Pile Driving Formulas — Past and Present

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ABSTRACT

Dynamic formulas were in common use in the early part of the 1900s to estimate capacity of a driven pile, and many comparisons were then made with static loading tests. An ASCE Committee was formed in the 1930s to review and make recommendations on the proper use of dynamic formulas; after almost a decade long study, a report was issued in May 1941. The report generated considerable controversy and a remarkable 28 discussions in the Proceedings of the ASCE by several very high profile engineers. Considering the current renewed search by some agencies to find a better dynamic formula, primarily to increase the LRFD resistance factor to make designs more economical, it is prudent that we revisit this work to avoid repeating some of the same mistakes. Our review of the extensive discussion comments is presented to better define the problem, and to produce more realistic expectations of what can be achieved by a dynamic formula. The discussions also included to a lesser extent considerations of static loading test procedures and interpretations, which are also discussed in this paper.

INTRODUCTION

A look at the past is often helpful in understanding what should (or should not) be done in the present. George Santayana said "*Those who cannot remember the past are condemned to repeat it*", and this philosophy has been echoed by many, most famously, Winston Churchill. The statement applies not just to historical events, but also to the hard-won experience of those who went before us. The authors were alerted to a series of Discussions published seventy years ago in the ASCE Proceedings concerning pile driving formulas. One would be excused for believing that in current practice dynamic formulas would have been replaced by modern methods based on predictive dynamic analysis (WEAP) coupled with dynamic monitoring (PDA and CAPWAP®). However, curiously, there has been a revival in the use of dynamic formulas triggered by the emerging Load and Resistance Factor Design (LRFD) in response to its emphasis on capacity. It is therefore of interest to see what the "giants" of two to three generations ago, long before the advent of computer-aided design, thought about pile driving formulas, when it was "the only trick in the book".

In the 1930s, a “Committee on Pile Driving Formulae and Tests” made a more than decade long study under the leadership of U.S. Navy Admiral (Ret.) Bakenhus. This Committee produced two reports in May 1941. Report A focused on evaluations of various dynamic formulas. Report B focused more on loading tests, but also included additional advice on dynamic formulas. These two reports sparked a remarkable series of 28 Discussions by 30 engineers in the ASCE Proceedings and Foundation Engineering from September 1941 through March 1942, covering approximately 140 pages of text. Discussers include many very recognizable names, e.g., Terzaghi, Casagrande, Peck, Tschebotarioff, and Proctor to mention only a few who should be known also by most young engineers. Discussers came from prestigious universities as well as companies still well known today.

Any terms used in these Discussions about “*dynamic analysis*”, “*dynamic test*”, or similar, refer to the now common term “*dynamic formula*”, since modern dynamic pile measurements with a Pile Driving Analyzer® and signal matching CAPWAP® software, as well as “wave equation analysis” (e.g., WEAP) were still decades into the future. The terms used of “*load testing*” or “*loading tests*” or simply “*tests*” similarly refer to “*static loading tests*” (as now performed according to ASTM D 1143 procedures, which guidelines has incorporated much from the 1941-1942 Discussion).

PILE DRIVING FORMULAS

We must remember the conditions prevailing during the creation of most formulas. Pile sizes were typically twelve inches or smaller. Wood piles were common. Drop hammers or single-acting steam hammers dominated, although the then recently introduced double-acting or differential-acting steam hammers are mentioned by several of the discussers as being problematic for formulas. The diesel hammer, so common today, had not yet been introduced into American practice. Soil mechanics was still very much in its infancy in this "pre-Terzaghi-Peck" era. There were, at that time, no accepted standards for either conducting static loading tests or interpreting the resulting data.

The first significant use in America was probably developed by a military engineer, Major John Stanton, in 1851 for piling on Pea Patch Island in the Delaware River to support Fort Delaware, designed to protect Philadelphia from sea attack. The 6,000 timber piles took three years to install using a 2000 pound drop weight operated from a floating barge. Stanton’s simple formula ($R = Wh/8s$, where R is the allowable load, W the ram weight, h the drop height, s the pile penetration per blow, and "8" is the factor of safety). Fort Delaware was completed in 1859.

Decades later, Arthur Mellen Wellington, a renowned railway civil engineer, published a formula in the December 29, 1888 issue of Engineering News. This ‘Engineering News’ formula, again designed for drop hammers and timber piles (Chellis 1951), was widely used for decades and is still used by some today. Wellington was a realist, however, and stated “*In so very uncertain a matter, it is wrong in principle to start from high ultimates, which are certainly unsafe as a unit, and allow foolish men to deceive themselves with the notion that they are being cautious, when they divide it by three or four, when they are really running great risks. The carnal mind longs for this comforting assurance, but the true formula for pile driving is one which is certainly safe in any kind of uniform material, leaving the engineer to realize that he is running risks (which yet may be justified and reduced by caution), if in special cases he goes beyond it.*”

“Engineering News’ was not the only formula used, however, as R.D. Chellis lists more than 30 different formulas in his 1951 textbook *Pile Foundations*. In 1925, Hiley produced a formula that was more “complete”, trying to account for various “losses”. It was in common use in England at the time of the 1941 Discussions, and continues in fairly wide use in the British Commonwealth nations. Several of these long-ago formulas are still in use today, but additional formulas arose after 1940, such as the Gates formula promoted by the U.S. Bureau of Public Road (later the Federal Highway Administration).

