Dynamic Pile Analysis Using CAPWAP and Multiple Sensors

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Abstract

A new system of multiple dynamic strain sensors and accelerometers embedded in test piles provides direct synchronous measurement of force and acceleration at various locations within a pile during high strain dynamic pile testing. This instrumentation system creates an opportunity to explore side and end bearing pile resistance distribution with a higher level of confidence and reliability than from top measurements alone. Dynamic testing results using embedded transducers are presented for a 16-inch Auger Pressure Grouted Displacement (APGD) pile. The procedure is explained to estimate static side and end bearing components by matching force and/or acceleration data at the pile top and tip using the CAPWAP program. Static load and displacement characteristics at the pile top predicted by CAPWAP are compared to static pile load test results.

Introduction

The need to predict and better understand the ultimate loads to which a cast-in-place pile foundation is capable is critical for pile design and optimization, as well as for quality assurance of such elements. The use of high strain dynamic testing of cast-in-place piles and drilled shafts has become a more frequent routine for bearing capacity evaluations in many countries around the world, increasing the levels of standardization and codification (Beim et al. 1998). Extensive correlation studies (Seidel and Rausche, 1984; Likins et al. 2004) between static load tests of cast-in-place pile foundations and simulated static load tests obtained from dynamic testing utilizing the Case Pile Wave Analysis Program (CAPWAP) have proven successful.

A system of multiple dynamic bended compensated sensors was embedded in a 16-inch Auger Pressure Grouted Displacement (APGD) pile installed at a jobsite in Los Angeles, California. For this particular test pile, sensors were installed near the pile's top and toe. Dynamic testing was performed while dynamic measurements were collected near the pile top as well as with the embedded dynamic sensors. Dynamic measurements were analyzed using CAPWAP to better assess the separation between side shear and end bearing. The simulated static results obtained using the dynamic measurements were then compared with a static pile load test.

Measurements and Instrumentation

A Pile Driving Analyzer (PDA) collected pile top strain and acceleration measurements during the high strain dynamic testing. The PDA immediately converts these strain and acceleration signals to force and velocity records which yield the dynamic compression stresses and the tension along the shaft, to determine if a higher energy drop can be performed without exceeding the recommended material stress levels. In this manner, dynamic testing was performed utilizing GRL's APPLE 15 ton drop hammer system at multiple drops heights varying between 23 inches and 36 inches, until a significant set (0.25 in) was obtained. In addition to PDA instrumentation, strain and acceleration signals were captured by two digital transducer modules embedded in the test pile near the pile top and toe. Each transducer module included a microprocessor, signal conditioning circuitry, a 16-bit analog-to-digital conversion circuit, and Controller Area Network (CAN) hardware. Each analog signal was digitized by the transducer module circuitry at a rate of 7,750 samples per second. The total number of strain and acceleration points is defined by the user and can range up to 8,000 samples per signal. Prior to conducting the high strain dynamic test, both transducers were placed into a dynamic testing mode by issuing a command via a field laptop computer. Samples were then acquired continuously by each transducer module, and every sample was compared to a user defined trigger level. Once a sample exceeded the specified threshold value, each transducer module reserved a user specified number of pre-trigger samples in SRAM and continued sampling until the user specified total number of samples was obtained. At the completion of sampling, data from each transducer module was transferred to a central controller via the CAN data bus where it was then sent to a laptop computer and stored to disk. Figure 1 presents a picture of the high strain testing setup and instrumentation.

Figure 1. Dynamic Testing and Instrumentation

Analytical Methods
After high strain dynamic data was collected in the field, it was processed utilizing the signal matching software CAPWAP (Case Pile Wave Analysis Program). CAPWAP separates static and damping soil characteristics and also allows for an estimation of the side shear distribution and the pile's end bearing. CAPWAP is based on the wave equation model, which analyses the pile as a series of elastic segments and the soil as a series of elasto-plastic elements with damping characteristics, where the stiffness represents the static soil resistance and the damping represents the dynamic soil resistance. Typically the pile top force and velocity measurements acquired under high strain hammer impacts can be analyzed utilizing the signal matching procedure yielding forces and velocities over time and along the pile length. Initial CAPWAP analysis results utilizing only the top force and velocity records yielded an ultimate soil resistance of 580 kips, of which 240 kips were estimated to be in the shaft and 340 kips in end bearing. Figure 2 presents the initial CAPWAP results which include the force and velocity traces and obtained shaft resistance distribution and end bearing.

