SCHOOL OF CIVIL ENGINEERING

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JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-87/1 -2

Executive Summary

COMPUTATIONAL PACKAGE FOR PREDICTING PILE STRESSES AND CAPACITY

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Introduction

Pile foundations are often used to support highway bridges to transmit the required structural loads to a firm layer by penetrating the upper weak strata. The design of such foundations is often a complex matter which requires that much information be available to the designer. Such information includes: the soil formation; groundwater conditions; expected total pile capacity; load transfer mechanism between the pile and the soil; pile installation procedure including hammer, cushions, etc. for driven piles; and expected relative displacement between the pile and the soil. Because of the many factors that affect pile foundations, a variety of techniques are used for prediction and design. These techniques include static formulas, dynamic formulas, wave equation analyses, pile load tests and dynamic measurements during pile driving. Regarding the above mentioned facts, the current research study had the following goals:

1. To review the state-of-the-art of the most recent advances in predicting the pile capacity using static formulas and procedures and the theoretical background behind these methods.

2. To review the current dynamic formulas that are extensively used for driven pile design and driving control and to show their advantages and disadvantages as tools for the evaluation of safe and economical design.

3. To review the wave equation approach that has been used increasingly for predicting capacity of driven piles based on driving data and for the

optimum choice of the driving equipment.

4. To prepare a computational package for the pile capacity and stresses prediction which incorporates the best available static equations, dynamic formulas and wave equation analysis. The purpose of this package is to provide the pile designer with a comprehensive, powerful tool to enable him to determine the most efficient design based on all the important aspects of the problem.

5. To review the state-of-the-art of pile load test methods, including the necessary equipment and instrumentation. Based on this review, specific recommendations are made concerning the most rapid and economical load test procedures that should be followed, including all of the required interpretation techniques.

6. To review the state-of-the-art of dynamic measurements made during pile driving, to illustrate their potential uses and to examine the feasibility of implementing this technique to pile foundations engineered by the IDOH.

7. To examine the phenomenon of residual stresses accumulating during pile driving and subsequently affecting the behavior of the pile foundations and the interpretation of load test results. A simple procedure is suggested for the prediction of such stresses.

8. To provide the computational package with a routine for predicting additional pile loads due to negative skin friction to avoid the unsuccessful performance of the pile foundation that experiences this phenomenon.

To meet the required goals, two reports have been prepared at Purdue. The first one was the interim report written by Tejidor (1984) which covered the first four goals stated above. The second report, which is also the final report, covers the remaining four items (5 through 8). These two reports serve the ultimate goal of helping the bridge design engineer and the construction engineer of the IDOH in the selection and placement of efficient and economic bridge foundations in the state of Indiana.

The following sections of this summary highlight the most important aspects of the two reports that served to meet the above mentioned goals.

Pile-Soil Design Capacity:

The static methods used for pile capacity prediction are in many ways analogous to the corresponding ones used for shallow foundations. The critical problem is to determine the ultimate load which a deep foundation can sustain. The ultimate load is then that load which can cause either the structural failure of the foundation itself or a bearing (shear) failure of the soil. For most cases, ultimate load is determined by soil failure. The failure mechanism is characterized by punching shear failure under the point, accompanied or preceded by direct shear failure along the shaft. The load transfer at ultimate capacity occurs simultaneously along the pile shaft and the bearing area of the pile point and involves a mass of soil extending to considerable distances from the pile. Usually, the ultimate skin resistance is reached much sooner than point resistance, and the portion of the load carried by the point is smaller at working conditions than at failure.

The installation technique has a significant effect on the response of the pile. The prominent effect of driving the piles in cohesionless soils is the compaction of the soil by displacement and vibration, resulting in changes of the soil characteristics. For cohesive soils, driving the piles causes structural alteration of the soil surrounding the pile. These alterations generate considerable excess pore pressures around the pile, with subsequent strength regain with the dissipation of the pore pressures.

For design purposes, the ultimate load is separated into two components: the point load, and the shaft load. The fundamental assumption involved is that the ultimate point and shaft resistances are mobilized simultaneously. The analytical models chosen for design purposes are distinguished with respect to soil type. For cohesionless soils, the ultimate load capacity in terms of both point and shaft resistance is expressed as a function of overburden pressure. However, the analytical relationships hold only when the pile point is above a certain critical depth. Below this depth, the point resistance and average unit skin friction remain practically constant in a homogeneous sand deposit, due to effects of soil compressiblity, crushing, arching and existence of driving residual stresses. A method was proposed by Meyerhof which determines the point and shaft capacities in terms of limit values. The model proposed by Vesic based on the cavity expansion theory requires detailed knowledge of the strength and deformation characteristics of the soil strata, and also of the variation of density and water content within those strata. The limit values can be determined empirically using in situ tests, such as the static cone penetration tests or the standard penetration tests.