Since there were so many formulas already in use for many decades, and giving quite different answers that likely usually did not match results of static tests, one primary goal of the Committee was to determine which formula to recommend. Some defended the more complete or complicated formulas, some adamantly opposed, while others essentially said "why bother with complexity" and suggested that the simpler formulas were just as accurate, or just as unreliable. Many suggested limiting them to cohesionless soils since cohesive soils change capacity with time.

While some discussions mentioned the efficiency of the hammer, and gave recommendations, the suggested efficiencies were only guesses based on correlation work with static tests, since no measurements were then possible. A weakness of using only a formula for any specific project is that the actual hammer performance of any individual hammer is variable — and unknown — and this serious limitation applies to any formula. Modern dynamic testing with the PDA clearly shows wide variability in measured transfer energy among supposedly identical hammer models and types. Finding factors of two in energy transfer are not unusual between supposedly identical hammers operating in the same hammer-pile-soil systems. It is no wonder that the discussers state that they had experienced poor correlation of dynamic formulas with static test results.

The stated main subject of the discussions is (dynamic) Formulas for Determining Pile Capacity. Terzaghi writes: "*The use of the (dynamic) formula in the design of pile(d) foundations is unsound on both economical and technical grounds*". This statement is echoed by Peck, Casagrande, and Cummings with some additional elaboration discouraging the use of and reliance of dynamic formulas. For example, G. Paaswell states "*soil mechanics and the pile (dynamic) formula are essentially* *incompatible*". Today, having the benefit of a vast body of dynamic tests and analyses, we know this to be very true.

It is of interest to see what Terzaghi wrote in December 1942 (date of preface) in his text book "Theoretical Soil Mechanics", published in 1943: "*In spite of their obvious deficiencies and their unreliability, the pile formulas still enjoy a great popularity among practicing engineers, because the use of these formulas reduces the design of pile foundations to a very simple procedure. The price one pays for this artificial simplification is very high. In some cases the factor of safety of foundations designed on the basis of the results obtained by means of pile formulas is excessive and, in other cases, significant settlements have been experienced. The opinions regarding the conditions for the legitimate use of the formulas are still divided. In this connection, the reader is referred to a recent and very illuminating discussion in the Proceedings of the American Society of Civil Engineers (Pile Driving Formulas. Progress Report of the Committee on the Bearing Value of Pile Foundations, Proc. Am. Soc. C. E., May 1941; discussions in every issue from September to December 1941, from January to March 1942; closure in May 1942)".*

The discussions almost universally acknowledge that dynamic formulas are unreliable. Since the more scientific 'wave equation analysis' (such as WEAP software) is so readily available and user-friendly, the question then is why are formulas still in use (perhaps infrequently in USA, but in some countries still rather extensively)?

STATIC LOADING TESTS

The discussions' comments on static testing are generally rather limited, but still quite interesting. Then, as now, the capacity determined in a static test was the standard reference to the accuracy of formulas. The capacity in a formula is logically the calculated soil resistance at a certain penetration resistance (blow-count value) or the value at an infinite penetration resistance—"absolute refusal". Similarly, the capacity in a static loading test can be defined as the load that provided a certain pile head movement. The difficulty lies in correlating these two very different definitions. The Committee defined capacity (failure load) as the load which produces an increase in pile movement disproportional to the increase in load, a vague, and only qualitative definition. Terzaghi in his contribution to the discussions criticized this rule and proposed to add the provision "*the failure load is not reached unless the penetration of the pile is at least equal to 10 % of the diameter at the* ***tip*** (toe) ***of the pile*** (authors' emphasis)". He stated that "*at smaller penetration, no more than a fraction of the ultimate resistance of the pile toe has been mobilized*".

From other portions of his discussion, it is clear that Terzaghi considered pile size to be 12 inches (300 mm) or smaller since timber piles were common. We agree, when testing such size piles, it is desirable to move the pile toe at least 30 mm before drawing any conclusion as to the ultimate resistance. However, Terzaghi's 10 % rule has been interpreted to mean that capacity is reached at 10 % movement of the pile **head**, which in our opinion is a misinterpretation. However, this is how Terzaghi's statement has been quoted in several publications, and applied liberally to any pile diameter. Note, Terzaghi stated that <u>first at 10 % of the pile toe diameter and beyond, one can start considering what the pile capacity might be for the test, which is very different than stating that the capacity is obtained at 10 % of the diameter (without considering the actual value of diameter)</u>. In our opinion, the displacement that the supported structure can tolerate has nothing in common with the diameter of the pile shaft. The structure cares not that it is on a foundation on a ten-foot or a one-foot diameter shaft as long as the load is supported and the settlement of the building is tolerable. The question becomes whether the settlement is tolerable or not.

SUMMARY OF THE 1941/1942 DISCUSSIONS

The following summary of the 1941-42 discussions reflects the basic thought of the early 1940s. Quotes are made from each discussion to illustrate the position of each discusser. Note that the quotes are neither complete nor necessarily continuous. Individuals eager to learn more and wishing to read the complete original can contact the second author for a copy of the full original text.

