Study of Dynamic Methods of Predicting Pile Axial Load Capacity by Louisiana Department of Transportation and Development

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The Louisiana Department of Transportation and Development (LADOTD) has undertaken the task of optimizing its use of dynamic prediction methods for pile axial load capacity. The immediate intention is to replace its current use of the *Engineering News Record* formula with a more reliable, yet comparably inexpensive dynamic method. Several alternative dynamic formulas and wave equation analyses are being considered. Through the University of New Orleans Civil Engineering Department, LADOTD is studying the ability of each method in predicting Louisiana load test results. After a replacement method has been selected, field implementation procedures and software will be developed. This paper presents a review of selected literature that has defined the current status of dynamic pile capacity prediction and influenced the direction of the LADOTD project. A description of the various components of the LADOTD project, which was completed in December 1989, is also presented.

Pile foundations are especially important for bridges in Louisiana, where the surface soils are often poor and the water table is high. Failure of piles under bridges can have disastrous consequences, but the high cost of piling makes extreme overdesign impractical. Therefore, in order to design economical bridge foundations, the capacity of virtually every pile must be estimated accurately.

Because of the critical nature of the problem, pile designers prefer to have several alternative methods of estimating pile capacity. On most projects, three sources of capacity estimates are available:

- Those based on analyses of soil-boring information or cone penetrometer testing,
- Those based on nearby load tests of similar piling, and
- Those based on the driving record and pile equipment characteristics for the particular pile (i.e., dynamic methods).

The Louisiana Department of Transportation and Development (LADOTD) is currently studying ways to optimize its use of dynamic methods of pile capacity prediction for bridges in Louisiana. Similar studies are under way in other parts of the country (*1,2*).

This paper describes the current status of dynamic prediction of pile axial load capacity by reviewing selected literature; it also describes the project completed by LADOTD.

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NEED FOR DYNAMIC METHODS

Most pile designs evolve in the same way. Once the project has been conceived, soil borings are taken. Based on soil-boring analyses, appropriate pile type and length are selected. Typically, the pile design load is the predicted ultimate capacity from soil boring analyses, divided by a safety factor between 2.0 and 3.0. One or more of the selected piles is then driven and load tested to two or two and one-half times the desired design load. Blow counts and equipment characteristics pertinent to the test are recorded.

Most test piles survive the test loading without soil or structural failure and are used as part of the permanent foundation. The remaining (untested) piles are driven with the same equipment, and their blow counts are recorded. These piles are usually driven to similar depths and with similar blow counts as the test piles, and it is thus assumed that the untested piles also have the desired capacity.

Unfortunately, this model process does not always occur as previously described for various reasons. Soil-boring information may be insufficient, especially in some of the swamp areas of Louisiana where good samples cannot be recovered. Some projects are too small to justify a load test. For emergency repairs, there may not be enough time to conduct a load test. Also, production piles often do not receive the same number of blow counts as the test piles. A relatively low blow count at design penetration suggests a capacity lower than the test pile capacity. However, if the test pile resisted at least twice the design load without failure, it is uncertain whether this lower blow count indicates the need for additional pile length. A relatively high blow count before design penetration indicates the possibility of stopping the pile short. Continued driving may damage the pile or take an uneconomical length of time, but the reduced penetration may not result in adequate static capacity.

Because of these less-than-ideal situations, foundation engineers often must include the so-called *dynamic* methods when predicting pile axial load capacity. These methods currently range from the basic *Engineering News Record* (ENR) formula to the wave equation analysis with pile analyzer input.

The ENR, and most other formulas, is based on the principle of energy conservation (i.e., the energy imparted by the hammer ram, minus any losses, should equal the pile ultimate capacity, multiplied by the incremental penetration due to the latest hammer blow—this is oversimplified for most cases).