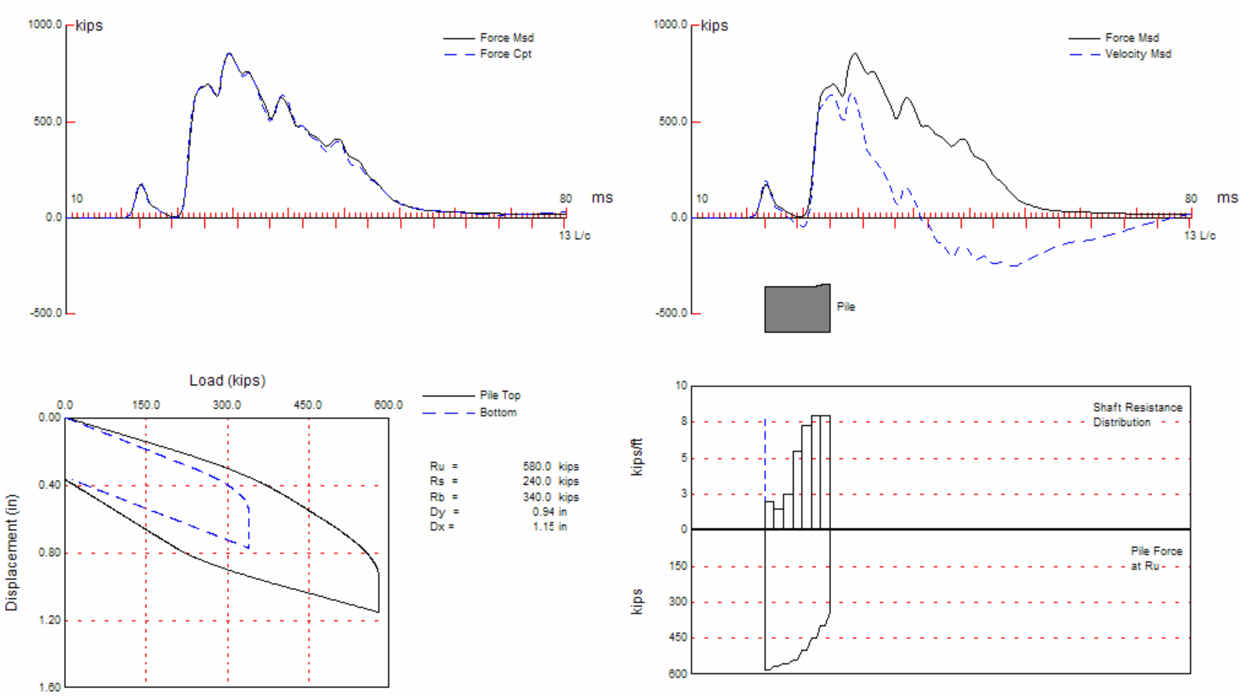

Figure 2. Initial CAPWAP analysis

Utilizing the bottom force and velocity measurements obtained with the dynamic sensors embedded in the pile, bottom force and velocity estimates from the CAPWAP program were matched to measurements by adjusting the magnitude of static resistance, quake and damping parameters for both shaft and toe. Initially the main separation between side shear and end bearing was determined utilizing both peak force and velocities at the pile tip. The side shear distribution and the damping coefficient were modified to obtain a better match utilizing the signal matching capabilities of CAPWAP. The ultimate soil resistance calculated by CAPWAP analysis for the dynamic test was 560 kips, of which 300 kips of those were estimated to be in side shear and 260 kips in end bearing. Figures 3 and 4 show a comparison between measured toe force and velocity, the latter multiplied by the pile impedance, and the equivalent readings from the embedded dynamic sensors.

