PILETALK INTERNATIONAL '91
13-14 August 1991 : K. Lumpur, Malaysia

BEARING CAPACITY OF DEEP FOUNDATIONS FROM DYNAMIC MEASUREMENTS AND STATIC TESTS - TEN CORRELATION CASES

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ABSTRACT: Bearing capacity of deep foundations is often confirmed by means of static load tests. This procedure, however, is expensive, time consuming, and in some cases physically impossible to perform. Due to these limitations, only a few piles are statically load tested on big projects, and perhaps none on smaller jobs. In recent years, dynamic pile top measurements performed under an impacting mass have been used to evaluate deep foundations for bearing capacity. Being quick and relatively inexpensive, these tests are becoming routine in many countries around the world. Continuous developments of analysis and measurements have improved their economy and reliability. This paper considers ten case histories where both dynamic and static tests were performed on the same piles. The cases cover driven piles and drilled shafts. Driven piles were installed with diesel and air/steam hammers. Special loading devices were constructed for the testing of drilled shafts. Soil conditions cover sand, silt, clay, calcarious soils, and rock. It is concluded that pile top dynamic measurements can be used to compute deep foundations static bearing capacity within 10% of that determined from static tests under a variety of conditions.

1. INTRODUCTION

The static bearing capability of a pile is limited by either the structural strength of the pile shaft or the capacity of the supporting soils. Pile structural capacity is limited by allowable pile stresses which are based on material properties and building code requirements. The capacity of the pile-soil system may be evaluated by static analysis taking into account soil strength parameters derived from both in-situ and laboratory geotechnical test methods. Various analytical procedures have been described in the soil mechanics literature. However, static analysis is considered preliminary and must be supported by additional field tests in most cases. Either static load testing, which consists of applying loads of known magnitude to the pile top and measuring corresponding pile movement, or dynamic measurements and analyses of pile force and motion records during impact of a falling mass are generally used to evaluate deep foundation elements for axial static bearing capacity.

This paper presents case histories where both static and dynamic tests were performed on ten piles. It describes the dynamic pile testing and analysis methods and discusses the use and merits of both static and dynamic tests. All case histories were recorded and are presented in the English unit system. Conversion factors between English and SI units are included in the Appendix.

2. STATIC LOAD TESTS

Traditionally, pile testing has meant the application of a static load test and the measurement of the resulting pile top movement. The failure load is defined as that load which causes excessive pile movement. Various definitions exist for the excessive pile set (2). For high capacity often a proof test to a certain load level is conducted when it is too expensive to load the piles to failure. This type of pile testing is expensive, time consuming, and in some cases physically impossible to perform. Because of these restraints, only a few piles are tested on larger projects, and perhaps none on smaller jobs. In many instances, information obtained from only one loading test is used to judge the rest of the piles in a foundation. Many factors such as subsurface variability, adequacy of construction techniques, and workmanship that affect pile bearing capacity and structural integrity can, of course, spoil such "engineering by association" approach. It has been reported in the literature (2) that, even under very well controlled conditions, the evaluation of piles for ultimate capacity based on static tests can easily contain errors of 10 or 20% relative to the true value. Static tests can even be totally misleading in some cases (1). Nevertheless, static load testing is still considered the best and only means for establishing a reference or standard pile static bearing capacity. Examples of static test results will be discussed in the Case studies presented below. As a failure criterion, the method of Davisson was usually chosen [see also (2)].

