Measurement of Stress Waves in EDC Piles

FDOT Contract No. BD545, RPWO #86
UF Project 00069606

Submitted to:
Peter Lai, P.E.
David Horhota, PhD, P.E.
Project Managers
Florida Department of Transportation
Tallahassee

Submitted by:
David Bloomquist, PhD, P.E.
Michael McVay, PhD

Department of Civil Engineering
365 Weil Hall
PO Box 116580
Gainesville, Fl 32611

Florida Department of Transportation

January 1, 2009

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the author and not necessarily those of the State of Florida Department of Transportation.

SI (MODERN METRIC) CONVERSION FACTORS (from FHWA)

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle ***Measurement of Stress Waves in EDC Piles***		5. Report Date December 2008	
		6. Performing Organization Code	
7. Author(s) David Bloomquist, PhD, PE		8. Performing Organization Report No.	
9. Performing Organization Name and Address: Department of Civil and Coastal Engineering 365 Weil Hall University of Florida Gainesville, Florida 32611-6580		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. BD-545, RPWO #86	
12. Sponsoring Agency Name and Address: Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report 10/03/07 - 1/1/09	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract A simultaneous sampling Data Acquisition system was designed and installed on an EDC (embedded data collector) pile to capture external strain and acceleration data during impact. Preliminary data reduction was performed and the results show that the system has performed as intended. Subsequent analyses (via a follow-up project) will be performed These data will then compared to the internal instrumentation currently used for pile capacity determination to validate its operational accuracy.			
17. Key Words Instrumentation, Accelerometers, Strain Gages, Instrumented Pile		18. Distribution Statement No restrictions.	
19. Security Classif. (of this report) Unclassified.	20. Security Classif. (of this page) Unclassified.	21. No. of Pages 38	22. Price N/A

EXECUTIVE SUMMARY

Based on conversations with various parties, it appears that anomalous stress/strain data is being generated while driving an EDC (Embedded Data Collector) Pile. For example, the lower internal accelerometer has shown higher accelerations at the pile tip compared to the top sensors when driving in rock. This is contrary to wave/particle propagation theory. Since this anomaly cannot be explained theoretically, it is therefore important to conduct several test scenarios to see if this is the actual case or else it is spurious pile response data.

The relevancy of this effort is based on the fact that FDOT is contemplating replacing existing precast piles with this new type of pile in a majority of projects. Without confidence in the data collected and subsequent load capacity analysis, using these "Instrumented piles" will not utilize their intrinsic capabilities. Hence, the necessity of validating the data was the primary objective of the research effort.

Objectives

In order to understand and quantify the wave response along a pile, a two prong approach was formulated. The first is to purchase the necessary instrumentation to conduct a series of tests on the internally instrumented EDC pile using external sensors in conjunction with the internal sensors. These data will then be analyzed to see if a rational explanation can be found as to what is producing the inconsistent results. This is the objective of this Proposal. However, the generated data will then be provided to Dr. Michael McVay, who will analyze the resulting wave motion as well as create an FEM model of the soil/pile interaction phenomena.

The first phase, i.e., data collection equipment, was completed by purchasing a variety of strain gages, piezo accelerometers and a portable data acquisition system. The system was configured such that simultaneous collection of sensor data was possible. This allows for precise measurement of arrival times between sensor locations and hence velocities. In addition, procedures for attaching them were investigated so that correct amplitudes would result.

The second phase consisted of attaching the various devices to concrete cylinders, impacting them and noting their operational characteristics. After numerous tests, they were then attached to the pile and the resulting data acquired during impact.
Several types of impact testing were performed.

1. **Free End**. Typically, prior to driving, a pile is tested while on the ground to ensure that all sensors are working correctly. This was completed and some resulting waveforms are provided in the report. A simultaneous high speed sampling logger (8 channels at 50 MS/s) was used and provided excellent results. Since it is a simultaneous capture of data, the resulting wave can be accurately observed as it travels down and back along the pile. The 16 bit A/D converter could resolve the strain to 5 microstrain and accelerations to 0.5 g.

Variables that will be considered by Dr. McVay in his subsequent analysis include:
   Assessment of particle velocity and force within the pile
   Accelerometer/strain gage location
   Energy imparted to the pile
   Wave motion up and wave motion down assessment within the pile

It is expected that a downward traveling compression wave will be reflected with a doubling of the tip velocity and a canceling of compression stresses with an upward traveling tension wave of similar magnitude.