A wave equation analysis predicts the penetrations and corresponding blow counts for a given pile-hammer system and ultimate capacities by performing one-dimensional dynamic analyses of the hammer blow stress waves. Using the resulting curve inversely, one obtains the capacity corresponding to the known blow count. An allowable design load is obtained by dividing the ultimate capacity predicted (by whichever dynamic method is used) by a safety factor. The safety factor ranges from 2.0 to 6.0, for the current popular methods, and is generally loosely tied to the relation between the method's predictions and selected load test results.

When load tests have been performed and a given production pile drives similarly to the test pile, actual capacity predictions of the dynamic method are generally ignored in favor of test pile results. However, when load tests are not performed, or when a pile drives much differently than the test pile, dynamic predictions are very influential to design decisions.

Despite its proven inaccuracy, the ENR is still the most commonly used dynamic prediction method. This is due to its simplicity and the popular belief that none of the more complicated methods has yet been proven to be sufficiently superior to warrant its adoption. All of the dynamic methods, including the wave equation, have been criticized for use as pile static capacity predictors. One problem often cited is the possibility of large time-dependent gains or losses in capacity that cannot be quantified by analysis of end-of-driving conditions. However, the necessity for using dynamic methods in many instances has resulted in their continued use and development.

LITERATURE REVIEW

Pile Foundations by Chellis (*3*) presents extensive information relevant to predicting pile axial capacity using dynamic formulas. The time-dependent nature of pile axial capacity is discussed. Chellis suggests redriving the test piles after time delays in order to quantify time effects on capacity. Chellis also summarizes the soil conditions under which certain increases or decreases in capacity might be expected.

The history and use of dynamic formulas are presented, including detailed guidance on hammer efficiencies and coefficients of restitution, as well as information on driving hammers, piles, and other items pertinent to contemporary pile driving. Derivations for many of the formulas and comparisons between formula predictions and load tests are also presented. On the basis of these results, Chellis concluded:

> The scattering of results from the Engineering News and Eytelwein formulas is too wide to be comprehended within any one factor of safety, and even a factor of 6 would not be adequate for a number of the results.

In 1971, Poplin (*4*) examined and evaluated test pile data collected by LADOTD between 1950 and 1970. Among the many tasks undertaken during the project was a comparison of test loads to ENR formula predictions for 24 square precast concrete piles (14-in. and 16-in.). The ratio of ENR allowable load to test load ranged from 0.11 (safety factor = 9.0) to 1.00 (safety factor = 1.0). The average ratio was 0.506 (safety factor = 2.0), but the standard deviation of 0.183 was quite high. Poplin also examined a soil mechanics prediction of capacity for the same 24 piles and found only slighty better accuracy on the average. However, the range of safety factors was much smaller.

In 1962, Smith (*5*) described the use of the wave equation for estimating pile capacities and stresses. Smith presented mathematical models for the hammer-pile system and the soil resistance, and outlined a numerical solution to the pile displacements. Recommended values for most of the procedure inputs are given along with a detailed illustrative problem.

Critiques of Smith's paper by several well-known foundation experts were published with the paper in *ASCE Transactions*. Soderberg is generally supportive of the wave equation development and use. Marvin Gates, originator of the Gates formula, objects strongly to the implication that "the wave equation can be used to solve for the bearing capacity as well as the driving stresses." Cornfield acknowledges Smith's reference to the poor performance of dynamic formulas but suggested that correlations with load test results would be better if piles suspected to have large setups were eliminated from the comparison. Cornfield notes that load tests are the best method of determining pile capacity, but that their high cost precludes extensive use. He is hopeful that the wave equation solution will be a "reasonably accurate method of making use of the driving data" when load test results are not available or not applicable.

In 1980, Blessey and Lee (*6*) investigated the use of the wave equation for predicting pile capacities in the New Orleans area. The scope of their study was defined as follows:

> The investigation of the input soil parameters, and the development of the relationship of soil resistance from the Wave Equation to actual pile load capacities obtained from the pile load tests performed in the field for both friction and end-bearing piles.

