Driven Concrete Pile Foundation Monitoring With Embedded Data Collector System

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ABSTRACT

Florida Department of Transportation (FDOT) sponsored research performed at the University of Florida resulted in developing a wireless monitoring and real time static capacity estimate technology for driven piles. This new technology, Embedded Data Collector (EDC), uses two levels of instrumentation, embedded in the body of precast prestressed concrete piles near the head and tip. Strain and acceleration measurements obtained at these instrumentation levels during driving are sent wirelessly to a receiver in the field, and analyzed in real time to provide the operator with estimates of static capacity, stresses in the pile, transfer energy, damping factor, stroke height, and other relevant parameters used to evaluate the pile driving process and the driving system. The EDC system is currently undergoing phase one of a two phase field evaluation program planned by the FDOT to determine the level of reliability that can be anticipated by its use. The first phase consists of monitoring piles with EDC instrumentation and concurrently monitoring them with the Pile Driving Analyzer (PDA), given that there is ample data supporting the reliability of PDA. Measurements of strain and particle acceleration converted to force and velocity traces can then be compared between the two systems, along with the corresponding calculated magnitude of downward and upward traveling stress waves as they move along the pile at any point in time. Selected hammer blows recorded by PDA equipment are analyzed by means of signal matching software (CAPWAP) and the estimated static skin, end bearing, and total resistance obtained are compared against EDC static resistance predictions. The second phase of the evaluation will compare EDC estimates of static capacity against instrumented static load test results. The purpose of this paper, is only to present a summary of results obtained thus far in phase one, and compares EDC estimates of static capacity results with those from PDA and CAPWAP.

INTRODUCTION

The majority of State owned Bridges in Florida are supported on deep foundation systems comprised of precast prestressed concrete piles (PPC). In general, Florida's geology is amenable to this pile type because bearing layers often consist of soft carbonate rocks, dense sands, or over-consolidated clays, overlain by soil layers that in general do not pose major difficulties to pile driving operations. Driving stresses can usually be handled by PPC piles with proper pile cushion thickness and hammer stroke heights. Monitoring of test pile installation is of critical importance to ensure integrity of the pile and adequate resistance as well as to develop guidelines for production pile driving. Smith (1960) analyzed the problem by dividing the pile into unit lengths that underwent wave action under the blow of a hammer, and major advances have been made since through the use of computerized calculations. A reasonably comprehensive presentation of the history of wave mechanics applied to pile driving monitoring can be found in Hussein and Goble (2004). Currently, the most common method for dynamic load testing is to monitor driving with the PDA. The method has gained wide acceptance given the clear advantages in time and cost it offers when compared to static load testing techniques.

In recent years, work has been performed to provide alternate methods and equipment for dynamic load testing of deep foundations. As a result of research conducted at the University of Florida, a new procedure was developed for field monitoring as well as analyses through the use of two (or more) levels of instrumentation. This method is theoretically capable of calculating the damping factor between levels of instrumentation for each every hammer blow (McVay 2002). Therefore, real time static resistance can be theoretically estimated using computed damping values during pile driving, thus eliminating the need for signal matching to obtain improved damping values on selected hammer blow(s). This approach was implemented and later enhanced by Smart Structures, Inc., who holds a license to the patent and manufactures the instrumentation.

To evaluate the performance of the EDC system, FDOT is conducting a program of concurrently monitoring PPC test piles using PDA and EDC instrumentation for several projects during driving. The data gathered during these projects is then analyzed and compared. In addition, selected hammer blows from PDA data are being analyzed with Case Pile Wave Analysis Program (CAPWAP) signal matching software. The PDA and CAPWAP estimated static resistances are compared with the EDC estimated static resistance.

This paper is focused only on presenting the data gathered thus far on piles monitored with the EDC and PDA as well as comparing the EDC results with both PDA and CAPWAP estimates. The mathematical model used by the UF Method is based on McVay (2002). The manufacturer is in the process of developing a manual that will include a summary of the method's mathematical background.