2. **Rigid End**. Once the above tests were completed, the pile was inserted into a compacted bed of soil and the tests redone. These series of tests were performed in lieu of a proposed "field" test outlined in the proposal. It was decided by the PIs that driving the pile in unknown soil conditions might introduce spurious data that could not be explained. Hence, a uniform soil was used for embedment material as well as to rigidly support it at its tip. In this case, it was expected that the downward traveling compression wave would have a doubling of compressive stresses at the pile tip along with zero velocities

due to an upward traveling compression wave. These two types of tests "bounded" the problem, since in actuality, a pile driven in soil falls between these two conditions.

In conclusion, the purpose of this research project was to:
A. Identify instrumentation needed to monitor impact loading of an EDC pile. This includes the recognition and acquisition of the needed equipment components, staff equipment training, and the refinement of the data acquisition work plan.
B. Purchase the various components and install them on the pile.
C. Position and mount the EDC pile into the horizontal support system - constructed on site, as well as arranging of the needed peripherals, such as the driving hammer and backstop.
D. Conduct a Fast Fourier Transform analysis on the Tracer DAQ Pro data acquisition results. This was performed in order to generate a spectral inventory of the stress waves encountered in the pile.

Based on the preliminary results, the project objectives were met, excellent data was captured and will be used in a subsequent analysis by Dr. McVay.

TABLE OF CONTENTS

LIST OF FIGURES

The following is an overview of the tests performed
with accompanying photos showing the test set-up.