Blessey and Lee studied 50 test pilings from the New Orleans area. R is the ratio of test-pile failure load to wave-equation-predicted failure load. The method of determining test-pile failure load was not stated, but the maximum load applied before pile plunging is probably intended. Classification of certain input was given and is reproduced in Table 1. Much of the input used, such as capblock and cushion stiffness, was not stated in the report.

For end-bearing prestressed concrete piles, the average R was 1.15 when minimum parameters were input to the wave equation. Mean R-values for average and maximum soil parameters were 0.9 and 0.5, respectively. The least variation between high and low R-values was obtained for minimum values. For end-bearing pipe piles, average R-values were 1.4, 1.1, and 0.9 for minimum, average, and maximum soil parameters, respectively. Again, the minimum parameters produced the most consistent results.

For friction piles, using the average blow count for the final 5 ft of penetration, average R-values for prestressed concrete piles were 6.0, 3.53, and 3.3 for minimum, average, and maximum soil parameters, respectively. For friction pipe piles, average R-values were 6.0, 4.5, and 3.3. For friction H-piles, average R-values were 5.0, 4.0, and 2.9. Minimum or average

TABLE 1 COMPUTER INPUT SOIL PARAMETERS (*6*)

Type of Input Parameters	Type of Soil	Quake(Q) (Inches)	Damping (J) (Sec/Ft) Side	Point	Hammer Efficiency
Minimum	Clay	0.30	0.20	0.01	0.65
Average	Clay	0.10	0.20	0.01	0.75
Maximum	Clay	0.05	0.10	0.01	0.85
Minimum	Sand	0.20	0.07	0.20	0.65
Average	Sand	0.10	0.05	0.15	0.75
Maximum	Sand	0.05	0.03	0.05	0.85

soil parameters produced the most consistent results in all cases.

In 1971, Rausche et al. (*7*) described the use of what is now commonly known as the *pile analyzer* to predict pile axial load capacities. Special instrumentation was used to measure actual pile force and acceleration due to the hammer blow. This information can be used directly or can be input to a wave-equation-type analysis for pile capacity prediction. The authors note that "the pile can be restruck a few days after driving to include strength changes of the pile-soil interface during set up." Dynamic records of 21 piles were analyzed. The dynamic data were obtained shortly (a few hours) before or after performing a static load test, thereby including the effects of set up in the dynamic method. The comparison between test pile failure load and pile analyzer prediction is reproduced in Table 2. The load test values given are those corresponding to the "largest pile displacement obtained under the [final?] hammer blow" and are substantially lower than actual maximum loads for many of the examples.

In 1982, Whited and Laughter (*8*) described the pile design process for the Arrowhead Bridge located between Superior, Wisconsin, and Duluth, Minnesota. Piles on this job were driven from 130 ft to 260 ft through loose sands and soft clays to a dense sand. Two pile types were considered: a 16-in. diameter cast-in-place (CIP) concrete pile driven closed end and an HP 14 × 73. Four H-piles and two pipe piles were load tested.

Whited and Laughter wrote that

> piles were to be driven to a minimum bearing of 172 tons-force as determined by the Wisconsin (modified EN) driving formula:
>
> $$P = 2WH/(S + 0.2) \quad (1)$$
>
> where
>
> P = bearing value (lb), (allowable)
> W = ram weight (lb),
> H = height of ram fall (ft), and
> S = penetration per blow (in).

Test piles were loaded to a maximum of 344 tons. Ultimate pile capacities were predicted from the resulting load-deflection curves using the methods of Davisson, Mazurkiewicz, Chin, the Swedish Pile Commission, and the American Association of State Highway and Transportation Officials (AASHTO). Davisson's method was selected as being most appropriate. The authors described this method as follows:

> Davisson's method defines the failure load as the load that corresponds to the movement that exceeds the elastic compression of the pile, when considered as a free column, by a value of 0.15 in plus a factor depending on the diameter of the pile. For the 16-in CIP piles and HP 14 × 73 this factor is approximately 0.1 inch. Thus, the pile reaches failure at a pile-head movement that exceeds the elastic compression by 0.25 in.

