DYNAMIC METHODS IN DESIGN AND INSPECTION FOR THE RIO MANATI BRIDGE

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ABSTRACT

Design and inspection of foundation piles for a 2.2 km bridge in Puerto Rico made extensive use of dynamic methods. Subsurface conditions included limestone bedrock and boulders, silts, clays and gravels with substantial lateral variability. Pile design and acceptance employed a combination of static soil analyses, static and dynamic pile loading tests, and wave equation analyses. Dynamic pile test results correlated well with static loading test results. The dynamic pile tests also provided soil setup data and dynamic soil resistance parameters for wave equation analysis. The comprehensive testing and analysis program provided timely information and recommendations for this project with difficult subsurface conditions.

INTRODUCTION

The optimum approach to design and quality assurance for pile foundations may often require a combination of several engineering tools. This was the case for H-piles driven for the foundation of the 2.2 km long Rio Manati Bridge, where subsoil conditions included deep compressible layers of silts and clays, sand and gravels and decomposed limestone with boulders. For this bridge, static pile analyses, static and dynamic loading tests and wave equation analysis were combined to establish pile driving criteria. The observed time-dependant soil setup was used to reduce the required installation resistance and blow count. This paper presents a portion of the data obtained on this project and the techniques used for analysis and inspection of pile installation.

SITE DETAILS

General

The Rio Manati Bridge is part of the De Diego Expressway between San Juan and Arecibo on the north coast of Puerto Rico. Due to frequent flooding of the Rio Grande de Manati, the bridge spans the entire 2.2 km wide flood plain. The bridge foundation consists primarily of 1759 driven steel HP 14x73 H-piles within 68 bents.

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The Highway Authority of Puerto Rico directed design and construction of the bridge. Employees and representatives of the Highway Authority provided inspection and approval of the foundation piles. Construction specifications provided for a series of static load tests, and for use of a Pile Driving Analyzer® (PDA) for test piles and for routine inspection. The PDA used for this project was owned and operated by the Highway Authority.

Subsurface Conditions

Karst topography derived from the solution of limestone rocks was present on the east and west abutments. The rock outcrops were Aymamom Limestone which is generally fine-grained, very pure, fossiliferous, and highly weathered. Across the flood plain the alluvium was composed primarily of sands and gravels, and soft to medium silts and clays, generally well stratified. However, soils beneath some bents consisted of compressible organic material at significant depths, and other soils were classified as very irregular with boulders and highly weathered limestone rock. The thickness of the alluvium typically ranged from 24 to 60 m, and pile penetrations ranged from 25 to 57 m. A high degree of lateral soil variability was evident in boring logs from the site investigation and in the pile driving logs.

Foundation Design

Each of the 68 bents was founded on HP 14x73 piles which have a cross-sectional area of 138 cm^2. Pile lengths were typically between 24 and 55 m and averaged 38 m. The required ultimate load for all piles was 1958 kN (440 kips). Construction documents specified a minimum tip elevation in each bent and contained provisions for both static and dynamic pile tests. During construction the results of static and dynamic pile tests supported further pile design, and were used to modify the minimum tip elevations and to give driving termination criteria.

Pile Driving Equipment

The construction contractor used a Kobe K-25 hammer and a IHC S-70 hammer to drive all piles. The Kobe K-25 hammer is an open end diesel hammer with a 25.5 kN ram and a rated energy of 69.5 kJ. The stroke length of the K-25 hammer varies with pile penetration resistance and fuel setting. The IHC S-70 is a hydraulic hammer with a 34.3 kN ram and a rated energy of 70 kJ. The S-70 hammer has an electronic monitoring system that computes the hammer energy based on the ram's velocity, and the hammer operator can adjust this energy to a desired level. In general, the contractor could use either hammer in any bent, and criteria for pile driving and pile acceptance were provided for both hammers at many bents.

TESTING AND ANALYSIS

Soil Resistance

Before the start of production driving in most bents, a test pile was installed in a production location. A Pile Driving Analyzer, manufactured by Pile Dynamics, Inc. was used for dynamic measurements during installation of these piles. Later, after a waiting period of approximately one week or longer, a brief restrike test was conducted. The restrike generally consisted of 20 to 60 hammer blows, with dynamic monitoring. The restrike test was often completed several days or more before the start of production driving in the same bent, such that test pile analysis could be completed before the start of further production driving.

