Pile Driving Formulas Revisited

Ryan Allin, P.E., M.ASCE[1], Garland Likins, P.E., M.ASCE[2], Jon Honeycutt, E.I.T.[3]

[1]Senior Engineer, Pile Dynamics, Inc., 30725 Aurora Road, Cleveland, OH 44139
[2]Senior Partner, Pile Dynamics, Inc., 30725 Aurora Road, Cleveland, OH 44139
[3]Staff Engineer, GRL Engineers, Inc., 511 Old Covington Highway, Hammond, LA 70403

ABSTRACT: Energy formulas have historically been used to estimate capacity for driven piles. Some engineers still rely on them today and researchers attempt to refine the safety factors or resistance factors to allow a more economic result. However, energy formulas make broad assumptions about "average hammer performance" that cannot always be properly accounted for during installation and thus leave themselves open to gross inaccuracies on any "individual project", and therefore significant risk. Additionally, since common energy formulas do not model the driving system or pile or soil, observing hammer stroke and blow count is not sufficient to guarantee a specific capacity has been achieved on an individual project.

It has been well documented by measurements that supposedly similarly rated hammers can transfer significantly different energies to the pile. Using the wave equation analysis to model these vastly different hammer system efficiencies, the resulting variance on calculated capacity from commonly used energy formulas is investigated and presented. Set-up assumptions contribute to further inaccuracies.

INTRODUCTION

Driven piles have long been a choice for foundations where the supported structure is on soft soils at the ground surface. Herodotus in his book "The Histories" dated around 450 B.C. reports on pile driving activity, and the Romans are well known to have used driven piles. As noted in FIG. 1, one can find use of pile drivers throughout the centuries, and that includes the very first European settlement in North America at Jamestown Virginia where a 1500 pound drop weight was discovered and the model presented at their museum. FIG. 1 likely represents the general process, although some have used groups of humans to hoist the drop weight rather than beasts of burden.

Obviously, timber piles were all that was then available and could only be installed to relatively low pile capacity, even when driven full length or to refusal. Due to then available drop or steam powered hammers of relatively small size, these low capacity timber piles dominated until the early to middle of the 20th century. Into this culture, "pile driving formulas" were developed to try and estimate the ultimate capacity of the installed piles based on the observed set of the pile and the energy rating of the hammer.

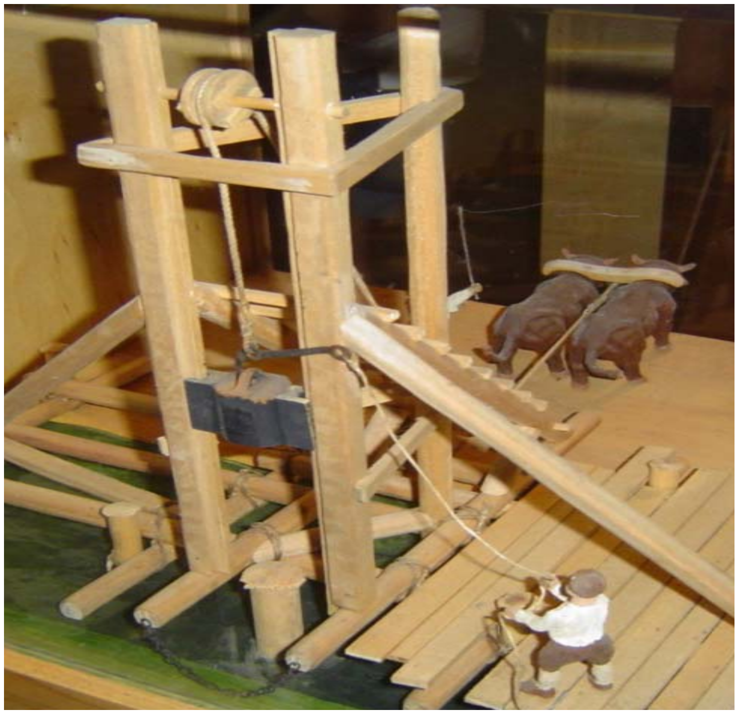

FIG. 1. Model pile driver at Jamestown Virginia.

The first North American uses of a "pile driving formula" (Howe, 1898) were in 1845 by Col. Mason for Fort Montgomery at Lake Champlain and in 1848 by Major Sanders for Fort Delaware on Pea Island to protect the harbors of Wilmington and Philadelphia. The 6000 yellow pine timber piles at Fort Delaware were installed over a period of three years by a steam hammer with a 2000 pound ram weight. Sanders' simple formula ($R = Wh/8s$, where R is the capacity, W the ram weight, h the drop height, and s the pile set per blow) used a nominal safety factor of eight, the term in the denominator.

