formulas, still perhaps the most popular method, are very easy to use. In their simplest form, only a measure of the permanent set under a single blow of the hammer is needed to predict capacity. Tables can be compiled for some of the formulas (such as Engineering News), so that no calculations are required. This has tremendous advantage because it means that determinations of pile capacity can be made in the field very quickly by field personnel. It is likely that this is the main reason for the popularity of formulas, especially the Engineering News formula.

The simplicity of most pile driving formulas leads to the major disadvantage--inaccuracy. As discussed later, the use of a pile driving formula exclusively can lead to dangerously low safety factors or uneconomically high ones. The difficulty with using formulas is the scatter in the correlation between predicted and actual pile capacity. In order to assure that the actual safety factor obtained is above 1.0, uneconomically high reductions in predicted capacity are needed.

Of the formulas discussed above, most would be suitable for WSDOT use from the point of view of ease of use. The Rabe formula is the major exception, due to the amount of computation required, especially prior to driving. The Janbu formula also involves somewhat more calculation than others, but is not particularly difficult to use. It is felt that all of the others are simple enough to at least consider for use if a formula is to be used in the future.

On the other extreme from dynamic formulas is the pile analyzer. On the negative side, this equipment is relatively expensive to purchase and maintain and requires highly trained individuals to operate it and evaluate the data it provides. Also, the equipment used is reasonably delicate and breakdowns can occur. The advantages are related to accuracy of the method. When properly used, very accurate estimates of pile capacity are obtained potentially leading to substantial reductions in cost. Also, a pile analyzer can be used to detect pile damage.

A wave equation analysis falls between the other two methods. Its major advantage is increased accuracy over dynamic formulas. The analysis can be used quite successfully to select a pile-cushion-hammer combination to maximize driving efficiency. Also, it can be used to accurately predict stresses which will be encountered during driving. It is sometimes used for these purposes even when other methods are used to estimate pile capacity. The disadvantage is that the analysis requires computer facilities (software is available for use on personal computers) and personnel trained in its use.

CURRENT PRACTICES OF STATE TRANSPORTATION DEPARTMENTS

To assess the current practices of state transportation departments, a letter was sent to each state and the District of Columbia requesting the following information:

1. Method(s) used for estimation of pile capacity during design.
2. Method(s) used for construction control of pile driving.
3. Any comparative studies of various pile driving formulas.
4. Any data comparing field load test results with results predicted from formulas or wave equation analyses.
5. Has a pile analyzer been used; if so were you satisfied?

Thirty-four responses were obtained from the 50 letters sent out. A list of those departments responding is presented in Table 2. All regions of the country are represented and, although several replies were quite brief, it is felt that on the whole a reasonably detailed picture of current practice has been obtained. The following discussions are based on the responses received.

Methods for Estimating Pile Capacity During Design

Answers to this question typically were brief and indicated a general method rather than specific design details. Most states use the results of a subsurface investigation, including soil sampling and laboratory testing, to determine soil properties which then are used in one or more static pile capacity equation. Nordlund's method was cited most frequently as the method used to predict capacity in sand (ID, MI, NV, NY, NM, WI). Other methods cited are those developed by Vesic (NC,PA); Meyerhof (CA); Jaky

TABLE 2. States Responding to Request for Information

AR	Arkansas	NV	Nevada
CA	California	NH	New Hamshire
CO	Colorado	NJ	New Jersey
CT	Connecticut	NM	New Mexico
DC	District of Columbia	NY	New York
FL	Florida	NC	North Carolina
ID	Idaho	ND	North Dakota
IA	Iowa	OK	Oklahoma
KS	Kansas	PA	Pennsylvania
KY	Kentucky	RI	Rhode Island
LA	Louisiana	SC	South Carolina
MA	Massachusetts	SD	South Dakota
MI	Michigan	TN	Tennessee
MN	Minnesota	VT	Vermont
MS	Mississippi	WV	West Virginia
MO	Missouri	WI	Wisconsin
NE	Nebraska	WY	Wyoming

(CO-for friction piles); Tomlinson (ID, NJ-for fine grained soil); and Thurman (NV-for end bearing). AASHTO standard specifications were cited by six states as the basis for their design (DC, MN, MA, ND, OK, VT-for end bearing); the FHWA method (described in "Soil and Foundation Workshop Manual") by two states (KY, MO), the Naydocks Design Manual by one (CT-for friction piles) and the Bureau of Public Roads method by one (VT-for end bearing). New Hampshire stated that piles were driven to refusal, while West Virginia drives all piles to rock. Other states were more vague, indicating that the design loads came from borings and calculations, experience, set values, load tests; were based on soil properties, or were obtained from a foundation engineer.

Clearly, a wide variety of methods are currently being used with no real favorite apparent. This is not surprising considering the multitude of methods which can be found in the literature.

Construction Control of Pile Driving

Despite the multitude of dynamic methods available for estimation of pile capacity only a handful appear to be used by transportation department engineers. Based on the response received, several points are clear. First, the Engineering News formula, either in its original form or more often a modified version, is by far the most popular dynamic formula used. Second, wave equation methods, such as the WEAP computer program, are widely used also. Third, use of pile analyzers is growing, but is still not very prevalent.

Table 3 summarizes the responses received. In three cases (DC, LA, NH) the question appears to have been interpreted to refer to alignment control; these responses are not included. Of the remaining 31 responses,

Table 3. Summary of Responses to Question No. 2: Methods Used for Construction Control of Pile Driving

State	ENR	Modified ENR*	Wave equation	Pile Load Test	Other/Comments
AR	X				
CA	X			Large jobs	Specified pile tip elevation
CO	X				
CT				X	Many piles driven to refusal
FL		X	To size hammer		
ID			WEAP		
IO		X		X	
KS	X				
KY			Selected projects		
MA	X				On very few occasions consultant hired for wave equation analyses
MI		X			
MN		X			
MS		X		X	
MO		X			
NE					"Dynamic Formulas" did not state which ones
NV				X	Minimum tip elevation--Note: ENR abandoned due to inaccuracy
NJ					"Blow count and depth penetration methods"
NM	X		WEAP, TTI		
NY			WEAP		Dynamic Load test (Goble pile analyzer)

Table 3. Continued

State	ENR	Modified ENR*	Wave equation	Pile Load Test	Other/Comments
NC	X				Wave equation methods used to determine drivability
ND	X				
OK		X			
PA			X		Minimum tip elevation
RI			X	X	Recently switched from ENR formula
SC	X			Large projects	Index piles
SD		X			Test piles
TN	X			X	
VT	X			X	Load test on selected piles
WV					Driven to refusal (20 blows/inch)
WI		X			Pile analyzer also used
WY		For end bearing piles	For friction piles		

*Refers to any modification of ENR formula, each state has a different modification.