3. DYNAMIC MEASUREMENTS AND ANALYSES

3.1 Background

Dynamic methods for bearing capacity evaluation were utilized by early pile drivers centuries before the underlying principles were recognized and understood. It seemed logical that higher loads should be supported by a pile for which more effort was needed to advance it into the ground. Also it was intuitively clear that impacting a pile with an excessively large mass or drop height, and was most likely to cause pile damage though it would advance the pile faster. Engineers have tried to express the relationship between effort needed to drive a pile and its bearing capacity in a simple formula (9) based on principles of Newtonian physics of bodies in motion. Actually, Newton himself warned against the use of his impact theory in pile driving analysis (8). This early dynamic approach was a crude analysis of the ram impact on a pile. Early in the last century, it was recognized that pile driving dynamics is better modeled by wave propagation rather than by idealized rigid body impacts. Mathematical closed form solutions for special cases were developed, but general purpose solutions were not easily obtained due to the complexity of the problem. The first measurements were taken during driving in 1938 in England in an attempt to better understand and more realistically control pile stresses and soil resistance.

In the 1950s, the availability of digital computers made a discrete solution of elastic one dimensional wave propagation possible and computer programs were written (7). This type of analysis became known as the "wave equation". The method models hammer, pile, and soil with a relatively high degree of realism. Results from wave equation analyses are widely used for assessing pile drivability and static bearing capacity during driving, or after installation with a restrike. Further discussions on this type analysis may be found in the literature (4,5). The wave equation is an excellent analytical tool for what-if type studies before going into the field. However, because the solution depends on assumptions, accurate stress or bearing capacity results can only be assessed through actual measurements of hammer and/or pile dynamic quantities occurring during a hammer blow in the field.

3.2 *Case Method*

The technique most widely employed today for both measurement and field analysis of piles were developed under the direction of Professor G.G. Goble at Case Institute of Technology. The technique is therefore called the Case Method (3). The Case Method encompasses the measurement of force and velocity during a hammer blow and the computation of some 40 dynamic variables in real time by employing reusable strain transducers, piezoelectric accelerometers, and a Pile Driving Analyzer (PDA). The PDA is a data acquisition system and user-friendly field computer that provides power supply and signal conditioning for the transducers. It applies Case Method solutions to the measured data to calculate: pile static bearing capacity, driving induced pile stresses (compressive and tensile), hammer/driving system performance parameters, and a structural pile integrity related value. Required PDA inputs include pile length, cross sectional area, elastic modulus, and density, in addition to specific calibration factors for the measuring gages, and an assumption of a soil damping factor that represents soil dynamic behavior under impact.

It can be shown (6) that given pile top records of force (F) and velocity (v) under a hammer impact on a uniform elastic pile, the total soil resistance can be calculated from:

$$R = [F(t_1) + F(t_2) + \{v(t_1) + v(t_2)\}\ Z]/2 \qquad (1)$$

where $t_2 = t_1 + 2L/c$, t_1 is a selected time during the hammer blow, Z is the pile impedance, equal to Mc/L (L is the pile length, M pile mass, and c the wave transmission speed related to material density and elastic modulus). This total resistance, R, is the sum of static, S (displacement dependent), and dynamic, D (velocity dependent), components. To find the static soil resistance S, the damping resistance D, must be calculated and subtracted from R. The damping resistance D may be approximated by the product of a non-dimensionalized damping factor, j_c, and the calculated pile toe velocity.

$$S = R - (j_c)[F(t_1) + Zv(t_1) - R] \qquad (2)$$

The toe velocity times pile impedance is found from pile top force and velocity and resistance as shown in the right hand term of Equation 2. The damping factor, j_c, can be solved directly from the above equation if the failure load from a static load test is substituted for S. In this way, the damping factor was found to be related to the soil grain size. Originally, the Case Method capacity, S, was calculated at the time, t, of highest pile velocity with relatively sensitive damping factors. Today, the time, t_1, is usually chosen such that it yields the maximum static resistance, i.e., at a time when the pile reaches maximum temporary penetration and starts to rebound. The pile velocity is then low and the calculated static resistance becomes insensitive to the choice of j_c.

Case studies 4.1 and 4.2 illustrate the data provided by the PDA and its Case Method interpretation to compute pile static capacity for a concrete and a steel pile, and a comparison with full scale static load tests.

