Robert Miner Dynamic Testing, Inc.

Dynamic Measurements and Analyses for Deep Foundations

May 20, 2013

Mr. Daniel Collins
American Piledriving Equipment, Inc.
7023 South 196th
Kent, WA 98032-2185

Re: Dynamic Pile Measurements and CAPWAP Analyses
Pile 1, Ungrouted 7.0" OD Helical, December 8, 2012
Pile 5, Grouted 7.0" OD Helical Pile, February, 20, 2013
APE Yard, Kent, WA RMDT Job No. 12F60

Dear Sir,

This report presents results obtained from dynamic pile measurements and CAPWAP analyses completed by Robert Miner Dynamic Testing, Inc. (RMDT) for the project referenced above. The objective of the testing and analysis was evaluation of the soil resistance to pile penetration during restrike.

PROJECT AND TESTING DETAILS

Piles

Restrike tests were completed on two 7.0" OD helical piles installed on the premises of American Pile Driving, Inc. (APE) in Kent WA. Pile 1 was an ungrouted pile installed approximately 77 ft below the adjacent soil. Pile 5 was a grouted pile installed approximately 47.5 ft below the soil line at the time of the test. We understand that both piles had a wall thickness of 0.453", and the bottom of the helix was located approximately 1 ft above pile tip in each case. For the test of Pile 5 on February 8, 2013 a 6 ft long heavy-wall pile extension (7"OD x 1.0" wall) was in place and our PDA sensors were located at the center of this extension. For details on each helix or the pile installation please refer to documents prepared by other project participants.

Hammers

An APE D50–42 and an APE D100-42 open end diesel hammer were used to test Piles P1 and P5, respectively. For the hammer blows used on our analyses these hammers were operated manually using a standard or reduced tripping stroke of approximately 5 to 7 ft. The D50-42 and D100-42 have rams weighing approximately 11 and 22 kips, respectively.

Instrumentation

Dynamic measurements were made with two strain sensors and two accelerometers bolted to the surface of the pile near the pile top. Signals from the sensors were processed and stored by a Pile Driving Analyzer® (PDA). For each hammer blow the PDA displayed the measurements as plots of force and velocity, and computed a variety of results. RMDT's engineer reviewed the measurements and the computed results during and after driving. Appendix A contains general information on our methods for measurement and analysis.

Test Sequence

On December 8, 2012 Piles P1 and P5 were tested during brief restrike tests. Pile P5 was also tested on February 20, 2013. Analyses given here for Pile P5 are based on the test of February 20 because the heavy wall upper pile section was necessary for effective dynamic measurements.

PRESENTATION AND DISCUSSION OF RESULTS

Following the field testing RMDT completed CAPWAP® analysis of the soil's resistance to downward pile movement as the pile was struck by the respective impact hammers. CAPWAP analysis is an iterative signal matching method which is based on use of the measured force and velocity as recorded by the Pile Driving Analyzer. Appendix B contains results of the two CAPWAP analyses and Table 1 summarizes the results.

Table 1. Summary of CAPWAP Results.

Pile	Test	Approximate Depth Below Grade (ft)	Computed Ultimate Soil Resistance, kips		
			Total	Shaft	Toe
Pile 1	Restrike, 12/8/12	77	170	125	45
Pile 5	Restrike, 2/20/13	48	660	360	300

The resistance values computed with CAPWAP and given in Table 1 are estimates of the ultimate soil resistance for downward axial pile loading.

Pile 1 was twice struck with the D50-42 ram falling from the tripping stroke of approximately 5.5 ft, and then once with lowest available fuel setting. These three hammer blows apparently caused no net pile advancement. Our CAPWAP analysis yielded an ultimate axial soil resistance of 170 kips, with 125 kips of friction and 25 kips of end bearing. The computed unit friction resistance (kips per lineal ft) increased gradually with depth and was primarily located on the lower 25 ft of the pile.

Pile 5 was struck using only the tripping stroke of the APE D100-42 hammer. Our CAPWAP analysis yielded an axial resistance of 660 kips derived from 360 kips of friction and 300 kips of end bearing. The computed shaft friction was primarily located in the lowest 15 ft of the pile. For Pile 5 the grout surrounding the steel section caused a change in the axial pile stiffness and pile impedance. Uncertainty in the dimensions of the grout column caused some uncertainty in the CAPWAP impedance and soil resistance model. Such uncertainty was expected to have little effect on the computed ultimate resistance, but likely did cause a modest increase in the uncertainty associated with the CAPWAP distribution of shaft friction and the relative balance of friction and end bearing.

Please to not hesitate to contact us if you have questions regarding this transmittal or the work we completed for this project.

Sincerely,

ROBERT F. MINER
STATE OF WASHINGTON
29099
REGISTERED
PROFESSIONAL ENGINEER

Robert Miner, P.E.

Robert Miner Dynamic Testing, Inc.

May 20, 2013

APPENDIX A
AN INTRODUCTION INTO DYNAMIC PILE TESTING METHODS

BACKGROUND

Modern procedures of design and construction control require verification of bearing capacity and integrity of deep foundations during preconstruction test programs and also production installation. Dynamic pile testing methods meet this need economically and reliably, and therefore, form an important part of a quality assurance program when deep foundations are executed. Several dynamic pile testing methods exist; they have different benefits and limitations and different requirements for proper execution.

The Case Method of dynamic pile testing, named after the Case Institute of Technology where it was developed between 1964 and 1975, requires that a substantial ram mass (such as that of a pile driving hammer) impacts the pile top such that the pile undergoes at least a small permanent set. The method is therefore also referred to as a "High Strain Method". The Case Method requires dynamic measurements on the pile or shaft under the ram impact and then an evaluation of various quantities based on closed form solutions of the wave equation, a partial differential equation describing the motion of a rod under the effect of an impact. Conveniently, measurements and analyses are done by a single piece of equipment: the Pile Driving Analyzer® (PDA). However, for bearing capacity evaluations an important additional method is CAPWAP® which performs a much more rigorous analysis of the dynamic records than the simpler Case Method.

A related analysis method is the "Wave Equation Analysis" which calculates a relationship between bearing capacity and pile stress and field blow count. The GRLWEAP™ program performs this analysis and provides a complete set of helpful information and input data.

The following description deals primarily with the Case Method or "High Strain Test" Method of pile testing, however, for the sake of completeness, the "Low Strain Test" performed with the Pile Integrity Test™ (PIT), mainly for pile integrity evaluation, will also be described.