10 states replied that they used the ENR formula and 11 states use a modified ENR formula. It should be noted that none of the states which indicated use of the ENR formula actually wrote the equation out, so it is possible that some or all may actually be using a modification of the original ENR formula. Six of the 11 states using a modified ENR formula gave the actual equations they use. Inspection of these formulas showed them to be modifications of the original ENR equation. No two of the states used the same formula. The other five states replied that they used a Modified ENR formula, but did not present the actual equation. One reply stated that "dynamic formulas" are used, but did not state which ones. Based on these responses, it is very clear that despite the multitude of formulas available, state transportation departments use only the ENR formula and modifications of it.

Wave equation methods are used by 10 states. However, Florida uses it only to size the pile driving hammer and North Carolina uses it to determine drivability. Both of these states use an ENR formula for estimation of pile capacity. Wyoming uses wave equation methods only for friction piles.

New York and Pennsylvania both have extensive experience with wave equation methods (PA indicated 10 years experience). Both require a wave equation analysis for all pile jobs. New York uses the WEAP program, Pennsylvania did not indicate the specific method used. Rhode Island and Nevada both stated that they abandoned the ENR formula in favor of wave equation analyses. In the case of Nevada, piles were being overdriven with the ENR formula and correlation with load tests was poor.

New York and Wisconsin are the only two states which indicated that they use a pile analyzer in connection with construction control. On certain jobs, New York performs their own Dynamic Pile Load Test using the Goble pile analyzer. They have their own equipment and state that they have performed over 100 pile load tests using this method. They find that it is quick and relatively inexpensive compared to static load testing. The Wisconsin reply merely stated that a pile analyzer is used in addition to a modified ENR formula.

Comparative Studies of Pile Driving Formulas

Twelve states indicated that some comparative studies have been made. Unfortunately, most of the studies cited were either quite old and no data are available, or informal. Only Michigan and South Dakota were able to provide reports documenting their work. A summary of the response from those states which replied in the affirmative is presented in Table 4. Three states volunteered opinions based on informal studies and/or experience. In New York's experience, WEAP is much better than any dynamic equation. In comparing WEAP predictions with the Dynamic Load test results, good agreement is found "for certain soils and hammer types." When the WEAP program is inaccurate, it appears to be due to either the assumed soil resistance distribution or the hammer model in WEAP. Diesel hammers present more problem than other types.

Wyoming's comparisons have shown that the modified ENR formula they use is overly conservative, while Oklahoma found that ENR and "more sophisticated formulas" vary only "under extreme conditions." The results of Michigan's study will be examined in detail in the following section.

Table 4. Summary of Responses to Question No. 3: Comparative Study of Pile Driving Formulas

State	Response
CO	Only informal comparisons have been made
KA	In a few projects wave equation analysis conducted to confirm present methods--results not analyzed to date
MI	Extensive comparative study--reference No. 18
MO	Some comparisons made in past, but data not available
NM	ENR and wave equation compared to load test (did not provide details with response)
NY	No formal studies; however, based on their experience they feel WEAP much better than any dynamic formula
ND	Studies were conducted approximately 25 years ago, data not available
OK	Studies show that sophisticated formulas (compared to modified ENR) not much different except in extreme cases--no details provided
PA	Some comparisons between modified ENR and wave equation--no conclusions to date
SD	Comparison between ENR and SD formula--reference No. 4
WI	Only if very expensive structures or very difficult soil conditions are involved will comparative studies be conducted
WY	Informal comparisons indicate modified ENR overly conservative

Comparison of Pile Load Tests Results with Formulas and/or Wave Equation

Most states responded in the negative to this question. Only four referenced published comparisons they had made (AK, LA, MI, SD). However, four are currently conducting tests or analyzing old test results (CA, KS, MS, PA), and one is contemplating a study in the near future (KY). A summary of all the responses is presented in Table 5. Details of the published comparisons will be presented in the following section.

Although the Pennsylvania study is not complete, they did say that they are finding that both the wave equation and pile analyzer underpredict capacity if there is no relaxation. The magnitude of the underprediction varies with the pile hammer system, and appears to be greatest with light piles driven by heavy hammers. They give as an example a Monotube driven with a Vulcan air hammer. They also stated that the driving stresses predicted by wave equation methods (WEAP, TTI) are reasonably accurate.

Use of a Pile Analyzer

Twelve states indicated some experience with a pile analyzer and three have plans to use one in the near future. Of those using an analyzer, New York and Pennsylvania appear to have the most experience. As discussed above, New York has conducted over 100 Dynamic Pile Load tests with a Goble analyzer and are satisfied with the results. Pennsylvania also is satisfied with their use of an analyzer but state that it underpredicts capacity, although not as much as a wave equation analysis.

Several states (FL, ID, ND, SC) have only very limited experience with the analyzer (typically a FHWA demonstration project). Neither Idaho nor South Carolina were completely satisfied with their use of an analyzer.

Table 5. Summary of Responses to Question No. 4: Comparative Studies of Pile Load Tests with Formulas and/or Wave Equation

State	Response
AK	Comparison of formulas and wave equation with pile load tests--Reference No. 28
CA	Study in progress comparing states and dynamic load test results with wave equation
IO	Some comparisons were attached, but no formal study has been conducted
KS	Study in progress
KY	Future study planned
LA	Comparison of formulas with pile load test results--Reference No. 20
MI	Major study in the 1960s--Reference No. 18
MN	Limited comparisons have been made, data not available
MS	Data being analyzed
NC	Wave equation analysis compared to field load tests--no data presented
PA	Comparisons of static load tests results, wave equation, pile analyzer and static analysis have been conducted--analyses of data in progress
SD	Results of study in Reference No. 4

Idaho stated that the analyzer failed to indicate damages which occurred to steel H piles during driving and South Carolina said that results were "uncertain." A summary of responses is presented in Table 6.

WSDOT Practice

WSDOT practice is similar to that employed by other states. For small pile driving jobs the Engineering News formula is used for estimation of pile capacity and construction control of pile driving. The majority of pile driving projects fit into this category. For larger projects, especially interstate construction, both wave equation analyses and pile analyzers are used. Wave equation analyses are used to qualify pile driving hammers which do not meet standard specifications, and when problems are encountered during pile driving. When a pile analyzer is employed, outside contractors are used, as WSDOT currently has no in-house capability for this type of work. Wave equation analyses, however, are conducted in-house. The feeling that improvements could be made in WSDOT procedures prompted the funding of this research project.

