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The Use of Superposition for Evaluating Pile Capacity

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Abstract

Evaluating static pile capacity by dynamic testing has become routine procedure in contemporary foundation engineering practice worldwide. Testing is typically performed during initial pile driving, and/or during restrike some time after installation. Situations limiting the accurate assessment of static pile capacity by dynamic methods include: (1) the pile capacity changes due to the time-dependent characteristics of the supporting soils and/or rock, and (2) the hammer energy is insufficient to fully mobilize all soil/rock resistance forces present during the test. This paper presents discussions on the fundamental mechanics of these two limitations and proposes the use of superposition of dynamic test results for evaluating total pile capacity. A case history where both a significant increase in pile capacity occurred after the end of initial driving, and insufficient hammer energy limited the activation of full resistance during restrike is presented that demonstrates the applicability of the proposed approach. Dynamic test results performed with end of initial driving (EOID) and beginning of restrike (BOR) data are provided along with full scale static loading test results. Using superposition by combining the pile end bearing resistance from EOID and shaft resistance from BOR dynamic test results produced excellent correlations with the static loading test results including the ultimate pile capacity as well as the pile top load-movement relationship.

Introduction

There are a number of analytical methods and testing procedures for evaluating the axial load carrying capacity of driven piles. They include purely analytical methods based on geotechnical soil properties obtained from laboratory tests, semi-empirical methods based on correlations with standard field investigation test results, statistical comparisons with data bases and local experience, crude dynamic methods based on energy considerations and driving resistance blow counts, computer simulations and dynamic analysis based on wave propagation theories, dynamic field testing and numerical analysis, and full-scale static loading tests. Each of these methods and procedures available today has disadvantages and limitations in practical application, accuracy, and precision for reliable and economical assessment of static load carrying capacity of pile foundations.

Preliminary designs and/or evaluations of pile foundations typically include calculation of static load bearing capacity using geotechnical soil parameters obtained from laboratory tests performed on "undisturbed" samples. Pile capacity is taken as the sum of shaft resistance and end bearing values computed from unit skin friction and unit toe resistance applied to the pile dimensions of size and length. The method assumes that the shaft resistance and end bearing are simultaneously fully activated. Every foundation engineering textbook contains equations to compute capacity values for piles in cohesive or cohesionless soils, some with completely different philosophies and fundamental assumptions regarding soil behavior and soil/pile interaction (Coduto. 2001). Basically, this approach computes "long term" static pile capacity since it utilizes soil parameters that represent natural ground conditions unaffected by the pile driving process. Depending on the subsurface conditions, soil type, and pile characteristics, the computed pile capacity value may be realized shortly after pile driving, or may require a very long time after installation. This has great effects on pile driveability studies since the soil resistance during pile driving is often different from the computed long term capacity, and also on construction scheduling since the pile should have sufficient capacity to support applied loads shortly after installation. In practice, this form of pile capacity assessment is used for desk studies and rarely utilized alone as a final means to determine pile capacity.

Full-scale field static loading tests are performed to measure the actual response of a pile to applied static load, they provide the best means of determining pile capacity. The procedures for conducting the test and interpretation of results are well documented in the literature (Kyfor et al. 1992). Static loading tests are conducted during the early stages of a project for foundation design purposes, at the beginning of construction to verify geotechnical and other design assumptions, or during the production phase to proof test the adequacy of a questionable pile. For design purposes, testing should always be performed to "failure"; verification or proof testing is often done to just twice the design load which may be well below the pile's ultimate capacity. Evaluation of shaft resistance and end bearing requires extensive planned pile instrumentation. Project specific geotechnical and other considerations, applicable building code and specifications, dictate when a static loading test is to be performed after initial pile installation. The waiting time can range from one day to more than a week. The test yields results about the pile load carrying capacity only at the time of testing, and about the ultimate static pile capacity only if performed to failure. Static load testing is a very involved procedure, time consuming, expensive, and difficult (if not impossible) to do in many situations which limit the application of this pile capacity evaluation method in practice.

Evaluating static pile capacity by high-strain dynamic testing methods has become routine procedure in contemporary foundation engineering practice in many countries worldwide (Niyama and Beim, 2000). Testing is performed under the hammer impacts during initial pile driving, or by restrike some time after initial installation. Testing and related numerical modeling and data analysis yield results regarding static pile capacity including separation of shaft resistance and end bearing at time of testing. The accurate assessment of static pile capacity is affected by two factors: (1) time-dependent soil strength changes and their effects on pile capacity, and (2) the ability of the hammer to fully mobilize all soil/rock resistance forces present during the test. The first factor is common to any kind of testing, and is also manifested in the static analysis methods. The second is analogous to a static loading test that could not be run to failure due to limited loading/reaction system capability. Presented in this paper is a method to combine the results of dynamic tests performed during initial driving and restrike to evaluate total pile capacity. A comprehensive case study is also presented.