RESULTS FROM DYNAMIC TESTING

There are two main objectives of high strain dynamic pile testing:

- *Dynamic Pile Monitoring* and
- *Dynamic Load Testing.*

Dynamic pile monitoring is conducted during the installation of impact driven piles to achieve a safe and economical pile installation. Dynamic load testing, on the other hand, has as its primary goal the assessment of pile bearing capacity. It is applicable to both cast *insitu* piles or drilled shafts and impact driven piles during restrike.

Dynamic Pile Monitoring

During pile installation, the sensors attached to the pile measure pile top force and velocity. A PDA conditions and processes these signals and calculates or evaluates:

- Bearing capacity at the time of testing, including an assessment of shaft resistance development and driving resistance. This information supports formulation of a driving criterion.

- Dynamic pile stresses, axial and averaged over the pile cross section, both tensile and compressive, during pile driving to limit the potential of damage either near the pile top or along its length. Bending stresses can be evaluated at the point of sensor attachment.

- Pile integrity assessment by the PDA is based on the recognition of certain wave reflections from along the pile. If detected early enough, a pile may be saved from complete destruction. On the other hand, once damage is recognized measures can be taken to prevent reoccurrence.

- Hammer performance parameters including the energy transferred to the pile, the hammer speed in blows per minute and the stroke of open ended diesel hammers.

Dynamic Pile Load Testing

Bearing capacity testing of either driven piles or drilled shafts applies the same basic measurement approach of dynamic pile monitoring. However, the test is done independent of the pile installation process and therefore a pile driving hammer or other dynamic loading device may not be available. If a special ram has to be mobilized then its weight should be between 0.8 and 2% of the test load (e.g. between 4 and 10 tons for a 500 ton test load) to assure sufficient soil resistance activation.

For a successful test, it most important that the test is conducted after a sufficient waiting time following pile installation for soil properties approaching their long term condition or concrete to properly set. During testing, PDA results of pile/shaft stresses and transferred energy are used to maintain safe stresses and assure sufficient resistance activation. For safe and sufficient testing of drilled shafts, ram energies are often increased from blow to blow until the test capacity has been activated. On the other hand, restrike tests on driven piles may require a warm hammer so that the very first blow produces a complete resistance activation. Data must be evaluated by CAPWAP for bearing capacity.

After the dynamic load test has been conducted with sufficient energy and safe stresses, the CAPWAP analysis provides the following results:

- Bearing capacity i.e. the mobilized capacity present at the time of testing
- Resistance distribution including shaft resistance and end bearing components
- Stresses in pile or shaft calculated for both the static load application and the dynamic test. These stresses are averages over the cross section and do not include bending effects or nonuniform contact stresses, e.g. when the pile toe is on uneven rock.
- Shaft impedance vs depth; this is an estimate of the shaft shape if it differs substantially from the planned profile
- Dynamic soil parameters for shaft and toe, i.e. damping factors and quakes (related to the dynamic stiffness of the resistance at the pile/soil interface.)

MEASUREMENTS

PDA

The basis for the results calculated by the PDA are pile top strain and acceleration measurements which are converted to force and velocity records, respectively. The PDA conditions, calibrates and displays these signals and immediately computes average pile force and velocity thereby eliminating bending effects. Using closed form Case Method solutions, based on the one-dimensional linear wave equation, the PDA calculates the results described in the analytical solutions section below.

HPA

The ram velocity may be directly obtained using radar technology in the Hammer Performance Analyzer™. For this unit to be applicable, the ram must be visible. The impact velocity results can be automatically processed with a PC or recorded on a strip chart.

Saximeter™

For open end diesel hammers, the time between two impacts indicates the magnitude of the ram fall height or stroke. This information is not only measured and calculated by the PDA but also by the convenient, hand-held Saximeter.

PIT

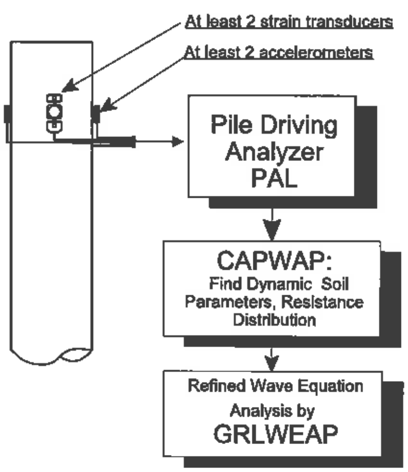
The Pile Integrity Tester™ (PIT) can be used to evaluate defects in concrete piles or shafts which may have occurred during driving or casting. Also timber piles of limited length can be tested in that manner. This so-called "Low Strain Method" or "Pulse-Echo Method" of integrity testing requires only the measurement of acceleration at the pile top. The stress wave producing impact is then generated by a small hand-held hammer and the records interpreted in the time domain. PIT also supports the so-called "Transient Response Method" which requires the additional measurement of the hammer force and an analysis in the frequency domain. This method may also be used to evaluate the unknown length of deep foundations under existing structures.

ANALYTICAL SOLUTIONS
BEARING CAPACITY

Wave Equation

GRL has written the GRLWEAP™ program which calculates a relationship between bearing capacity, pile stress and blow count. This relationship is often called the "bearing graph." Once the blow count is known from pile installation logs, the bearing graph yields the bearing capacity. This approach requires no measurements and therefore can be performed during the design stage of a project, for example for the selection of hammer, cushion and pile size.

After dynamic pile monitoring and/or dynamic load testing has been performed, the "Refined Wave Equation Analysis" or RWEA (see schematic below) is often performed by inputting the PDA and CAPWAP calculated parameters. Then the bearing graph from the RWEA is the basis for a safe and sufficient driving criteria.



Case Method

The Case Method is a closed form solution based on a few simplifying assumptions such as ideal plastic soil behavior and an ideally elastic and uniform pile. Given the measured pile top force F(t) and pile top velocity v(t), the total soil resistance is

$$R(t) = \frac{1}{2}\{[F(t) + F(t_2)] + Z[v(t) - v(t_2)]\} \quad (1)$$

where

- t = a point in time after impact
- t_2 = time $t + 2L/c$
- L = pile length below gages
- c = $(E/\rho)^{1/2}$ is the speed of the stress wave
- ρ = pile mass density
- Z = EA/c is the pile impedance
- E = elastic modulus of the pile ($\rho\, c^2$)
- A = pile cross sectional area

The total soil resistance consists of a dynamic (R_d) and a static (R_s) component. The static component is therefore

$$R_s(t) = R(t) - R_d(t) \quad (2)$$

The dynamic component may be computed from a soil damping factor, J, and a pile toe velocity, $v_t(t)$ which is conveniently calculated for the pile toe. Using wave considerations, this approach leads immediately to the dynamic resistance

$$R_d(t) = J[F(t) + Zv(t) - R(t)] \quad (3)$$

and finally to the static resistance by means of Equation 2.