Discussion

Based on the responses discussed above, it is clear that a large percentage of state transportation departments use the Engineering News formula or modifications to it. What is quite interesting is that no other formula, such as Hiley, Janbu, Gates, etc., is used. The alternative to an Engineering News formula is wave equation analyses and/or pile analyzers. The popularity of the Engineering News formula and its variations stems from its ease of use and tradition. It is one of the oldest formulas and

Table 6. Summary of Responses to Question No. 5: Use of a Pile Analyzer

State	Response
CA	Experimenting with the dynamic analyzer and satisfied with results so far--intend to eliminate static pile load tests
CO	No use to date, but plan to in the near future
FL	Used on one projectin 1981; did not indicate if satisfied
ID	Used once in FHWA demonstration project--analyzer failed to indicate damages which occurred in stec H piles during driving
KS	Experimental use planned in 1985
KY	Plan to purchase and use a Goble analyzer in 1985
MN	Some experience in use of an analyzer--do not feel they have expertise to interpret data from an analyzer
NE	Used on several projects with satisfactory results
NV	Not used recently
NY	Performed dynamic pile load test with Goble analyzer, satisfied with results
ND	A limited number of piles tested with an analyzer with satisfactory results
PA	Have used an analyzer and satisfied with results; however they have found it underpredicts capacity
RI	Have used an analyzerand are satisfied with results
SC	Used once with uncertain results
WI	Have been used and are satisfied with results

NOTE: All other states indicated no experience with a pile analyzer.

has been widely used in the United States for decades. Many other formulas, however, also are quite simple to use.

Those states which have abandoned the Engineering News formula have switched to wave equation analyses and/or analyzers and appear to be quite satisfied with the results. These methods clearly are more difficult to implement, and require more highly trained personnel. The intermediate step, using a more sophisticated equation, does not seem to have been implemented, based on the responses received.

COMPARATIVE STUDIES

Over the past several decades, many researchers have attempted to determine which of the many pile driving formulas is best by comparing formula predictions of pile capacity with pile load test results. Some of the more recent studies have included wave equation analyses and/or pile analyzer predictions. Because of the large number of formulas available, each study has concentrated on only a few of them, usually no more than five or six. To further complicate the problem of determining the best formula, the method of static pile load testing used in each study is different. Also, the amount of information provided on soil conditions, type of pile driving equipment, and selection of variables such as coefficient of restitution or hammer efficiency, varies considerably. At best then, studies such as those discussed below should be used primarily to indicate which formulas appear to be consistently among the better ones. Some information on effects of soil conditions, pile, and hammer type also can be obtained. Perhaps the most useful information is on variability of each formula. It is much better for a formula to consistently either underpredict or overpredict ultimate capacity by a constant ratio rather than to predict the ultimate load on the average but be just as likely to grossly overpredict as underpredict.

One of the older references which cites comparisons between predicted versus measured pile capacity is Chellis (5). He reports the results of comparisons using 45 individual piles in which the static capacity is predicted by the Engineering News, Hiley, a Modified Engineering News, a modified Eytelwein, the Navy-McKay, the Canadian National Building Code (Canadian NBC), and the Pacific Coast Uniform Building Code (PCUBC) formulas. The measured capacity is defined as the load on the net settlement versus load curve where the "rate of movement begins to increase sharply in proportion to the increase in load." The data include several different types of piles (thin, mandrel-driven corrugated shells, fluted steel shells, pre-cast concrete, wood, and H sections) and hammers (double acting, differential acting, and drop). The author used the ultimate capacity predicted by each formula. Those formulas which provide a working load by incorporation of a safety factor were increased by the safety factor appropriate for each (i.e., Engineering News, Eytelwein, and Navy-McKay formulas were multiplied by 6 and the Canadian National Building Code was multiplied by 3).

The Hiley formula gave the best results, followed closely by the PCUBC and Canadian NBC formulas. The average predicted values of ultimate capacity were 92%, 112%, and 80%, respectively of the measured pile capacities. Of equal importance is the range of predicted values measured as a percentage of actual pile capacity. The Hiley formula produced a range of 55%-125%, the PCUBC formula range was 55%-220%, and the Canadian NBC formula range was 55%-140%. The other formulas were considerably worse. For example, the average and range for the Engineering News formula are 289% and 100%-700%, respectively. A summary of the results is presented in Table 7.

The author reports that for wood piles and fluted steel shell piles (which are lightweight also), the safety factor for the Engineering News formula is often nearer 2.5 than 6. However, for heavier piles and the small sets, the Engineering News, Eytelwein, and Navy-McKay formulas all become more dangerous to use.

The author concludes that the Hiley, Canadian NBC, and the PCUBC formulas provide sufficiently good agreement with load test values to be used with a safety factor of 2.5-3. He also states "there would not seem to be much point in continued use of the Engineering-News formula, except as a matter of interest in comparing it to results of more modern methods."

Table 7. Summary of Results from Chellis (5)

Formula	Ratio of Predicted Load to Measured Ultimate Load (%)	
	Average	Range
Hiley	92	55-125
Pacific Coast UBC	112	55-220
Canadian National Builders Code	80	55-140
Engineering News	289	100-700
Modified Engineering News (Michigan Formula)	182	98-430
Eytelwein	292	90-1800
Modified Eytelwein	202	98-508
Navy-McKay		99-∞

Although use of the modified forms of the Engineering-News and Eytelwein formulas with heavy piles appears to reduce the range of results compared to load tests, these tests do not indicate that sufficient improvement is obtained to justify their use instead of a formula of the Hiley type.

Spangler and Mumma (27) compared the predictions of four formulas (Engineering News, Eytelwein, PCUBC, and Rabe) with load tests on 59 piles. A variety of pile types including H-piles, concrete, timber, Raymond step tapered, and pipe piles were included. The locations of the piles were spread throughout the country and soil conditions varied considerably.

In this study, the authors compared the working load predicted by the formula (for the PCUBC formula the predicted load was divided by 4) with the results of pile load tests and calculated a resulting safety factor. A summary of their results is given in Table 8.

To obtain the ultimate load used in these comparisons, the authors calculated four failure loads for each test and averaged the results. These failure loads were defined as: (a) the load at which net settlement equals 0.25 in, (b) the load at which the incremental gross settlement divided by the incremental load exceeds 0.03 in per ton, (c) the load at which the gross settlement curve breaks and passes into a deep straight tangent, and (d) the load at which the tangents to the early flat portion and the steep portion of the load-settlement curve intersect.