Dynamic Pile Testing

Dynamic methods for bearing capacity evaluation of driven piles originated over a century ago when engineers tried to expresses the intuitive relationship between driving resistance expressed in blow count and load bearing capacity by utilizing the principles of Newtonian physics of bodies in motion. In the 1950s, the availability of digital computers made a discrete solution of elastic one-dimensional wave propagation possible. This type of analysis became known as the "Wave Equation" of pile driving used for assessment of pile driving stresses and static capacity (Smith, 1960). The wave equation analysis method is far superior to the earlier energy approach, but like any other analytical method it suffers from some limitations (Hussein et al., 1988). In 1964, an FHWA sponsored research program was initiated at Case Western Reserve University in Cleveland, Ohio, for the purpose of developing a practical, economical, and accurate method for determining static pile capacity from dynamic measurements (Goble et al., 1975). This successful research resulted in modern dynamic pile testing and analysis methods, collectively called the Case Method, performed today routinely on thousands of job sites around the world.

Dynamic pile testing is based on the measurement of pile top force and velocity under driving hammer impacts during initial installation or restrike. Field testing is performed with a Pile Driving Analyzer (PDA) unit, shown in Figure 1, that receives and processes data obtained from instrumentation that typically consists of two each strain transducers and accelerometers bolted approximately one meter below the pile top. In real-time during field testing, the PDA provides estimates of soil resistance and static pile capacity based on simplifying assumptions regarding the soil dynamic behavior. Testing results also include parameters for the evaluation of hammer/driving system performance, dynamic pile driving stresses, and pile structural integrity.

For a more accurate and extensive evaluation of the soil resistance and static pile capacity, the measured pile top dynamic force and velocity records are analyzed with the CAse Pile Wave Analysis Program (CAPWAP) which employs a sophisticated soil model (Figure 2) to analyze pile dynamic measurements in a system identification process employing signal matching techniques. This method combines actual field measurements, wave equation type simulations, and signal matching in an interactive dynamic environment. The pile is divided into segments of uniform, continuous, linearly elastic properties. Each segment length and the associated analysis time increment represent the dynamic event in the measured records in time and space. The soil model includes shaft resistance elements as well as a toe resistance. The basic model represents resistance by an elastic-plastic spring and a dashpot requiring an ultimate resistance, quake, and damping at each element. The extended model also includes devices to represent energy dissipation due to radiation damping. In the analysis, the magnitudes and distribution of ultimate soil resistance forces can be directly determined from the measured pile top records between times of impact and the time of the first wave return. Quakes can be determined from the time rate of resistance increase, and damping factors are indicated by the duration of the resistance activation. CAPWAP analysis results also include simulated static load test results showing pile top and toe load-movement relationships.

Testing for Pile Capacity

The scientific foundation of the measurements and analytical procedures constituting dynamic pile testing methods, along with countless case histories confirming the accuracy of static pile capacity predictions are well documented in the engineering technical literature (e.g., the proceedings of the six international application of stress wave theory to piles conferences alone contain more than 4000 pages). There are, however, situations that limit the accurate assessment of static pile capacity by dynamic pile testing methods. These limitations are imposed by natural soil/rock behavior and by physical and mechanical constraints. Situations limiting the accurate assessment of static pile capacity by dynamic methods include: (1) the pile capacity changes due to the time-dependent characteristics of the supporting soils and/or rock, and (2) the hammer energy is insufficient to fully mobilize all soil/rock resistance forces present during the test. The following presents discussions on the mechanics of these two limitations and proposes the use of superposition of dynamic test results for evaluating total "long term" pile capacity.

Impact pile driving causes dramatic changes in the geotechnical conditions of the natural ground (Poulos and Davis, 1980). The nature and degree of the effects are mainly dependent on the type and condition of soil and rock, and on pile characteristics (i.e., displacement or low-displacement, uniform or tapered, etc.). Pile driving tends to have compacting and densification effects on cohesionless soils resulting in an increase of lateral pressure around the pile which enhances pile capacity. In calcareous materials, crushing of the particles occurs with degrading permanent effects on the soil structure and strength. Saturated dense fine grained cohensionless soils (silts and silty sands) can develop negative pore pressures when the pile is driven, temporarily increasing the (mostly end bearing) resistance of the pile during driving; dissipation of these excess pore pressures has a detrimental effect on the pile capacity. The effects of pile driving on clays are mainly soil disturbance or remolding, alteration in the state of stress around the pile, and development of excess pore water pressures. Time-dependent changes of clay soil characteristics and pile/soil interaction behavior have pronounced beneficial effects on initial pile driving resistance and "long term" static load bearing capacity. Development of excess pore pressures reduces the soils strength making initial pile driving installation relatively easy. Dissipation of these pore pressures, along with thixotropic regain and other effects, strengthens the clays resulting in dramatic increase in pile capacity. This phenomenon is known as pile "freeze" or "set-up". While advantageous to pile capacity, set-up can be a hindrance to pile installation in extreme cases where it happens quickly and pile driving has to be temporarily interrupted for pile splicing, hammer repair, or other reasons. The reduction of bearing capacity of piles with time (a phenomenon known as relaxation) in shale is generally attributed to relief of high locked-in lateral stresses. In some cases, piles flutter or wobble during driving creating an oversize hole in the ground which also affects the development of pile capacity. For accurate assessment of "long term" pile capacity, and for proper correlation between dynamic pile testing results with static analysis or loading test results, time effects on pile capacity must be appropriately considered.