3.3 *CAPWAP*

CAPWAP (the CAse Pile Wave Analysis Program) is a procedure which allows the computation of soil resistance forces and their distribution, along with other dynamic soil parameters from measured pile top force and velocity histories during a hammer blow (6).

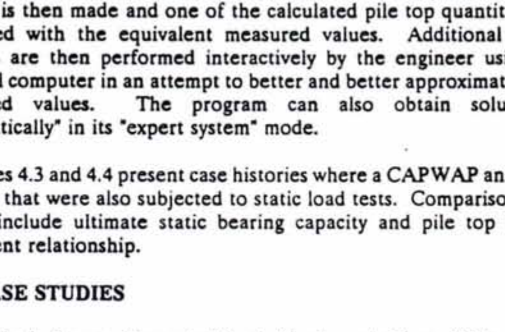
The CAPWAP pile model consists of a series of segments of equal stress wave travel time corresponding to approximately 1 m length. The soil reaction forces are represented by passive, static (elasto-plastic) and dynamic (linearly viscous) components, as originally proposed by Smith (7). Such resistance forces act both along the shaft and below the pile tip. They can be calculated from pile displacement and velocity given at each segment, an ultimate static resistance and quake value (static component) and a dashpot constant (dynamic component). Note that ultimate resistance divided by quake yields the soil stiffness. The sum of all segment ultimate resistance values is the total ultimate capacity of the pile. At first, a complete set of assumptions (i.e., static capacity, quakes and damping at each pile segment) along with pile model are entered into the computer. A trial analysis is then made and one of the calculated pile top quantities is compared with the equivalent measured values. Additional trial analyses are then performed interactively by the engineer using a personal computer in an attempt to better and better approximate the measured values. The program can also obtain solutions "automatically" in its "expert system" mode.

Examples 4.3 and 4.4 present case histories where a CAPWAP analysis on piles that were also subjected to static load tests. Comparisons of results include ultimate static bearing capacity and pile top load-movement relationship.

4. CASE STUDIES

4.1 *12-inch Square Concrete Pile in Sandy and Clayey Silts- Case Method Prediction*

A prestressed concrete pile, (length of 60 ft and area 144 in^2) was driven with a Conmaco 65E5 single acting air hammer (6.5 kip ram, 5 ft stroke, 32.5 kip-ft rate energy) to a depth of 45.5 ft and a driving resistance of 5 blows per inch (BPI). Three days after installation, the pile was restruck and had a driving resistance of 10 BPI. The pile was dynamically monitored during both initial driving and restrike. The soil conditions consisted of residual soils composed of sandy and clayey silts. Dynamic records of pile top force and velocity along with a complete Case Method interpretation for static capacity during a restrike hammer blow are presented in Figure 1. In this example, the



$$\begin{aligned} F(t_1) &= 530 \text{ kips} \quad F(t_2) = 340 \text{ kips} \\ Zv(t_1) &= 490 \text{ kips} \quad Zv(t_2) = 90 \text{ kips} \\ R &= [F(t_1) + F(t_2) + Zv(t_1) - Zv(t_2)]/2 \\ &= [530 + 340 + 490 - 90]/2 = 635 \text{ kips} \\ S &= R - j_c\,[F(t_1) + Zv(t_1) - R] \\ &= 635 - [530 + 490 - 635] = 423 \text{ kips} \end{aligned}$$