There are a number of ways in which Eq. 1 through 3 can be evaluated. Most commonly, t_2 is set to that time at which the static resistance becomes maximum. The result is the so-called **RMX** capacity. Damping factors for RMX typically range between 0.5 for coarse grained materials to 1.0 for clays. The **RSP** capacity (this method is most commonly referred to in the literature, yet it is not very frequently used) requires damping factors between 0.1 for sand and 1.0 for clay. Another capacity, **RA2**, determines the capacity at a time when the pile is essentially at rest and thus damping is small; RA2 therefore requires no damping parameter. In any event, the proper Case Method and its associated damping parameter is most conveniently found after a CAPWAP analysis has been performed.

The static resistance calculated by Case Method or CAPWAP is the mobilized resistance at the time of testing. Consideration therefore has to be given to soil setup or relaxation effects and whether or not a sufficient set has been achieved under the test loading that would correspond to a full activation of the ultimate soil resistance.

The PDA also calculates an estimate of shaft resistance as the difference between force and velocity times impedance at the time immediately prior to the return of the stress wave from the pile toe. This shaft resistance is not reduced by damping effects and is therefore called the total shaft resistance **SFT**. A correction for damping effects produces the static shaft resistance estimate, **SFR**.

The Case Method solution is simple enough to be evaluated "in real time," i.e. between hammer blows, using the PDA. It is therefore possible to calculate all relevant results for all hammer blows and plot these results as a function of depth or blow number. This is done in the PDAPLOT program.

CAPWAP

The CAse Pile Wave Analysis Program combines the wave equation pile and soil model with the Case Method measurements. Thus, the solution includes not only the total and static bearing capacity values but also the shaft resistance, end bearing, damping factors and soil stiffnesses. The method iteratively calculates a number of unknowns by signal matching. While it is necessary to make hammer performance assumptions for a GRLWEAP analysis, the CAPWAP program works with the pile top measurements. Furthermore, while GRLWEAP and Case Method require certain assumptions regarding the soil behavior, CAPWAP calculates these soil parameters.

STRESSES

During pile monitoring, it is important that compressive stress maxima at pile top and toe and tensile stress maxima somewhere along the pile be calculated for each hammer blow.

At the pile top (location of sensors) both the maximum compression stress, **CSX**, and the maximum stress from individual strain transducers, **CSI**, are directly obtained from the measurements. Note that CSI is greater than or equal to CSX and the difference between CSI and CSX is a measure of bending in the plane of the strain transducers. Note also that all stresses calculated for locations below the sensors are averaged over the pile cross section and therefore do not include components from either bending or eccentric soil resistance effects.

The PDA calculates the compressive stress at the pile bottom, **CSB**, assuming (a) a uniform pile and (b) that the pile toe force is the maximum value of the total resistance R(t) minus the total shaft resistance, SFT. Again, for this stress estimation uniform resistance force are assumed (e.g. not a sloping rock.)

For concrete piles, the maximum tension stress, **TSX**, is also of great importance. It occurs at some point below the pile top. The maximum tension stress can be computed from the pile top measurements by finding the maximum tension wave (either traveling upward, W_u, or downward, W_d) and reducing it by the minimum compressive wave traveling in opposite direction.

$$W_u = \tfrac{1}{2}[F(t) - Zv(t)] \qquad (4)$$

$$W_d = \tfrac{1}{2}[F(t) + Zv(t)] \qquad (5)$$

CAPWAP also calculates tensile and compressive stresses along the pile and, in general, more accurately than the PDA. In fact, for non-uniform piles or piles with joints, cracks or other discontinuities, the closed form solutions from the PDA may be in error.

PILE INTEGRITY

High Strain Tests (PDA)

Stress waves in a pile are reflected wherever the pile impedance, $Z = EA/c = \rho cA = A\sqrt{(E\,\rho)}$, changes. Therefore, the pile impedance is a measure of the quality of the pile material (E, ρ, c) and the size of its cross section (A). The reflected waves arrive at the pile top at a time which is greater the farther away from the pile top the reflection occurs. The magnitude of the change of the upward traveling wave (calculated from the measured force and velocity, Eq. 4) indicates the extent of the cross sectional change. Thus, with β_i (**BTA**) being a relative integrity factor which is unity for no impedance change and zero for the pile end, the following is calculated by the PDA.

$$\beta_i = (1 - \alpha_i)/(1 + \alpha_i) \quad (6)$$

with

$$\alpha_i = \tfrac{1}{2}(W_{UR} - W_{UD})/(W_{Di} - W_{UR}) \quad (7)$$

where

W_{UR} is the upward traveling wave at the onset of the reflected wave. It is caused by resistance.

W_{UD} is the upwards traveling wave due to the damage reflection.

W_{Di} is the maximum downward traveling wave due to impact.

It can be shown that this formulation is quite accurate as long as individual reflections from different pile impedance changes have no overlapping effects on the stress wave reflections.

Without rigorous derivation, it has been proposed to consider as slight damage when β is above 0.8 and a serious damage when β is less than 0.6.

Low Strain Tests (PIT)

The pile top is struck with a held hand hammer and the resulting pile top velocity is measured, displayed and interpreted for signs of wave reflections. In general, a comparison of the reflected acceleration leads to a relative measure of extent of damage, again the location of the problem is indicated by the arrival time of the reflection. PIT records can also be interpreted by the β-Method. However, low strain tests do not activate much resistance which simplifies Eq. 7 since W_{UR} is then equal to zero.

For drilled shafts and PIT records that clearly show a toe reflection, an approximate shaft profile can be calculated from low strain records using the PITSTOP program's PROFILE routine.

HAMMER PERFORMANCE

The PDA calculates the energy transferred to the pile top from:

$$E(t) = {}_0\int^t F(t)v(t)\,dt \quad (8a)$$

The maximum of the E(t) curve is the most important information for an overall evaluation of the performance of a hammer and driving system. This **EMX** value allows for a classification of the hammer's performance when presented as the rated transfer efficiency, also called energy transfer ratio (**ETR**) or global efficiency

$$e_T = EMX/E_R \quad (8b)$$

where

E_R is the manufacturer's rated energy value.

Both Saximeter and PDA calculate the stroke (**STK**) of an open end diesel hammer using

$$STK = (g/8)\,T_B^2 - h_L \quad (9)$$

where

g is the earth's gravitational acceleration,
T_B is the time between two hammer blows,
h_L is a stroke loss value due to gas compression and time losses during impact (usually 0.3 ft or 0.1 m).