Arthur Wellington in the December 29, 1888 issue of Engineering News published his 'Engineering News' formula, again designed for drop hammers and timber piles and it added a "lost set" term into the basic equation used by Sanders (Chellis, 1951: Chellis lists 20 different formulas in this classic book). In 1925, A. Hiley introduced a more "complete" formula trying to account for various "losses". More recent formulas developed after 1940 include the Gates formula, promoted by the U.S. Bureau of Public Roads (later the Federal Highway Administration). Several of these long-ago formulas (some simple and others complex) are still in some use today.

Pile driving formulas were commonly used in the early 1900s to estimate driven pile capacity, because then there was really not much alternative, and many comparisons were then made with static loading tests. ASCE formed a Committee in 1930 to review the accuracy of the pile driving formulas then in use. After a decade long study, the "Committee on Pile Driving Formulae and Tests" produced two reports in May 1941 and sparked a remarkable series in the ASCE Proceedings of 28 discussions by Terzaghi, Casagrande, Peck, Tschebotarioff, Dames & Moore, and

Proctor, to mention only a few very prominent responding engineers. It is prudent to review what these geotechnical "giants" said about pile driving formulas. A summary (Likins et al. 2012) has reported on the main conclusions of each discussion. Remembering this past should guide the current engineering community to understand what should, or should not, be done in the present. But the end result of this extensive study was all pile driving formulas, including both simple and complex formulas, were widely discouraged as inaccurate, and the only reliable method for capacity determination was deemed to be a static loading test which was then the only other alternative.

In the last few decades, pile dimensions have greatly increased and pile driving hammer rated energies have grown enormously, resulting in significant increases in the typical loads assigned to the installed piles, far beyond the meager loads achieved for timber piles driven by drop hammers which are the basis for pile driving formulas. Yet, amazingly, these formulas are still applied, even when they are far from the original experience database for their development. It should be further noted that these formula are crude and generally do not consider pile length, or pile weight, or soil type, or driving system components such as cushions or helmets, or the significantly different impact features of now-common diesel hammers. Formulas incorrectly consider the pile to be rigid, rather than transmitting stress waves.

Pile driving formulas were developed to be used with end of drive data since that was correlated with static tests; they then assume the soil damping during driving will balance the set-up usually experienced with time. This premise, while true on average, remains dangerously false for any individual project site as discussed by Rausche et.al. (2004).

While it had been long recognized that pile driving created travelling “stress waves”, solutions solving real issues were not available until the advent of the digital computer. A practical solution called the “wave equation” was first developed and implemented on IBM computers by the mid 1950’s by E.A.L. Smith of the Raymond Concrete Pile Company. Smith (1960) published his method which was a finite difference solution using masses and springs to realistically model the various components using the engineering properties of the hammer, driving system components (helmet and cushions), elastic pile allowing stress wave propagation, and soils of various types having both static and damping behavior. This analysis kept track of the each mass’s relative movement, allowing investigation of driving stresses which were before impossible to determine with simple pile driving formulas. For a series of assumed ultimate capacities at one depth and with the same relative resistance distribution, the corresponding computed net displacement (“set” per blow) could be computed and then compiled in a resistance versus blow count (inverse of “set”) plot called a “bearing graph”.

The wave equation allowed modeling of their non-uniform mandrels for their proprietary step taper piles, and to investigate the driving stresses in concrete piles, particularly tension stresses that were causing considerable pile damage.

This wave equation method became widely available in the mid 1970’s with the advent of the “WEAP” program (“Wave Equation Analysis of Piles”) which included an enhanced thermodynamic model for diesel hammers and comparison against actual field measurements (Goble and Rausche, 1976). This program has been subsequently extensively expanded to include analysis of residual stresses and additional input and output options including “Inspector’s Charts” and “Drivability Analysis” (which incorporates static analyses versus depth with factors to account for changed stress conditions during driving) to predict the blow count as a function of pile embedment during installation and the subsequent effects of set-up or relaxation.

Lawton et al (1986) made an extensive literature study, including results of nine published correlation studies by others, and a survey of most of the State Departments of Transportation. They found that “*the ENR formula, either in its original form or more often in a modified version, is by far the most popular dynamic formula used.*” This is alarming since 8 of the 9 correlation studies “*found the ENR and modified ENR formulas to be among the worst.*” Lawton also found “*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, despite old versions of wave equation computer programs being used in many studies in which input information was not always accurate.*” They reasonably surmise better correlations with newer wave equation programs and accurate input information.