Current Practice In Florida

Driven pile design and construction requirements for bridges are outlined in FDOT's Structures Design Guidelines, Soils and Foundations Handbook, Design

Standards, and the Standard Specifications for Road and Bridge Construction. The following is a brief description of the general procedure followed by the pile driving industry when performing dynamic load tests.

Typically dynamic load tests including PDA monitoring and signal matching with CAPWAP are used to set the criteria for driven pile installation. The PDA utilizes two accelerometers and two strain transducers connected diametrically on the pile at least one and one-half times the pile width or diameter from its head. Prior to driving, the PDA operator selects damping factors (J_c) that will be used for resistance estimates throughout the driving process in the PDA unit. This usually is based on previous experience with similar subsurface conditions. After driving, the engineer usually selects one blow per drive for CAPWAP analysis to obtain improved estimates of static resistance, as well as quake and damping factors. Using the calculated J_c and quake for skin and toe resistances, driving criteria for production piles (e.g., required number of blows per meter (foot) at prescribed stroke heights) is developed through the use of GRLWEAP software. Production piles are then driven to meet the driving criteria and embedment requirements for each pier or bent. However, quake and damping factors obtained through CAPWAP and the associated static resistance predictions are not unique solutions and different users may provide differing results depending on their level of expertise (Lai and Kuo 1994).

EMBEDDED DATA COLLECTOR

Because the PDA requires the user to assume a constant damping factor for static resistance estimates in the field, and CAPWAP analyses do not produce unique solutions, FDOT sought an alternate method to calculate static resistance from dynamic load test results. The EDC system was developed based on FDOT funded research project "Estimating Driven Pile Capacities during Construction", (McVay et al., 2002), at the University of Florida (UF). The research focused on the use of two levels of instrumentation consisting of one accelerometer and one strain transducer per level placed along the axis of the PPC piles prior to concreting. Currently, the top set of instruments is located two pile widths below the pile head, and the bottom set at one pile width above the pile tip. The bottom instrumentation is physically connected to the top level through insulated wiring. The top level includes a signal conditioner and connects to an antenna located at the face of the pile that transmits data from both levels of instruments to a receiver in the field. The receiver collects and analyzes the data in real time and provides the field inspector with estimates of static capacity, pile stresses and the energy transferred to the pile. These parameters allow the inspector to adequately assess the driving system and soil resistance is of major importance.

FDOT recognized the need to build a database of EDC records and to compare its results with the industry standard PDA-CAPWAP before it can be used as an alternate standard pile driving monitoring system. When enough data is collected, FDOT will eventually develop a resistance factor for Load Resistance Factor Design (LRFD).

EVALUATION OF EMBEDDED DATA COLLECTOR FIELD PERFORMANCE

FDOT has a two-phase field evaluation program planned to create a database and assess EDC performance. Phase I consists of comparing EDC predictions with PDA and CAPWAP results and is an ongoing effort. The field data for this phase were collected by Smart Structures, Inc., Applied Foundation Testing, Inc., Williams Earth Sciences, Inc., Foundation & Geotechnical Engineering, Inc., and Nodarse & Associates, Inc. As a future effort, Phase II is planned to compare EDC results with instrumented static load tests. PDA–EDC monitoring of test piles for Bridge structures has been an ongoing effort for approximately two years. However, project specific decisions during that time have been made based solely on PDA data. Some of the isolated issues encountered with the system during the evaluation period have included CPU overload of the field receiver, lost radio links resulting in missed blows during driving, and improper settings used in the field resulting in no data collection. Similarly, PDA problems were occasionally observed when EDC collected good data. FDOT considers that the evaluation phase has been of value to the development of the system and provided the manufacturer an opportunity to recognize and correct problems that have arisen in the field.

Comparison of EDC and PDA Predictions

Prior to the release of software that did not require user input for analysis other than the data gathered in the field, FDOT's evaluation of EDC was qualitative and compared field collected data between the systems. In May of 2008, the manufacturer provided software with a pre-determined set of calculation parameters that were to remain constant throughout the evaluation to eliminate any bias that could be attributed to user's input. This allowed a qualitative and quantitative evaluation of the previously collected and future data gathered by the EDC and PDA systems to begin.