DETERMINATION OF WAVE SPEED

An important facet of dynamic pile testing is an assessment of pile material properties. Since in general force is determined from strain by multiplication with elastic modulus, E, and cross sectional area, A, the dynamic elastic modulus has to be determined for pile materials other than steel. In general, the records measured by the PDA clearly indicate a pile toe reflection as long as pile penetration per blow is greater than 1 mm or .04 inches. The time between the onset of the force and velocity records at impact and the onset of the reflection from the toe (usually apparent by a local maximum of the wave up curve) is the so-called wave travel time, T. Dividing 2L (L is here the length of the pile below sensors) by T leads to the stress wave speed in the pile:

$$c = 2L/T \quad (10)$$

The elastic modulus of the pile material is related to the wave speed according to the linear elastic wave equation theory by

$$E = c^2\rho \qquad (11)$$

Since the mass density of the pile material, ρ, is usually well known (an exception is timber for which samples should be weighed), the elastic modulus is easily found from the wave speed. Note, however, that this is a dynamic modulus which is generally higher than the static one and that the wave speed depends to some degree on the strain level of the stress wave. For example, experience shows that the wave speed from PIT is roughly 5% higher than the wave speed observed during a high strain test.

Other Notes:

- If the pile material is nonuniform then the wave speed c, according to Eq. 10, is an average wave speed and does not necessarily reflect the pile material properties of the location where the strain sensors are attached to the pile top. For example, pile driving often causes fine tension cracks some distance below the top of concrete piles. Then the average c is slower than that at the pile top. It is therefore recommended to determine E in the beginning of pile driving and not adjust it when the average c changes.

- If the pile has such a high resistance that there is no clear indication of a toe reflection then the wave speed of the pile material must be determined either by assumption or by taking a sample of the concrete and measuring its wave speed in a simple free column test. Another possibility is to use the proportionality relationship, discussed under "DATA QUALITY CHECKS" to find c as the ratio between the measured velocity and measured strain.

DATA QUALITY CHECKS

Quality data is the first and foremost requirement for accurate dynamic testing results. It is therefore important that the measurement engineer performing PDA or PIT tests has the experience necessary to recognize measurement problems and take appropriate corrective action should problems develop. Fortunately, dynamic pile testing allows for certain data quality checks because two independent measurements are taken that have to conform to certain relationships.

Proportionality

As long as there is only a wave traveling in one direction, as is the case during impact when only a downward traveling wave exists in the pile, force and velocity measured at the pile top are proportional

$$F = v\,Z = v\,(EA/c) \qquad (12a)$$

This relationship can also be expressed in terms of stress

$$\sigma = v\,(E/c) \qquad (12b)$$

or strain

$$\varepsilon = v\,/\,c \qquad (12c)$$

This means that the early portion of strain times wave speed must be equal to the velocity unless the proportionality is affected by high friction near the pile top or by a pile cross sectional change not far below the sensors. Checking the proportionality is an excellent means of assuring meaningful measurements.

Measurements are always taken at opposite sides of the pile as a means of calculating the average force and velocity in the pile. The velocity on the two sides of the pile is very similar even when high bending exists. Thus, an independent check of the velocity measurements is easy and simple.

Strain measurements may differ greatly between the two sides of the pile when bending exists. It is even possible that tension is measured on one side while very high compression exists on the other side of the pile. In extreme cases, bending might be so high that it leads to a nonlinear stress distribution. The averaging of the two strain signals does then not lead to the average pile force and proportionality will not be achieved.

When testing drilled shafts, measurements of strain may also be affected by local concrete quality variations. It is then often necessary to use four strain transducers spaced at 90 degrees around the pile for an improved strain data quality. The use of four transducers is also recommended for large pile diameters, particularly when it is difficult to mount the sensors at least two pile widths or diameters below the pile top.

LIMITATIONS, ADDITIONAL CONSIDERATIONS

Mobilization of capacity

Estimates of pile capacity from dynamic testing indicate the **mobilized pile capacity at the time of testing**. At very high blow counts (low set per blow), dynamic test methods tend to produce lower bound capacity estimates as not all resistance (particularly at and near the toe) is fully activated.

Time dependent soil resistance effects

Static pile capacity from dynamic method calculations provide an estimate of the axial pile capacity. Increases and decreases in the pile capacity with time typically occur (soil setup/relaxation). Therefore, **restrike testing usually yields a better indication of long term pile capacity than a test at the end of pile driving**. Often a wait period of one or two days between end of driving and restrike is satisfactory for a realistic prediction of pile capacity but this waiting time depends, among other factors, on the permeability of the soil.

(A) Soil setup

Because excess positive pore pressures often develop during pile driving in fine grained soil (clays, silts or even fine sands), the capacity of a pile at the time of driving may often be less than the long term pile capacity. These pore pressures reduce the effective stress acting on the pile thereby reducing the soil resistance to pile penetration, and thus the pile capacity at the time of driving. As these pore pressures dissipate, the soil resistance acting on the pile increases as does the axial pile capacity. This phenomena is routinely called soil setup or soil freeze.

(B) Relaxation

Relaxation (capacity reduction with time) has been observed for piles driven into weathered shale, and may take several days to fully develop. Pile capacity estimates based upon initial driving or short term restrike tests can significantly overpredict long term pile capacity. Therefore, piles driven into shale should be tested after a minimum one week wait either statically or dynamically (with particular emphasis than on the first few blows). Relaxation has also been observed for displacement piles driven into dense saturated silts or fine sands due to a negative pore pressure effect at the pile toe. Again, restrike tests should be used, with great emphasis on early blows.

Capacity results for open pile profiles

Larger diameter open ended pipe piles (or H-piles which do not bear on rock) may behave differently under dynamic and static loading conditions. Under dynamic loads the soil inside the pile or between its flanges may slip and produce internal friction while under static loads the plug may move with the pile, thereby creating end bearing over the full pile cross section. As a result both friction and end bearing components may be different under static and dynamic conditions.

CAPWAP Analysis Results

A portion of the soil resistance calculated on an individual soil segment in a CAPWAP analysis can usually be shifted up or down the shaft one soil segment without significantly altering the match quality. Therefore, use of the CAPWAP resistance distribution for uplift, downdrag, scour, or other geotechnical considerations should be made with an understanding of these analysis limitations.

Stresses

PDA and CAPWAP calculated stresses are average values over the cross section. Additional allowance has to be made for bending or non-uniform contact stresses. To prevent damage it is therefore important to maintain good hammer-pile alignment and to protect the pile toes using appropriate devices or an increased cross sectional area.

In the United States is has become generally acceptable to limit the dynamic installation stresses of driven piles to the following levels:

90% of yield strength for steel piles

85% of the concrete compressive strength - after subtraction of the effective prestress - for concrete piles in compression

100% of effective prestress plus ½ of the concrete's tension strength for prestressed piles in tension

70% of the reinforcement strength for regularly reinforced concrete piles in tension

300% of the static design allowable stress for timber

Note that the dynamic stresses may either be directly measured at the pile top by the PDA or calculated by the PDA for other locations along the pile based on the pile top measurements.