PILE DRIVING VARIABLES

One of the many deficiencies in using pile driving formulas is the assumption that the pile is rigid, or that the elastic nature of a pile can be accounted for in some broad based ‘set loss’. FIG. 2 shows wave equation results from an HP14x89 H-pile driven to refusal blow counts with a J&M 82 hydraulic hammer (operated at full 4 ft stroke; rated at 32.8 kip ft). The soil model had 90% end bearing and 10% shaft resistance, all quakes were 0.1 inch and Smith damping was 0.15 sec/ft for both shaft and toe. Note the analysis, which models the pile as a linear elastic rod, indicates a great variance of capacity based only on varying the pile length. For the short 20 ft pile length, 20.9 kip-ft energy is transferred to pile top but only 9.9 kip ft is transmitted to the bottom, while for the 80 ft pile the respective energies are higher at the top (23.9 kip ft) and lower at the bottom (8.0 kip ft). The wave equation demonstrates longer piles accept more energy initially before part is returned to the hammer, but much of the energy is used by storing as elastic pile compression and less is actually available at the pile toe to advance the pile or activate the resistance. With less energy available at the toe, the longer piles reach refusal at a lower capacity, as the wave equation demonstrates. Pile driving formulas however, would yield the same pile capacity regardless of pile length, which is obviously incorrect. Further, these pile driving formulas do not even take into account the pile section size which is absurd considering even the most basic static analysis method would require knowledge of the pile section area and circumference to estimate pile capacity.

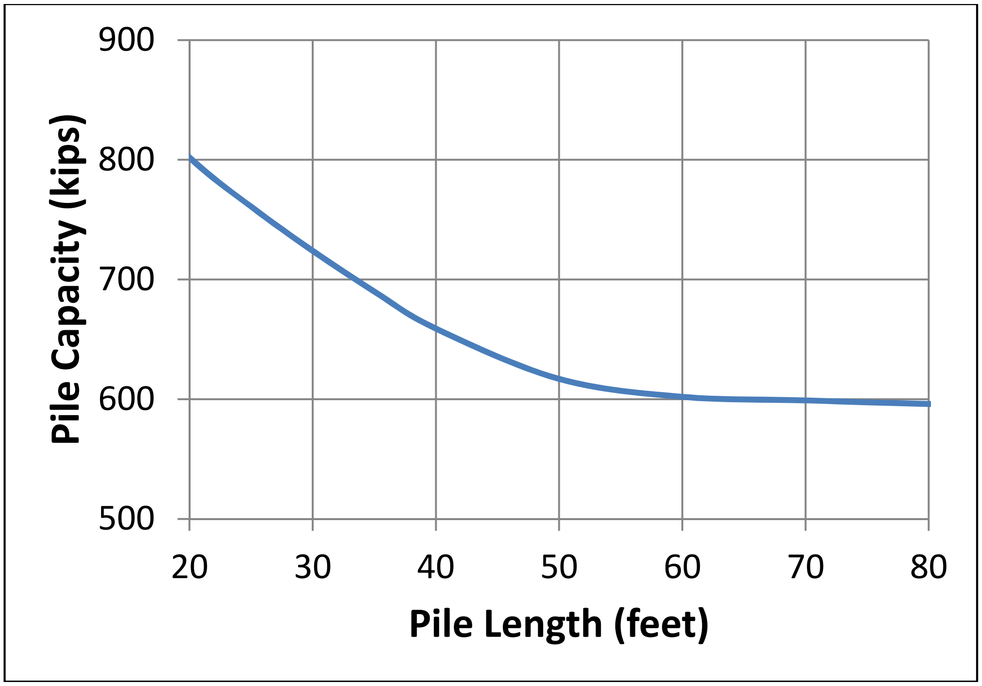

FIG. 2. Wave equation shows capacity depends on pile length at refusal.

Beyond the issue of pile length, pile driving formulas generally do not included any consideration for pile cross sectional area, pile or hammer cushions, helmets weights, motive power (cable, air pressure, diesel cycle), or soil behavior (soil type or pile embedment). These components can all be modeled in a wave equation and each variable makes a difference in the solutions obtained in wave equation. But the real major problems are likely to be soil and hammer performance. These major difficulties are further discussed in the following sections.

Another potential difference is drop height for same energy rating. A diesel hammer with a high stroke and relatively low ram weight will create a higher impact force than a hydraulic or air hammer at same rated energy but with fixed lower stroke and heavier ram. From basic wave mechanics considerations, the higher stroke diesel hammer will then outperform the low stroke air hammer when the driving gets hard since the higher impact force, resulting from the diesel hammer's higher stroke, will overcome higher soil resistances and drive the pile further. Any pile driving formula will not recognize this difference and give the same result for a similar rated energy.

