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Applications of Wave-Equation Analysis to Offshore Pile Foundations

By

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ABSTRACT

A wave-equation-formulated computer solution of the pile-driving process is shown to have considerable application to offshore foundations as a design and installation aid. Using the method, it is now possible to optimize pile drivability by proper selection of pile size, hammer, driving accessories, and field procedures. Impact stresses in both pile and hammer may be analyzed. Typical design curves are shown which are similar to those that could be developed for a handbook-type approach to preliminary design for pile drivability.

INTRODUCTION

The basic problem confronting foundation engineers with regard to high-capacity pile foundations is one of designing a pile foundation that is both structurally sound and economical. The designer may choose to support large foundation loads by either a large number of small piles or by a smaller number of large piles. Although design philosophies in this regard may differ, the common goal is a safe but economical structure. Generally, it is thought to be more economical to install a few large piles

than to install a greater number of small piles, providing the piles can be installed without great difficulty. This situation obviously leads to the problem of deciding early in the design procedure what upper limits, based on expected driving characteristics, must be set on pile diameter and depth of penetration. Where sufficient experience in the construction area or a similar area is available, this may not be too difficult a decision; in cases where experience is lacking, however, very little has been available to aid the decision making.

In order to meet the need for greater driving capabilities, hammer manufacturers have developed new pile drivers with greater energy output. Unfortunately, these new hammers are correspondingly more massive and more difficult to handle in the offshore environment than their smaller predecessors. In addition, sometimes even these larger hammers may have difficulty driving piling unassisted.

Additional techniques must therefore be applied in the design and installation of pile foundations if we expect to fully meet the challenge of larger structures. These techniques should permit the following questions to be answered:

References and illustrations at end of paper.

1. Can field installation problems be anticipated in the design stage in order to provide for alternate installation techniques, or even redesign of the pile foundation?
2. Can a pile be designed to improve its driving characteristics?
3. Can a more efficient set of pile-driver accessories be developed, or can driving accessories be tailored to the individual job?
4. Can new pile drivers with more driving capability be developed by means other than making them more massive?

E.A.L. Smith¹ was successful in the early 1950's in developing a rational method of analysis for the dynamic behavior of piling. For practical application his method required the use of a high-speed digital computer and was not widely accepted initially. In 1963 Samson, Hirsch, and Lowery² programmed a more detailed version of Smith's method³ for computer solution and presented results of parameter studies and field-test correlations. Subsequent investigations by Hirsch and Edwards⁴ and Lowery⁵ have resulted in refinements of input data so that the simulation of pile-driving problems can be performed with acceptable accuracy.

Difficult conditions of large pile diameter and deep penetration requirements make wave-equation analysis especially useful for offshore applications. This approach enables the engineer to obtain a more rational solution to pile-driving problems.

THE MODEL

The pile penetration that is produced by each stroke of a pile driver ram is the result of a force pulse that is generated in the pile (Fig. 1). The force pulse travels down the pile at a constant speed, undiminished in amplitude in the free-standing portion. As the force pulse travels into the embedded portion of the pile, the amplitude of the pulse is reduced because the soil absorbs energy from the pulse as it causes the pile to displace downward. The final downward displacement of the pile is commonly called the permanent set.

Smith modeled the pile-driving system as a series of weights and weightless springs. He derived a technique to describe the motion of the weights and the compression of the springs in a manner numerically

equivalent to the one-dimensional wave equation. Fig. 2 compares an actual pile-driving system, its idealization, and its model. The ram and follow block are usually considered to be single, rigid weights separated by a spring which represents the cushion material. The pile, being relatively compressible, is represented by a series of weights and springs. Soil resistance acting on embedded weights is modeled as an elastoplastic spring in parallel with a dashpot. The model can easily be modified to accommodate additions to or deletions from the pile-driving system. This is particularly useful because of the wide variety of pile drivers and accessories available. A list of variables that can be included in a solution is shown in Table 1. The computer solution is capable of treating variations in all these parameters, and with careful and accurate descriptive input, a remarkably accurate solution of pile driving is possible. Figs. 3 and 4 illustrate the degree of accuracy that can be obtained using the procedure. These two figures show driving records as predicted by wave-equation analysis superimposed on a plot of actual driving records. For clarity, the plot of the actual records has been shaded to provide a band which contains the individual pile driving records.