September 1941 issue

Greulich (Carnegie-Illinois Steel Co.) "*The use of formulas, without a thorough knowledge of all factors at the site that might influence pile behavior and without check tests, may lead to serious error – either by an unsafe or a very uneconomical and extravagant design*." Reviewing the most used formulas (the Hiley and several variations of the Engineering News), he concludes: "*general study of at least six times as many cases indicates equally erratic comparison between driving-formula values and test results. The writer would be opposed to the publication of any formula unless the dangers and pitfalls of its use are made very clear*".

Emerson and Northrup (Carnegie-Illinois Steel Co.) mention timber and steel piles, and discussed double-acting hammer effects (stated to reduce set-up between blows, but complicates driving in dense water bearing sands).

Engel (Modjeski and Masters) discusses "freeze" (set-up) for timber piles in Louisiana. "*Any dynamic formula would assign totally different allowable loads to these piles before and after their rest periods, and it would seem the wisest course, therefore, to use no dynamic formula for friction piles*". Engel suggests static tests be made to "*complete failure*" which is "*plunging*" for friction piles.

Watson (Assistant Professor, Duke University) "*Report B recommends nothing except load testing of piles to failure. … the writer wishes further to deplore the moribund attitude that prompted other members of the Committee to prepare 'Report A – Pile Formulas'. Although they may fervently wish to have a formula for the ready solution of their problems, they should not ask the Society to fulfill their prayer by promulgating a Committee formula, unless they can prove their case in court*". He then refers to a report of the U.S. Engineer Office on the Sepulveda Dam (California) that "*states categorically that 'no dependable correlation has been found between driving resistance and static safe loads'.*".

October 1941 issue

Chellis (Stone and Webster) – presented a 20-page discussion, where he first cautions of the need for complete soil site information. "*… several years has shown the writer that the Engineering News formula is not the general answer to the problem*". Chellis states that problem lies with the simplicity of the Engineering News formula and writes that he has used the Hiley formula (published only in 1925) and "*found its use very practicable. The older formulas give widely varying results with different types of piles and hammers, entirely out of reason*". He mentions that the safety factor for the Engineering News formula ranges from 0.5 to 16 and that such wide divergence of results leads to grave doubts about the entire practice of its use. He declares "*non-validity of a dynamic formula when driving into cohesive soils*". In addition, he cautions that "*the* (pile driving)*formula is very sensitive at small penetrations*". He mentions measuring the set-rebound with pencil and paper on the pile, which is considered a serious safety concern today. He considered the variability of hammer efficiency (by hammer type), but he likely did not recognize the variability within a hammer type other than to say: "*the energy varies with the speed*", meaning rate in blows per minute (BPM). "*It is possible that the theory of longitudinal impact* (eventually available through the PDA) *will also furnish a good yardstick, but literature and data are not sufficiently available as yet to enable judgment to be formed*". He further mentions that the BPM should be noted by the inspector, the stroke for single-acting hammers should be measured, and that capacity should be determined only during continuous driving (not restrike).

White (President, Spencer, White and Prentis) writes "*The proposed formula (Report A) has the failings of all previous pile formulas – it can only give the value at the time of driving (if it can even do that) and not 24 h later. The proposed formula has the basic form of the Engineering News formula …. Moreover, the writer's firm has repeatedly underpinned structures that should not have suffered from settlements – were the Engineering News formula reliable.*" He mentions the proposed formula is derived from the Hiley formula and cautions that "*it has not been checked sufficiently against actual tests. … Furthermore, it would be a calamity for the Society to lend its authority to the promulgation of any pile driving formula as yet described*". He describes disagreement in the Committee, and writes "*no formula should have been proposed; and that the disagreement should have been clearly reported. … Reports A and B are divergent and opposed. Report A still expresses faith in pile driving formula and proposes one of its own – a modified Hiley formula. Report B expresses doubt on all pile driving formulas and load testing of piles is the only reliable method for determining the load which a pile can safely carry in relation to the shearing strength of the soil surrounding the pile*". He mentions that settlements could only be computed after 1929 (by application of Boussinesq theory and Terzaghi's contribution on consolidation).

Mason (Bridge Engineer, State of Nebraska) "*Pile driving formulas are a necessity*". He made reference to having assembled a database with comparison to results of static tests in order to try to determine safety factors and hammer efficiency factors (to account for energy losses).

Proctor (Moran, Proctor, Freeman, and Mueser) "*the large immediate value of this Report is in its warning to designing engineers as to the fallacies of pile formulas and the weaknesses of pile tests*".

Paaswell (Spenser and Ross) "*When one persists in the quest for a pile formula, one ignores or merely gives lip service to the science of soil mechanics. Soil mechanics and the pile formula are essentially incompatible* (authors' emphasis). *A simple formula gives a definite procedure to secure a 'good' pile and, when all piles have been placed in accordance with such procedure, one has a conventional foundation and obviously a satisfactory alibi when unexpected* (?) *settlement occurs*".

Woolf (Albert Kahn, Inc.) mentions "*Terzaghi, in 1925, gave his soil mechanics lectures discussing the validity of pile driving formulas. It was then emphasized that one should be careful with formulas, particularly the Engineering News formula. Report B definitely proposes that no formula be used, but that load tests be resorted to. This proposal is a difficult one to accept, but basically it is sound and correct*". He then discusses that timber piles were used when the Engineering News formula was developed, but now (1941) the design loads are orders of magnitude larger. He discusses settlement issues and static loading tests which he calls "*long time tests*".