SOIL EFFECTS

In addition to pile length effects, soil "quakes" (elasticity limits) and damping parameters can have drastic effects on capacity versus blow count. FIG. 3 models a 75 ft long 14x89 H-pile being driven with a Vulcan 506 air hammer with a 5 ft stroke. The wave equation used the standard efficiency of 67%, which account for reductions due to friction losses during the drop, and two different soil conditions, namely a sand

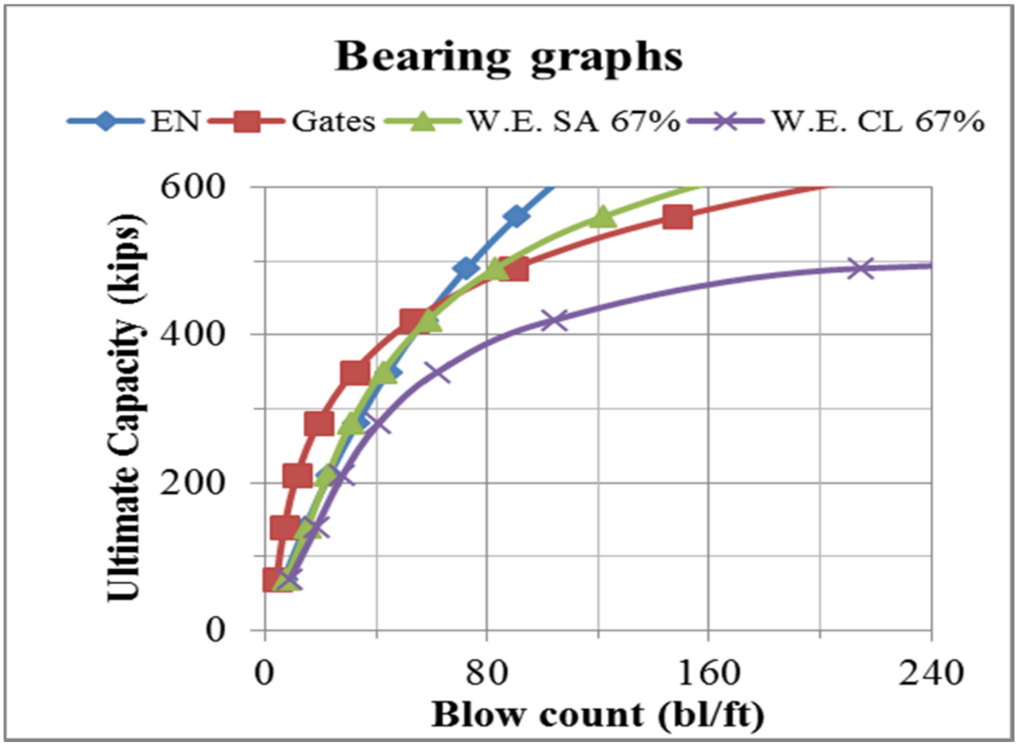

FIG. 3. Comparison of formula with wave equation.

(SA) having 22% of the resistance with a triangular shaft resistance distribution, and a clay (CL) with 90% of the resistance on the shaft. Note that just by modifying the dynamic soil parameters (soil damping and quake, nad resistance distribution) that the wave equation model will yield quite different results. It is further noted from this comparison that above about 500 kips that EN formula overpredicts the capacity substantially while the Gates formula overpredicts capacity at the lower blow counts or if the soil conditions are cohesive. Caution is given to assume formulas are safe at any level since changing the pile cross section can alter the wave equation result substantially, so the "relative" differences in FIG. 3 cannot be reliable either.

Several discussers in the 1940's study noted that formulas should be restricted to cohesionless soil applications. Chellis (1951) states "*a formula can apply only in the case of cohesionless strata, such as sand, gravel or permeable fill*". Yet today this intended restriction is ignored.

HAMMER EFFICIENCY

The Hiley formula tries to at least account for total pile weight; however this formula, or any formula, generally assumes normal hammer performance. In addition there are considerable safety concerns of requiring an individual to record the "set-rebound" of the pile, as required by Hiley, while standing adjacent to the pile directly below the operating pile hammer; in the USA this would be prohibited as unsafe.

An extremely serious weakness of using only a pile driving formula or even wave equation analysis for any specific project is that the actual hammer performance of any individual hammer can be quite variable — and unknown — and this serious limitation applies to any pure analysis method that lacks measurements. Modern dynamic testing (Likins et al, 2008) measures the force and velocity during the pile impact which can be used to estimate capacity, driving stresses, pile integrity and energy transferred to the pile; energy transfer is particularly relevant to this discussion. These measurements clearly show wide variability in measured transfer energy in their ratio to the manufacturer's rated energy; differences of factors of two in energy transfer are common between supposedly identical hammers operating in the same hammer-pile-soil systems, and for most formulas this would result in factor of two differences in capacity!