This degree of accuracy is not always possible, especially in the preliminary design phase when field observations are not available. However, much information often may be obtained from two or three solutions in which the parameters are varied to encompass the probable range to be encountered. In fact, considerable information can be obtained even when several of the variables must be roughly approximated.

DESIGN CONSIDERATIONS

Ability to forecast difficulties in installing pile foundations has been a definite problem in the design of a prototype structure, as for example, the first structure using significantly larger diameter piles than other structures in the area. Design decisions based on estimates of pile drivability can be costly if made too conservatively or too boldly. Until the advent of wave-equation analysis, no rigorous analytical approach to this problem was available. Now, however, it is possible to explore pile drivability in relation to pile foundation design.

Pile Drivability

Fig. 5 is an illustration of pile drivability in the form of a plot of resistance to driving versus number of blows required to drive a pile one foot. The term "resistance

to driving" refers to the force opposing the impact of the ram and should not be confused with static ultimate pile capacity. This form of presentation has been found to be a convenient way of displaying results of wave-equation computer analyses. For a given set of variables, the only quantity varied in developing this curve is the magnitude of resistance to driving. Comparisons can be easily made by changing any one of the variables. A more familiar presentation of pile-driving data is one in which the vertical axis represents pile penetration below the mudline. Graphs of this latter form require specific soils data and apply only to the special case being studied.

Curves such as Fig. 5 enable the engineer to evaluate the pile-driving process. For example, it can be seen (Fig. 5) that for a particular combination of pile, soil resistance, and driving apparatus, the maximum resistance to driving that can be overcome is about 3200 kips. Greater values of driving resistance cannot be overcome with the driving apparatus regardless of the number of times the ram strikes the pile. This soil resistance value corresponds to a penetration beyond which additional penetration cannot be attained, i.e., absolute refusal.

Before absolute refusal is reached, however, a point is reached at which practical refusal occurs. Above this point, the time invested in advancing the pile to deeper penetrations is not economically sound, so a new pile design or better driving apparatus should be sought. The specific value of practical refusal has been the center of some debate, and wave-equation analysis cannot completely settle this question because of economic factors that vary from job to job.

Design Curves

The design of any pile-founded structure involves the use of preliminary designs based on approximations. The part of the preliminary design concerned with the pile foundation usually deals primarily with the transfer of structural loads to the soil. The feasibility of installing the piling has been difficult to evaluate. It appears that the many variables involved in the pile-driving process (Table 1) would preclude a practical preliminary evaluation of feasibility. However, it has been found that certain of the pile-driving variables are of relatively minor significance for the range of problems being considered, and the remaining variables lend themselves to handbook-type design curve formulation. The design curves can then be used as the starting

point for determining the feasibility of installing a pile foundation on the basis of pile size, available hammers, available accessories, etc. Information obtained from the curves is only approximate, and final feasibility determination should be based on individual computer analysis.

Since typical piles used in offshore construction are not uniform in cross section, but rather are usually made up of sections of varying wall thickness to provide the necessary structural integrity, tabulating piles by exact cross-section makeup would not be feasible. But for the range of problems encountered by the authors, a fairly accurate wave-equation solution may be obtained by using the pile cross section at the centroid of the assumed soil resistance distribution. For example, if the soil resistance distribution is uniform, the cross section at one-half the embedment depth should be used as the approximate uniform section for the entire pile. This procedure usually results in a close approximation as is shown by Fig. 6. Because of this cross-section approximation, piles may be cataloged by single cross section and the volume of any design handbook reduced considerably.