Table 8. Summary of Results from Spangler and Mumma (27)

Factor of Safety	EN	Eytelwein	PCUBC	Rabe
Less than 1.0	4	6	0	0
1.0-1.5	10	7	1	1
1.5-2.0	10	7	2	13
2.0-3.0	21	21	12	30
3.0-4.0	7	7	5	13
4.0-5.0	5	7	11	1
5.0-8.0	1	3	20	0
Over 8.0	0	0	7	0
Average range	.83-5.38	.72-5.49	1.22-9.27	1.3-4.0

An examination of the data for the Engineering-News formula indicates that all the piles with safety factors under 1.0 had a set of 0.10 inches or less, and those piles with a safety factor below 1.5 had sets of less than 0.25 inches. The authors found no correlation between safety factor and type of pile material or length of penetration; however, friction piles tended to have higher safety factors than end bearing piles.

There was more scatter in the results predicted by the Eytelwein formula, compared to the other three. Like the Engineering-News formula, the worst predictions came from small sets. When the pile hammer was heavier than the pile, safety factors were particularly low. Again, friction piles had higher safety factors than end bearing piles.

The PCUBC formula was found to be most accurate for piles with deep penetration (greater than 45 feet) driven with a heavy hammer. For other cases, uneconomically high safety factors resulted.

The Rabe formula gave the best results of the four with no safety factor below 1.0 and only one above 4.0. As with the other formulas, friction piles had the highest safety factor. There was no apparent correlation between safety factor and pile set, pile type, material or hammer weight ratio. To illustrate the differences among the four formulas, plots of predicted pile capacity vs. measured capacity are shown in Figures 2 to 5. A straight line fit to the data is shown also. The scatter in the Engineering News and Eytelwein formulas is striking. It is considerably greater than in the data from the PCUBC or Rabe formulas.

Agerschou (1) has compared load test results from 171 piles with predicted capacity based on seven different formulas and the wave equation. All of the piles extended into sand or gravel. The failure load is defined as the load at which the total settlment equals 10% of the pile diameter,

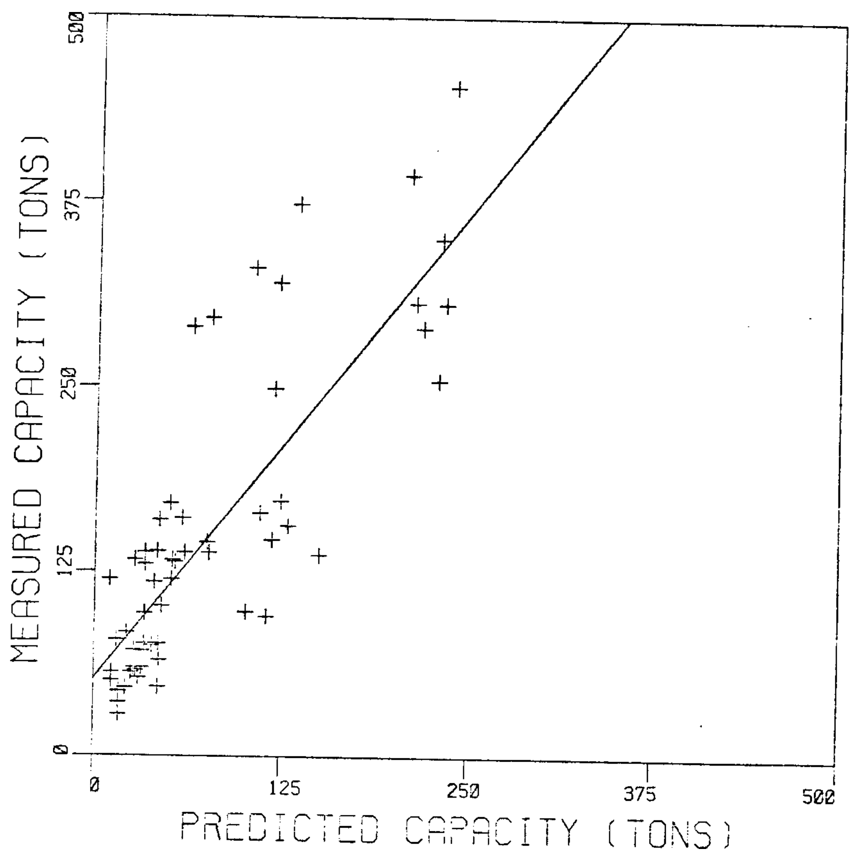

Figure 2. Engineering News Formula predicted pile capacity versus measured capacity based on Spangler and Mumma (27).

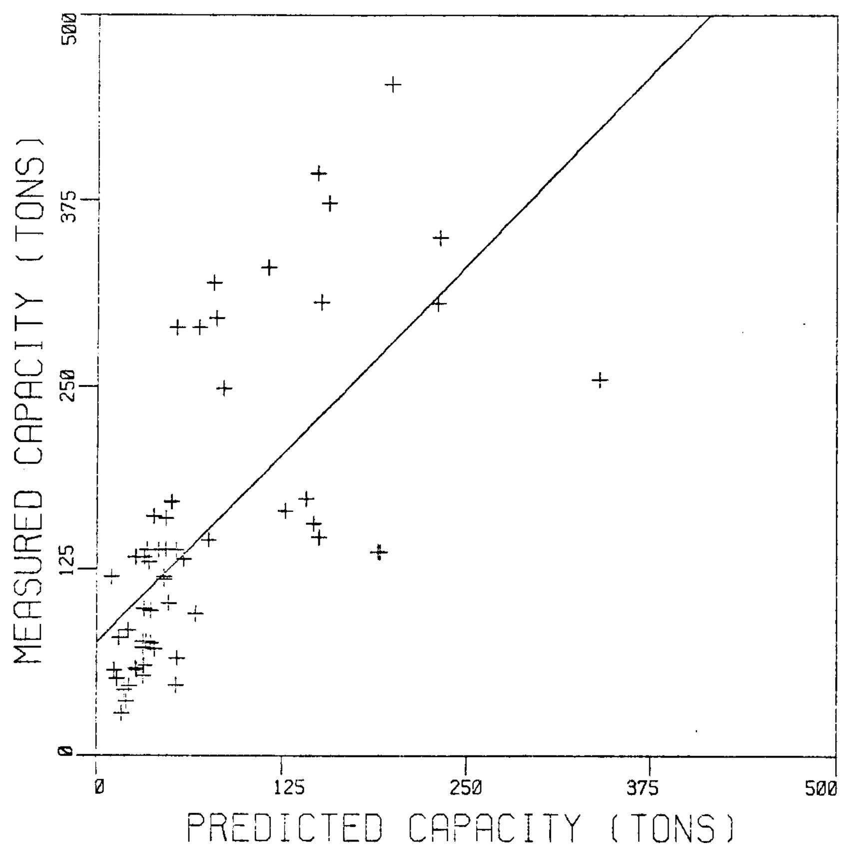

Figure 3. Eytelwein Formula predicted pile capacity versus measured capacity based on Spangler and Mumma (27).