The PDA system (Vanikar, 1985) consisted of two strain gages and two accelerometers bolted to the pile near the pile top, a signal cable between the pile and a Model GCPC, PDA. For each hammer blow the PDA digitized the signals from both strain gages, and both accelerometers. It then computes and prints a variety of values such as energy transfer to the pile, pile stress, and soil resistance. Dynamic measurements and computed results for each hammer blow may be stored on the hard drive of the PDA. Figure 1 presents a schematic of the PDA system.

Dynamic measurements from each test pile were used as input to the CAPWAP computer program. CAPWAP® (CAse Pile Wave Analysis Program) is an iterative signal matching program used to compute a model of the soil's response to axial pile movement (Hussein et al. 1988). Results from each CAPWAP analysis included the magnitude and distribution of shaft friction, the magnitude of end bearing, and dynamic soil resistance parameters used in wave equation analysis.

CAPWAP analyses were made for hammer blows from the End of Driving (EOD) and the Beginning of Restrike (BOR) on test piles. The time elapsing between installation and restrike ranged from 4 to 217 days, but was typically between 10 and 33 days. For setup times of one day or more the Setup factors, defined as BOR resistance divided by EOD resistance at equal tip elevation ranged from 0.97 to 1.99, and averaged 1.4. The difference between soil resistance at EOD and BOR, often called soil setup, was attributed to time dependant soil strength gain resulting from dissipation of excess pore pressure that developed as the piles were initially driven at EOD conditions.

Table 1. Summary of Static Load Test Data and CAPWAP Results

Pile	Static Load Test kN	CAPWAP of BOR kN	Ratio CAPWAP/Static
Bent 8R P8	2580	2010	0.78
Bent 19R P13	2710	2270	0.84
Bent 49L P7	1870	1870	1.00
Bent 59L P13	1870	1860	0.99