The Mazurkiewicz, Chin, and Swedish methods gave somewhat higher estimates of ultimate load, whereas the AASHTO limiting load, defined as the "load that, after a continuous application of 48 hours, produces a permanent settlement not greater than 0.25 inch," was significantly lower.

The performance of the pile analyzer in predicting load test results was described as "reliable" for the H-piles but not for the CIP piles. Errors for the CIP piles were attributed to larger setups together with the nonavailability of restrike data. The wave equation method (without pile analyzer input) was also used to predict load test results, but the predictions were poor.

On the basis of the test pile program, the HP 14 × 73 was selected for use on all foundations. The allowable load and assumed ultimate load were 150 and 300 tons, respectively. Most production piles were driven into the dense sand layer until the blow count indicated an allowable load of 150 tons by the Wisconsin formula. A blow count indicating an allowable load of 200 tons was required when penetration into the dense sand was not achieved. Hammers used to drive production piling were not the same as those used to drive test piling, but the rated energies were higher.

The pile analyzer was also used to monitor production piling by instrumenting one or two piles from each bent. A high instrument-damage rate led to reduced use of the analyzer only during pile restrikes after embedments were indicated to be adequate by the Wisconsin Department of Transportation formula. The analyzer was also found to be useful in identifying piles that were damaged by driving.

A 1985 report by Fragaszy et al. (*1*) to the Washington State Transportation Center presents a review of the literature

TABLE 2 PILE ANALYZER PREDICTIONS OF TEST PILE CAPACITIES (7)

Pile	Load Test,kips	Pile Analyzer,kips
1	151	159
2	97	91
3	107	136
4	172	163
5	200	233
6	176	210
7	174	180
8	137	166
9	183	204
10	60	69
11	93	119
12	32	56
13	75	122
14	165	173
15	90	151
16	125	151
17	152	163
18	40	45
19	64	84
20	176	184
21	174	187

with regard to the use of dynamic pile driving equations, wave equation methods, and pile analyzers. Approximately 200 technical references were reviewed, and the results were given of a survey of state transportation departments to determine what dynamic methods they were currently using.

With regard to the survey results, Fragaszy reported the following:

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

Fragaszy's review of technical literature indicated that, among the simple formulas, the Hiley, Janbu, and Gates were generally superior, and he found the ENR formula and its modifications to be generally inferior. The wave equation was found to be equal to or better than the best formula. Fragaszy summarized the use of the pile analyzer as follows:

> A pile analyzer can produce very accurate estimations of pile capacity. However, a pile analyzer is relatively expensive to purchase and maintain and requires highly trained individuals to interpret the data it collects.

As a result, Fragaszy recommended increased use of, but by no means total reliance on, the wave equation and pile analyzer. Discontinued use of the ENR formula in favor of a more accurate one was also recommended. The best formula would be determined through statistical analyses of regional load test data and the ability of the formulas to predict those load test results.

DISCUSSION OF THE LITERATURE

Review of the above papers and reports leads to the conclusion that much is still to be achieved in the area of dynamic prediction of pile capacity. None of the simple formulas has been proven to be adequate, although several have not been proven totally inadequate. Furthermore, the simplicity of their

application makes their sudden and complete discard highly unlikely. Some have found the wave equation analysis to be accurate, but others have found it to be practically useless. The required availability of a computer and software for its execution generally is no longer a major obstacle; however, the uncertainty of proper input for many of its variables remains a problem for most potential users. The pile analyzer has been praised by most who have used it, but its requirement for additional instrumentation and experienced personnel makes most engineers unwilling to abandon all other alternatives. Furthermore, it is not a precise predictor in all cases.