November 1941 issue

Evans (Bethlehem Steel) seems to agree with the concept of a formula (specifically the recommended one or perhaps the Hiley formula since he includes discussion of the C-constants). "*The method of assuming the ultimate bearing value and solving for the corresponding penetration per blow eliminates the 'cut-and-dry' procedure required if the reverse process is followed. The traditional approach comes, of course, from the fact that, in the field, 's' is observed and known, and 'R' is the value it is desired to find; but the solution of the formula is much more easy and direct if it is taken the other way around*". But he summarizes: "*In conclusion, the writer protests against the development or use of any 'pile driving formula' as such. It is misleading and unsafe to seek a magic combination of terms, in a formula, that will fit any and all cases regardless, and which is supposed to indicate just what load the pile will support. Evidence of this fact is the manner in which 'practical' men, for years, have applied the Engineering News formula blindly and have stated flatly that such and such a pile was good for exactly so many tons. As long as there is a formula of any kind, this attitude will be encouraged. Instead, the engineer should seek to promote a 'method of analysis', to be handled by engineers the same as the design of a girder or truss, for example*".

Atwood (Consulting Engineer) "*Report A presents several formulas of questionable value. It would seem that there are no formulas of general or even local value unless they are treated with good judgment and corroborated by many tests. If that is true, why try to use a formula? It would seem, with the knowledge now available, that the best the Committee could do would be to make some very general statements as to the unsafeness of using formulas, and the necessity for testing and the exercise of judgment*".

Burmister (Assistant Professor, Columbia University) "*In view of the limitations of any pile driving formula and of the uncertainties involved in the successful application to the installation of pile foundations in any given situation, it is believed that Report B (*tests) *represents the better practice.* <u>*Once a formula has been printed, it takes on a more or less authoritative character, and the assumption on which it is based and the limitations in its use tend to be forgotten or overlooked*</u> (authors' emphasis). *It seems doubtful that any consistent relationship can exist … that will be of general application for different types of soil and for the extremely varied subsurface conditions usually encountered in practice at a given site*". He continues: "… <u>*bearing capacity must be determined in relation to some maximum allowable safe settlement*</u>"(authors' emphasis), and concludes that knowledge of the soils, driving logs for all piles on site, "*and load testing of piles represent the only safe basis for design and installation. With experience and application of suitable factors based on loading tests and on these other factors, almost any formula can be used as a yardstick to help the engineer secure reasonably safe and uniform results over the entire job*".

Belcher (United Engineers and Constructors, Inc.) remarks that "*neither Report A nor Report B places any reliance on the Engineering News formula. The attempt to introduce a new formula (Report A) is of very doubtful value, as it is based on the same fundamental data that invalidate the Engineering News formula. It is the opinion of the writer that additional emphasis should be placed on the redriving of piles after a rest period to be taken in connection with the test loads prescribed. The number of test loads that can be applied is very limited, in any case; whereas, it would be comparatively easy to make a redriving test on a large number of piles including one pile in each group*".

Williams (President, Lehigh University) "*The Committee is to be commended for their orderly statements of the general significance of pile driving formulas and for their cautions relative to their use. A formula having complicated refinements is not consistent with the nature of the problem*".

Krynine (Research Associate, Yale University): "*Of the two reports, A and B, the latter is preferable*". He then discusses the sensitivity of the Hiley formula to the C-constants, particularly at hard driving conditions, to the weight of the hammer and to the pile length and states: "*All these questions should be clarified in the Manual, if, unfortunately, the Hiley formula is recommended for the general use. The writer sincerely hopes, however, that this will not happen*". He then says local experience may find a locally calibrated formula and notes that the data presented are mainly European and do not include double acting hammers.

December 1941 issue

Dames and Moore (Dames and Moore Inc.) state their preference for Report B, and note "*dynamic formulas that are restricted to drop hammers and single acting steam hammers will be of limited value at best. The scatter of data is so wide that the only conclusion possible is that the dynamic formulas are unreliable and, in most cases, are likely to lead to unnecessarily expensive construction costs*". They note the "*intervals between driving and testing should be given*" and discuss static test procedures writing: "*Hydraulic jacks operating against an adequate reaction may prove satisfactory, but because of the frictional drag between the jack cylinder and the piston and cup washer, the calibration is seldom reliable for movements requiring both extension and retraction of the jack*". Many other suggestions on static test procedures are well made.

Upson (Raymond Concrete Pile Company) writes "*… the simplest possible formulas and information should be advocated. Each formula should be accompanied by a clear statement of its usefulness and limitations. It is the writer's apprehension that the presentation of complicated formula such as Eq. 9, requiring so many assumptions, may well lead the uninitiated engineer astray. It would seem that in Report A, as written, the Committee is trying to prove that Eq. 9 is the only pile driving formula that is based on reasonable assumptions. Actually, there are as many doubtful and unwarranted assumptions in Eq. 9 as there are in any other pile driving formula in existence*". He cites an example of a 0.307-inch wall pipe versus a 0.259-inch wall pipe where the heavier pipe drove deeper ("*contrary to the principle set forth in Eq. 9*" (from wave equation analysis, we understand why the heavier pile drove deeper and we can now model this accurately).