During initial installation, dynamic pile testing is performed with the same hammer blows that are used for driving the pile. The hammer impacts should deliver sufficient energy and loading force to the pile in order to overcome the soil resistance (in skin friction and end bearing generated by static strength, stiffness and viscous dynamic effects) and cause permanent pile penetration/set. The pile should be of sufficient strength, stiffness and impedance to withstand and transmit the forces (also possibly combined with resistance forces) needed for pile driving, otherwise the pile will fail structurally. The nature and magnitude of the driving energy and force waves in the pile are functions of the hammer ram weight, drop height (i.e., stroke), mechanical efficiency, hammer and cushion characteristics (i.e., stiffness, etc.), and pile size and material properties, soil resistance effects also play a dynamic interactive role. As the pile penetrates into the ground, the activated soil resistance increases during an elastic loading process, reaching, and then exceeding maximum (i.e., ultimate) values; the excess energy then works on advancing the pile and securing permanent penetration. Typically, piles are installed with permanent sets of 30 to 3 mm/blow (i.e., driving blow count of 33 to 333 blows/m). Pile refusal (sometimes defined as blow count of more than 700 blows/m) occurs if the driving system is incapable of producing sufficient pile displacement beyond the elastic, and into the plastic soil deformation ranges. Under refusal pile driving conditions, dynamic pile testing can only measure the mobilized portion of the ultimate pile capacity activated by the limited pile movement. Dynamic pile testing during restrike is performed under a limited number of hammer blows. The same original pile driving hammer, or another one may be used to restrike the pile. The pile should experience sufficient permanent penetration under the restrike hammer blow if the ultimate pile capacity is to be reached, and measured.

For accurate assessment of "long term" ultimate pile capacity, dynamic pile testing should be performed during restrike with a hammer powerful enough to fully mobilize soil/rock resistance that incorporate time-dependent soil strength changes and their effects. In practice, construction scheduling constraints generally do not allow for more than a week or two of waiting time, so actual pile capacity is rarely tested. The size of the pile driving hammer is often chosen to initially drive the pile, but not necessarily to test it after set-up. In many cases where the pile capacity consists of shaft resistance realized due to set-up and end bearing achieved at the end of initial driving, the same pile driving hammer may not be able to fully mobilize pile capacity during a restrike test. In fact, restriking with an undersized hammer may produce misleading results. The ability of dynamic pile testing and related data analysis methods to separate the shaft resistance and end bearing components of pile capacity at the time of testing makes it possible to combine the results of tests performed during initial installation and restrike by using superposition of shaft resistance from restrike and end bearing from end of driving tests. This evaluation method can also be expanded to combine the results of several tests where the shaft resistance is only partially activated (such as for long piles) during each test. This proposed approach, of course, assumes that there is no relaxation effects in the end bearing component of pile capacity.

A case history where both a significant increase in pile capacity occurred after the end of initial driving, and insufficient hammer energy limited the activation of full resistance during restrike is presented that demonstrates the applicability and accuracy of the proposed approach.

Case Study

Project Description. The Florida Department of Transportation (FDOT) recently widened the existing State Road (SR) 20 crossing of the Apalachicola River in Calhoun County, Florida, by constructing a new two-lane bridge parallel to the existing two-lane structure. The existing steel and concrete bridge was constructed in the 1930's and has been designated as an historic structure. Each of the structures consists of a trestle portion crossing the surrounding flood plain as well as a high-level portion spanning the river itself. The trestle portion of the new structure is about 1,360 meters long while the approaches and main span comprise 1,185 meters, resulting in a total structure length of 2,545 meters. The main span provides a vertical clearance of 16.7 meters from the normal high water level of the river. The river is about 213 meters wide at the crossing.

The trestle portion of the new structure is supported by 42 pile bents each containing five 762-mm square, prestressed concrete piles with 457-mm circular voids cast to within 1.2 m of each pile end. The 1.2 m end sections are solid. The approach and main spans are supported on twin columns each rising from a single drilled shaft foundation. The design compressive capacity for each trestle bent pile was 1922 kN while end bent piles had a design compressive capacity of 1,183 kN. In addition, the potential for loss of pile resistance due to scour was a concern at bents approaching the river. Scour resistances provided in the project plans ranged from about 35 to 578 kN. There were no tension load requirements.

The project included a testing program that included dynamically testing 19 piles at representative production locations. In addition, three piles were installed and dynamically tested in non-production locations and were subsequently statically load tested. Following the static load tests, the piles were subjected to restrike to obtain data for comparison with the static load test results. This case history will focus on data from one of the test piles that was both dynamically and statically tested.