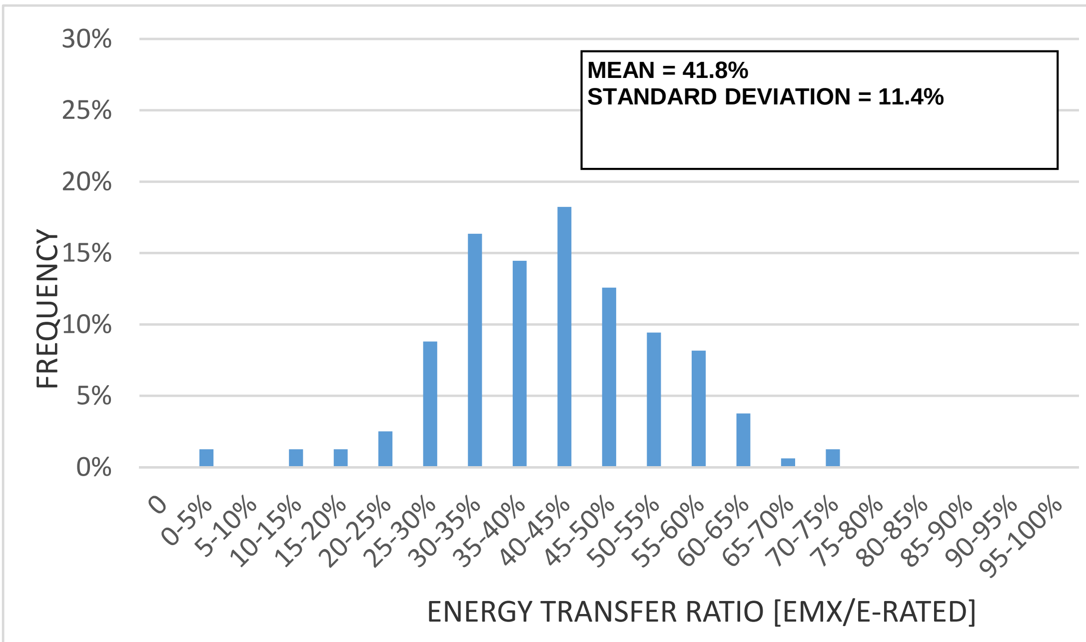

FIG. 4: Measured transfer ratio of air/steam hammers on concrete piles (n=156); courtesy GRL.

FIG. 4 shows the measured transfer efficiency of Air/Steam hammers on Concrete piles compiled over 30 years. As is shown in FIG. 4, the average transfer efficiency is approximately 42% with a standard deviation of 11.4%. If we model a Vulcan 506 driving a 16" square concrete pile so that the transfer efficiency mimics the average values reported in FIG. 4 at 420 kips and then vary the hammer efficiency even within one standard deviation of the mean transfer efficiency, that would result in a change in blow count of as much as 57% of the value derived by assuming the standard transfer efficiency (FIG. 5). From FIG. 5 the potential variation within two standard deviations (one in twenty tests would fall outside even this generous limit) would result in a variance of the capacity versus blow count that would render any connection with the original development of the formula meaningless. Most of the deviations compared to normal hammer performance are due to malfunctions in the hammer such as excess friction on the guides, pile cushion issues for concrete piles, valve timing irregularities causing preadmission of the motive air pressure for air hammers, or preignition in diesel hammers. The result would be a premature higher blow count indicating an overprediction of capacity, but at a reduced embedment depth and reduced actual capacity compared with the correct depth required for the true desired capacity, an unsafe situation that easily leads to distress or failure in the foundation.