Certain recommendations are made to modify the estimates of ultimate load capacity to account for the effects of pile type and installation procedures. In addition, scale effects for large diameter piles are taken into account by means of a reduction factor. Recent correlations have suggested that both ultimate point and shaft resistance may not reach a limit value but may continue to increase with the mean normal stress, although at a lesser rate. However, several inconsistencies have been observed in the results of these recent correlations. Further research is needed to examine these discrepancies and clarify the actual pile behavior.

Deep foundations in cohesive soils are more critically affected by the rate of loading of the pile. Significant pore pressures may be generated during the loading stage. The rate of pore pressure dissipation implicitly determines the analytical method chosen for an assessment of bearing capacity. If significant pore pressures are expected to be induced due to the nature of the soil, an undrained, short-term ultimate load capacity should be computed. However, if pore pressures induced for normal rates of load application dissipate fairly rapidly, then an effective stress, drained analysis may be more appropriate.

For point capacity, an analysis based on drained conditions is performed similarly to the method developed for cohesionless soils. Otherwise, a semi-empirical bearing capacity factor is applied to the undrained cohesion of the soil at the pile base. Several methods are available to determine the ultimate shaft capacity of piles in clay. Not all of the methods are universally applicable, and best results are obtained with discrete applications of the models with respect to soil type and loading rate.

The alpha method is conventionally used to evaluate the ultimate shaft capacity in clay in undrained conditions. The shaft friction is a function of the undrained strength of the clay modified by the alpha factor. The factor is a ratio of the pile-soil adhesion and the undrained shear strength of the clay. The beta method may be employed when it is determined that the rate of pore pressure dissipation is to be so rapid that for normal rates of load application, drained conditions will generally prevail in the soil near the pile shaft. The beta factor modifies the effective overburden pressure. The lambda method has been successfully used to predict the shaft capacity of heavily loaded pipe piles for offshore structures. The lambda coefficient was found to be a function of pile penetration.

The alpha method is highly sensitive to measured variation in undrained shear strength, whereas variations of this parameter may be surpassed by the effective overburden pressure explicit in the lambda method. The beta and the lambda methods have been found to give better results for normally consolidated soils. The alpha and the lambda methods provide reasonable correlations for overconsolidated soils.

Pile foundations are normally constructed as groups of closely spaced piles. Pile spacing should be such that the group capacity is not less than the sum of the capacities of the individual piles. However, the ultimate load of a group may be less than the sum depending on soil type, size and shape of the group, spacing and length of the piles, and construction procedures.

The allowable design load for groups is often determined from settlement considerations. The group settlement is usually larger than that of an individual pile, depending on the mechanism of load transfer from the pile to the soil. Predictions of total settlement can be greatly improved by experience obtained from observations on a regional basis.

Dynamic Formulas

Dynamic formulas were developed to indicate the static pile capacity based on the resistance to pile driving. The rate of pile penetration offered a means of relating driving resistance to ultimate capacity. There are dozens of such formulas reported in the literature. The fundamental assumption of all of them is that the dynamic resistance encountered during driving is equal to the load capacity of the pile under static loading. Most formulas are based on the principles of a kinetic energy converted to the work of penetrating the soil for a certain distance. Not all of the formulas are equally reliable and only experience on a regional basis can improve their predictability. The most common of these formulas are reviewed in the interim report by Tejidor (1984), along with their limitations and applicability for specific pile driving jobs.

Wave Equation Analysis

With the introduction of computers to the engineering profession, it was possible to analyze the mechanics of pile driving using the wave theory. The wave equation analysis examines the transmission of elastic waves along the length of the pile. The main objective of using the wave equation approach is to obtain a better relationship between ultimate pile load and pile set, as well as providing a means of assessing the drivability of a pile with a particular set of equipment. The approach also enables a rational analysis to be made of the stresses in the pile during driving. The hammer-pile-soil system is discretized and represented by a system of springs, dashpots and mass elements. The second order differential wave equation is expressed in finite difference form. The resulting equations are solved simultaneously for each element for each time interval considered. A number of parameters is required, with varying degrees of importance, to perform the analysis. The reliability of this analysis is dependent on the quality of the hammer-pile-soil model used to represent the in-situ conditions.

Computational Package for Pile Capacity and Stresses Prediction

A computer program "PPILE" has been developed at Purdue to enable the designer to analyze pile foundations statically and dynamically in an integrated and comprehensive manner. The analytical models for static analysis were chosen on the basis of extensive empirical evidence and the facility with which the pertinent and required parameters may be obtained. For the dynamic analysis, five of the most reliable pile driving formulas are provided to accommodate present design practice. In addition, by integrating the wave equation analysis into the package, it was possible to simplify and reduce the amount of input data previously required to successfully perform a wave equation analysis. Experience with the computational package resulted in the following conclusions:

1. Estimates of ultimate load capacities have been shown to be of reasonable accuracy for some 50 cases, including a variety of soils and pile types.

2. Results of the dynamic formulas can be predicted only within wide limits but can be improved on a regional basis. This is actually due to the limitations of the dynamic formulas themselves, which can be overcome by using the wave equation analysis.