Subsurface Conditions. Subsurface conditions at the test site, as inferred from a review of the boring logs included in the project plans, generally can be described as consisting of a surficial layer of loose clayey sand and very stiff sandy to silty fat clay extending to a depth of about 2.3 meters, underlain by dense to medium dense fine to coarse sand extending to a depth of about 14.6 meters. Beneath the sands, a hard, partially-cemented calcareous mixture of clay, sand, shell, and gravel was indicated that extended to the boring termination depth of about 21.3 meters below existing grade. Groundwater was encountered at the bottom of the surficial clay layer at a depth of about 2.3 meters. A graphic summary of the subsurface profile at the site is presented in Figure 3.

Test Pile Installation. The 19.8-meter long test pile was installed using a Menck MHF Model 5-12 hammer. A Manitowoc 4100W Series-2 crane was used to lift the hammer and leads. The Menck 5-12 is a hydraulic free fall hammer with a maximum rated energy of 120 kN-m. The ram weight is approximately 120 kN and the maximum stroke height is one meter. The hammer energy can be incrementally controlled by selecting stroke heights. The hammer cushion consisted of polymer 50 mm thick and a 12 mm thick aluminum disk. The pile top cushion consisted of plywood sheets with a total thickness of 150 mm. The test pile was dynamically instrumented using a PDA, with instrumentation located below the solid end section of the pile, to evaluate the hammer/driving system performance, pile driving stresses, energy transfer to the pile, pile structural integrity, pile capacity, and soil behavior.

The pile was initially driven with the hammer set to operate at a stroke of 0.33 m to reduce the potential for excessive tension stresses during early driving. When PDA data indicated that tension stresses were consistently within allowable levels, the stroke was increased to 0.66 m and finally to one meter. The pile generally drove at resistances of 20 to

40 blows per 300 mm to a tip depth of about 16.7 meters at which point driving resistance began to gradually increase to a depth of about 18.3 meters. Below this penetration, the resistance rapidly increased to a hammer blow count of 129 blows per 300 mm at a tip penetration of 18.9 meters and, since this pile was to be subsequently statically load tested, driving was terminated. Figure 3 shows the soil conditions with the pile driving log and indicates that the pile was tipped in the very dense to hard calcareous material that appears to be limestone that is weathered to varying degrees.

Using PDA data from a selected end of driving (EOID) hammer blow, CAPWAP analyses were performed to estimate ultimate static pile capacity, soil quake and damping parameters, and soil resistance distribution. These results were to be incorporated into wave equation analyses to establish installation criteria for production piles. The CAPWAP results are summarized in Table 1 and include ultimate static capacity along with soil quake and damping parameters and the capacity that is derived from skin friction (890 kN) and end bearing (3960 kN). CAPWAP results are shown in Figure 4.

Static Load Test. Forty one days after it's installation, the test pile was statically load tested in compression. One meter of the pile top was cut off to accommodate the load frame making the pile's tested length 18.8 meters. Compressive load was applied to the pile using a 11,120-kN hydraulic jack reacting against a double reaction beam. A load transfer assembly was utilized to transfer load from the reaction beam to four groups of six steel HP356x132 reaction piles driven to depths of 12.2 meters below existing grade. The H-piles resisted the compressive load applied to the test pile through uplift in skin friction. An 8,896-kN load cell and a calibrated pressure gauge were used to verify the imposed loading.

The compressive loads were applied in general accordance with the FDOT modified quick test procedure. Using this procedure, the load is applied in increments equal to approximately five percent of the specified maximum test load (8,896 kN) until the failure load is reached. Each load increment is applied immediately after a complete set of gauge and instrument readings is taken, usually within five to fifteen minutes per increment. The load is removed in decrements of ten percent of the maximum test load obtained following the same procedure as that for loading. The primary system used to monitor pile deflections consisted of two dial gauges that measure in increments of 0.025 mm and have 50 mm of travel. The dial gauges were mounted on independent wood reference beams located along opposite sides of the pile. A secondary system employed to record pile deflections included a wire, mirror, and a scale marked with 0.25-mm increments. The mirror and scale were attached to the pile with the wire aligned such that it passed across the face of the scale. Deflections were measured by aligning the wire with its reflection in the mirror and recording the corresponding scale reading. As a further check on pile deflections, a scale was attached to the top of the pile and movement was monitored using a survey level. In addition, four reaction piles (one in each group) were monitored for movement by reading attached scales with a survey level.