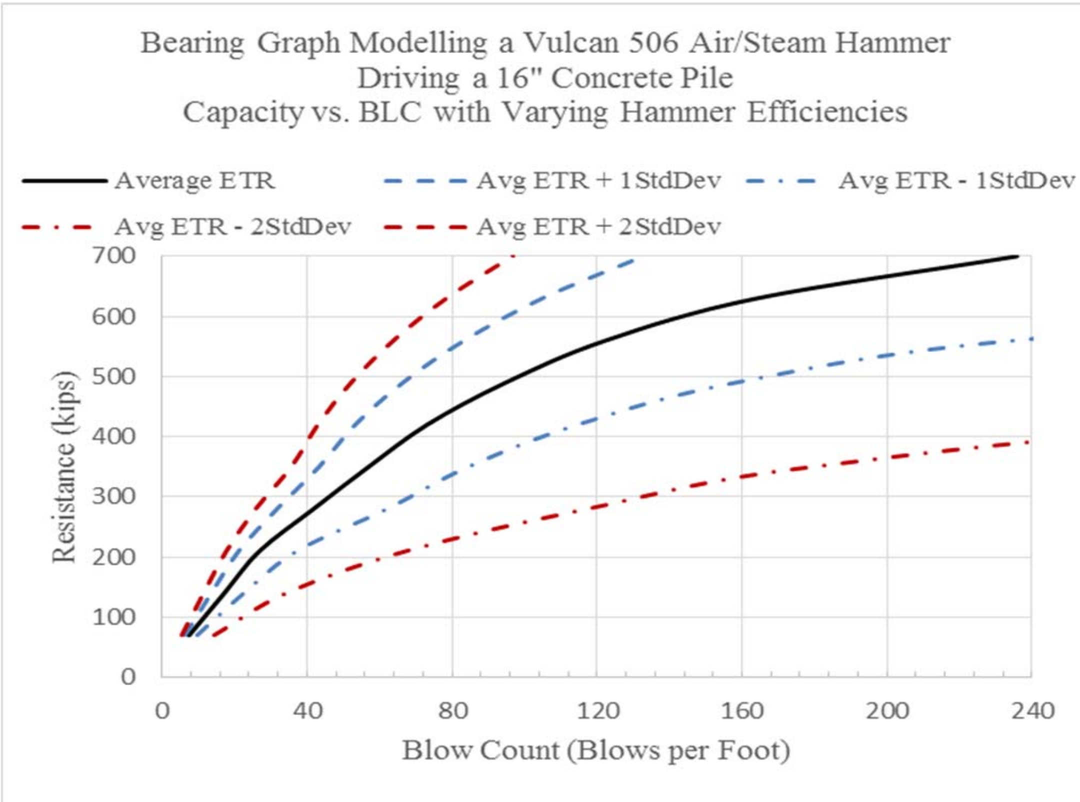

FIG. 5: Capacity and blow count variation with varying hammer efficiencies.

Using a Vulcan 506 air hammer and the same H-pile and soils as the study of FIG. 3. Comparison of formula with wave equation. (with both sand-SA and clay-CL soils), the effect of hammer performance is shown in FIG. 6 for both soil types and varying hammer efficiencies. The hammer efficiencies causing a normal energy transfer ratio (hammer efficiency 62%; transfer ratio 56%) and two standard deviations above normal (efficiency 85%; transfer ratio 81%) and two standard deviations below normal (efficiency 33%; transfer ratio 31%) are investigated. It becomes clear that soil type and hammer efficiency cannot be ignored since at any given observed blow count the capacity determined may then vary by more than a factor of two. By contrast, pile driving formulas would not consider these important parameters and produce the curves for pile driving formulas already shown in FIG. 3.