Tschebotarioff (Assistant Professor, Princeton University) cites Report B as follows: "*any dynamic pile driving formula is nothing more than a yardstick to help the engineer secure a reasonably safe and uniform results over the entire job. The use of a complicated formula is not recommended since such formulas have no greater claim to accuracy than the more simple ones*" He laments the lack of clear explanations for all limitations of formula and states: "*The importance of precise instructions concerning details of pile testing procedures cannot be overemphasized*".

Leggett (Assistant Professor, University of Toronto) emphasizes "*Since pile foundations are only one of many types of foundation structures, it is strange to find no attempt in the Report to describe the relation of pile foundations to foundations in general. In order to determine whether bearing piles should or should not be used as foundation elements in any design, it is imperative that the nature of the soil at the prospective site be known to a depth of at least twice the width of the structure proposed*" (and thus the need for "*an adequate program of test borings*") *… it is always desirable, if not essential, to be able to check the penetration of the various piles of any group, especially in relation to the corresponding test pile penetration. Admittedly, it is not necessary to have a formula for this purpose if the same driving equipment is used, but a formula is necessary if different pile drivers are used either together, or for test and service piles respectively*".

Feld (Consulting Engineer, New York) writes "*… the true difference between the two reports is whether the design of piles shall be based on a dynamic test* (formula) *as checked by the static test, or on the static test alone. Personally, the writer would prefer to have the Manual covering pile driving formulas include a definite formula for granular soils, a definite formula for plastic soils, and a definite formula for such conditions as end-bearing piles in which no lateral restraint or resistance is to be expected. The recommended formula* (the simplification of the Hiley formula) *is* *basically of the same type as the Engineering News formula. However, the writer does not believe that any more accuracy can be obtained from the recommended formula than from the Engineering News formula, if the designer does not have sufficient knowledge to evaluate the factors in each*". He then mentions that failures seldom show improper use of formulas, but rather in the assumptions made in the application of the formula. "*Dynamic tests* (i.e., applying a dynamic formula) *are useless in plastic soil. One criticism of Report B can be seriously made: The requirement that the allowable load on a pile shall not exceed one half the load at failure should be defined more carefully, since (in the writer's opinion)* <u>*failure for piles is a function of settlement and not a physical* (bearing) *failure of the pile*</u> (authors' emphasis). … *the allowable load should be limited by the desired* (safe) *settlement*".

January 1942 issue

Wilcoxen (Detroit City Engineer's Office) had conducted model pile tests (made up of wood) in clays and sands with 1 in^2 (6 cm^2) cross section and 6 in (150 mm) length, driven by 1.0 and 0.1 pound (0.5 and 0.05 kg) gravity hammer with a height-of-fall of 1.0 to 0.1 ft (300 and 30 mm) and , and subjected to a static loading test after driving. He found good agreement, but needing factors of 0.6 for clay and 1.0 for sand in his very simple formula (R = Wh/S), which is the original Stanton formula of 1859 applied with no factor of safety (Stanton applied a factor of 8), concluding that "… *until field test results are checked against formulas including a proper soil factor, investigators are not warranted in denying the possibility of developing a practical one*". Wilcoxen, of course, did not in 1942 have the benefit of knowing that unit gravity model tests are useless in representing full-scale response, which insight was still more than 20 years in the future.

Mohr (M. ASCE) writes "*After studying the formula derived in Report A and 'worrying' through Mr. Hiley's published work* (1930), *upon which analysis the proposed formulas are based, it is the writer's firm conviction that their inclusion in the proposed Manual would be a grave mistake. That analysis is quite detailed and reads well, but it is still theory, and the conclusions otherwise are based upon a paucity of practical data. Answers obtained by its use are no more consistent and logical than those obtained by the use of other formulas. Its only obvious advantage to those who wish to be critical of present formulas is the great number of unknowns to which a series of values may be applied until an answer satisfactory to the interested party is finally reached*". After listing various factors and compounding assumptions, he states "*Obviously, no pile driving formula is adequate for these variable conditions. Engineers are 'getting nowhere fast' by inserting new assumptions, ever so often, into a basic formula that has been worn thin*". Thereafter, he discusses static analysis. "*The science of soil mechanics will not produce a static pile formula of any greater accuracy for universal application than present dynamic formulas, because those same variables are inherent in the solution of any pile formula problem. One needs but very little practical experience in pile driving to know that radical changes in pile lengths occur on many jobs and in many instances even within small footings*". He notes the need for a "*complete subsurface data and samples of soil for identification and laboratory tests. Theoretical refinements* (static analysis and pile formula) *probably have less justification in the field of pile foundations than in any other department of technical design and construction. So, rather than guess at a variety of coefficients, would it not be preferable to judge the result by experience in the first place and do away with a complicated mathematical process to obtain a questionable answer?*".