To evaluate the contribution of skin friction and end bearing to the total capacity of the pile, the relative movement between the pile head and pile tip was measured using two tell-tales located at opposite corners of the pile. Each tell-tale consisted of an unstressed steel rod placed in a constant diameter PVC pipe that rests on a steel plate located about 300 mm above the pile tip. Two dial gauges that measure in 0.025-mm increments and have 25.4 mm of travel were mounted on the top of the pile. The dial gauge stems rested on flat steel plates fixed to the top of the tell-tale rods. A modified Davisson Method was used to establish the pile "failure" load. For piles greater than 610 mm in width, the failure load is defined as the load that causes a pile head deflection equal to the calculated elastic pile compression plus 1/30 of the pile minimum width. To calculate the elastic pile compression, the modulus of elasticity was estimated based on the results of tests performed on concrete cylinders that were cast at the same time as the piles. Results of the static load test are included in Table 1 including the failure load as well as an estimated breakdown of toe resistance and skin friction based on the tell-tale data. Figure 5 presents the pile head load-settlement response as well as the theoretical elastic pile compression and the parallel failure load intercept. Modified Davisson Method interpretation indicates a (plunging type) failure at 7340 kN. The tell-tale readings indicated 3217 kN in shaft resistance and 4123 kN in end bearing.

Test Pile Restrike. A PDA-instrumented restrike was performed on the test pile two days after completion of the static load test. The restrike was performed with the hammer operating at full stroke (one meter); however, as shown in Table 1, the transferred hammer energy was significantly less during the restrike compared to that of the original drive. Under the initial 10 blows of the restrike the pile experienced a permanent set of approximately 2.5 mm. CAPWAP analysis using data from an early restrike hammer blow indicated a mobilized pile capacity of 4340 kN with contributions of 3315 kN in shaft resistance and 1025 kN in end bearing. CAPWAP analysis results are presented in Figure 6 and are summarized in Table 1.

Superposition of Dynamic Test Results. Based on the low pile set under the restrike hammer blows (due to the added pile capacity and lower transferred energy), it was concluded that the pile capacity was not fully mobilized during the test. Combining the CAPWAP analyses results from the end of driving and beginning of restrike data would provide a more accurate assessment of the total "long term" pile capacity incorporating set-up effects. A total pile capacity value of 7275 kN is achieved by adding the 3315 kN in shaft resistance from restrike to the 3960 kN end bearing from end of drive analyses. One additional CAPWAP analysis was performed in a novel approach to produce a simulated static test load-movement relationship using combined restrike shaft resistance and end of initial driving end bearing models taken from the two previous independent CAPWAP analyses. Figure 7 provides a comparison of the actual static load test load-settlement curve with the resulting simulated CAPWAP curve.

Correlation of Dynamic and Static Load Testing Results. As shown in Table 1, the use of superposition results in a total capacity as well as a distribution of skin friction and end bearing that correlates well with the static load test results. In addition, the good correlation of the actual static load test load-settlement curve and the CAPWAP simulated curve shown in Figure 7 indicates that the proposed method of superposition of dynamic test data can provide an excellent prediction of static load test load-settlement behavior.

Summary

Each of the analysis or testing methods and procedures available today has limitations in practical application, accuracy, and precision for reliable and economical assessment of static load carrying capacity of pile foundations. The ability of dynamic pile testing and related data analysis methods to evaluate and separate the shaft resistance and end bearing components of pile capacity at the time of testing makes it possible to combine the results of tests performed during initial installation and restrike. Superposition of shaft resistance from restrike and end bearing from end of driving tests allows for an economic and accurate assessment of pile capacity including time-dependent soil strength effects utilizing the same pile driving hammer system already available on site. A case study is presented where this approach was applied and showed excellent agreement of results with full-scale static loading test performed to failure.

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Table 1. Summary of CAPWAP and Static Load Test Results

Test	Quake (mm)		Damping (s/m)		Static Capacity (kN)			Blows/Set	Maximum Transferred Energy (kN-m)
	Skin	Toe	Skin	Toe	Skin	Toe	Total		
End of Initial Drive	2.54	10.67	.09	.02	890	3960	4850	129/300 mm	65
Static Load Test	----	----	----	----	3217	4123	7340	----	----
Restrike	2.54	1.78	.08	.03	3315	1025	4340	10/2.5 mm	38
Superposed Results	----	----	----	----	3315	3960	7275	----	----