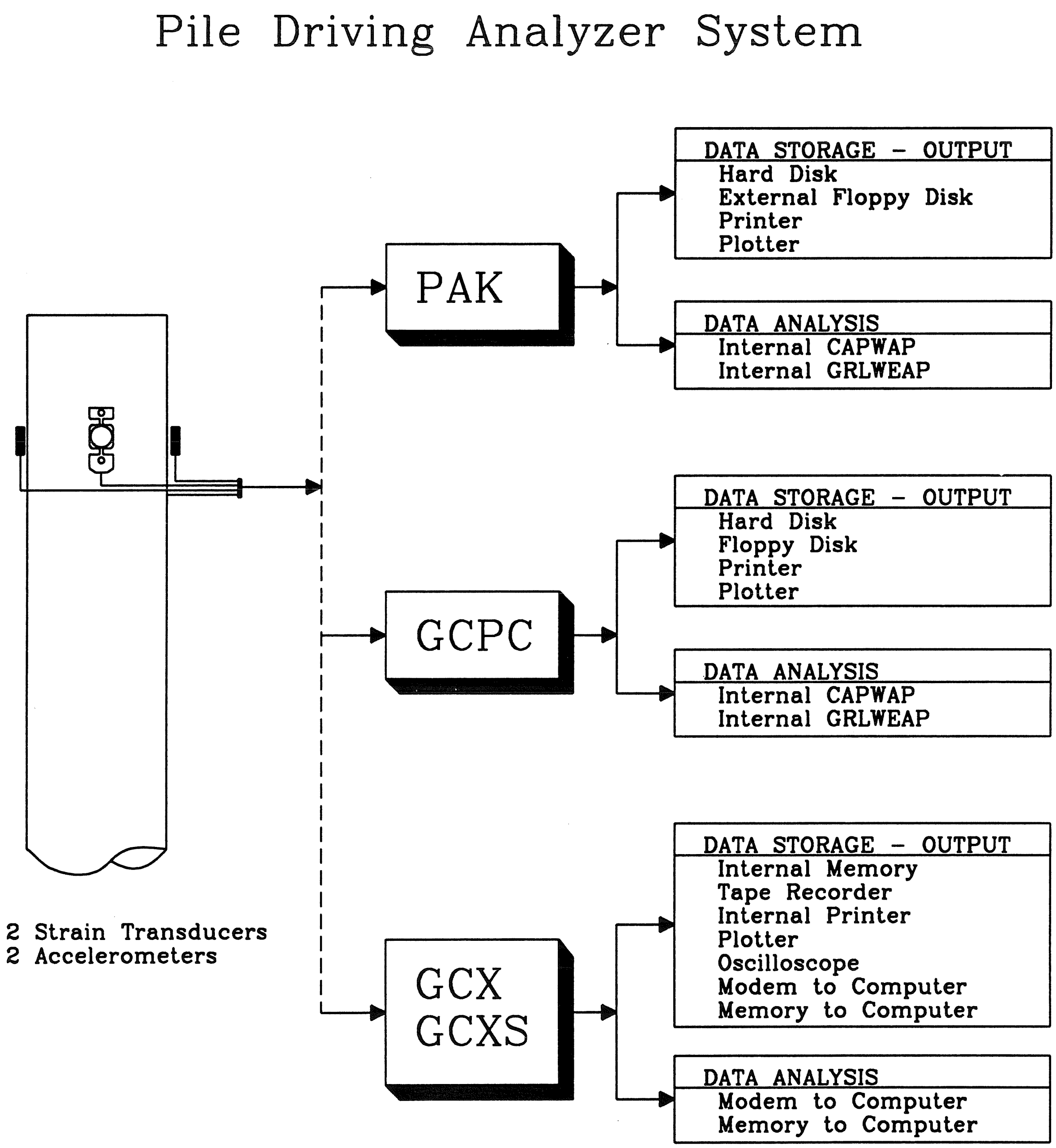

Figure 1. Schematic of the Pile Driving Analyzer

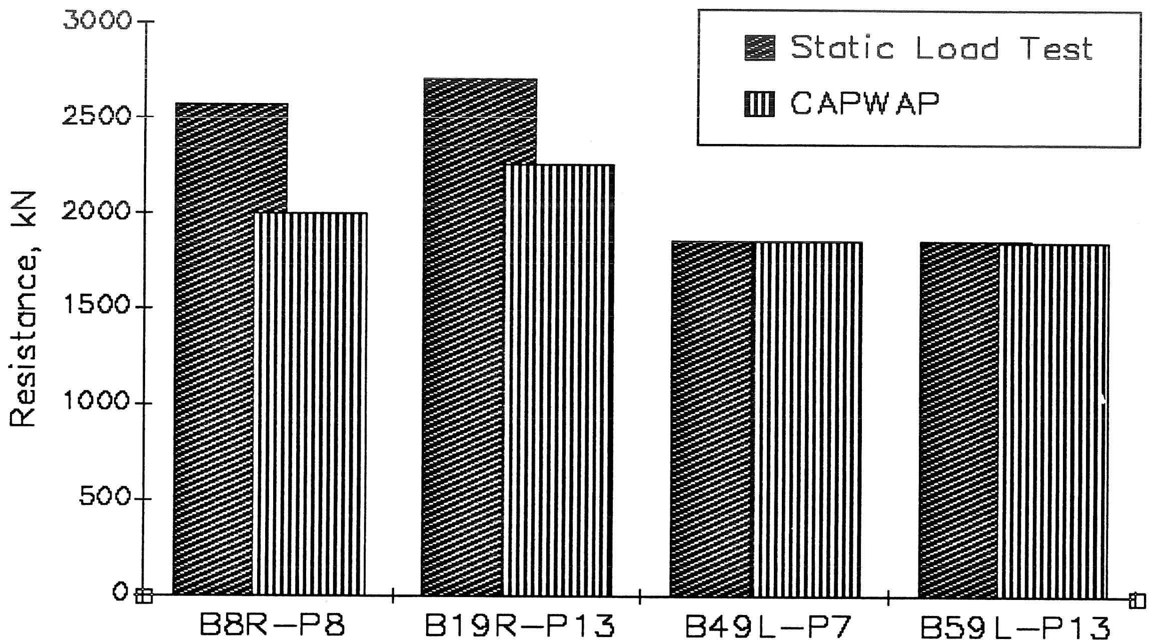

Figure 2. Summary of Test Pile Results

In addition to the test piles in each bent, 6 static load tests were made. The Davisson limit load criterion was used to compute a failure load for each static test (Fellenius, 1980). Four of the statically tested piles were also dynamically monitored during installation and restrike, and analyzed with CAPWAP. Figure 2 and Table 1 compare the static test results with the CAPWAP analyses. These static and dynamic data verified the effectiveness of CAPWAP for this site, and gave a sound basis for use of CAPWAP results across the site.