Cummings (Raymond Pile Driving Company) states "*In the writer's opinion, the publication of Report A in a Manual of Engineering Practice would be a serious mistake. All of the formulas given in the Report were published at least fifty years ago and engineers have been 'tinkering' with them ever since. The usual procedure is to make one assumption after another; to retain some terms and cast out others; and then to publish a 'new' pile driving formula. For example, Eq. 4 is said to have been proposed by Hiley in 1930. Actually, this equation is nothing more than the so-called 'complete' pile driving formula published by Redtenbacher in 1859* (1852 actually). *There are only five basic types of dynamic pile driving formulas in use at the present time and all of them can be represented by the formula* $Wh = Rs + Q$ *in which Q represents all the energy losses that occur during impact. For many years, engineers have been making all kinds of assumptions as to what should and what should not be included in Q. The profusion of pile driving formulas that can be found in engineering literature is simply the result of these assumptions*".

Cummings then discusses in detail the five types and assumptions contained in the formulas (characterized as questionable), even quoting Isaac Newton's warning that his Newtonian impact methods can be applied to various elastic bodies '*except where they suffer some such extension as occurs under the strokes of a hammer*', and that Newton's experiments were done on spheres suspended with no external resistance as opposed to long slender rods with surrounding soil resistance. Newton's conditions invalidate at least two of the five assumptions included in the 'complete' and 'Hiley' formulas.

Cummings continues: "*The most unfortunate thing about Report A is the manner in which it presents the derivations of Eqs. 8 and 9. Whenever an assumption is made in the derivation of these equations, the assumption is said to be 'reasonable' or 'logical.' Assumptions made in the derivation of other formulas are called 'unwarranted.' Eq. 4 is presented as an equation that 'involves no simplifying assumptions'. Actually, this equation involves assumptions that are fundamentally unsound from the standpoint of elementary mechanics. For example, Eq. 4 is based on the assumption that Newton's theory of impact with its coefficient of restitution can be applied to the impact problem involving more than two bodies. The error in this assumption is not a matter of opinion. It is a matter of fact, which was clearly stated by Newton himself several hundred years ago. In the writer's opinion, a Manual of Engineering Practice should not present technical information in the manner in which these pile driving formulas are presented in Report A. Eqs. 8 and 9 are described as being reliable and of relatively recent origin. As far as reliability is concerned, there is an abundance of field evidence available to show that such formulas are quite erratic. Furthermore, these formulas are not new since they were first published at least eighty years ago* (circa 1860)".

"*As a matter of fact, the only new concept that has been introduced into pile driving formula in the past fifty years is the theory of the longitudinal impact of long elastic rods. This theory is not new, as it was developed by St. Venant* (1857) *and Boussinesq* (1885) *many years ago. The application of the theory to pile dynamics was first suggested by D.V. Isaacs* (1931) *and the British Building Research Board in 1938* (in a report by Glanville et al.) *and demonstrated the fact that the behavior of full size piles under actual field conditions can be predicted with considerable accuracy by means of this theory. The theory is concerned with the question of stress transmission through the pile and, unfortunately, it involves some rather difficult mathematics.* <u>*However, there is a considerable amount of field evidence available which shows that the stress transmission characteristics of a pile are of great importance not only in determining its behavior during driving but also with respect to its subsequent ability to carry static load. This method of investigating the phenomena of pile driving dynamics is one that deserves the careful attention of all engineers engaged in pile driving work. It is a new and promising field for investigation*</u> (author's emphasis)". Fortunately, this method has been further developed and dynamic pile testing with the PDA is now in common use.

"*… the static* (analysis) *method represents a rational approach to a static problem that has been confused with dynamics for at least a century. Furthermore, the results obtained by static methods should scarcely be more erratic than the results now being obtained with dynamic formulas*".

"*The erratic nature of the results obtained with dynamic formulas is a subject to which engineers have paid far too little attention. There is available a very considerable amount of pile driving data from which it is possible to determine indicated bearing capacities by means of a number of dynamic formulas and then to compare these computed results with the actual bearing capacity determined by a load test to failure. When such data are tabulated, it is always seen that some of the computed results are several hundred per cent above or below the actual test results. Many engineers tabulate data of this kind for a set of 25 or 30 experiments and then compute the numerical average of the test results apparently on the assumption that the numerical average is a figure with practical significance. Actually, the calculation of the numerical average is only the first step in the statistical analysis of a set of data of this kind. When the numerical average is compared with the individual test results, it is seen that only a few of the results are close to the average and that the remainder vary from the average by as much as several hundred percent in either direction. In the language of statistical mathematics the 'deviations' of the individual results from the mean are very large and it is practically impossible to predict even the 'most probable' value that could be expected in a given case*". And, finally: "*The complicated formulas are no more accurate than the simple ones although the complicated formulas may look authoritative*"

February 1942 issue

Terzaghi (Harvard University) "*If a manual recommends the use of one of several yardsticks, the reader is entitled to ask (a) which one of the yardsticks is the best, and (b) to what extent can he rely upon the results of the measurements with this yardstick.*

These vital questions can be approached in the following manner: The defects of the pile driving formulas are either due to disregarding variable and vital factors (Engineering News formula), or they are due to the inadequate evaluation of the influence of these factors on the effect of the blow of the hammer (general equation and its derivatives). The formulas of both groups share the defect that they disregard the energy transmission through the pile by elastic waves. The degree of reliability of a formula can be measured by the range of scattering of the ratio between computed and real values about the statistical average".