PROJECT SCOPE OVERVIEW

This project focused on instrumentation analysis of one Smart Structures Incorporated, EDC pile. In general, the EDC pile is a pre-stressed 18" × 18" concrete pile that has been outfitted with embedded strain gages and accelerometers at six locations along the pile's neutral axis. The purpose for these sensors is to provide the engineer with improved bearing capacity and pile stress estimates each time the pile is struck by the driving hammer. The primary objective of this project was to compare the data collected from these transducers with externally mounted sensors (accelerometers and strain gages) via two complementary and independent data acquisition systems.
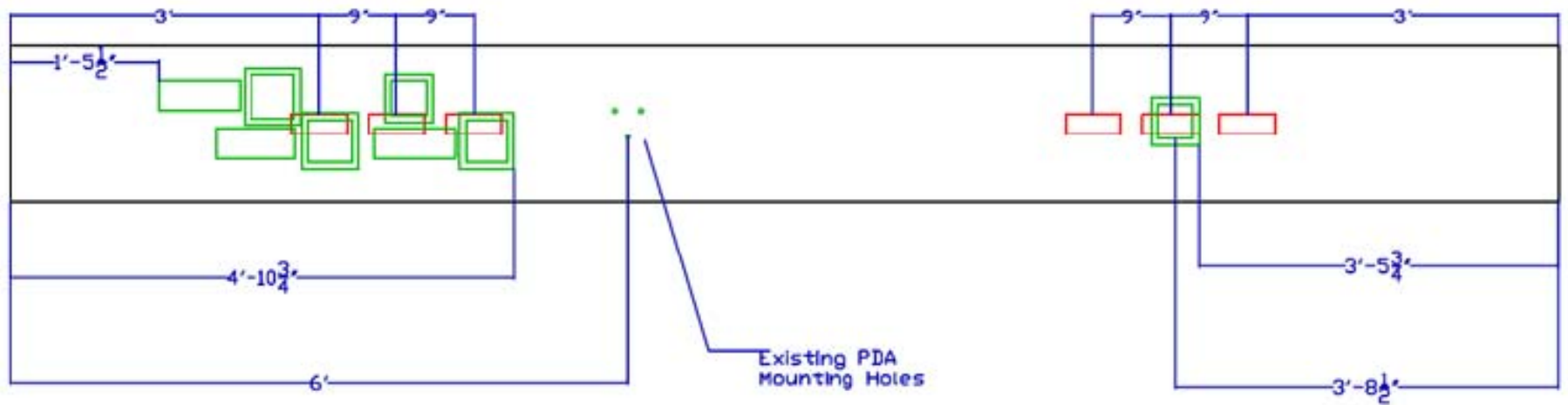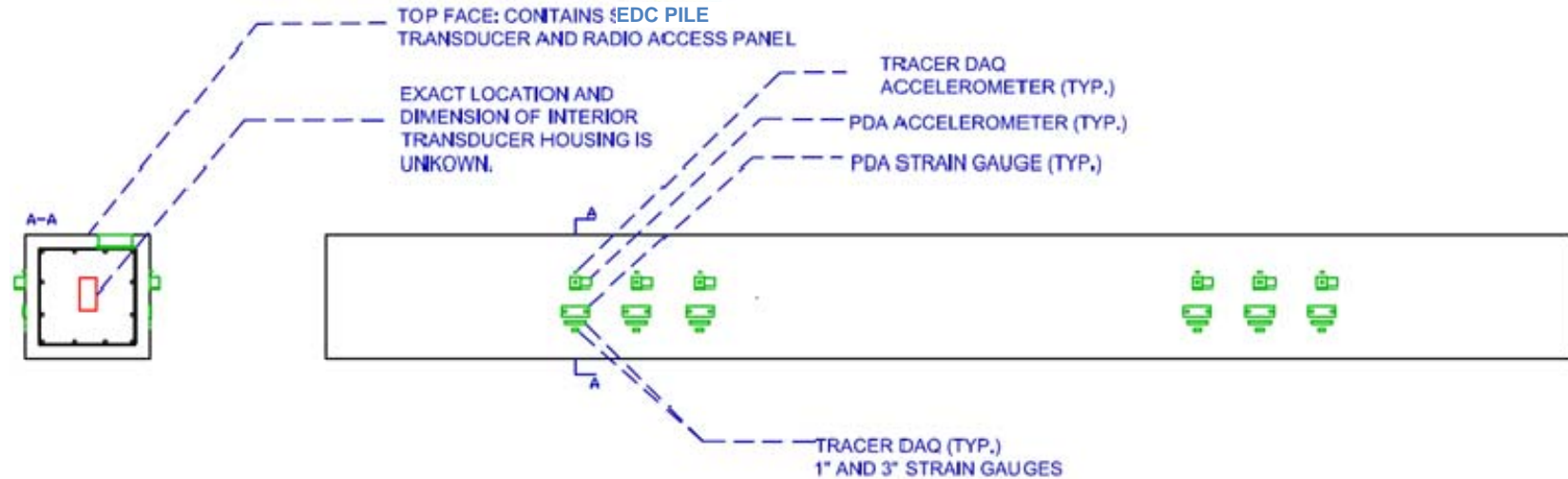
Figure 1. The EDC pile instrumentation layout. The green surface mounted panels provide access to the EDC pile raw data output as well as the pile's wireless data transmitters. The red boxes indicate the approximate location of the embedded transducers.

TOP FACE: CONTAINS EDC PILE TRANSDUCER AND RADIO ACCESS PANEL

EXACT LOCATION AND DIMENSION OF INTERIOR TRANSDUCER HOUSING IS UNKOWN.

TRACER DAQ ACCELEROMETER (TYP.)

PDA ACCELEROMETER (TYP.)

PDA STRAIN GAUGE (TYP.)

A-A

TRACER DAQ (TYP.) 1" AND 3" STRAIN GAUGES

NOTES:

THIS MOUNTING PATTERN REPRESENTS THE EXTERNAL INSTRUMENTATION LAYOUT THAT WILL BE ADDED ON BOTH SIDE FACES OF THE PILE. THE TOP FACE, AS NOTED ON THE CROSS SECTION A-A, CONTAINS THE ACCESS PANELS FOR THE INTERNAL SMARTPILE TRANSDUCER AND RADIO EQUIPMENT.

EACH TRANSDUCER GROUPING SHOWN ABOVE IS POSITIONED ON THE EXPECTED CENTER LINE OF THE INTERIOR SMARTPILE TRANSDUCERS. THE POSITION OF THE FIRST SET OF INTERNAL TRANSDUCERS IS EXPECTED TO BE 36" ON CENTER FROM THE PILE TOP, WITH THE SECOND AND THIRD SET EACH SPACED 9" ON CENTER FOLLOWING THE FIRST SET. THIS SPACING SCHEME IS ALSO EXPECTED FOR THE PILE TIP WHERE THE LOWEST TRANSDUCER PAIR IS 36" ON CENTER FROM THE PILE TIP.