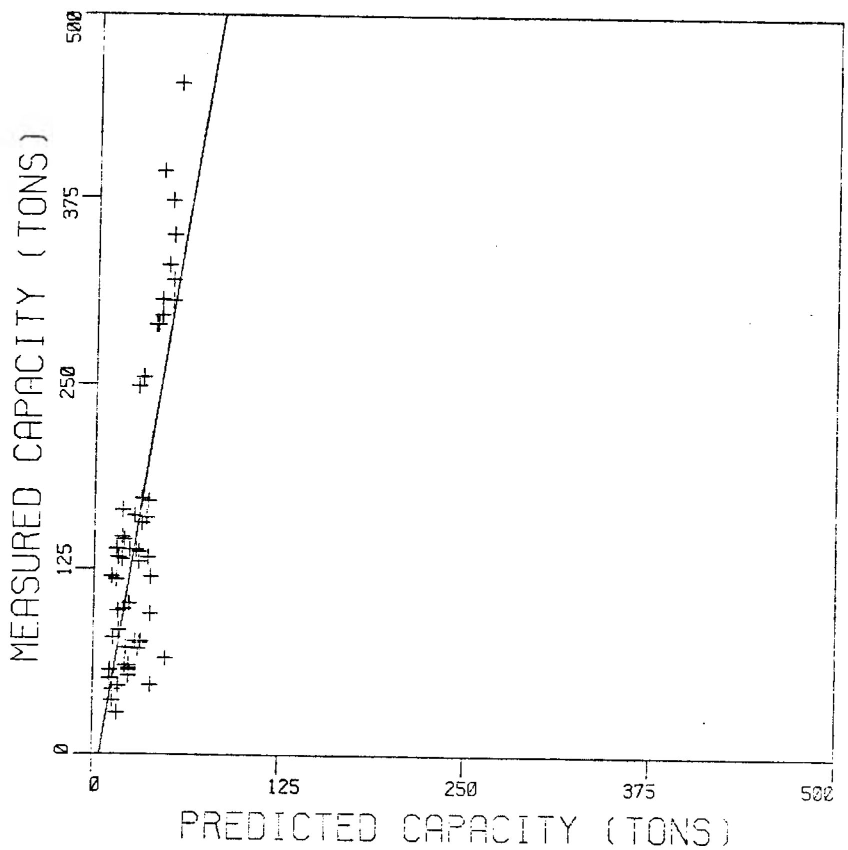

Figure 4. Pacific Coast Uniform Building Code Formula predicted pile capacity versus measured capacity based on Spangler and Mumma (27).

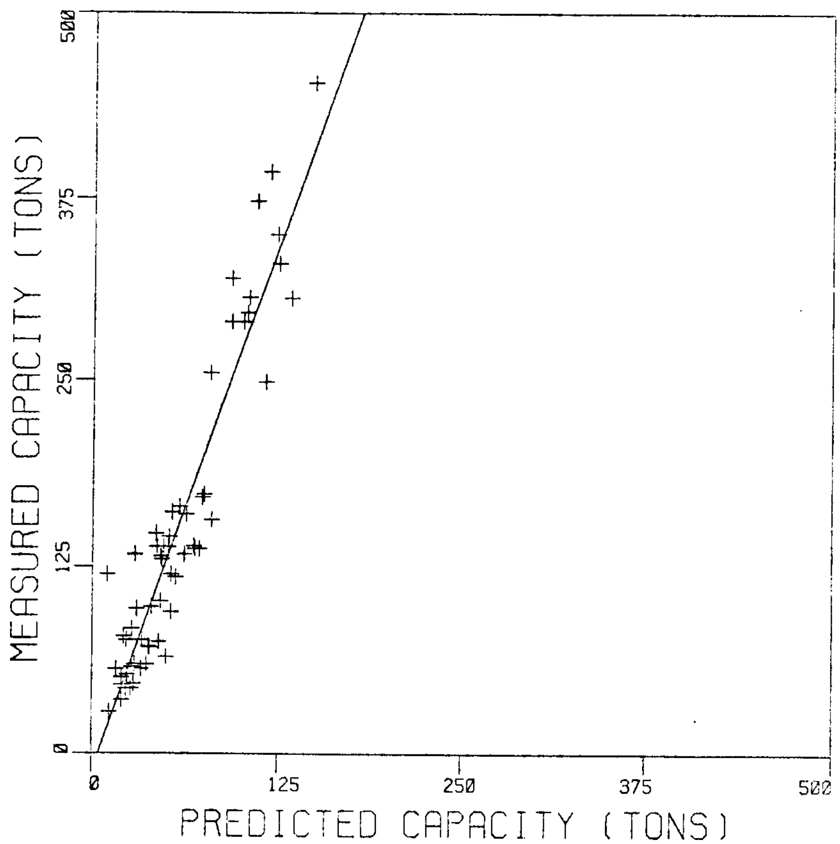

Figure 5. Rabe formula predicted pile capacity versus measured capacity based on Spangler and Mumma (27).

Table 9. Summary of Statistical Analysis by Agerschou (1)

Formula	Standard Deviation on $\log \frac{Q\ failure}{Q\ formula}$	Upper Limit for 96% Safety if Lower Limit is 1.0	Nominal Safety Factor	Number of Load Tests
Engineering News	0.78	26.0	0.86	171
Eytelwein's, from Sorensen and Hansen (26)	0.57	17.0	7.1	78
Hiley's, from Sorensen and Hansen (26)	0.27	3.8	1.4	50
Janbu's, from Sorensen and Hansen (26)	0.25	3.6	2.3	78
Danish	0.30	4.2	2.3	123
Danish from Sorensen and Hansen (26)	0.26	3.8	2.0	78
Wave Equation, as numerically integrated by Sorensen and Hansen (26)	0.23	3.9	2.6	78
Weisbach's	0.36	6.0	2.6	123

except for those tests which involved hydraulic jacking. When jacking was used, failure is defined as the maximum load that can be reached by jacking. Statistical evaluations of each formula were performed and are summarized in Table 9. The actual safety factor is expressed by the ratio of failure load to predicted ultimate load; however, the statistical evaluations are performed using the logarithm of the safety factor. In the first column of Table 9, the standard deviation is shown. The Engineering-News and Eytelwein's formulas have by far the largest standard deviation, indicating a great scatter in the safety factors obtained from the use of these equations. The wave equation analysis, although an early implementation not as accurate as current codes, has the lowest standard deviation.