Additional design considerations

Numerous factors have to be considered in pile foundation design. Some of these considerations include

- additional pile loading from downdrag or negative skin friction,
- lateral and uplift loading requirements
- effective stress changes (due to changes in water table, excavations, fills or other changes in overburden),
- long term settlements in general and settlement from underlying weaker layers and/or pile group effects,

These factors have not been evaluated by GRL and have not been considered in the interpretation of the dynamic testing results. The foundation designer should determine if these or any other considerations are applicable to this project and the foundation design.

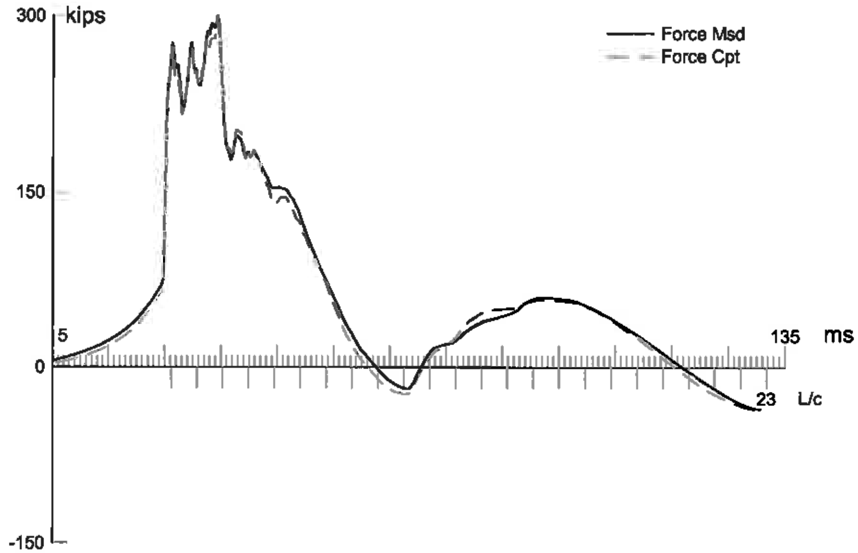
Wave equation analysis results

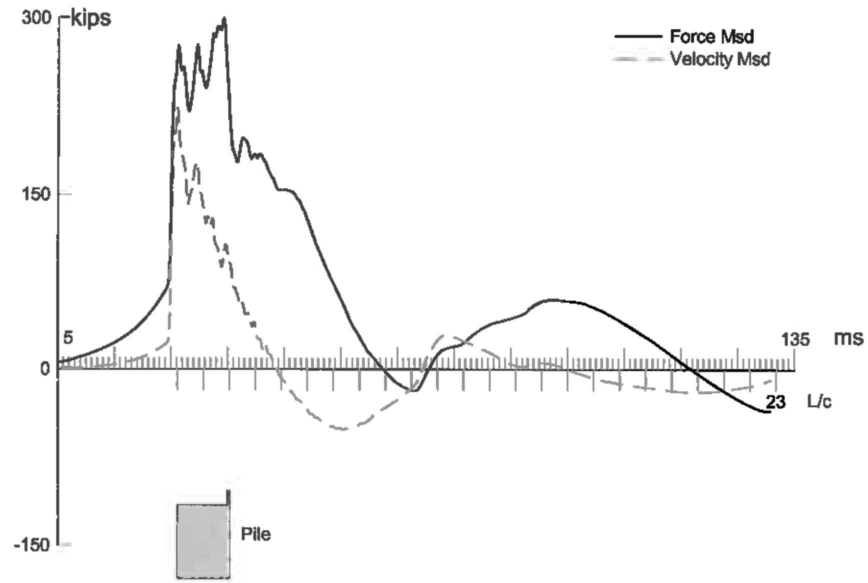
The results calculated by the wave equation analysis program depend on a variety of hammer, pile and soil input parameters. Although attempts have been made to base the analysis on the best available information, actual field conditions may vary and therefore stresses and blow counts may differ from the predictions reported. Capacity predictions derived from wave equation analyses should use restrike information. However, because of the uncertainties associated with restrike blow counts and restrike hammer energies, correlations of such results with static test capacities with have often displayed considerable scatter.

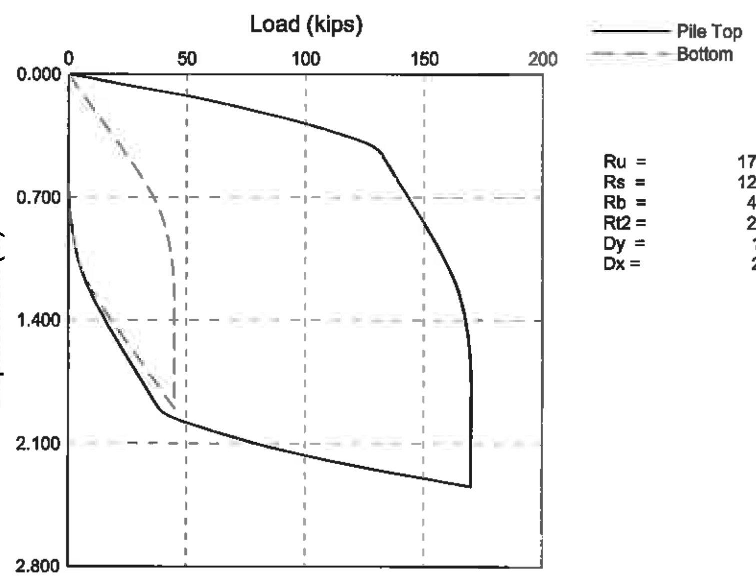
As for PDA and CAPWAP, the theory on which GRLWEAP is based is the one-dimensional wave equation. For that reason, stress predictions by the wave equation analysis can only be averages over the pile cross section. Thus, bending stresses or stress concentrations due to non-uniform impact or uneven soil or rock resistance are not considered in these results. Stress maxima calculated by the wave equation are usually subjected to the same limits as those measured directly or calculated from measurements by the PDA.