Figure 1. Pile Driving Analyzer

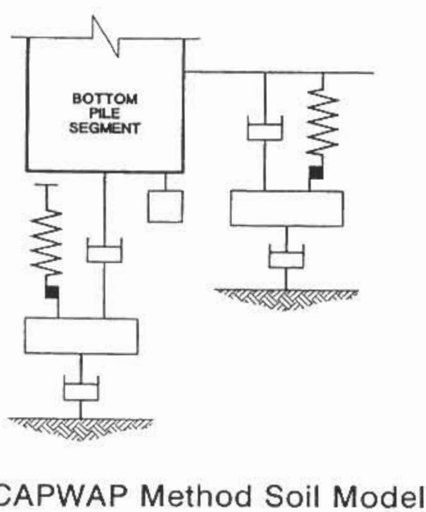

Figure 2. CAPWAP Method Soil Model

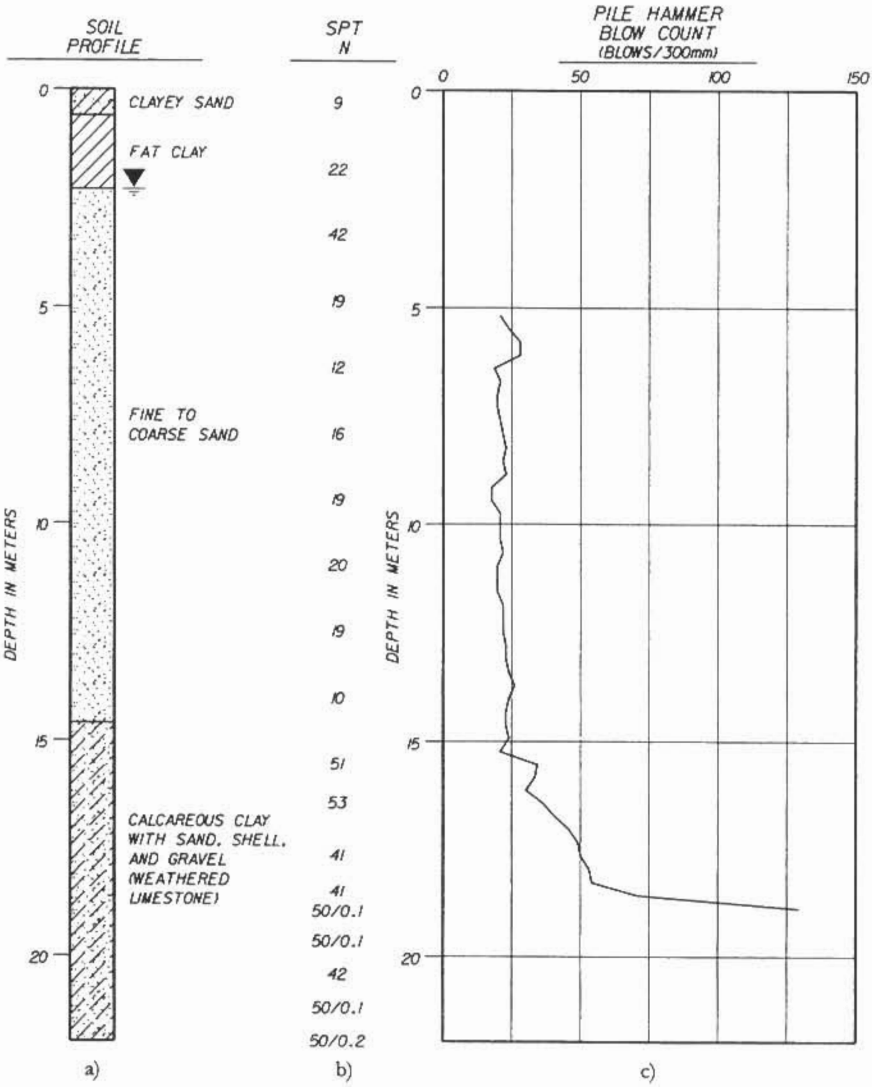

Figure 3. a) Soil Profile, b) SPT N-values, c) Pile Driving Log