Figure 1: Case Method Results, Case 4.1

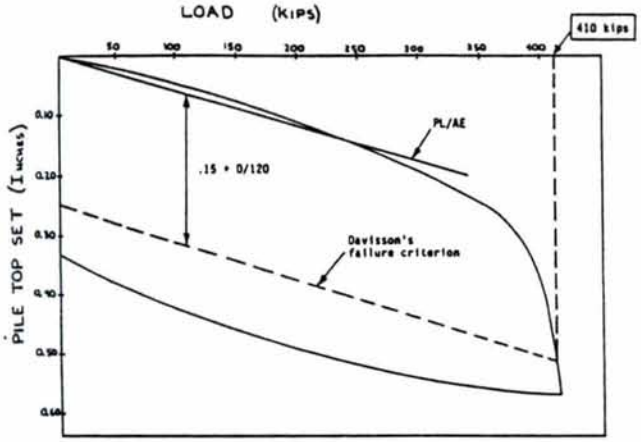
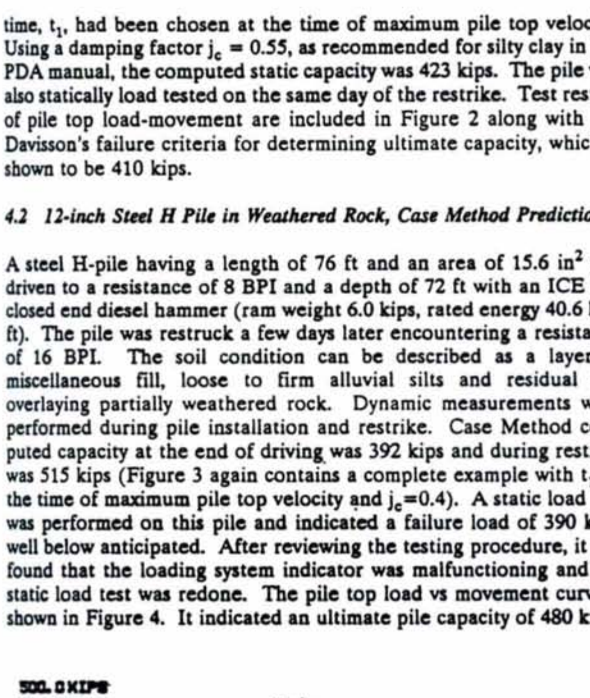


Figure 2: Static Load Test Results and Interpretation, Case 4.1

time, t_1, had been chosen at the time of maximum pile top velocity. Using a damping factor $j_c = 0.55$, as recommended for silty clay in the PDA manual, the computed static capacity was 423 kips. The pile was also statically load tested on the same day of the restrike. Test results of pile top load-movement are included in Figure 2 along with the Davisson's failure criteria for determining ultimate capacity, which is shown to be 410 kips.

4.2 12-inch Steel H Pile in Weathered Rock, Case Method Prediction

A steel H-pile having a length of 76 ft and an area of 15.6 in^2 was driven to a resistance of 8 BPI and a depth of 72 ft with an ICE 640 closed end diesel hammer (ram weight 6.0 kips, rated energy 40.6 kip-ft). The pile was restruck a few days later encountering a resistance of 16 BPI. The soil condition can be described as a layer of miscellaneous fill, loose to firm alluvial silts and residual soil overlaying partially weathered rock. Dynamic measurements were performed during pile installation and restrike. Case Method computed capacity at the end of driving was 392 kips and during restrike was 515 kips (Figure 3 again contains a complete example with t_1, at the time of maximum pile top velocity and j_c=0.4). A static load test was performed on this pile and indicated a failure load of 390 kips, well below anticipated. After reviewing the testing procedure, it was found that the loading system indicator was malfunctioning and the static load test was redone. The pile top load vs movement curve is shown in Figure 4. It indicated an ultimate pile capacity of 480 kips.



$F(t_1)$ = 420 kips $F(t_2)$ = 415 kips
$Zv(t_1)$ = 327 kips $Zv(t_2)$ = 0 kips
R = $[F(t_1) + F(t_2) + Zv(t_1) - Zv(t_2)]2$
= [420 + 415 + 327 - 0]/2 = 581 kips
S = $R - j_c\,[F(t_1) + Zv(t_1) - R]$
= 581 - 0.4 [420 + 327 -581] = 515 kips