One important issue in the use of any of the methods is the treatment of the time effects on pile capacity. The logical and seemingly simple solution to this problem is to use restrike blow counts or force-and-acceleration data, or both. However, restriking brings about several problems:

1. The restriking must be performed after an appropriate time delay. Pile accessibility is often impaired by installation of surrounding piling. Furthermore, resetting the pile driver over each pile can be quite expensive.
2. In soils of considerable setup, the pile hammer used for production driving may not be of adequate size to restart the pile. A suitable starter hammer or other device for obtaining an after-setup blow count or pile analyzer data may not be suitable for driving additional pile length, should it be required.
3. Very little restrike data have been gathered for test piles. Thus, it is impossible to check any method's ability to predict historic load test results by using restrike blow counts.
4. Significant increases or decreases in capacity may occur after restriking.

In the research described below, time effects are estimated by applying a setup factor to the end-of-driving side friction capacity.

LADOTD PROJECT

In common with many state transportation departments and other agencies, LADOTD currently uses the ENR formula or its modifications to some extent. Through an ongoing project with the University of New Orleans, LADOTD intends to replace its use of the ENR with a more reliable dynamic method. The project currently is focusing on evaluating alternative dynamic formulas and the wave equation. Pile failure load predictions of the various methods under study are being compared with pile load tests performed in Louisiana.

The pile analyzer has been proven relatively accurate, and LADOTD is already using it on some projects. However, its requirement for additional instrumentation and personnel eliminates the pile analyzer as an ENR replacement requiring roughly equivalent effort and expense. Furthermore, it is impossible to evaluate the ability of the pile analyzer to predict historical load test results, because pile force and acceleration data have rarely been taken.

The growing practice of restriking will contribute greatly to pile capacity prediction in Louisiana, where setup factors are often very high. However, the costs and access problems associated with restriking preclude its specification for every pile. Again, the lack of restrike data on historical load tests makes evaluation of its effectiveness difficult.

The following dynamic methods are currently being studied (*9*):

1. ENR,
2. Hiley,
3. Gates,
4. Janbu,
5. Pacific Coast Uniform Building Code (PCUBC), and
6. Wave equation.

Suitable Louisiana load test results have been, and are being, computerized as part of the effort. For each load test entered into the data base, six ratios involving test load and the prediction of each of these methods are calculated:

$R1$ = maximum test load/predicted ultimate load
$R2$ = maximum test load/adjusted predicted ultimate
$R3$ = estimated failure load at time of test/predicted ultimate load
$R4$ = estimated failure load at time of test/adjusted predicted ultimate
$R5$ = estimated failure load at end of driving/predicted ultimate load
$R6$ = estimated failure load at end of driving/adjusted predicted ultimate

The adjusted predicted ultimate is the predicted ultimate load divided by the applicable theoretical safety factor: ENR 6.0, Hiley 3.0, Gates 3.0, Janbu 4.5, PCUBC 4.0, WEAP (wave equation analysis of pile) 2.0; then multiplied by 2.0. This adjusts a method's ultimate prediction to be 2.0 times its customary allowable load.

The maximum test load is not always the failure load, because many load tests are not carried to failure. Furthermore, the failure load of a load test carried to failure varies according to the interpretation method. The estimated failure load at time of test is the maximum test load multiplied by a factor intended to account for this difference. The following methods were studied for possible use in deriving the failure load from test-pile-load versus deflection data: Van der Veen, Mazurkiewicz, Davisson, Chin, AASHTO, Swedish Pile Commission. The Van der Veen method was selected for this project because it was used previously with Louisiana test piles (*10*). Van der Veen proposed the following relation between a pile's ultimate capacity and its load-versus-deflection behavior:

$$Q = Q_u (1. - e^{-rz}) \tag{2}$$

where

Q = applied load causing butt deflection z,
Q_u = pile ultimate capacity, and
r = coefficient determined from load-deflection curve.