Pile Integrity

In some portions of the project site, piles encountered difficult driving conditions that were attributed to boulders and variable degrees of weathering of the Aymamom Limestone. Dynamic measurements of force and velocity measured near the pile top may be used to evaluate the extent and the location of subsurface pile damage (Rausche and Goble, 1978). Figure 3 contains plots of dynamic measurements of Pile 17 in Bent 52R and indicates severe pile damage 4.9 m below the gage location; the pile length was approximately 50 m. For this pile the damage was apparently associated with an obstruction encountered during driving. In other cases damage occurred at splice locations and led to modifications of splice details.

Pile driving logs were routinely reviewed for abnormal blow counts due to obstructions or pile damage. When damage was indicated in the driving log, the pile was tested with the PDA. If the dynamic measurements proved significant pile damage the pile was replaced, or supplemented by one or more additional piles.

PILE INSTALLATION CRITERIA

Procedure for Setting Installation Criteria

Pile installation criteria for most bents were established using the results from the nearest dynamic test pile. The installation criteria included a minimum tip elevation, and a minimum and maximum final blow count that depended on the ram stroke or hammer energy. In most cases a dynamic test pile was driven and restruck in each bent for the purpose of establishing the installation criteria. These test piles were typically installed well in advance of adjacent production driving, and restruck at least several days before driving the final sections of adjacent production piles. The contractor and the inspection staff were not given criteria for pile approval until any necessary test piles were installed, restruck and analyzed.

Pile installation criteria were established using the following procedure:

1. Perform CAPWAP analysis of dynamic measurements from EOD (End of Driving) and BOR (Beginning of Restrike). The CAPWAP analyses provide computed values for shaft resistance distribution, end resistance, total resistance, and wave equation soil parameters.

2. Compare the CAPWAP results for EOD and BOR to determine the magnitude of soil setup that occurred during the period between EOD and BOR.

3. Use the measured soil setup data to establish a *Target EOD Resistance* for production piles. This Target EOD Resistance was generally less than the required 1958 kN ultimate resistance, the difference being equal to the anticipated soil setup.

4. Use the available data and the GRLWEAP™ wave equation analysis program (Hannigan, 1990) to post-predict the EOD blow count for the CAPWAP EOD soil resistance. For this prediction the measured energy transfer, ram stroke, peak force and penetration resistance are matched as close as possible by adjusting other parameters based on available data. Soil resistance was assumed to be equal to the predicted EOD CAPWAP resistance. The CAPWAP computed soil damping and quakes were starting values for GRLWEAP. If necessary, these soil parameters were adjusted to obtain the match between GRLWEAP and field EOD values for penetration resistance.

5. Use the wave equation parameters from Step 4 to predict the penetration resistance and pile stress for a pile driven to the Target EOD Resistance defined in Step 3. Compute required final penetration resistances for a range of ram stroke lengths (Kobe K-25) and a range of hammer energy readings (IHC-S70). Also compute a stroke and energy limit and associated penetration resistance that may be required to avoid excessive driving stress in the pile.