Figure 3: Case Method Computation, Case 4.2

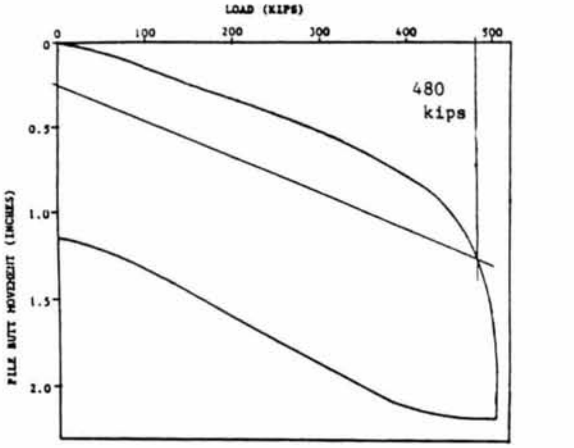


Figure 4: Static Load Test Results and Interpretation, Case 4.2

4.3 24-inch Octagonal Prestressed Concrete Pile, Silty Sand over Calcareous Sand - CAPWAP Prediction

A prestressed concrete pile with a length of 79 ft and an area of 477 in^2 was driven with a Vulcan 520 single acting air hammer (20 kip ram weight, 5 ft maximum stroke, 100 kip-ft rated energy, using only a 3 ft stroke) to a depth of 78 ft and a blow count of 3 BPI. The pile was restruck with the same hammer (but with a 5 ft stroke) and encountered a resistance of 2 BPI. The subsurface conditions can be described as a 44 ft layer of silty sand under which a two foot thick limestone cap existed over a deep layer of medium to very dense coarse calcareous sand. The pile was monitored dynamically during the restrike. Analysis performed according to the CAPWAP method was performed on data during the restrike test. Results from a CAPWAPC include (see Figure 5): measured pile top force and velocity records (upper right), comparisons of measured and computed forces (upper left), both soil resistance distribution and pile forces along the shaft at ultimate capacity (lower right) and a statically calculated load-set curve based on CAPWAP's predicted resistance and quake values (lower left). Furthermore, for each pile segment, ultimate static soil resistance, (unit friction and unit end bearing values), soil quake and damping factors are tabulated.

The results indicate a CAPWAP computed ultimate pile capacity of 550 kips. Figure 6 presents results of a static load test performed on the same pile (indicating an ultimate capacity of 512 kips), along with the CAPWAP simulated pile top load-movement plot.