Appendix B

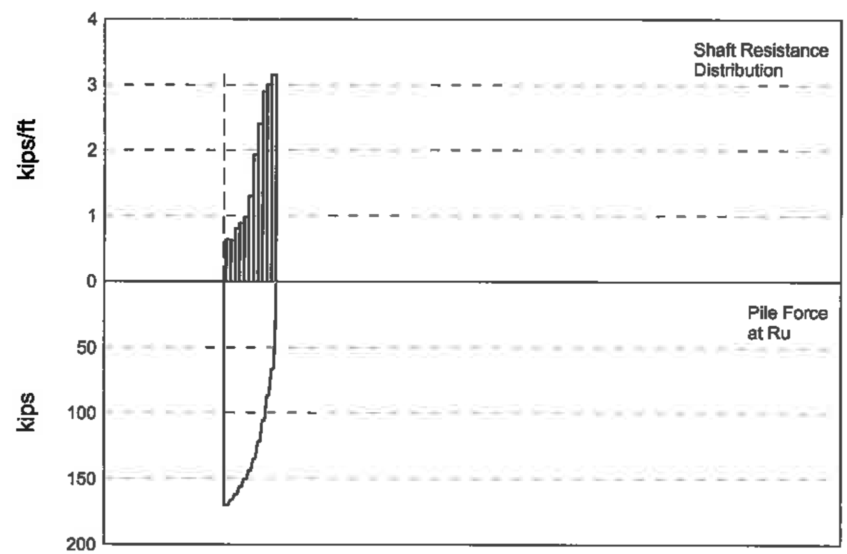
Results of CAPWAP Analysis







Ru =	170.0 kips
Rs =	125.0 kips
Rb =	45.0 kips
Rt2 =	25.0 kips
Dy =	1.75 in
Dx =	2.35 in



CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 170.0; along Shaft 125.0; at Toe 45.0 kips

Soil Sgmnt No.	Dist. Below Gages ft	Depth Below Grade ft	Ru kips	Force in Pile kips	Sum of Ru kips	Unit Resist. (Depth) kips/ft	Unit Resist. (Area) ksf	Smith Damping Factor s/ft	Quake in
				170.0					
1	10.0	9.5	4.3	165.7	4.3	0.45	0.25	0.120	0.100
2	16.7	16.2	4.2	161.5	8.5	0.63	0.34	0.120	0.100
3	23.4	22.9	5.5	156.0	14.0	0.82	0.45	0.120	0.100
4	30.1	29.6	6.0	150.0	20.0	0.90	0.49	0.120	0.100
5	36.8	36.3	6.6	143.4	26.6	0.99	0.54	0.120	0.100
6	43.5	43.0	8.7	134.7	35.3	1.30	0.71	0.120	0.100
7	50.2	49.7	13.0	121.7	48.3	1.94	1.06	0.120	0.100
8	56.9	56.4	16.1	105.6	64.4	2.40	1.31	0.120	0.100
9	63.6	63.1	19.4	86.2	83.8	2.90	1.58	0.120	0.100
10	70.3	69.8	20.1	66.1	103.9	3.00	1.64	0.120	0.100
11	77.0	76.5	21.1	45.0	125.0	3.15	1.72	0.120	0.100
2nd	Toe		25.0					0.126	1.000
Avg. Shaft			11.4			1.63	0.89	0.120	0.100
Toe			20.0				74.84	0.150	0.700

Soil Model Parameters/Extensions		Shaft	Toe
Case Damping Factor		0.904	0.181
Damping Type			Smith
Reloading Level	(% of Ru)	100	100
Unloading Level	(% of Ru)	80	
Soil Plug Weight	(kips)		0.22
Soil Support Dashpot		2.300	0.000
Soil Support Weight	(kips)	1.28	0.00

max. Top Comp. Stress = 31.8 ksi (T= 34.3 ms, max= 1.033 x Top)
max. Comp. Stress = 32.9 ksi (Z= 16.7 ft, T= 33.5 ms)
max. Tens. Stress = -3.91 ksi (Z= 10.0 ft, T= 130.9 ms)
max. Energy (EMX) = 27.5 kip-ft; max. Measured Top Displ. (DMX)= 1.42 in

EXTREMA TABLE

Pile Sgmnt No.	Dist. Below Gages ft	max. Force kips	min. Force kips	max. Comp. Stress ksi	max. Tens. Stress ksi	max. Trnsfd. Energy kip-ft	max. Veloc. ft/s	max. Displ. in
1	3.3	296.5	-35.9	31.8	-3.85	27.47	13.5	1.490
2	6.7	300.0	-36.2	32.2	-3.88	27.34	13.4	1.469
4	13.4	299.0	-33.1	32.1	-3.55	26.14	13.1	1.426
5	16.7	306.2	-33.4	32.9	-3.58	26.01	12.9	1.405
6	20.1	286.9	-30.2	30.8	-3.24	25.00	12.7	1.383
7	23.4	282.9	-30.4	30.3	-3.26	24.86	12.5	1.361
8	26.8	276.6	-26.1	29.7	-2.80	23.64	12.3	1.340
9	30.1	281.5	-26.3	30.2	-2.82	23.52	12.1	1.319
10	33.5	276.1	-21.4	29.6	-2.30	22.28	11.9	1.300
11	36.8	289.3	-21.6	31.0	-2.32	22.17	11.6	1.281
12	40.2	284.5	-16.2	30.5	-1.74	20.88	11.4	1.262
13	43.5	273.7	-16.3	29.4	-1.75	20.78	11.0	1.244
14	46.9	242.2	-9.3	26.0	-1.00	19.21	10.7	1.227
15	50.2	243.6	-9.3	26.1	-1.00	19.12	10.3	1.209
16	53.6	222.2	-0.3	23.8	-0.03	16.96	10.0	1.194
17	56.9	231.1	-0.3	24.8	-0.04	16.89	9.7	1.179
18	60.3	212.3	0.0	22.8	0.00	14.38	9.5	1.165
19	63.6	218.4	0.0	23.4	0.00	14.33	9.2	1.152
20	67.0	196.4	0.0	21.1	0.00	11.47	8.8	1.141
21	70.3	190.2	0.0	20.4	0.00	11.43	9.5	1.131
22	73.7	145.8	0.0	15.6	0.00	8.55	9.9	1.122
23	77.0	122.9	0.0	11.0	0.00	2.36	10.3	1.115
Absolute	16.7			32.9			(T =	33.5 ms)
	10.0				-3.91		(T =	130.9 ms)

CASE METHOD

J =	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
RP	312.4	293.6	274.7	255.9	237.0	218.2	199.4	180.5	161.7	142.8
RX	312.4	293.6	274.7	255.9	237.0	223.7	211.5	199.2	187.0	176.7
RU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

RAU = 45.2 (kips); RA2 = 261.0 (kips)

Current CAPWAP Ru = 170.0 (kips); Corresponding J(RP)= 0.76; matches RX9 within 5%

VMX	TVP	VT1*Z	FT1	FMX	DMX	DFN	SET	EMX	QUS
ft/s	ms	kips	kips	kips	in	in	in	kip-ft	kips
13.50	26.35	224.1	276.7	299.9	1.422	0.690	0.600	27.3	323.6