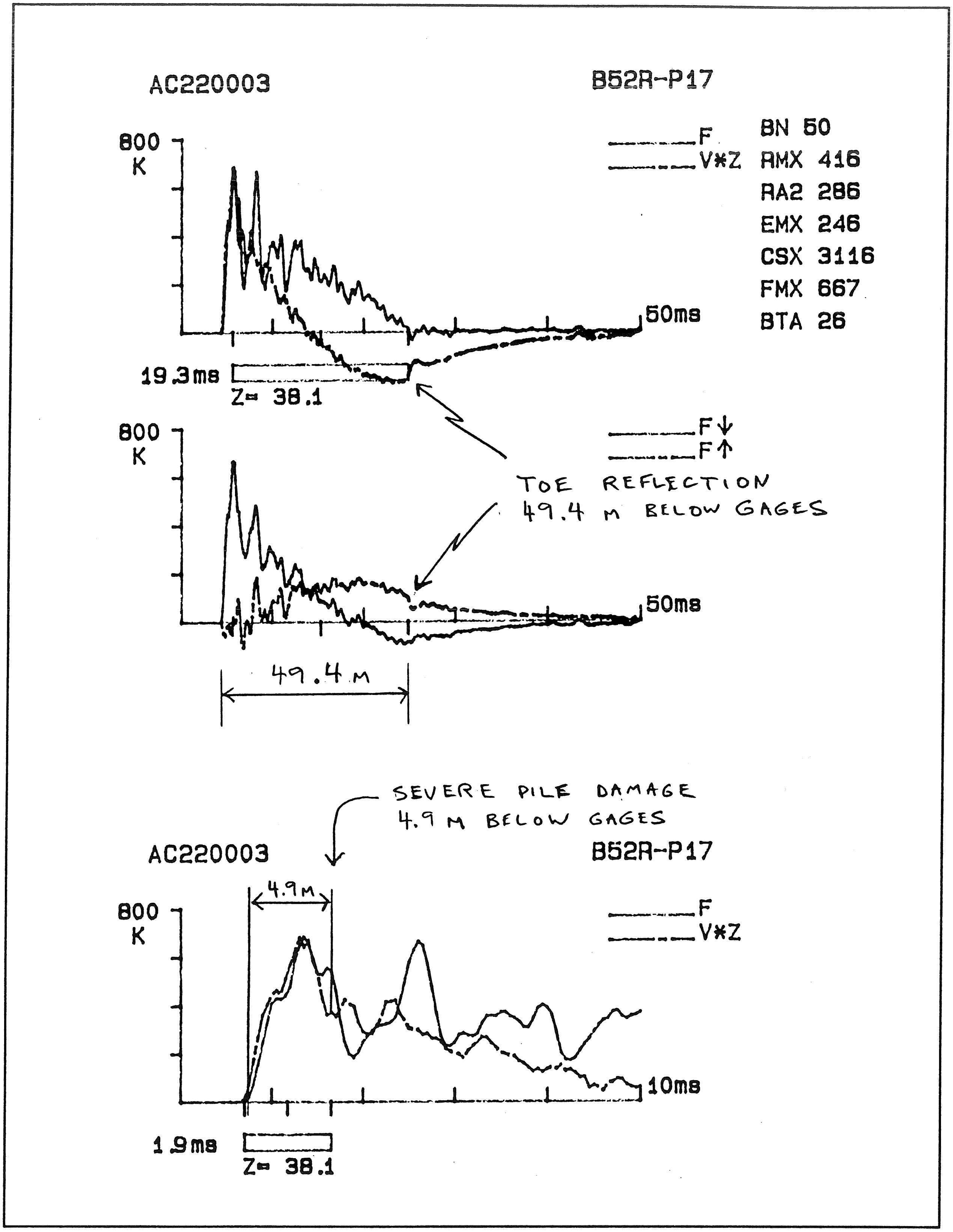

Figure 3. Pile Integrity Evaluation

Example

The following example of the procedure outlined above is based on data from the dynamic test pile driven in Bent 18 with the Kobe K-25 hammer, summarized in Table 2.

The measured soil setup for the test pile may be expressed as a ratio of the BOR and EOD total resistance, and as a difference between the BOR and EOD shaft friction resistance. Considering total resistances, the setup ratio was 1.88. Considering the change in shaft friction the setup was 773 kN. Thus, potential EOD target resistances of 1041 kN (1958/1.88) and 1185 kN (1958-773) were computed based on considering the setup ratio and the amount of shaft setup, respectively. The conservative selection of these two values provided an 1185 kN Target EOD Resistance. (This projected setup value was assumed to apply to production piles with penetrations similar to the test pile's 28 m penetration. Production piles stopping significantly shallower or deeper than the test pile would be reviewed separately because the Target EOD Resistance may not be applicable.)

Table 2. Summary of Bent 18 Test Pile Data

For EOD (End of Driving)					
CAPWAP Shaft Resistance:	935 kN			Transfer Energy:	27kJ
CAPWAP Total Resistance:	1068 kN			K-25 Stroke:	2.0 m
Shaft Quake:	2.8 mm	Toe Quake:	10.16 mm	Peak Stress:	176 MPa
Shaft Damping:	0.49 s/m	Toe Damping:	0.87 s/m	Blow Count:	98 blows/m
For BOR (Restrike)					
CAPWAP Shaft Resistance:	1708 kN				
CAPWAP Total Resistance:	2002 kN				

The initial GRLWEAP analysis for this pile focused on matching the observed stroke, and especially the transferred energy measured with the PDA. Through several attempts by trial and error, the hammer efficiency was adjusted to 0.65; the default GRLWEAP value for the K-25 is 0.72. Also, the combustion pressure was increased 5.0% above the GRLWEAP default value. These changes were made to match the field stroke and transfer energy. Soil parameters computed from CAPWAP of EOD were used for the initial wave equation analyses with GRLWEAP.