Terzaghi continues: "*In spite of the waste of material and labor involved in an average factor of safety of 4, an occasional failure is inevitable. Loading tests are justified economically, if the cost of the tests is smaller than half the cost of the piles, labor included, because, on average, the saving amounts to about 50 % of the cost of the foundation designed on the basis of the Engineering News formula. In addition to saving money, the tests also eliminate the risk of overloading the piles. This risk always exists, when the formula is used. Whoever uses the formula is in exactly the same position as the man who tries his luck on a gambling machine. He is at the mercy of the laws of probability*". Terzaghi states the standard deviations of results for the complicated formula are no better than those obtained by the Engineering News formula.

In discussing static analysis (Report B), Terzaghi states: "*All scientific theories … are based on the assumption that a cylindrical part of the soil has been replaced, through some act of magic, by the pile. Before the load is applied, the state of stress in the soil should be identical with what it was before the was created. In reality, the pile must be driven or jetted into the ground. Either process produces a profound change in the state of stress in the soil and in some cases alters the physical properties of the soil which surround the pile. … Almost all the successful theories* (i.e., those showing best correlation to the test results; Class C 'predictions') *were made after the load test was finished and not before*".

In a key contribution, Terzaghi makes a case for: "*… the meaning of the term 'load at failure' should be defined. According to prevalent usage, the term indicates 'the load that produces an increase in settlement disproportionate to the increase in pile load'. … The Manual should specify somewhere that the failure load is not reached unless the penetration of the pile is at least equal to 10% of the diameter of the tip of the pile. At smaller penetrations, not more than a fraction of the ultimate point resistance of the pile has been mobilized*". It should be appreciated that the pile sizes in the 1930s and 1940s were typically no more than 12 inches. Terzaghi also mentions timber piles which obviously have even smaller pile toe dimension. Such a requirement is reasonable for piles of such size. However, for modern engineers to extrapolate this rule to load tests for driven concrete cylinder piles—typical size being several feet— or to large diameter drilled shafts or bored piles is surely well beyond Terzaghi's original intent. Terzaghi did not realize (many don't realize it yet) that there is no such thing as an ultimate toe resistance. The pile toe response to load follows a curved load-movement line having no distinct point that could be defined as a failure load. What some mistake for an ultimate toe resistance is the sometimes occurring "kink" in the curve revealing where the applied stress exceeds the residual load at the pile toe. In a static loading test on any pile, it is desirable to move the pile toe at least an inch or two (i.e., at least 30 to 50 mm, broadly converted). Few structures will accept a load-transfer movement that exceeds this value.

Peck (Engineering Dept. City of Chicago) contributes "*Report A carries the implication that pile driving formulas give the results that have some relationship to the ultimate bearing capacity of piles. The validity of some or any of these formulas can be determined only by comparison of ultimate loads found by loading tests and by the formulas. On the basis of the data in Table 2, it can be demonstrated by a purely statistical approach that the chances of guessing the bearing capacity of a pile are better than of computing it by a pile driving formula. Assume that a new and very simple pile formula is advanced. It is merely the statement that the most probably bearing capacity of every pile is 91 tons. (This value happens to be the geometric mean of the tested bearing capacities taken from Table 2). The standard deviation of the individual bearing capacities about this value is 1.55, which is less than the standard deviation determined for any of the pile driving formulas. To determine the ultimate capacity of a pile, the following procedure then would be justified: Take 100 poker chips and label them with numbers so as to form a geometrically normal array having a mean value of 91 tons and a standard deviation of 1.55. Mix the poker chips and select one. The value written on the chip will be the bearing capacity of the pile. The statistical study indicates that the use of a pile driving formula is merely a somewhat inferior method of permitting the laws of chance to operate in the determination of pile capacity*".

Casagrande (Associate Professor, Harvard University) "*The question of 'pile formulas' has without doubt been the most controversial issue in the field of civil engineering for a hundred years. Judging from the work of the Committee, and from other evidence, opinions on this subject are today more divided than ever*". He then discusses "fallacy" in losses contained in the recommended formula and makes a nice illustration of wave propagation in an analogy to a string of billiard balls touching each other, stating: "*In 1940, Mr. Cummings suggested in a lecture that the Engineering News formula may be preferable to the more complicated formulas, particularly to those formulas containing the elastic compression of the pile, etc. The writer concurs in this opinion*".

Over three pages of text—too long to quote here—Casagrande discusses Newtonian impact on a row of billiard balls as opposed the driving of a pile in soil and concludes "*to measure the temporary (that is, elastic) compression of the pile and soil and deduct the corresponding energy as "loss" is fundamentally wrong. It would be more correct to consider the elastic compression of the pile as a measure of the force with which the soil is tested*". Casagrande explains the statement by presenting results of his experiment with measuring 'elastic' shortening (force) over time due to impact on a model pile that is a forerunner of his understanding of pile driving yet a decade and more in the future for the piling community.

On static testing Casagrande writes: "*The writer realizes that pile loading tests cannot be made a general requirement and that, although on large projects they should be used and pay for themselves, they are often too expensive for small projects.*

Therefore, the problem is to find a more reliable basis than formulas for designing and constructing pile foundations for small projects". Local experience is cited: "*… first, a few exploratory borings are much cheaper than pile loading tests; and second, that the subsoil conditions should be known fairly accurately even for small projects. The writer has also observed that confidence in pile formulas is often the result of experience derived with one type of pile only, usually wood piles*".