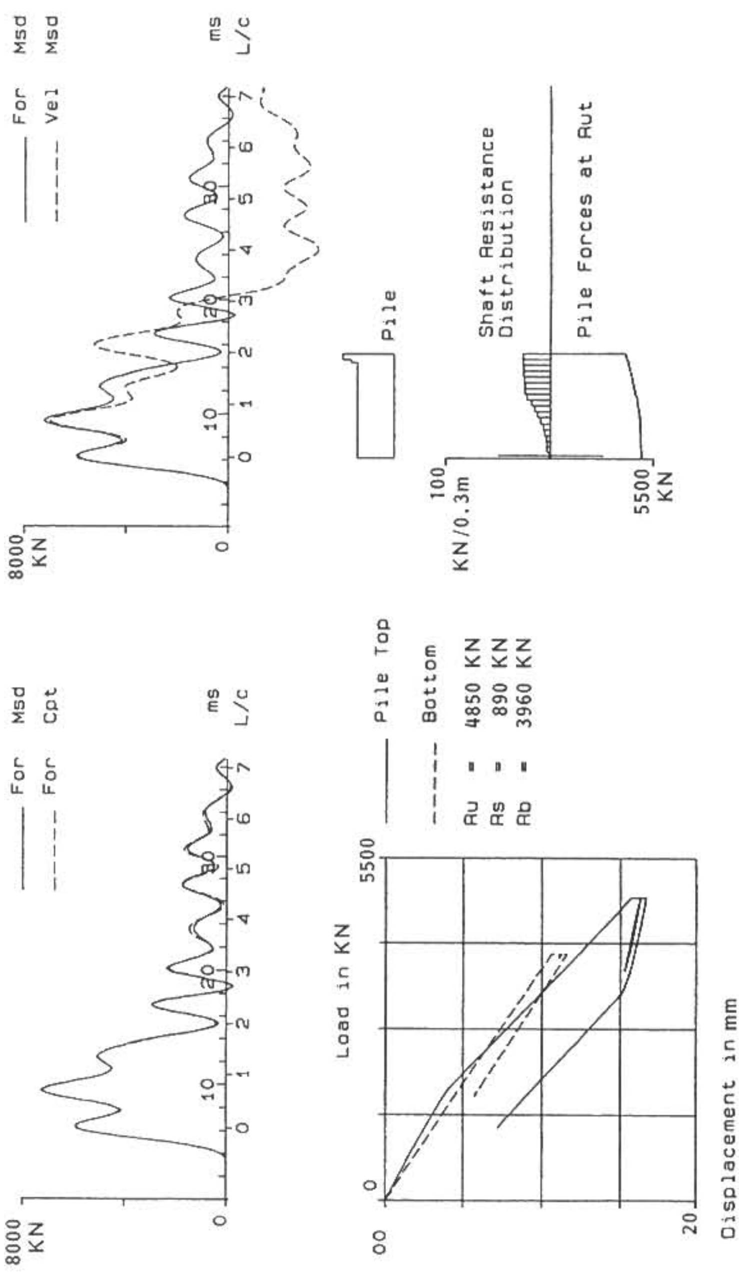

Figure 4. Dynamic Pile Testing and Data Analysis Results – End of Initial Drive

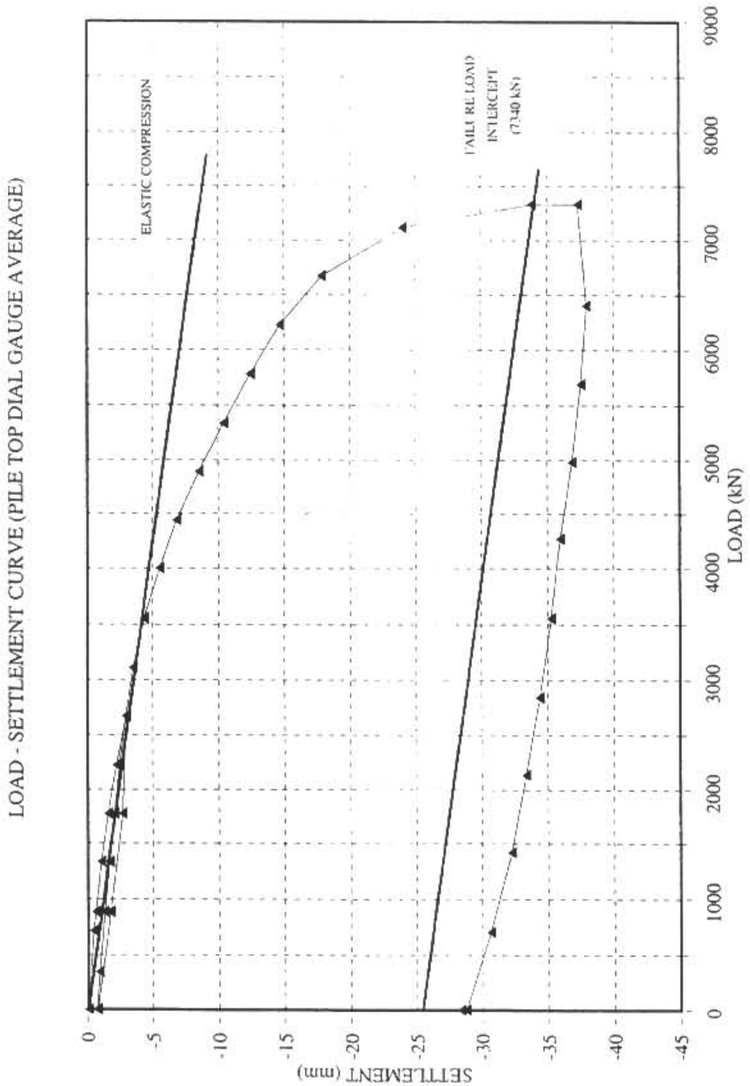

Figure 5. Static Loading Test Result

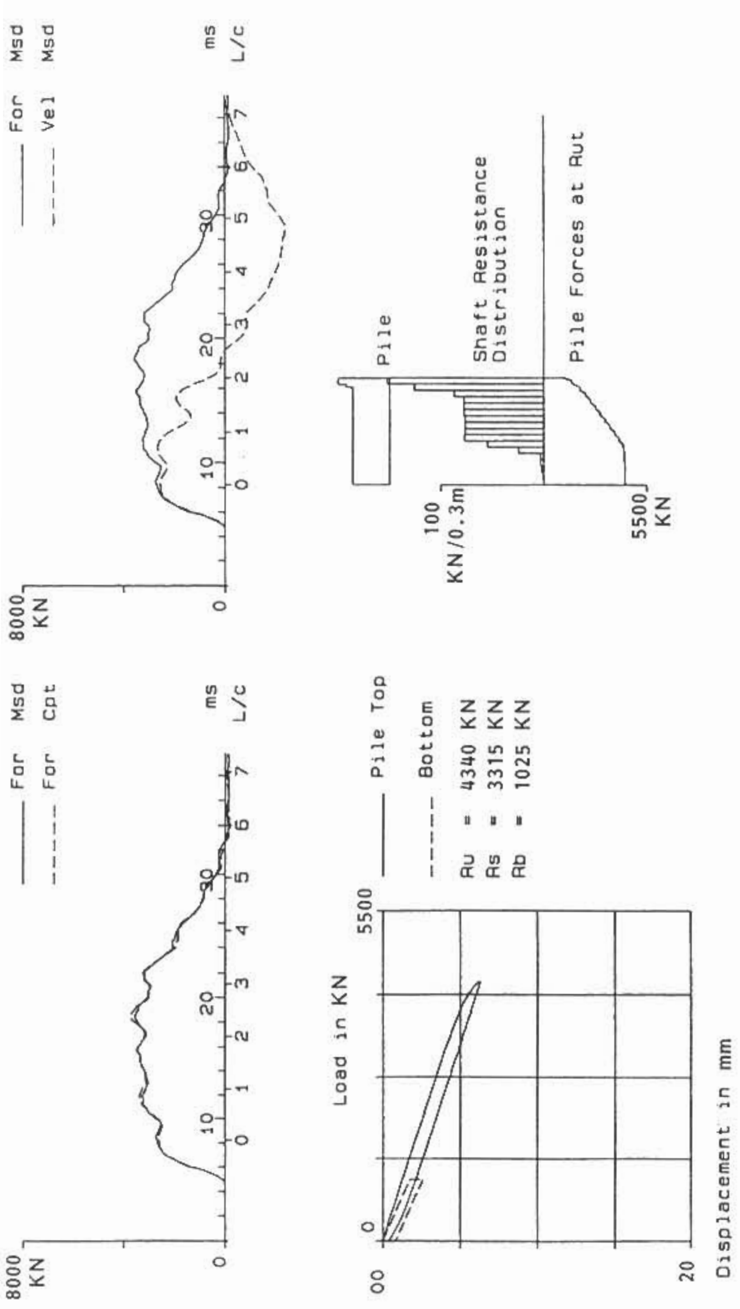