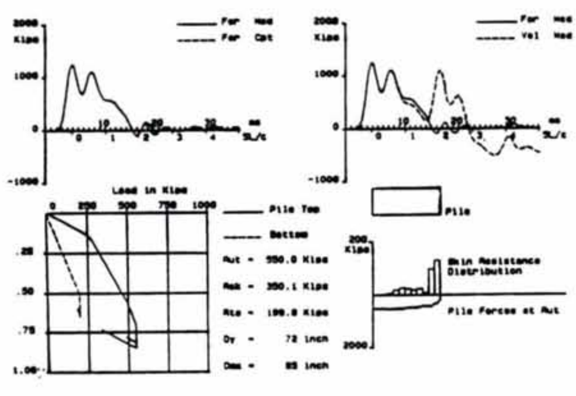


Figure 5: CAPWAP Analysis Results, Case 4.3

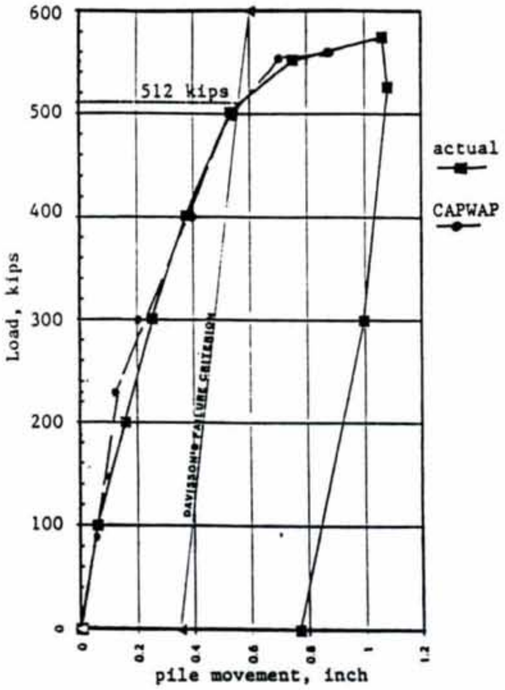


Figure 6: Static Load Test and CAPWAP Simulated Load-Movement, Case 4.3

4.4 30-inch Square Concrete Pile in Sandy Clay, CAPWAP Example

A 30-inch square prestressed concrete pile with an 18-inch circular void (effective area = 645.5 in^2) and a length of 109 ft was driven to a depth of 104 ft and a resistance of 3.3 BPI with a Conmaco 300E5 single acting hammer (300 kip ram weight, 5 ft stroke, 150 kip-ft rated energy). The soil at this site consisted of loose sand overlaying sandy clay. End of drive dynamically computed static pile capacity was 580 kips. Two weeks after installation, the pile was subjected to a static load test. A few days after that, dynamic measurements were obtained on the pile during a restrike. Results of a CAPWAP analysis performed with data taken during the restrike are presented in Figure 7, and indicate a computed pile static capacity of 881 kips. Static load testing indicated a pile ultimate static capacity of 850 kips according to the client's load test interpretation. Actual and simulated pile top load-movement curves are presented in Figure 8.

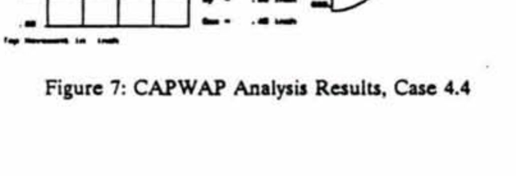


Figure 7: CAPWAP Analysis Results, Case 4.4

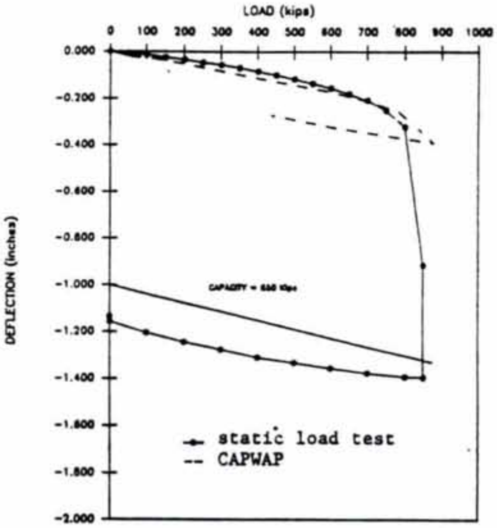


Figure 8: Static Load Test and CAPWAP Simulation, Case 4.4 (capacity definition according to client's specification)

4.5 70-foot Timber Pile in Sandy Clay

A 70 ft long timber pile (17-inch and 8.5-inch diameters at the top and toe, respectively) was driven with a Vulcan 06 single acting air hammer (6.5 kip ram weight, 3 ft stroke, 19.5 kip-ft energy) through sandy clay to a depth of 66 ft and a resistance of 0.5 BPI. The pile was instrumented and restruck one week later and then reached a driving resistance of 3 BPI. CAPWAP analyses performed on data from the second blow of restrike computed an ultimate pile static capacity of 123 kips. A static load test indicated a pile ultimate pile capacity of 129 kips.

4.6 24-inch Square Concrete Pile in Limerock

A 24-inch square (area = 576 in^2) 31 ft long prestressed concrete pile was driven with a Delmag D46-02 open end diesel hammer (10.1 kip ram weight, 10.6 ft rated stroke, 107 kip-ft rated energy) to a penetration of 28 ft and a blow count of 5 BPI. Subsurface conditions generally consisted of upper layers of dense sand over soft limerock. Dynamic measurements and analyses performed for the end of driving computed a pile capacity of 450 kips. A static load test performed on this pile indicated an ultimate static capacity of 450 kips. Dynamic data obtained during pile restrike after the static load test computed a pile capacity of 443 kips.