A "nominal safety factor" was computed for each formula. This number is determined mathematically such that if the actual formula prediction is divided by the nominal safety factor to obtain a working load, the ratio of this working load to actual capacity will be less than 1.0 only 2% of the time. In other words if the bearing capacity predicted by the formula is divided by the nominal safety factor, 98% of all piles will have an actual safety factor of 1.0 or more.

Of perhaps more use than the nominal safety factor is the upper limit for 96% safety shown in the second column. If the nominal safety factor is used, 98% of all actual safety factors will be less than or equal to this value. For the Engineering News formula the value is 26, which means that if only 2% of the actual safety factors were allowed to be below 1.0, one would have to accept actual safety factors as high as 26 on some predictions. This clearly shows the scatter in the data and how uneconomical the Engineering News formula can be. The Eytelwein formula is not much better, with an upper limit for 96% safety of 17.0.

Weisbach's formula is in the middle with much lower standard deviation and upper limit than Engineering-News or Eytelwein, but considerably higher than the others. The Hiley, Janbu, and Danish formulas and the wave equation are all roughly comparable.

Mansur and Hunter (17), as part of a larger scope investigation, compared the ultimate capacity based on pile load tests for 12 piles with computed capacities based on the PCUBC, Janbu, and Engineering-News formulas. As did Spangler and Mumma (27), they used the average of four criteria to calculate ultimate capacity. These criteria are: (a) the load on the load-gross settlement curve where the slope equals 0.01 inch per ton, (b) the load on the net movement curve where the settlement equals 0.25 inch, (c) the load where the tangents to the initial and final portions of the load-gross settlement curve intersect, and (d) the load where the slope of the gross movement curve becomes disproportionate to the load applied. The piles included 4 steel pipes, 2 concrete, 2 steel H-piles, and 1 timber pile. Excellent correlation was found between predicted loads and test failure loads for the PCUBC and Janbu equations. Significantly worse results were obtained using the Engineering News formula. The ratio of actual failure load to predicted failure load for both PCUBC and Janbu averaged 1.07, and for ENR, 0.64. The range of ratios for PCUBC, Janbu, and ENR, respectively are 0.85-1.34, 0.88-1.43, and 0.48-0.93. Both PCUBC and Janbu, on the average, underpredict the actual failure load, while the ENR formula overpredicted in all cases by factors ranging from approximately 1.1 to 2.1.

Poplin (20) studied test pile data collected by the Louisiana Department of Highways, concentrating on 14-inch and 16-inch square precast concrete piles. Results of 24 load tests were compared with allowable capacity based on the Engineering News formula and a static soil mechanics analysis. The ultimate load based on load tests was the "load at onset of large displacement" or the load at which 1 inch of settlement occurs. On the average, predicted capacity based on static soil mechanics techniques was very close to actual capacity. The average ratio of predicted to actual capacity is 0.964; however, the range is 0.40 to 1.84. The Engineering News formula, in the form which includes a safety factor of 6.0, provided an average safety factor of approximately 2.0 (average predicted to actual capacity = 0.506). The ratio of predicted allowable load to actual failure load ranged from 0.107 to 1.0, corresponding to actual safety factors between 1.0 and 9.4. As with other studies, the extreme variability of the Engineering News formula is demonstrated. Poplin was unable to find any correlation between actual safety factor and either pile weight or pile size.

Kazmierowski and Devata (16) report the results of a pile load testing program undertaken in Ontario, Canada. Five test piles were driven into a soil profile consisting of irregular cohesive layers of clayey silt and granular layers of silt to silty sand with some gravel. The five piles consisted of an H-section with a reinforced top flange, a closed end steel pipe filled with concrete, two precast reinforced concrete piles, and a timber pile. All piles were driven by diesel hammers.

The ultimate capacity of each pile was predicted by the Modified Engineering News formula (Michigan equation), the Gates, Janbu, and Hiley formulas. In addition, a pile analyzer was used to predict ultimate bearing capacity, and to measure the stress and energy developed in the pile during driving. Static analyses also were conducted using Meyerhof's method for the portion of the pile embedded in cohesionless soil and Tomlinson's method for the portion in cohesive soil.

Kazmierowski and Devata calculate the ultimate pile capacity based on three different criteria (M.T.C., Davisson, and Flaate). The three criteria produced reasonably good agreement with a maximum deviation of 31%. Load test results and predicted capacities are shown in Table 10.

Based on these comparisons, the authors conclude that the Hiley, Janbu, and Gates formulas all give acceptable consistency, with the Hiley formula generally predicting the highest capacity and the Gates prediction generally on the low side. The Janbu formula was best for the concrete piles, Gates was best for the pipe and timber piles, while the Hiley equation was closest for the H-section.

Three different estimates of ultimate capacity were made for each pile using the analyzer--an initial field prediction, an initial re-analysis before the load test and a final re-analysis after the load test. These predictions are shown in Table 11 along with the load test results. Except for the longer of the two concrete piles, the field predictions were very accurate. (The consultants who operated the analyzer attributed the large error in the longer concrete pile to incorrect wave speed estimates in the field.) However, since two re-analyses were deemed necessary by the analyzer consultants, it is difficult to have much confidence in the initial values. This brings to home an important consideration concerning use of an analyzer: the results are subject to interpretation and can be very sensitive to the assumptions made.