Other factors which could preclude the design handbook concept are the variable nature of soil resistance distribution and depth of pile embedment. Wave-equation analysis has indicated that the distribution of soil resistance along the pile and the depth of embedment generally have only minor effects on the driving characteristic of a pile; whereas, the total amount of resistance to driving has the predominant effect. Further, a study of the effect of the length of the free-standing portion of the pile has shown it to be relatively small. Fig. 7 shows the effect of changing the length of the embedded portion of a 260-foot pile.

The ability to approximate cross-sectional variations and to eliminate specific soils information, pile embedments, and free-standing length is what actually makes the handbook concept a plausible approach. If it were not possible to make these simplifications, it would be impractical to attempt to cover the virtually infinite number of combinations of pile cross-sectional makeup, exact total length, specific embedment, and unique soil conditions in handbook form. Since these approximations can be made, it is not an impossible task to catalog wave-equation results in the form of curves or tables based on data representative of the range of problems being considered.

While the arrangement of these design curves can take many different forms, the

arrangement shown in Figs. 8a and 8b has been found to be useful. A set of curves should be developed for each hammer that is commonly used. Each set of curves for one hammer may consist of several pages, each page corresponding to a particular diameter pile. The curves on a given page are for various equivalent wall thickness values. During the course of a preliminary design, the design engineer determines from the structural loads and pile foundation configuration the necessary pile diameter. He also can estimate the equivalent wall thickness value for the pile and the expected resistance to penetration when the pile is at design embedment. Knowing the available driving equipment, the design engineer can then determine whether the pile can actually be installed by driving.

For example, consider that a preliminary design calls for 42-inch diameter piles to be driven with either hammer A or hammer B. The equivalent wall thickness is estimated at 1.00 inch, and the resistance to driving is estimated at 2500 kips. The first step would be to turn to Fig. 8a. Enter the vertical axis at 2500 kips and read across; it is obvious that the pile cannot be driven to design penetration, because the 1.00-inch curve approaches 2500 kips asymptotically. Turn now to Fig. 8b for hammer B. Enter the vertical axis at 2500 kips and read across until the 1.00-inch equivalent wall thickness curve is intersected. Moving vertically downward from this intersection shows that approximately 160 blows per foot will be required at final embedment. Thus, the design curves show that the pile can be driven if hammer B is used. The curves also show that a small increase in pile wall thickness can provide additional pile drivability. If none of the curves had shown that the pile could be driven, then the design engineer could redesign the foundation for a greater number of smaller piles which could be driven, or he could warn the construction engineer that alternate installation techniques would be needed.

It was mentioned earlier that soil resistance distribution was of secondary importance in comparison to the effect of total driving resistance. This does not mean that the distribution is not needed. To the contrary, it is needed in order to calculate the total soil resistance and to obtain the location of the equivalent cross-sectional value to be used with the design curves.

The determination of soil resistance distribution at the present cannot be exact. The nonhomogeneous, anisotropic nature of soils, and their complicated behavior during dynamic penetration has resulted in only

semirational methods for this determination. In spite of these difficulties, satisfactory results have been obtained by using soil parameters that can be computed from data commonly found in soil investigation reports.

Driving Stresses

Driving stresses in steel piles are often of little concern to design and construction engineers because the material and cross-sectional properties are such that usually very little trouble is encountered. Excessive driving stresses are more commonly the problem of engineers dealing with concrete piles. The lower compressive strength of concrete and its negligible tensile strength are sometimes insufficient to prevent extensive damage. Fig. 9a is a photograph of concrete piles damaged by driving.

Even though steel piles are usually capable of resisting driving stresses, this is not always the case. The piles shown in Fig. 9b were obviously inadequate as the driving ends were subjected to considerable plastic deformation. Damage such as this usually does not affect serviceability (the damaged portion can be cut off), but during driving, considerable energy may be expended in this deformation, and the collapsed or bent pile heads frequently jam in the hammer leads and delay the driving operation.

Although the head of a pile is often an area of concern, significant stresses can also develop elsewhere. The static bending stresses induced into a battered pile by the hammer weight can combine with driving stress to produce failure at the point of support.