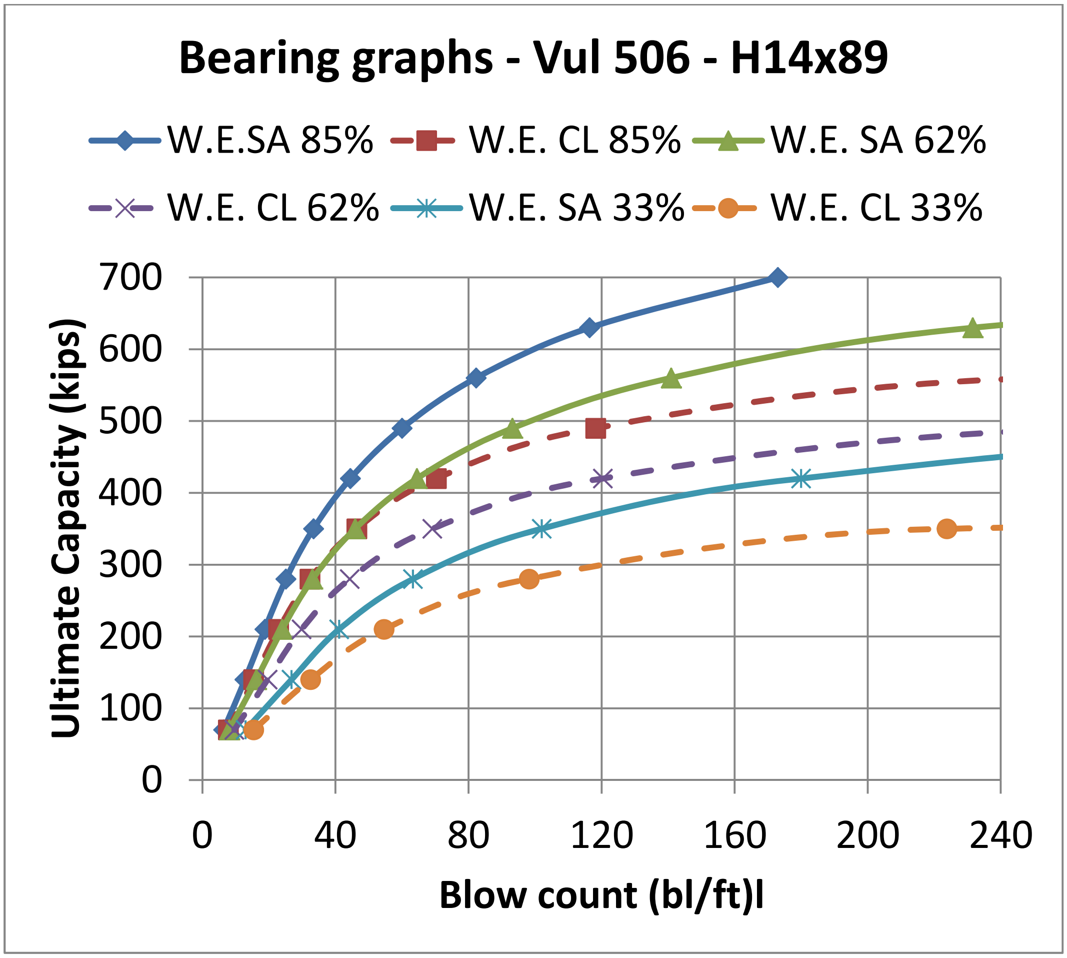

FIG. 6. Wave equation with varying soil type and hammer efficiency.

The soil types should be known on a site from a proper soils investigation, and can therefore be properly modeled in a wave equation analysis (but not in a pile driving formula). However soil strength from the typical SPT N-values has shown wide variability so a simple static analysis is widely viewed with caution with knowledgeable engineers selecting properties very conservatively for very small projects, or by requiring either static testing or dynamic testing on projects of any reasonable size and importance.

However, hammer performance can only be properly assessed by dynamic testing measurements during pile installation. The risk of not detecting an underperforming hammer, causing a less than sufficient embedment and low capacity, can be avoided by simply requiring even a minimum amount of dynamic testing to assure the hammer is performing to normal expectations, and on larger projects to have periodic tests to assure consistent performance for the duration of the pile driving activity. Once hammer performance is known from measurements, and soil resistance assessed, then a "refined wave equation analysis" (Rausche, 2009) would provide a good method to select the final termination criteria for installation.

Table 1. Statistical comparisons of methods

Method	Status	Mean	C.O.V
WEAP	BOR	1.22	0.35
CAPWAP	BOR	0.92	0.22
EN	EOD	1.22	0.74
EN	BOR	1.89	0.46
Gates	EOD	0.96	0.41
Gates	BOR	1.33	0.48

Hannigan et al (2006) presents statistical results (Table 1) from comparing static load tests with pile driving formulas, wave equation (WEAP), and dynamic testing from the signal matching software CAPWAP® for both end of drive (EOD) and begin of restrike (BOR). As observed in Table 1, the statistical mean for the formulas are both better for EOD than for BOR, although the coefficient of variation (C.O.V.), which is a better measure of the reliability, are higher (worse) for formulas than for the other methods. If a static test is not available, dynamic testing with CAPWAP at BOR has the lowest or best C.O.V. and, with a mean of just under unity, is clearly then the preferred method to confirm capacity. A dynamic test at BOR best considers the changing soil response, usually due to strength gains from set-up, but in some soil conditions from losses in relaxation.

CONCLUSIONS

While pile driving formulas have been widely used historically in the pile driving industry, their use is coupled with the acceptance of gross assumptions and therefore gross inaccuracies. Pile Driving formula, assuming a rigid pile while ignoring the soil type, and not taking into account various hammer components or hammer type or the actual transfer efficiency of a specific hammer, make any positive correlation of capacity to driving resistance coincidental at best. Considering that pile driving formulas were developed for conditions far removed from today's common practice, and that the correlation with static load tests is very poor, the recommendations of an esteemed 1930's task group studying formulas to discredit formulas and avoid their use remains the best advice for today.

The Wave Equation offers a much more realistic pile, soil and hammer model and can better correlate a capacity to an observed blow count, based on normal hammer efficiency and reasonable assumptions of soil properties based on a soil boring. The remaining problem then becomes how to verify the hammer and soil assumptions are correct. Assuming the soils are reasonably known from a proper soils investigation, wave equation analysis is useful to refine the driving criteria after some dynamic testing has been performed to confirm the actual hammer performance.

Load testing, either statically or dynamically, are both viable means to verify pile capacity. In addition to lower cost, dynamic testing has the major benefit of assessing hammer performance to avoid otherwise undetected hammer malfunctions and evaluating piles stresses during installation which both aid in developing driving criteria during the installation process. Ultimately field measurements of some kind will always be necessary to assure proper pile serviceability and for any driving criteria to be meaningful.

REFERENCES

Chellis, R.D. (1951). Pile Foundations. McGraw Hill Book Company

Goble, G. and Rausche, F., 1976, "Wave Equation Analysis of Piles – WEAP Program, U.S. Department of Transportation, Federal Highway Administration, Office of Research and Development, Washington D.C., (Volumes I-IV).