Using two (Q,z) points near the upper end of the load-deflection curve, Q_u and r can be determined.

The failure load at end of driving is not the same as the failure load at time of test if setup or relaxation occurs. The end-of-driving blow counts available for historical load tests can logically be expected only to indicate failure load at end of driving, even for the best of prediction methods. The estimated failure load at time of test is divided by an input setup factor to obtain the estimated failure load at end of driving. This setup factor, SUF, is computed as follows:

$$SUF = S(P_s) + 1.0(P_t) \tag{3}$$

where

P_s = fraction of total pile resistance coming from side friction,
P_t = fraction of total pile resistance coming from tip bearing,
S = 1.0 if predominant side soil has high permeability (sand or gravel),
= 2.0 if predominant side soil is medium to stiff clay,
= 3.0 if predominant side soil is soft to medium clay, and
= 4.0 if predominant side soil is very soft to soft clay.

The fraction, P_s, of total resistance coming from side friction refers to end-of-driving conditions and is computed as follows:

P_s = 0.95 if the final blow count is less than 3.5 times the average blow count,
= 0.75 if the final blow count is between 3.5 and 4.0 times the average blow count,
= 0.50 if the final blow count is more than 4.0 times the average blow count.

For the rare cases in which load tests are carried to failure as defined by Van Der Veen, without substantial setup, and the prediction method's theoretical safety factor is 2.0, all six ratios will be equal. If the method is also "perfect," all ratios will be 1.0. It is hoped and expected that by examining and analyzing these ratios for many load tests, the best prediction method for Louisiana will become evident.

To perform the above calculations, it was necessary to develop appropriate computer software and data-entry formats. A standard form was developed for manual extraction of applicable data from LADOTD's file of pile load tests. An interactive FORTRAN computer program was then written to accept keyboard data entry and to create an equivalent computer data file. Although each load test has its own file, a cumulative catalog file, containing key information from each test, is updated automatically with each additional load test entered.

A second FORTRAN program, PLCAP, was written to perform the comparisons between load test results and the predictions of the various dynamic methods. Formula methods were easily programmed. However, an early attempt to incorporate the WEAP program was abandoned in favor of running WEAP87 separately and simply inputting its prediction to the developed program for calculation of the described ratios.

Parameter studies were conducted with many of the input items for the WEAP87 program in order to determine the sensitivity of results to reasonable variations in those parameters that are not generally precisely known. These parameters include capblock stiffness, cushion stiffness, hammer efficiency, coefficients of restitution, pile internal damping, soil side and tip damping, soil side and tip quake, percentage skin friction, and skin friction distribution type. As expected, it was concluded that predicted blow count for a given pile ultimate capacity often varied greatly with changes in certain parameters within plausible limits. In practice, one or more key parameters, such as side damping, are often calibrated to site load test results, such that the wave equation precisely predicts the load test results when those calibrated values are used. These same parameter values are used for wave equation predictions of the production pile capacities. This calibration procedure, which can also be used with any of the dynamic prediction methods, is often successful. However, it is dependent on the availability of load test results and is obviously not appropriate for an evaluation of methods for independent use. In this research, two wave equation predictions per load test are determined. For the first prediction, the best information available is used for the WEAP87 input. This information is derived from the literature, the WEAP87 user's manual, and conversations with experienced individuals in the pile-driving industry. For the second prediction, referred to as WEAPDF, a set of default average parameters was input.

Summary statistics for several groupings of the compiled load test data base are given in Tables 3 through 7. These results should be regarded as preliminary because analysis of the results has not yet been completed.