"*Since pile formulas are basically incapable of yielding the desired information, and since they do not contain any provisions to prevent overdriving of piles, the writer has found it preferable to use the following empirical rule: 'A pile driven to the maximum permissible resistance that will not harm the pile can be loaded safely to the maximum allowable loads permitted in building codes'*". This simple rule would be difficult to accomplish in practice without some dynamic measurements showing that the piles indeed are unharmed — and if one has today's dynamic measurements then there is little need for the rule.

"*A Difficult Task. – The question of how to treat the chapter on pile formulas is indeed a difficult one, particularly in view of the desired standard expressed in the first paragraph of the Manual manuscript: 'This manual ... endeavors to enunciate sound principles which are based on established facts, and to avoid stating rules or giving formulas which might lead to its unintelligent use. Rigorous adherence to this desirable goal would eliminate all pile formulas, since they are certainly not based on 'established facts'; nor can one say that one can recommend any formula and feel reasonably sure that it might not lead to its unintelligent use*".

March 1942 issue

Dunham (Assistant Professor, Yale University) writes "*A formula … which depends upon various and variable coefficients, whose values are subject to guessing and change without notice, is confusing and deluding. Everyone agrees that the results obtained from such a formula are not correct but, if they are reasonably so and moderately conservative, one may as well arrive at the results simply rather than through devious mathematical procedures whose greater value is probably psychological rather than real*".

May 1941

Closure by Admiral Bakenhus (U.S. Navy Ret.) "*…'pile formulas' is the one subject upon which the Committee has reached no definite stated conclusions*" He also notes that dynamic formulas are only one chapter out of twelve total chapters and continues: "*Tests cost relatively little in extensive operations, but may be relatively large and even out of the question with the smaller project. At its best, the pile driving formulas are merely an empirical method for predicting the safe bearing load for a single pile. Experience has shown that there is no determinable fixed relation between the safe bearing value of a pile and the factors used in the formula. It is, therefore, a dangerous proceeding for an engineer to design or build a piled foundation solely on the information obtained by the usual test of measuring penetration per blow, height of fall, and weight of hammer*" (authors' emphasis)". He mentions that the Engineering News formula was developed at a time when only timber piles were in common use and refers to "*non-validity of a dynamic formula when driving in cohesive soils*", and states that the capacity of the group must also be assessed in addition to the capacity of the individual pile, and a variety of energy loss situations. His Closure addresses many of the discussers' points specifically, but points out that "*he does not suggest what the engineer in the Midwest prairies should do when he has a total of perhaps twelve piles under some bridge foundation, and when neither funds nor time permit load tests or soil analysis. This is one of the difficult problems before the Committee*". Today, of course, the quandary is resolved by means of dynamic monitoring of the piles.

DISCUSSION and CONCLUSIONS

The typical pile, pile driving hammer, and pile capacities of today greatly exceed (by at least one order of magnitude, if not two orders) the capacities in the original database used to develop the formulas. It is noteworthy that the current version of AASHTO at least prohibits formula use above a capacity of 600 kips (3,000 KN). The authors would prefer to see this limit lowered to at most the limit prescribed by the International Building Code (IBC), i.e., restricting formulas to use below a capacity below 160 kips (800 KN), which lies at least closer to the realm of the original data base.

Several discussers note 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*". Today, this intended restriction is all but forgotten. Current thought is that the long-term set-up gain in cohesive soils is balanced by the dynamic viscosity of the soil during installation. This assumption may work statistically to give the mean formula result similar to the mean static test result, but on any individual site the coefficient of variation may result in gross errors. The reason for both agreement statistically and disparity individually is well explained by Rausche et al. (2004).

The Discussers from the early 1940's show a clear consensus about the unreliability, unscientific basis, uncertain outcome, and risk for the practice in using dynamic formulas. Later research (e.g., Olson and Flaate 1967; Lawton et al., 1986) has further confirmed these failings of the formulas. Olson and Flaate studied 93 piles driven in sands and subjected to static loading tests. They wrote: "*None of the formulas was clearly best for the precast concrete piles. Single adjusted formulas may be used for all types of piles, but the calculated capacities are likely to be slightly less accurate than when a different adjusted form of the formulas used for each type of pile*." They suggested different forms for the Gates formula for different pile types, which includes "constants" multiplying the energy term that differ by almost a factor of two between wood and steel piles. An argument could be made for using a similar approach as with different pile types with regard to different soil types, but, then, what would be the appropriate formula for layered soils?

Wave equation analysis was developed in the 1950s and, since the mid-1970s, scientifically appropriate means of analysis are available to the profession, supplemented with actual measurements — dynamic monitoring— which clearly indicated the capacity at the time of testing (during installation or during restrike after some wait period) more accurately. The understanding of what is involved when a pile receives an impact that drives it into the ground is generally available. It is therefore quite bewildering to encounter specifications for project to be constructed today that still refer to evaluation of pile capacity by means of any dynamic formula. One large and here unnamed department of transportation even includes in project specifications nomograms to use that are developed from the Hiley formula (no doubt, to save those still using the slide rule from laborious calculations). It is surprising to note that a few DOTs recently funded studies and development of new formulas. Wes hope that this summary of the 1941-42 report and discussions will not just provide information of historical interest — and an appreciation of past methods— but also encourage using up-to-date methods in engineering of piled foundations.

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