All the information that has been gathered from EDC instrumented piles driven for State projects has been compiled into a database. The majority of those piles were concurrently monitored with PDA for comparison purposes, and current efforts are focused on evaluating the data when the PDA indicates a total resistance of 445 kN (50 tons) or more and providing statistical parameters for analysis since piles with such low resistance are of negligible value to FDOT. Table 1 includes a summary of concurrent data in the existing database.

Table 1. Summary of Database

File Type	Number of Concurrent Data Files
PDA (.W01)	122
EDC (.ssn)	122
CAPWAP (.cww or .pdf)	60

Of the four calculation methods currently implemented in the EDC software (i.e., Dynamic Case, Fixed Case, Paikowsky, and University of Florida), two were selected for evaluation; the Fixed-Case (Fixed) and the University of Florida (UF) methods.

The Fixed method was selected because the manufacturer implemented the same equations published in the PDA user manual (Pile Dynamics Inc., 2004). This method uses data collected only from the top EDC gages, and provides static capacity estimates based on a constant operator selected damping factor. The UF method uses EDC instrumentation located near the pile head and tip and provides estimates of static resistance based on a calculated damping factor for every hammer blow obtained from the measured stress wave characteristics.

A comparison of static resistance predictions by the two systems was accomplished by transferring PDA and EDC field collected data into an Excel spreadsheet and comparing the capacity predictions qualitatively and quantitatively for each drive. Of interest were the statistical characteristics of the EDC/PDA ratios (i.e., mean, standard deviation and coefficient of variation [COV]) to determine the level of consistency between predictions.

Analyses of the data revealed that during some drives the two systems did not always compute similar results (e.g., UF/PDA Method capacity > 1.9). To determine whether these large differences in predictions were common occurrences or outliers in the data, as suggested by qualitative inspection of the static capacity traces, two analytical methods were used. The first computed the mean +/- three standard deviations (μ +/- 3σ), and the second consisted in calculating a 95 percent confidence interval around the mean based on the standard deviation and the population size. The first method was selected because it includes a wider range of data. Data outside the analysis range are not reported in Tables 2, 3 and Figures 1, 2.

Table 2. EDC/PDA Ratio of Static Capacity Predictions
(n =116,048 blows from 68 piles)

Parameter	Fixed Method/PDA	UF Method/PDA
Percent of Total Population "n" within μ +/- 3σ	100	98.5
Mean (μ)	1.02	1.12
Median	0.97	1.07
Standard Deviation (σ)	0.25	0.24
COV	0.25	0.21

Table 3. EDC/PDA Stress, Energy, Integrity and Blow Count
(n = 65,288 blows from 38 piles)

	CSX	CSB	TSX	EMX	BTA	B.C.
Mean	0.88	0.80	1.18	0.94	0.95	1.00
Median	0.92	0.85	1.24	0.96	0.98	1.00
Std. Dev.	0.10	0.30	0.46	0.29	0.09	0.18
COV	0.11	0.38	0.39	0.31	0.09	0.18