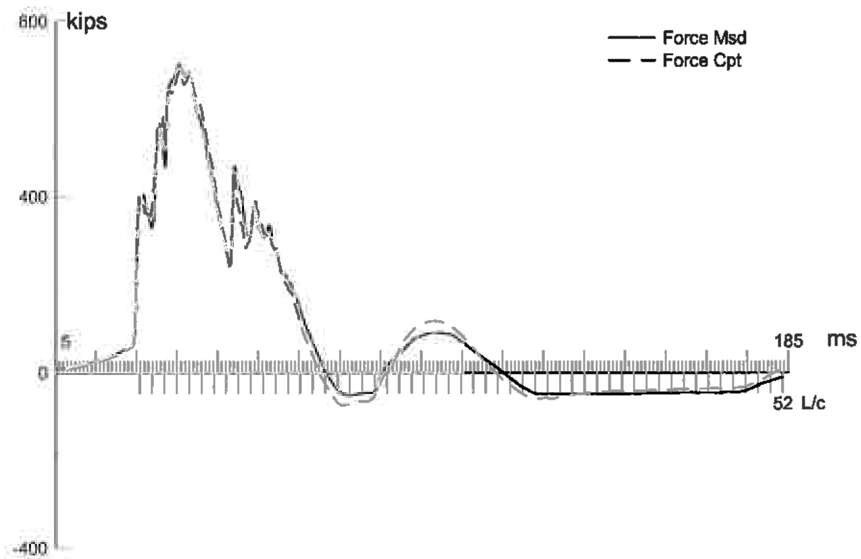
PILE PROFILE AND PILE MODEL

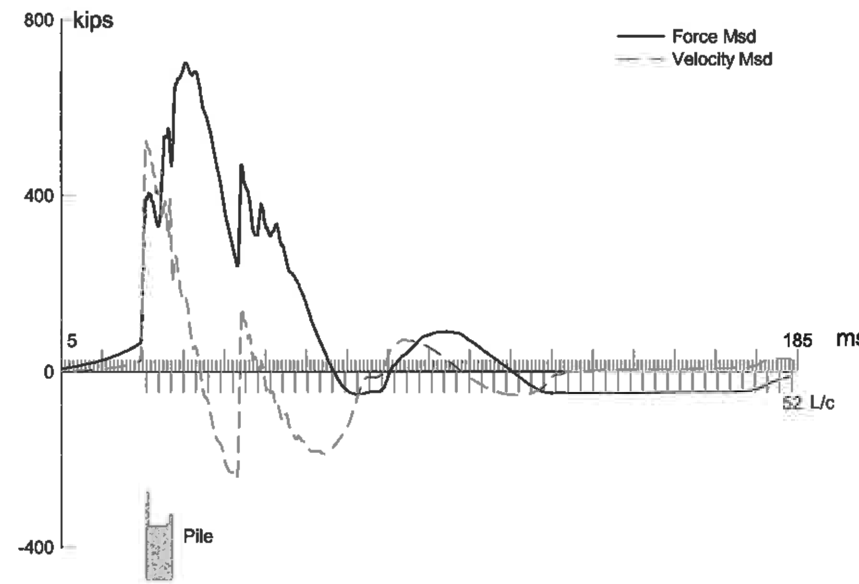
Depth	Area	E-Modulus	Spec. Weight	Perim.
ft	in^2	ksi	lb/ft^3	ft
0.00	9.32	29861.2	492.000	1.833
75.00	9.32	29861.2	492.000	1.833
75.00	15.60	29861.2	492.000	1.833
76.00	15.60	29861.2	492.000	1.833
76.00	9.32	29861.2	492.000	1.833
77.00	9.32	29861.2	492.000	1.833

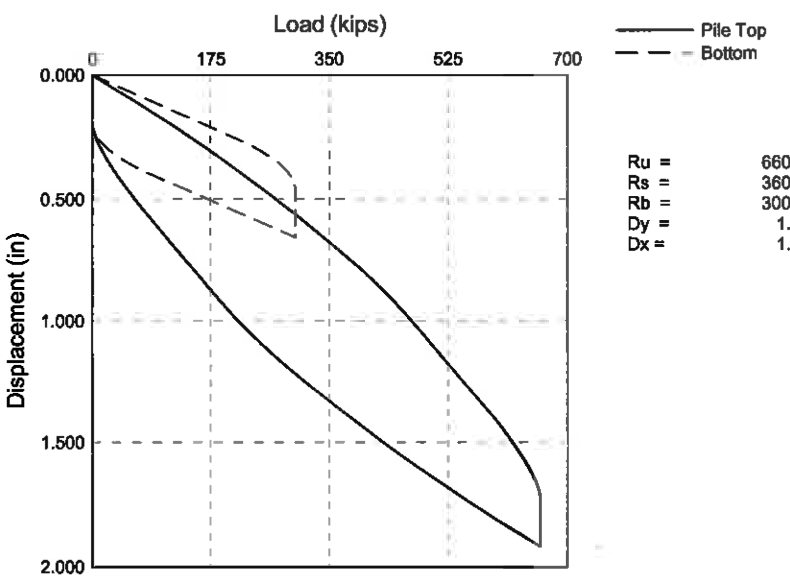
Toe Area 0.267 ft^2

Segmnt Number	Dist. B.G.	Impedance	Imped. Change	Tension		Compression		Perim.
				Slack	Eff.	Slack	Eff.	
	ft	kips/ft/s	%	in		in		ft
1	3.35	16.60	0.00	0.000	0.000	-0.000	0.000	1.833
23	77.00	19.94	0.00	0.000	0.000	-0.000	0.000	1.833

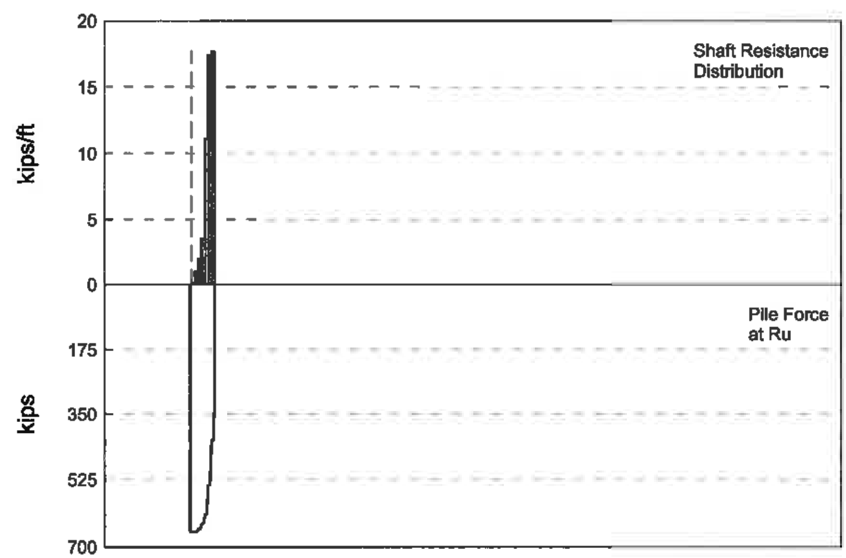
Pile Damping 1.0 %, Time Incr 0.200 ms, Wave Speed 16771.1 ft/s, 2L/c 9.2 ms