3. The wave equation has proven to be a most versatile tool. A detailed analysis of case histories has demonstrated that the wave equation analysis offers a useful means of assessing the driveability of a pile with a particular set of equipment, and is the only means of rationally evaluating the stresses generated during driving. Finally, the analysis renders, at least qualitatively, a correct picture of the driving mechanism.

4. The computational package is unique in its comprehensive integration of static and dynamic pile analyses. This package is expected to be of considerable value to pile design in general, and to highway bridge designers in particular.

Static Pile Load Tests

In addition to the above mentioned techniques for predicting pile capacity, static full-scale load tests remain the best means to determine this capacity for specific site conditions. The importance of routine performance of pile load tests, even for small-scale jobs, is emphasized in the report. Planning the testing program and the application of test results are discussed. Emphasis is given to axial compression load tests, although other forms of tests, e.g. lateral, uplift and torsional testing are described. For each type of test, the state-of-the-art information about the following items is given: the loading systems; the measurement of pile movements; the potential sources of error; and the available testing procedures with the interpretation of their results. For axial load tests, the following methods are described: the maintained loading test (ML); the constant rate of penetration tests (CRP); the method of equilibrium; and the Texas Highway Department quick testing method. It is shown that quick load testing techniques correlate well with the traditional time consuming methods, and are more economical, which justifies their routine use for all types of jobs. Based on these studies, recommendations are made to the IDOH regarding procedures for performing pile load tests.

Dynamic Measurements for Pile Driving

Another type of pile testing involves the use of dynamic measurements during pile driving. These techniques are the best ones introduced thus far for monitoring the pile during driving. They can be applied, together with the wave equation analysis, in a variety of ways. Among their uses are pile capacity predictions; evaluation of the driving system with respect to the hammer efficiency and performance; measurement of pile stresses; and verification of the pile integrity.

The historical background of equipment development is described in the final report. The most recent advances for force, velocity and acceleration measurements, together with the appropriate recording devices, are reviewed. A brief description of the theoretical background behind these measurements is given.

Dynamic measurements have been used to predict the geotechnical pile capacity, either in-situ using a field computer and the approximate CASE method, or in the office using a more sophisticated analysis (CAPWAP). The latter analysis can also be used to predict the load transfer along the pile shaft, and the load deformation curve that would be obtained from a pile load test. Dynamic measurements have also been used to monitor driving hammers; evaluate their efficiencies under different operating pressures, strokes or batters; and to check the driving elements, i.e. cushions, capblocks, etc. Finally, dynamic measurements have been used to examine the performance of pile, detect any damage, and evaluate the actual pile lengths if not known.

It is recommended that the IDOH acquire the equipment used for dynamic measurements and provide the required personnel with appropriate training. The savings that can be achieved by using these measurements in several jobs would very soon cover the price of the equipment. More important will be the improvement in design and performance of the pile foundations, which will not only save money in the short term, but will also reduce the maintenance and replacement costs that might have been otherwise necessary in the long run.

Residual Stresses Due to Pile Driving

A driven pile is usually not stress free at the start of loading. Residual point and shaft stresses accumulate during the pile driving. Although the total pile capacity of the pile is not changed, these stresses may result in substantial changes in the mechanism of load transfer between the pile and the soil. The observed tip load is lower and the observed shaft friction is higher than the true values. The existence of residual stresses affects the driveability of the pile. Higher resistance can be reached with a smaller number of blows. In addition, driving stresses may increase by about 5% on the average, up to as high as about 15% due to the existence of residual stresses. Hence, it is of extreme importance to include these stresses in both static and dynamic analyses of the pile.

The general shape of the residual force distribution along the pile shaft does not vary, irrespective of the variables involved in the problem. Only the magnitude of these stresses change, according to the variations in the different parameters.

The main factors affecting residual stresses are examined in the report. It was found that the magnitude of the residual loads increases as the total soil resistance increases, as the length of the pile increases, as the cross sectional area of the pile decreases, as the elastic modulus of the pile decreases, and as the skin friction percent increases. The effect of the driving system and driving components is minor.

The methods that have been suggested thus far for residual stresses prediction were reviewed. The review showed that none of the available methods can give satisfactory predictions. Based on extensive parametric studies, a new procedure was developed at Purdue for the prediction of magnitude and distribution of residual stresses. This procedure is introduced by means of easy-to-use-charts and nomograms, with the help of illustrative examples. Predictions made by this technique were compared with actual measurements, and good agreements were shown.

Negative Skin Friction

In many situations, bridge pile foundations may be subjected to additional loads due to negative skin friction. These loads can lead to foundation failures if not taken into account in design. Available techniques for predicting these loads are not satisfactory and additional research is needed to overcome this problem. Until this research is developed, it is recommended that an upperbound prediction for a conservative design be used.

A computer program "PPILENF" has been developed at Purdue to complete the computational package for predicting pile stresses and capacity. This program predicts additional loads due to negative skin friction. It is recommended that the IDOH use this program for the design of pile foundations in situations where negative friction is involved. This will avoid serious prediction errors and long-term problems.

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