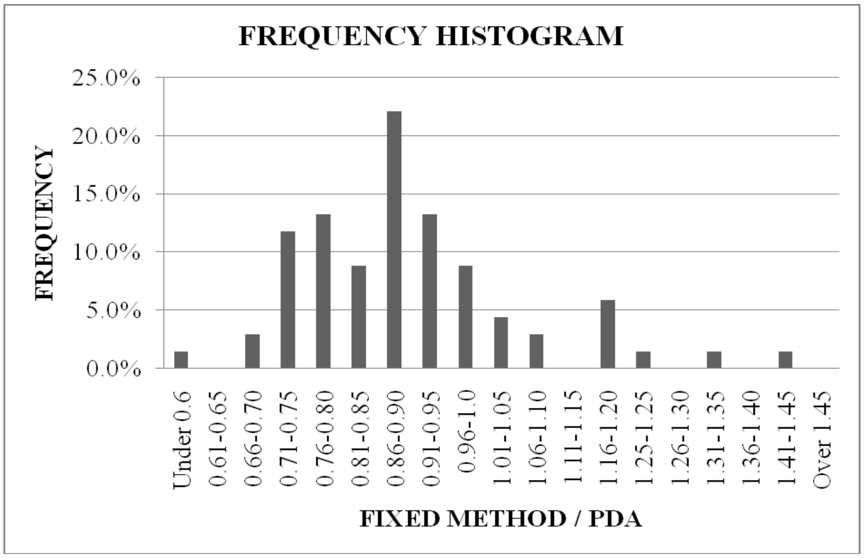

Figure 1. Fixed Method/PDA Static Capacity Frequency Histogram

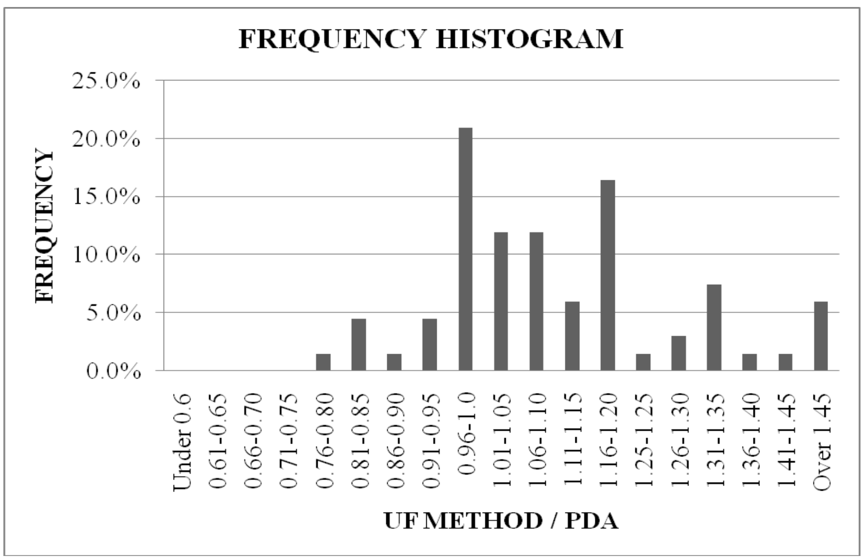

Figure 2. UF Method/PDA Static Capacity Frequency Histogram

In general, qualitative analysis of stress predictions between the two systems indicates, an acceptable correlation exists with the exception of compressive stress at the pile bottom, where significant discrepancies have been observed with EDC reporting noticeably smaller magnitudes of stress. FDOT funded research on force and velocity wave propagation currently being conducted at the UF is anticipated to shed light on actual stress levels after impact and provide additional data for comparison with both PDA and EDC predictions**.**

Comparison of CAPWAP and EDC Predictions

As with PDA-EDC data, only data points that fell within the range covered by three standard deviations from the mean was used in the analysis. The geotechnical engineers managing test pile programs during construction generally perform

CAPWAP analyses on high capacity blows near the end of drive. Additional CAPWAP analyses were subsequently performed on various blows from the drive by in-house or consultant engineers, to obtain a comparison that is not limited to high blow count conditions. Table 4 and Figures 2 and 3 summarize the findings.

Table 4. EDC/CAPWAP Ratio of Static Capacity (n = 60 blows from 40 piles)

Parameter	Total Resistance Fixed/CW	Total Resistance UF/CW	Skin Friction Fixed/CW	Skin Friction UF/CW	End Bearing Fixed/CW	End Bearing UF/CW
% n	98.3	98.3	98.3	96.7	98.3	100
Mean (μ)	0.98	1.08	0.63	1.55	1.20	1.04
Std. Deviation	0.22	0.18	0.63	1.14	0.54	0.37
COV	0.22	0.17	1.00	0.74	0.45	0.36