Table 10. Results of Dynamic and Static Formula, Wave Equation and Load Test Analysis after Kazmierowski and Devata (16)

Test Pile Number and Name	Pile Load Test Failure Criteria			Dynamic Formula				Static Formula	Wave Equation
	M.T.C.	Davisson	Flaate	Hiley	Janbu	Gates	M.E.N.F.	After Meyerhoff & Tomlinson	Pile Analyser (Field)
1. Steel H	400	410	---	258	232	179	896	470	404
2. Steel pipe	225	270	230	210	184	216	1465	338	230
3. Deep concrete	200	188	265	280	206	176	510	568	360
4. Shallow concrete	225	263	278	383	311	166	593	172	230
5. Timber	100	88	110	272	217	140	693	140	80

Table 11. Comparison of Load Test and Pile Capacity Analyser Results after Kazmierowski and Devata (16)

Test Pile No.	Pile Type	Load-Test Capacities (tons)	Ultimate Bearing Capacity Predictions (tons)		
			Prior to Load Test		After Load Test
			(A) Field	(B) Initial Reanalysis	(C) Final Reanalysis
1	12HP74	400	404	400	402
2	Steel pipe 12 3/4" O.D.	225	230	340	230
3	Deep concrete 12" x 12"	200	360	400	242
4	Shallow concrete 12" x 12"	225	230	240	235
5	Timber	100	80	100	104

(A) Actual field analyser predictions obtained at the time of pile driving.

(B) Adjusted predictions (Class I Predictions) based on driving characteristics of piles and previous experience with analyser results by the Trow Group Ltd. Submitted before load testing operations.

(C) Second reanalysis of analyser field data as process in the laboratory after the completion of pile loading operations.

Olson and Flaate (19) measured the capacities of 93 piles driven into sandy soils and compared these values with predicted capacities using the Engineering News, Hiley, Gow, PCUBC, Janbu, Danish, and Gates formulas. Several different criteria were used to measure ultimate pile capacity from field tests. The authors state that this results in a scatter in the results of about 15%, but do not provide any specific information on the load test results. They performed linear regression analyses on the data to determine the slope and intercept of a straight line fit and calculated a correlation coefficient. Separate analyses were performed for timber piles (N=37), concrete piles (N=15), steel piles (N=41), and all 93 piles combined. A summary of statistical data they compiled is presented in Table 12. The authors found that in all cases the Engineering News and the Gow formulas were clearly inferior to the others. Janbu's formula was found to be most accurate for timber and steel piles, but no formula was determined to be best for concrete piles. This probably is due to the small number of concrete piles analyzed. The Janbu, Danish, and Gates formulas had the highest average correlation coefficients, although the PCUBC and Hiley formulas were not much lower.

The authors adjusted the three best formulas statistically to fit all observed data. They present three versions of the adjusted Gates formula, one each for timber, precast concrete, and steel piles:

Timber: $$Q_c = 7.2 \; e_h E_h \log (10/s) - 17 \qquad (2)$$

Precast Concrete: $$Q_c = 9.0 \; e_h E_h \log (10/s) - 27 \qquad (3)$$

Steel: $$Q_c = 123.0 \; e_h E_h \log (10/s) - 83 \qquad (4)$$

Table 12. Compilation of Statistical Parameters after Olson and Flaate (19)

Pile	Formula	N	A	B, in tons	r
Timber	Engineering News	37	0.45	16	0.28
	Gow	37	0.37	18	0.43
	Hiley	37	0.64	19	0.77
	Pacific Coast	37	0.80	14	0.74
	Janbu (C_d = 1)	37	0.98	9	0.86
	Danish	37	0.71	9	0.86
	Gates	37	1.30	-17	0.86
Concrete	Engineering News	15	0.20	72	0.11
	Gow	15	0.32	69	0.12
	Hiley	15	1.08	24	0.43
	Pacific Coast	15	1.57	-19	0.75
	Janbu (C_d = 1)	15	0.66	23	0.64
	Danish	15	0.60	11	0.69
	Gates	15	1.62	-27	0.65
Steel	Engineering News	41	0.28	43	0.37
	Gow	41	0.28	42	0.38
	Hiley	41	1.14	-10	0.76
	Pacific Coast	41	1.07	0	0.79
	Janbu (C_d = 1)	41	0.91	7	0.83
	Danish	41	0.89	-16	0.82
	Gates	41	2.34	-83	0.84
All	Engineering News	93	0.33	37	0.29
	Gow	93	0.32	37	0.36
	Hiley	93	0.92	7	0.72
	Pacific Coast	93	1.04	2	0.76
	Janbu (C_d = 1)	93	0.87	10	0.81
	Danish	93	0.77	-2	0.81
	Gates	93	1.81	-48	0.81

where e_h is the efficiency of the hammer, E_h is the nominal energy of the pile hammer in inch-tons per blow, s is the average set (in inches per blow) for the final 10 blows of the hammer, and Q_c is the predicted capacity in tons.

The authors did not use the actual pile hammer efficiencies on their study, as those data were not available to them. They used information on efficiency found in the literature. As they point out "the actual field values of e_h depend greatly on the condition of the hammer at the time of driving and may differ significantly from the values used in this study." Because of this, the general applicability of their adjusted formulas can be questioned. Their method of analysis, however, appears sound. In areas where a sufficiently large data base is available, the use of adjusted formulas might be very beneficial.

The authors state that similarly adjusted versions of the Janbu and Danish equations should be more accurate than the unadjusted versions, but are somewhat more difficult to use than the adjusted Gates equations. Therefore, they recommend use of the adjusted Gates equations. The accuracy of the adjusted equation, of course, is related to how well the data from this study are representative of all data. The authors state that the number of tests using timber and steel piles gives them "moderate confidence" in these data, however, additional data are needed on precast concrete piles.

Ramey and Hudgins (22) compared pile load test results with predictions by five dynamic equations, a wave equation analysis, and static soil mechanics methods. The load tests were all on piles located in Alabama and adjacent southeastern states. The ultimate capacity was defined as the load at which the slope of the load-settlement curve reached

0.01 inch/kip. The formulas used were the Engineering News, Modified Engineering News, Hiley, Gates, and Danish formulas. A total of 153 pile load tests were used with the following breakdown according to pile type: Steel-H (48), steel pipe (38), precast concrete (32), and timber (35). Forty-eight of the piles were driven into clayey soils, the remaining 105 were driven into predominately sandy soils. Statistical analyses were performed on the data in a manner similar to that done by Olson and Flaate (19). The analyses were broken down into different pile types, hammer energy, and soil type. In reviewing their results, one finding is quite surprising and overshadows all the others. In direct contrast to all other investigations reviewed, the Engineering News formula was found to give the best overall correlation with pile load test results. The Gates formula was almost as good as the Engineering News formula, but the Hiley equation was found to be the worst. Table 13 presents the results of statistical analyses performed on Alabama piles driven in sand. The statistical properties α, β, r, and S_e are, respectively, the intercept and slope of a straight line fit to the data, the correlation coefficient and the standard error of estimates. For a perfect fit, the values of α, β, r, and S_e would be 0, 1.0, 1.0, and 0, respectively. The data are divided into high energy and low energy hammers because it was found that hammer energy was a significant factor. For the same predicted capacity, steel-H piles driven with low energy hammers consistently have higher failure capacities than those driven with high energy hammers.