TABLE 3 SUMMARY STATISTICS FOR 56 SQUARE CONCRETE PILES

	Mean		COV	Mean		COV
Method	R3	R4	R3 and R4	R5	R6	R5 and R6
ENR	0.599	1.797	0.61	0.348	1.044	0.60
Hiley	1.598	2.398	0.50	0.953	1.429	0.53
Gates	2.239	3.359	0.46	1.361	2.041	0.54
Janbu	2.186	4.918	0.55	1.264	2.844	0.51
PCUBC	2.972	5.944	0.52	1.730	3.460	0.50
WEAP87	2.605	2.605	0.64	1.461	1.461	0.58
WEAPDF	2.682	2.682	0.72	1.514	1.514	0.65

TABLE 4 SUMMARY STATISTICS FOR 12 TIMBER PILES

	Mean		COV	Mean		COV
Method	R3	R4	R3 and R4	R5	R6	R5 and R6
ENR	0.436	1.308	0.30	0.389	1.168	0.30
Hiley	1.429	2.143	0.24	1.280	1.920	0.24
Gates	1.643	2.464	0.24	1.471	2.206	0.24
Janbu	1.670	3.758	0.24	1.497	3.369	0.25
PCUBC	2.056	4.112	0.24	1.841	3.683	0.25
WEAP87	1.728	1.728	0.24	1.553	1.553	0.26
WEAPDF	1.704	1.704	0.25	1.527	1.527	0.26

TABLE 5 SUMMARY STATISTICS FOR 60 PILES DRIVEN WITH SINGLE-ACTING AIR/STEAM HAMMERS

	Mean		COV	Mean		COV
Method	R3	R4	R3 and R4	R5	R6	R5 and R6
ENR	0.650	1.949	0.60	0.391	1.172	0.50
Hiley	1.727	2.591	0.42	1.084	1.626	0.42
Gates	2.251	3.377	0.43	1.438	2.157	0.49
Janbu	2.278	5.126	0.52	1.381	3.106	0.44
PCUBC	2.954	5.908	0.50	1.805	3.609	0.44
WEAP87	2.685	2.685	0.63	1.573	1.573	0.49
WEAPDF	2.686	2.686	0.72	1.560	1.560	0.54

TABLE 6 SUMMARY STATISTICS FOR 43 PILES BEARING IN CLAY

	Mean		COV	Mean		COV
Method	R3	R4	R3 and R4	R5	R6	R5 and R6
ENR	0.619	1.858	0.60	0.360	1.079	0.53
Hiley	1.609	2.414	0.42	0.993	1.489	0.50
Gates	2.032	3.048	0.46	1.259	1.888	0.54
Janbu	2.204	4.959	0.49	1.298	2.921	0.48
PCUBC	2.828	5.657	0.47	1.678	3.355	0.49
WEAP87	2.728	2.728	0.60	1.529	1.529	0.48
WEAPDF	2.611	2.611	0.61	1.468	1.468	0.50

TABLE 7 SUMMARY STATISTICS FOR 12 PILES BEARING IN SAND

	Mean		COV	Mean		COV
Method	R3	R4	R3 and R4	R5	R6	R5 and R6
ENR	0.469	1.408	0.56	0.367	1.102	0.79
Hiley	1.498	2.247	0.58	1.091	1.636	0.59
Gates	2.450	3.676	0.63	1.925	2.887	0.85
Janbu	1.873	4.213	0.47	1.421	3.198	0.60
PCUBC	2.473	4.945	0.47	1.822	3.644	0.53
WEAP87	1.977	1.977	0.61	1.563	1.563	0.83
WEAPDF	2.087	2.087	0.57	1.643	1.643	0.78

CONCLUSIONS

1. Dynamic methods remain an important component in predicting pile axial load capacity.
2. Wave equation analysis with pile analyzer input and the practice of restriking are becoming recognized means of improving dynamic predictions. However, associated additional expenses and effort prevent their use on every pile.
3. Still needed are reliable dynamic prediction methods that can be used economically on every pile. The so-called best method may vary from location to location and should be selected by comparing the method's predictions to appropriate load test results.
4. Quantifying time effects on pile capacities remains a difficult component in the use of dynamic methods.

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