After matching the energy and stroke, the predicted and observed penetration resistance was compared. In this case the quakes and damping taken directly from CAPWAP caused GRLWEAP to slightly underpredict the field penetration resistance. Thus, the shaft and toe damping parameters were increased slightly, as compared against CAPWAP values, to .52 and .88 s/m, respectively. Figure 4 is a bearing curve computed with the final model. The penetration resistance predicted for the 1068 kN EOD CAPWAP resistance is 99 blows per meter and is in good agreement with the observed 98 blows per meter value. Thus, the adjusted wave equation parameters provided a good match between observed and predicted values. Table 3 summarizes the parameters before and after adjustment, and the observed and predicted quantities.

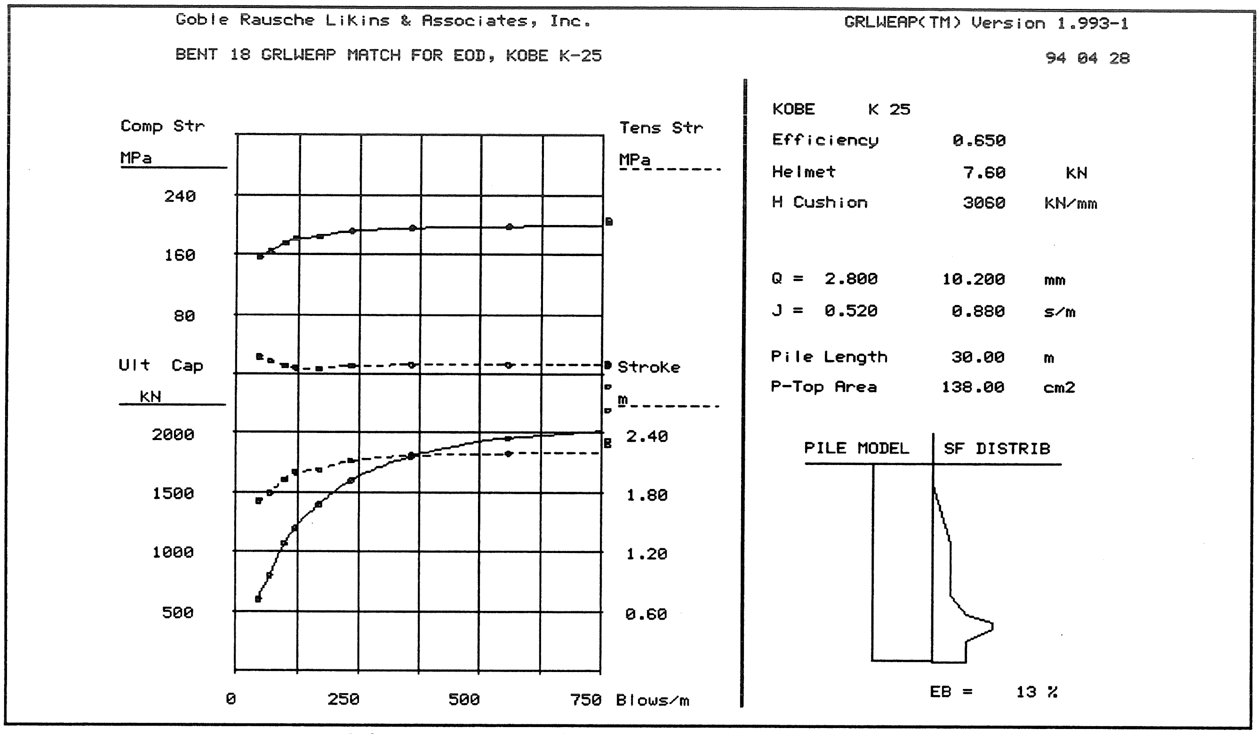

Figure 4. Bearing Graph, Bent 18 EOD

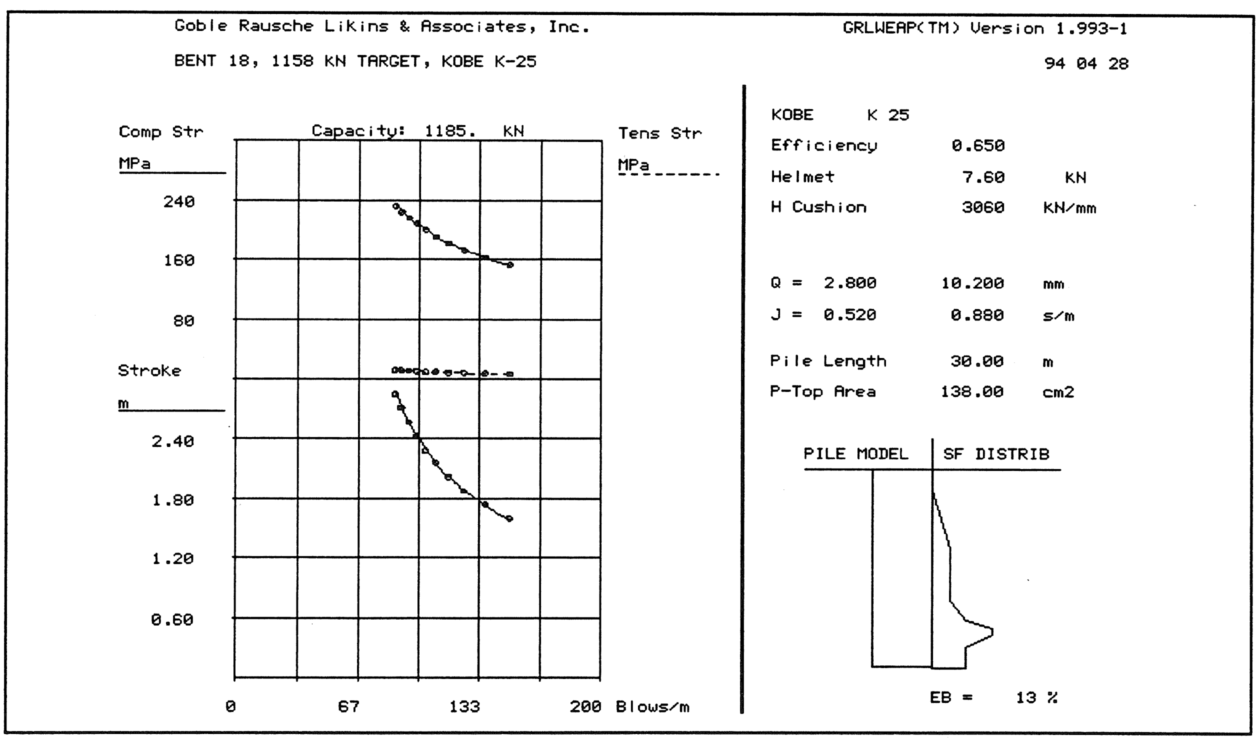

Figure 5. Summary of GRLWEAP Results, EOD Bent 18, Variable Stroke

Because the adjusted GRLWEAP model provided a good post-prediction it could now be used to predict the penetration resistance and driving stress for the Target EOD Resistance. If the stroke during driving matches the stroke at EOD of the test pile the required blow count would be 120 blows per meter. However, the hammer stroke and transfer energy during production driving will vary and may not be equal to the values observed during installation of the dynamic test pile. Thus, GRLWEAP was used to predict the blow counts required to obtain the Target EOD Resistance for a range of hammer stroke lengths. Figure 5 presents a summary of the wave equation results for strokes between 1.6 and 2.8 m. The relation between stroke and penetration resistance was tabulated and given to inspectors for use on site with the Kobe K-25 hammer.