Ru =	660.4	kips
Rs =	360.3	kips
Rb =	300.1	kips
Dy =	1.73	in
Dx =	1.92	in



CAPWAP SUMMARY RESULTS

Total CAPWAP Capacity: 660.4; along Shaft 360.3; at Toe 300.1 kips

Soil Sgmnt No.	Dist. Below Gages ft	Depth Below Grade ft	Ru kips	Force in Pile kips	Sum of Ru kips	Unit Resist. (Depth) kips/ft	Unit Resist. (Area) ksf	Smith Damping Factor s/ft
				660.4				
1	10.2	6.7	0.9	659.5	0.9	0.13	0.07	0.160
2	17.0	13.5	6.8	652.7	7.7	1.00	0.55	0.160
3	23.8	20.3	13.7	639.0	21.4	2.01	1.10	0.160
4	30.6	27.1	24.3	614.7	45.7	3.57	1.95	0.160
5	37.4	33.9	76.0	538.7	121.7	11.18	6.10	0.160
6	44.2	40.7	118.4	420.3	240.1	17.41	9.50	0.160
7	51.0	47.5	120.2	300.1	360.3	17.68	9.64	0.160
Avg. Shaft			51.5			7.59	4.14	0.160
Toe			300.1				1122.90	0.100

Soil Model Parameters/Extensions		Shaft	Toe
Quake	(in)	0.100	0.360
Case Damping Factor		1.713	0.892
Damping Type			Smith
Unloading Quake	(% of loading quake)	30	100
Reloading Level	(% of Ru)	100	100
Unloading Level	(% of Ru)	20	
Resistance Gap (included in Toe Quake) (in)			0.100
Soil Support Dashpot		4.000	0.000
Soil Support Weight	(kips)	1.30	0.00

max. Top Comp. Stress = 36.8 ksi (T= 36.2 ms, max= 2.088 x Top)
max. Comp. Stress = 76.8 ksi (Z= 23.8 ft, T= 37.2 ms)
max. Tens. Stress = -9.80 ksi (Z= 23.8 ft, T= 77.1 ms)
max. Energy (EMX) = 55.1 kip-ft; max. Measured Top Displ. (DMX)= 1.46 in

EXTREMA TABLE

Pile Sgmnt No.	Dist. Below Gages ft	max. Force kips	min. Force kips	max. Comp. Stress ksi	max. Tens. Stress ksi	max. Trnsfd. Energy kip-ft	max. Veloc. ft/s	max. Displ. in
1	3.4	693.3	-79.0	36.8	-4.19	55.10	16.0	1.454
2	6.8	698.5	-82.0	75.1	-8.82	52.88	15.9	1.375
3	10.2	703.0	-84.9	75.6	-9.12	50.63	15.7	1.294
4	13.6	708.8	-87.1	76.2	-9.37	48.13	15.4	1.214
5	17.0	714.1	-89.8	76.8	-9.65	45.86	15.0	1.134
6	20.4	710.5	-88.8	76.4	-9.54	42.25	14.4	1.055
7	23.8	714.2	-91.1	76.8	-9.80	40.11	13.8	0.976
8	27.2	700.2	-87.1	75.3	-9.36	35.87	13.0	0.901
9	30.6	703.6	-89.0	75.6	-9.57	33.91	11.8	0.826
10	34.0	676.0	-80.9	72.7	-8.70	29.26	10.3	0.755
11	37.4	679.6	-82.6	73.1	-8.88	27.63	8.6	0.687
12	40.8	604.9	-59.7	65.0	-6.41	21.04	7.2	0.630
13	44.2	606.4	-61.0	65.2	-6.56	20.04	6.4	0.578
14	47.6	508.9	-34.1	54.7	-3.66	13.98	6.4	0.534
15	51.0	509.5	-35.3	45.7	-3.16	8.04	6.1	0.499
Absolute	23.8			76.8			(T =	37.2 ms)
	23.8				-9.80		(T =	77.1 ms)

CASE METHOD

J =	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
RP	530.4	491.3	452.2	413.1	374.0	334.9	295.7	256.6	217.5	178.4
RX	774.5	760.2	745.8	731.4	717.1	702.7	688.3	676.3	664.5	653.0
RU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

RAU = 537.3 (kips); RA2 = 746.6 (kips)

Current CAPWAP Ru = 660.4 (kips); Corresponding J(RP)= 0.00; J(RX) = 0.84

VMX ft/s	TVP ms	VT1*Z kips	FT1 kips	FMX kips	DMX in	DFN in	SET in	EMX kip-ft	QUS kips
15.60	26.09	524.8	396.7	703.3	1.465	0.121	0.188	55.6	807.7

PILE PROFILE AND PILE MODEL

Depth ft	Area in^2	E-Modulus ksi	Spec. Weight lb/ft^3	Perim. ft
0.00	18.85	29992.2	492.000	1.833
2.50	18.85	29992.2	492.000	1.833
2.50	9.30	29992.2	492.000	1.833
49.00	9.30	29992.2	492.000	1.833
49.00	15.60	29992.2	492.000	1.833

PILE PROFILE AND PILE MODEL

Depth ft	Area in^2	E-Modulus ksi	Spec. Weight lb/ft^3	Perim. ft
50.00	15.60	29992.2	492.000	1.833
50.00	9.30	29992.2	492.000	1.833
51.00	9.30	29992.2	492.000	1.833

Toe Area 0.267 ft^2

Segmnt Number	Dist. B.G. ft	Impedance kips/ft/s	Imped. Change %	Tension Slack in	Tension Eff.	Compression Slack in	Compression Eff.	Perim. ft
1	3.40	33.65	0.00	0.000	0.000	-0.000	0.000	1.833
2	6.80	20.60	24.10	0.000	0.000	-0.000	0.000	1.833
13	44.20	21.60	30.12	0.000	0.000	-0.000	0.000	1.833
15	51.00	24.91	25.12	0.000	0.000	-0.000	0.000	1.833

Pile Damping 1.0 %, Time Incr 0.202 ms, Wave Speed 16807.9 ft/s, 2L/c 6.1 ms