Since the wave-equation solution is based on the progress of the force pulse (stress wave) along the pile, stress data is a ready by-product of the solution. Maximum compressive and tensile stresses are determined at selected positions along the pile. The location of excessive stresses may be predicted, and the feasibility of sizing the pile cross section for these stresses can be considered. Of course, flexural pulses resulting from eccentric impact are not a part of this solution, and the resulting dynamic flexural stresses are not easily included in a stress analysis.

In addition to determining pile stresses, it is possible to determine hammer stresses. This could be of some interest to hammer manufacturers and construction engineers striving for hammer reliability.

Economics

Material and installation costs are very

high for large-capacity pile foundations, and poorly made design decisions can have far reaching economical effects. For example, the decision to use a large number of small piles because of uncertainty as to pile drivability can result in structural changes which cause significant increases in material and installation costs. On the other hand, an overly optimistic design decision can result in piles being left above design penetration. If this produces unacceptable reductions in pile capacity, expensive construction delays may be necessary while alternate installation techniques are arranged. Any significant aid to making pile foundation design decisions can produce significant savings.

The application of wave-equation analysis to design of pile wall thickness in offshore piles deserves mention at this time. Historically, pile wall thickness design has been based on structural load-carrying requirements. The result was a pile with a thick section at the mudline and somewhat thinner sections above and below this. Recent wave-equation studies have shown that this type of pile design often does not result in the most efficient driving characteristics. In fact, increasing the wall thickness of a pile has been shown to be an effective way of improving the driving characteristic of a pile. McClelland, Focht, and Emrich⁶ offered evidence that increasing the wall thickness uniformly from top of pile to bottom increased drivability. The authors have found for a given pile that about the same increase in pile drivability can be attained if only that portion of the pile to be embedded is made of thicker wall. An application of this "thick-wall" concept is shown in Fig. 10. All except the lower 120 feet of the pile was designed to satisfy structural requirements. The lower 120-foot section was designed for improved drivability. For the design penetration of 180 feet, the "thin-wall" design cannot be driven to the desired penetration while the two designs using thicker walls can easily be driven to grade.

The economic implications of the thick-wall concept are: (1) the drivability of a pile can be improved to such an extent that a previously unattainable design penetration can be reached, (2) a pile that may barely reach design penetration can be almost assured of attaining penetration by a sufficient wall thickness increase, and (3) the time required to drive a pile can be substantially reduced. All this is obtained at the cost of increased steel tonnage.

The economic benefit obtained from improving driving characteristics (i.e., better driving equipment and thick-wall design) is measured by the savings in installation time. Offshore construction costs depend to a great extent on the time spent on the job location, so a time savings is easily converted to a dollar savings.

Wave-equation analysis can provide data for estimating installation time for piling. Fig. 11 shows a plot of pile penetration versus rate of penetration, which can be used to calculate driving time. As shown, the number of blows required to drive a pile to design penetration is equal to the shaded area. This area can be determined easily by graphical or numerical integration techniques. Since the blow rate of a hammer in blows per minute is generally available, the blow rate can be divided into the total number of blows to yield total driving time in minutes. To complete the estimate of installation time, estimates of time required for handling and welding add-ons should be added to the driving time. A driving time comparison for the thin-wall and thick-wall designs of Fig. 10 to the 160-foot depth shows a thick-wall time savings of approximately 40 minutes per pile, or a 45 percent decrease in driving time.

INSTALLATION

Wave-equation analysis of the pile-driving process is not only an invaluable tool for the design engineer but also for construction and field engineers. Hammer selection, driving accessory selection, and the value of hammer maintenance are some of the factors that can be evaluated through this analysis.

Hammer Selection

The proper selection of driving equipment is of paramount importance to the construction engineer. If the minimum hammer required for driving the pile has been established by the design engineer, the construction engineer only needs to insure that the proper hammer is available when installation takes place. However, if the hammer has not been chosen, the construction engineer may use design curves similar to those of Fig. 8 for making the choice.

The construction engineer may also be faced with scheduling pile-driving equipment for several simultaneous jobs. It would be economically unsound to schedule the equipment for jobs where it is overadequate and could have been used more effectively at another site.