Table 3. Comparison of Observations and Post-predictions, Bent 18 Dynamic Test Pile

	Observed EOD	CAPWAP EOD	GRLWEAP Match EOD
Transfer Energy	27.0 kJ	--	27.0 kJ
Peak Stress	176 MPa	--	176 MPa
K-25 Stroke	2.0 m	--	1.9 m
Soil Resistance	--	1068	1068
Penetration Resistance	98 blows/m	--	99 blows/m
Shaft Quake	--	2.8 mm	2.8 mm
Toe Quake	--	10.16 mm	10.2 mm
Shaft Damping	--	.49 s/m	.52 s/m
Toe Damping	--	.87 s/m	.88 s/m

An IHC S-70 hammer was also in use on this project and it was necessary to provide inspection criteria for both hammers. These criteria were obtained by running GRLWEAP analyses with the same adjusted soil model and with the standard GRLWEAP S-70 hammer model in place of the K-25. The IHC S-70 hammer does not use a hammer cushion, or employ a helmet between the hammer and the pile. A sleeve on the bottom of the hammer assembly functions in place of a conventional helmet. Thus, the striker plate weighing 4.5 kN was the only element between the ram and the pile. This weight was entered as the helmet weight for the GRLWEAP model. Based on data from the Rio Manati Bridge and other projects, the hammer efficiency was left at the 0.95 GRLWEAP default value. This constant efficiency was used for the full range of applicable ram stroke lengths.

In practice, the IHC S-70 hammer operated at a variety of strokes or energy levels. The GRLWEAP Constant Capacity option analyzed a range of effective strokes for the given Target EOD Resistance. For each effective stroke the GRLWEAP results included an associated transfer energy value that could be compared with the energy transfer measured with the PDA. Although the actual stroke of the S-70 cannot be observed the control panel of the S-70 includes an energy reading that is based on electronic measurement of the ram velocity near impact. For the Rio Manati Bridge, PDA measurements of energy transferred to the pile ranged from 77 to 99 percent of the S-70 panel reading, and were typically between 80 and 90 percent of the panel reading. Thus, the GRLWEAP transfer energies could be converted to equivalent IHC panel readings, and the site inspectors could use the panel energy reading in place of a stroke length value. For higher energy levels, the S-70 hammer generated piles stresses greater than 90 percent of the nominal steel yield strength. Thus, the inspection criteria provided a maximum energy level as well as a relation between energy and required blow counts.

For inspection, it was important to note that the penetration resistance developed above applied to continuous driving. If driving was interrupted the recommended blow count would not apply until the pile was continuously driven at least three feet deeper.

CONCLUSION

The Rio Manati Bridge provides a case study that supports several useful observations. Due to difficult subsoil conditions, pile driving at this site posed special difficulties for inspection and quality assurance. These difficulties were reduced through a combination of dynamic pile measurements, CAPWAP analyses, wave equation analyses and static loading tests. The program of static load tests was fully integrated with the dynamic measurements and CAPWAP so that dynamic methods could be used with increased confidence, based on site specific experience. As the subsoil and hammer performance varied, the pile penetrations and driving behavior varied. However, dynamic methods could be used as a basis for rapid modifications of the pile driving criteria. Moreover, when the driving record of individual piles indicated unusual behavior, dynamic measurements conducted by the owner were a cost effective way to evaluate individual piles.

The pile testing and analysis procedures used on this project provided timely recommendations for the inspection staff and aided in quick assessment of piles that required special review, such as those that encountered obstructions, driving interruptions, or were suspected of damage. Both the owner and the construction contractor derived benefits from the timely application of dynamic methods. Of the 156 dynamic tests conducted on this project, most were in response to difficulties or concerns over individual piles and the results allowed the owner and contractor to avoid costly delays and to reduce the uncertainty of pile performance.

Time dependant soil resistance increases at this site were carefully evaluated by comparing installation (EOD) and restrike (BOR) measurements. Soil setup evaluated in this manner was used to reduce pile lengths by reducing EOD penetration resistances. To make full use of restrike test data it is necessary to have a pile driving hammer that can mobilize the restrike soil resistance. Ideally the restrike soil resistance should be less that 300 blows per meter. Due to the large amounts of setup at this site restrike resistances often exceeded 400 blows per meter. Under these conditions the pile capacity may not be fully mobilized, and the resistance predicted with dynamic methods may reflect only the mobilized resistance.

For an H-pile section it is common to expect that setup acts upon shaft resistance but not end bearing. For this project the CAPWAP data often indicated time-dependant increases of end bearing. These increases in end bearing were attributed to soil setup within the flanges of the H-section, leading to an increased effective end area.

ACKNOWLEDGEMENTS

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