Hannigan, P.J., Goble, G., Likins, G. and Rausche, F. (2006). Design and Construction of Driven Pile Foundations, (Volume II), *Report FHWA-NHI-05-043*, National Highway Institute, Federal Highway Administration.

Howe, Horace, 1898. "Some Instances of Piles and Pile Driving, New and Old", Journal of the Association of Engineering Societies, (Volume XX, No. 4), pp 257-312.

Lawton, E. C., Fragaszy, R. J., Higgins, J. D., Kilian, A. P., and Peters, A. J. (1986). "Review of Methods for Estimating Pile Capacity*," Transportation Research Record No. 1105: Structure Foundations,* Transportation Research Board, pp. 32-40.

Likins, G.E., Fellenius, B.H., and Holtz, R.D., (2012). "Pile Driving Formulas—Past and Present.." Full-Scale Testing in Foundation Design, Geotechnical Special Publication 227, ASCE, Reston, VA, pp. 17.

Likins, G. E., Piscsalko, G., Roppel, S., Rausche, F., September 2008. *PDA Testing: 2008 State of the Art*. Proceedings of the Eighth International Conference on the Application of Stress Wave Theory to Piles 2008: Lisbon, Portugal; pp. 395-402

Rausche, F., Nagy, M., Webster, S., Liang, L., May 2009. *CAPWAP and Refined Wave Equation Analyses for Drivability Predictions and Capacity Assessment of Offshore Pile Installations*. Proceedings of the ASME 28TH International Conference on Ocean, Offshore and Arctic Engineering: Honolulu, Hawaii; 1-9.

Rausche, F., Robinson, B., Likins, G.E. (2004). On the prediction of long term pile capacity from end-of-driving information". Current Practices and Future Trends in Deep Foundations, ASCE Geotechnical Special Publication, GSP125, pp. 77-95.

Smith, E.A.L. (1960) *Pile-Driving Analysis by the Wave Equation.* Journal of the Engineering Mechanics Division, Proceedings of the American Society of Civil Engineers. (Volume 86, No. EM 4), August, pp.35-61

Committee on the Bearing Value of Pile Foundations (1941). "Pile Driving Formulas: Progress Report of the Committee," Proceedings of the American Society of Civil Engineers, (Volume 67, No. 5), pp. 853-866.

Discussions in Proceedings of the American Society of Civil Engineers:

67(7) Issue of September 1941

G.G. Greulich pp. 1391 - 1396

C.O. Emerson D.O. Northrup pp. 1396 - 1398

H.J. Engel pp. 1398 - 1400

J.D. Watson pp. 1400 - 1401

67(8) Issue of October 1941

R.D. Chellis pp. 1517 - 1537

L. White pp. 1538 - 1541

J. G. Mason pp. 1541 - 1544

C.S. Proctor pp. 1544 - 1545

G. Paaswell pp. 1545 - 1547

A. Woolf pp. 1547 - 1548

67(9) Issue of November 1941

H.T. Evans pp. 1784 - 1789

W.G. Atwood pp. 1789 – 1790

D.M. Burmister pp. 1790 - 1791

W.E. Belcher pp. 1791 - 1793

C.C. Williams pp. 1793 - 1794

D.P. Krynine pp. 1794 – 1798

67(10) Issue of December 1941

T. Dames & W. Moore pp. 1939 - 1946

M.M. Upson pp. 1947 - 1949

G.G. Tschebotarioff pp. 1949 - 1951

R.F. Legget pp. 1951 - 1954

J. Feld pp. 1954 - 1956

68(1) Issue of January 1942

L.C. Wilcoxen pp. 169 - 170

H.A. Mohr pp. 170 - 172

A.E. Cummings pp. 172 - 181

68(2) Issue of February 1942

K. Terzaghi pp. 311 - 323

R.B. Peck pp. 323 - 324

A. Casagrande pp. 324 - 331

68(3) Issue of March 1942

C.W. Dunham pp. 445 - 446

68(5) Issue of May 1942

R.E. Bakenhus (Closure) pp. 7885 - 800

GEOTECHNICAL SPECIAL PUBLICATION NO. 256

IFCEE 2015

PROCEEDINGS OF THE INTERNATIONAL FOUNDATIONS CONGRESS AND EQUIPMENT EXPO 2015

March 17-21, 2015
San Antonio, Texas

SPONSORED BY
International Association of Foundation Drilling
Deep Foundations Institute
Pile Driving Contractors Association
The Geo-Institute of the American Society of Civil Engineers

EDITED BY
Magued Iskander, Ph.D., P.E.
Muhannad T. Suleiman, Ph.D.
J. Brian Anderson, Ph.D., P.E.
Debra F. Laefer, Ph.D.

Published by the American Society of Civil Engineers