4.7 14-inch H-Pile in Cooper Marl

An H-pile (HP 14x73, area = 21.4 in^2) with a length of 90 ft was driven with a Vulcan 320 single acting air hammer (20 kips ram weight, 3 ft stroke, 60 kip-ft rated energy) to a depth of 87 ft and a resistance of 0.8 BPI. The soil conditions indicated a soft overburden of 25 ft thickness over a thick strata of calcareous clay which is referred to as Cooper Marl. A series of four static load tests were performed on this pile after 1, 14, 26, and 33 days from initial installation with corresponding indicated ultimate static capacities of 520, 640, 640, and 600 kips, respectively. The pile was then subjected to a restrike with the same driving hammer and was dynamically instrumented. A dynamic analysis performed on this restrike data computed a pile ultimate static capacity of 566 kips.

4.8 24-inch Square Concrete Pile with Steel Stinger in Calcareous Sand

A 64 ft long, 24-inch square (area = 576 in^2) prestressed concrete pile with a 2.25 ft long steel H-pile added to the pile at its bottom (stinger) was driven with a Conmaco 520 single acting air hammer (20 kip ram weight, 5 ft stroke, 100 kip-ft rated energy) to a driving resistance of 72 blows per foot at a depth of 62 ft. Soil conditions consisted of silty clayey sand to a depth of 45 ft under which medium dense, fine to coarse, calcareous sand with some cementation existed. Analysis performed on data from a restrike blow computed a pile static bearing capacity of 1126 kips. Static load testing indicated a pile ultimate capacity of 1100 kips.

4.9 28-inch Diameter Drilled Shaft in Sand over Limestone

A 45 ft long drilled shaft with a diameter of 28 inches to a depth of 20 ft and a 24 inch diameter for the remaining 25 ft was tested both dynamically and statically. A specially constructed 20 kip weight was used to impact the pile top for the dynamic test. During the test, four blows were applied with respective drop heights of 1.5, 5.5, and two of 6.5 ft. In the field, the PDA interpreted measured dynamic data according to the Case Method and computed pile static capacity and stress maxima for each blow. The dynamic data from each blow was also analyzed with the CAPWAP program. Pile capacities computed by the Case Method ranged between 564 and 680 kips with an average of 638 kips. According to the CAPWAP analysis, the predicted capacities ranged between 610 and 656 kips with an average of 644 kips. The static load test performed on this pile indicated an ultimate static pile apacity of 600 kips.

4.10 36-inch Diameter Drilled Shaft in Very dense Sand

Another drilled shaft 36 inches in diameter, 30 ft long was installed in very dense, dry to slightly moist sand. Dynamic measurements were obtained near the pile top under the impact of a 19.5 kip weight falling 10 ft. Dynamic analysis of the data computed a pile static capacity of 1555 kips (1187 kips in skin friction and 368 kips in end bearing). A static load test performed on the pile indicated a pile ultimate capacity of 1700 kips.

5. CONCLUSION

Carefully executed static load tests are the most reliable means of bearing capacity verification for deep foundations. However, they have time and cost limitations which severely limit their practical application in many cases. Dynamic testing provides a viable alternative that also furnishes additional information regarding performance of the total hammer-pile-soil system. This type of testing is equally applicable to driven as well as cast in-situ piles. All types of pile materials lend themselves to these tests and good correlation can be expected in most soil types if restrikes are performed and pile sets are sufficiently large to activate the full soil resistance. The ten case histories presented in this paper show a close correlation of pile capacity calculated from static and dynamic tests.

6. REFERENCES

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APPENDIX

Conversion Factors

To Convert	To	Multiply By
ft	m	0.305
in	cm	2.54
in^2	cm^2	6.45
kip	kN	4.45
kip-ft	kJ	1.36
blows per inch	blows per m	39.4