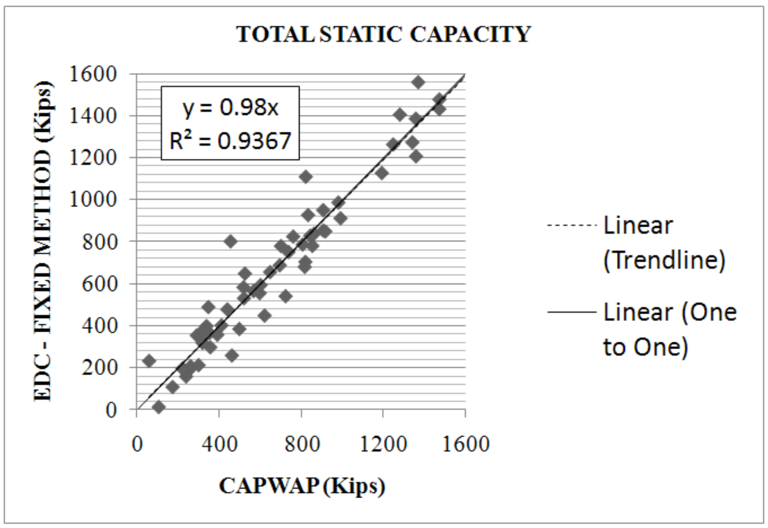

Figure 3. Fixed Method/CAPWAP Total Static Capacity Predictions

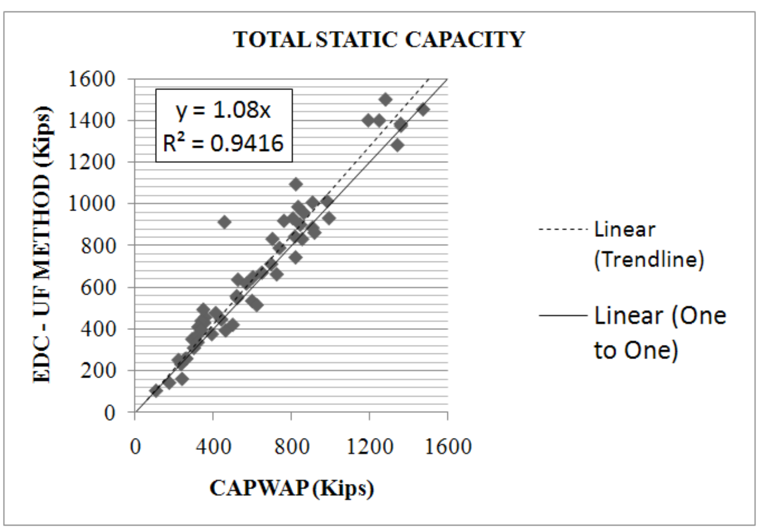

Figure 4. UF Method/CAPWAP Total Static Capacity Predictions

SUMMARY

The results obtained thus far in Phase I indicate that EDC provides total static resistance estimates that are comparable to PDA predictions, with COV values below 0.3 for the Fixed and UF methods. Comparisons to CAPWAP estimates also indicate total static resistance predictions by EDC are similar to CAPWAP with minor variation as indicated by COV values under 0.25. EDC distribution of resistance, namely end bearing and skin friction estimates for the methods investigated, are not always in close agreement with CAPWAP. The differences may be attributed to the proficiency of CAPWAP operators, the calculation approach used by the UF method or possibly due to differences in signal processing between PDA and EDC for the Fixed method, since the calculation method is reportedly the same. Discrepancies in reported stress levels during driving are still to be resolved. Current research efforts at UF are anticipated to provide further insight into the matter.

CONCLUSIONS

The evaluation program thus far has revealed that the EDC methods investigated provide results that are on average within 15 percent of PDA and CAPWAP estimates of total static resistance. An ongoing wave propagation research study will provide additional data points with which to gauge EDC's accuracy of predictions. EDC's theoretical ability to compute a new damping factor for every hammer blow and provide revised estimates of static resistance in real time, is considered a major potential advancement in dynamic load testing.

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