While the results described above may be surprising, the comparison of pile load tests with wave equation predictions is in line with the findings of other investigators. The authors found that the wave equation gave consistently better predictions of pile capacity compared to dynamic

Table 13. Summary of Regression Analyses Statistical Parameters for Alabama Piles in Sands after Ramey and Hudgins (22)

Pile Type	Hammer Category	Dynamic Equation	Parameters			
			α	β	r	S_e
Steel H	All Hammers	EN	48.30	.24	.638	35.79
		MEN	67.29	.162	.270	44.74
		Hiley	116.61	-.267	-.193	45.60
		Gates	37.38	.668	.292	44.45
		Danish	39.42	.397	.349	43.55
	High Energy	EN	9.23	.432	.827	7.83
		MEN	38.41	.121	.748	9.24
		Hiley	26.03	.271	.685	10.15
		Gates	13.10	.513	.773	8.82
		Danish	15.83	.307	.749	9.22
	Low Energy	EN	67.82	.191	.552	40.87
		MEN	65.62	.314	.476	43.09
		Hiley	100.02	.094	.049	48.96
		Gates	-9.04	1.547	.609	38.87
		Danish	35.40	.582	.530	41.55
Precast Concrete	All Hammers	EN	85.75	.185	.830	122.24
		MEN	41.16	.809	.805	129.67
		Hiley	-87.41	2.686	.844	117.41
		Gates	-68.83	2.293	.822	124.67
		Danish	77.48	.360	.850	115.29
	High Energy	EN	184.43	.140	.706	140.59
		MEN	160.76	.602	.693	143.08
		Hiley	30.39	2.201	.786	122.53
		Gates	62.01	1.744	.664	148.42
		Danish	171.34	.280	.749	131.40
	Low Energy	EN	42.14	.148	.480	24.76
		MEN	51.85	.238	.412	26.20
		Hiley	57.54	.304	.287	27.54
		Gates	-39.83	1.439	.581	23.41
		Danish	55.61	.175	.297	27.45

formulas. Table 14 presents a comparison of the wave equation method with dynamic formulas. The authors state that they had little information regarding pile driving accessories, capblocks, or condition of the hammer used, and therefore they expect that the accuracy of their wave equation analyses could be improved. The authors conclude that the wave equation method "should become a valuable tool for the foundation engineer."

Housel (13) presents the data gathered by the Michigan State Highway Department in their study of pile driving. The Engineering News formula and the Modified Engineering News formula predicted copacities were compared to failure loads of 19 test piles. Fourteen of the piles were 12-in (OD) steel pipes filled with concrete and driven closed-end; two were H-piles; three were open-end pipes, two of which were driven in clayey soils and one driven in granular soil.

While the results of the comparison show that the Modified Engineering News formula gives somewhat better results on the average, the authors conclude that: "from the standpoint of a reliable estimate of capacity, the range of variation improved only slightly and there seems to be no practicable way of increasing the formula's accuracy in predicting pile capacity for the great variety of field conditions under which piles must be driven."

In the Arkansas study cited in the previous chapter (28), seven piles were tested and predictions of capacity based on a wave equation analysis and the Engineering News, Hiley, and Danish formulas were compared to pile load test results. The Engineering News formula consistently overpredicted capacity by as much as 900%, while the Hiley formula and the wave equation predictions were quite accurate. The author recommends the use of both the Hiley equation and wave equation analyses.

Table 14. Comparison of Wave Equation and Dynamic Equation Statistical Parameters after Ramey and Hudgins (22)

Pile Type	Prediction Equation	Number of Tests	Standard Error	Correlation Coefficient
Steel-H	Wave	22	34.1	.725
	EN	22	36.2	.683
	MEN	22	49.4	.083
	Hiley	22	47.9	.259
	Gates	22	48.9	.165
	Danish	22	46.8	.330
Concrete 12" x 12"	Wave	6	6.5	.929
	EN	6	6.9	.906
	MEN	6	10.2	.782
	Hiley	6	13.1	.600
	Gates	6	7.0	.904
	Danish	6	9.9	.797

The literature cited above clearly shows that no one formula is consistently better than the others. Even when specific combinations of pile type, hammer, and soil conditions are considered, it is not possible to be sure which formula will be best. It does appear, however, that the Hiley, Janbu, and Gates equations are better on average, than the others examined. The PCUBC formula also gives reasonable estimates of pile capacity. With a single exception, all investigators found the Engineering News and Modified Engineering News formulas to be among the worst.

One of the difficulties in comparing the different studies presented above is that the methods used to determine the ultimate capacity from load tests varies from study to study. It was originally thought that the data from many studies could be combined so that plots similar to those shown in Figures 2-5 could be made and statistical analyses performed. Because of the large differences in load test interpretation, however, it was decided that the results of such an analysis would not be reliable.

All investigators were consistent with regard to wave equation methods. A wave equation analysis of static pile capacity was consistently equal to or better than the best formula predictions. This is despite the fact that old versions of wave equation computer programs were used in many studies, and input information was not always very accurate. It is likely that modern computer codes which include accurate information on specific hammers, combined with good geotechnical data, would compare even more favorably with dynamic formulas.

PRELIMINARY RECOMMENDATIONS

Based on the literature reviewed and the experiences of other state transportation departments, it appears that current WSDOT practice can be improved significantly. The Engineering News formula has been shown to be very inaccurate in most cases and can lead to both unacceptably high and low safety factors. Replacement of this formula is recommended. From a purely technical point of view, the use of a pile analyzer on all projects probably would be the best solution. The authors feel, however, that this is not practical for several reasons. An analyzer is expensive, difficult to maintain and requires very experienced personnel. For most pile driving jobs the benefits would probably not justify the costs. Scheduling problems could occur if only one analyzer and crew were available and there were several pile driving projects spread out across the state. In those cases where use of a pile analyzer is justified, a private company specializing in pile analyzer work could be used, as is the case now.

Expanded use of wave equation analysis is recommended with the goal of performing such an analysis on all pile driving projects. This will require training programs for project engineering staff and should be phased in over a period of time.

It is recommended that the Engineering News formula be replaced by one or more of the following: Hiley, Gates, Janbu, or PCUBC. Until such time as the necessary research has been completed, it is not known which of these formulas would be best for Washington soil conditions. However, any one of them should be an improvement.

Final recommendations will have to wait until the proposed research has been completed.

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