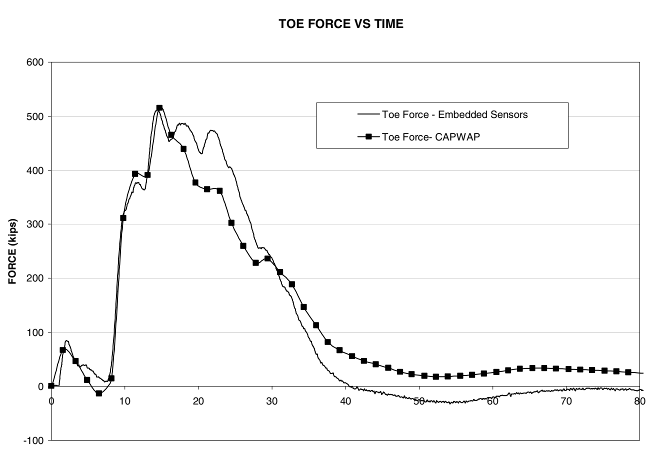

Figure 3. Toe Force

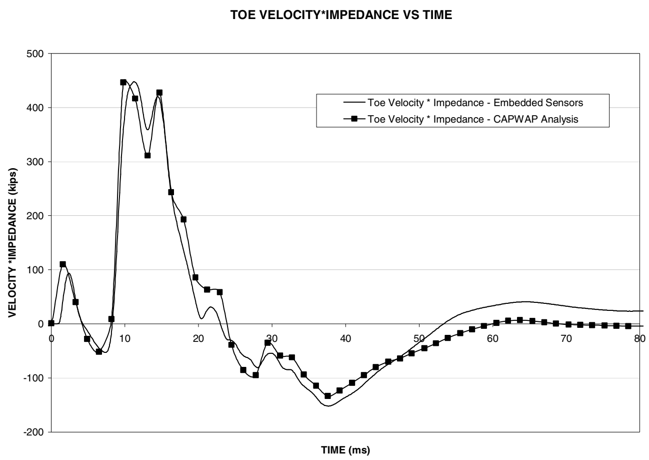

Figure 4. Toe Velocity*Impedance

CAPWAP also allows for a computation of a simulated load set curve utilizing the static components of the calculated total resistance. Thus, after signal and dynamic sensor matching was achieved a simulated load-set curve was generated and compared to the results of a static load test. The static load test was conducted using a standard load schedule, and the maximum test load was maintained for about 12 hours. High strain dynamic testing models a quick load test and does not account for any additional settlements associated with the long-term static test method. Both load-set curves are given as a visual comparison with the understanding that results are not meant to be directly compared. Figure 5 presents load-set curves from both the static load test and the CAPWAP simulation.

Figure 5. Static and Dynamic Load Set Curves

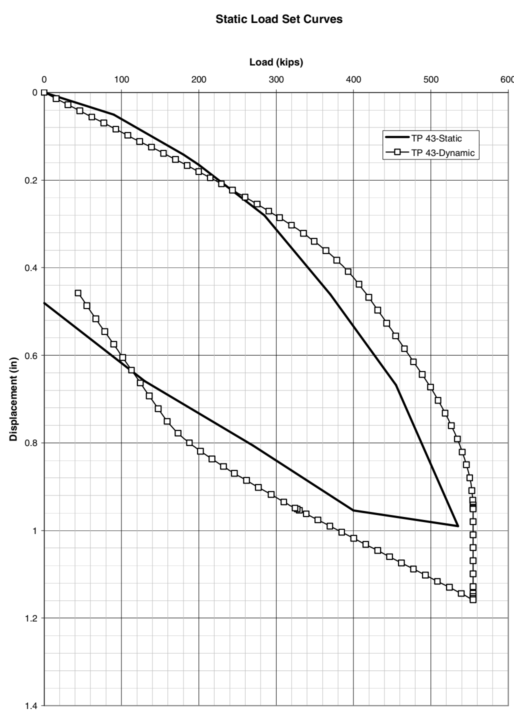

Table 1. Comparison of calculated with static test loads

Table 1. Summary of Pile Capacity Estimates Using Standard PDA and Embedded Sensors

Resistance Component	Capacity Estimates Using CAPWAP with Standard PDA Instrumentation (kips)	Capacity Estimates Using CAPWAP with Embedded Dynamic Sensor Modules (kips)	Percent Change
Total	580	560	4
Side	240	300	20
Tip	340	260	31

Conclusions

A dynamic testing procedure utilizing standard PDA top transducers, an accelerometer and strain transducer embedded at the pile bottom, plus the Case Pile Wave Analysis Program (CAPWAP), was devised to calculate with an increased degree of confidence side shear and end bearing components of an augercast displacement pile than possible from top measurements alone. Results of this study indicate that estimates of side and end bearing components of the total capacity changed by 20 to 31 percent, respectively, using embedded dynamic strain and acceleration sensors, while the total capacity estimate was changed by 4 percent. Additional case histories are needed to further characterize the potential benefit of using multiple embedded dynamic sensors and to further improve the multiple signal matching techniques described in this paper.

References

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