Figure 6. Dynamic Pile Testing and Data Analysis Results – Restrike After Static Load Test

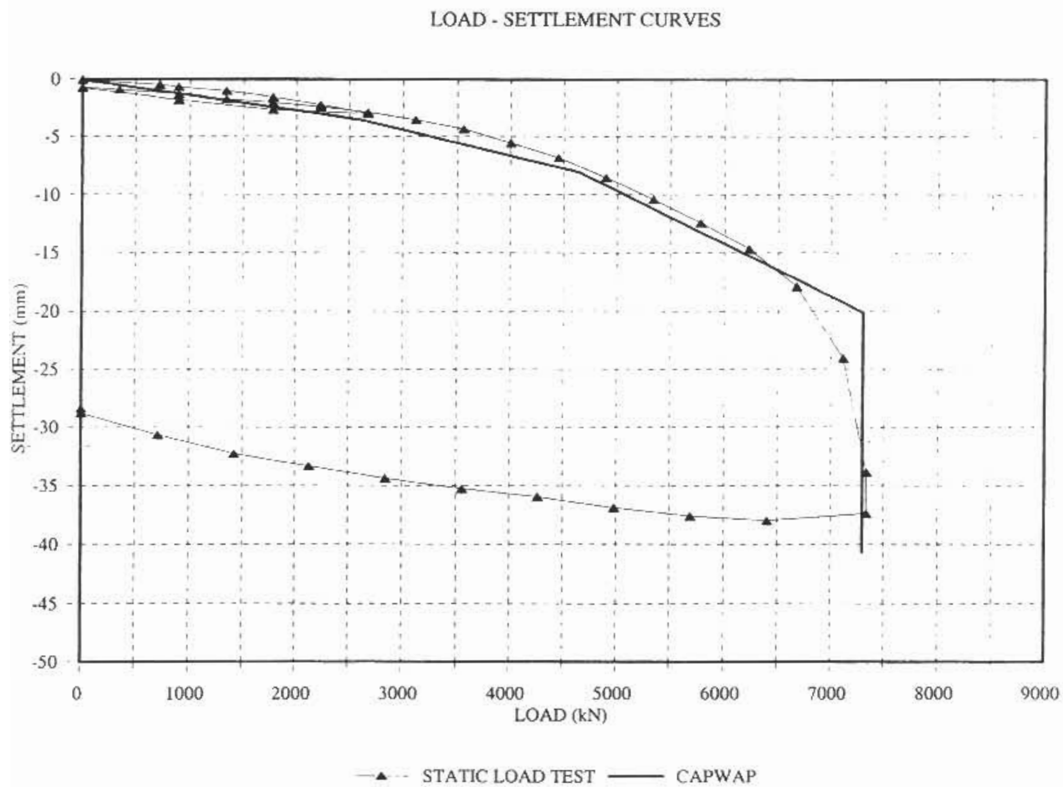

Figure 7. Comparison Between Static Loading Test and CAPWAP Analysis Results