BOTH EXTERNAL DATA AQUISITION SYSTEMS ARE CAPABLE OF COLLECTING DATA FROM 8 CHANNELS AT ONCE. SINCE IT WILL REQUIRE 4 EXTERNAL CHANNELS TO MONITOR ONE INTERNAL TRANSDUCER LOCATION THE EXTERNAL TRANSDUCERS WILL BE ADJACENTLY MOUNTED TO ONLY TWO OF THE SIX INTERNAL LOCATIONS AT ANY ONE TIME. THE DATA COLLECTION PROTOCOL WILL THEN CALL FOR THE INTERMITTENT RELOCATION OF THE EXTERNAL TRANSDUCERS IN ORDER TO COLLECT DATA AT ALL SIX EDC PILE TRANSDUCER LOCATIONS.

Figure 2. A side view and cross section of the EDC pile showing the layout of the independent, external transducers and their relative position to the interior EDC pile transducers.

DATA ACQUISITION SYSTEMS

Tracer DAQ Pro

Since it is critical to measure the stress wave's speed and amplitude as it transverses the length of the pile, a data acquisition system that could provide simultaneous wave capture was deemed important. After an extensive search, the Tracer DAQ Pro Data Acquisition System was chosen. It provides eight channels of simultaneous data collection which is then minimally processed and stored via a window's based control program. In addition, shown in the photo below, the system consists of the transducers (currently, accelerometers mounted to a concrete cylinder), the data acquisition board and individual power supplies, and a portable computer.
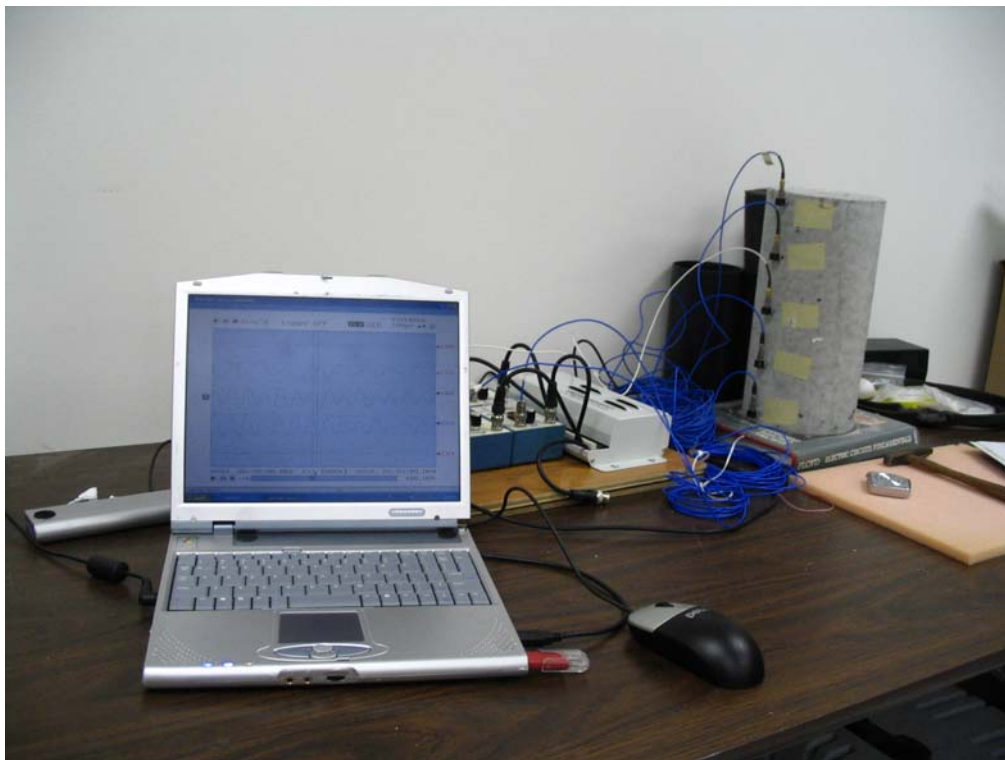

Figure 3. The Tracer DAQ Pro data acquisition system.

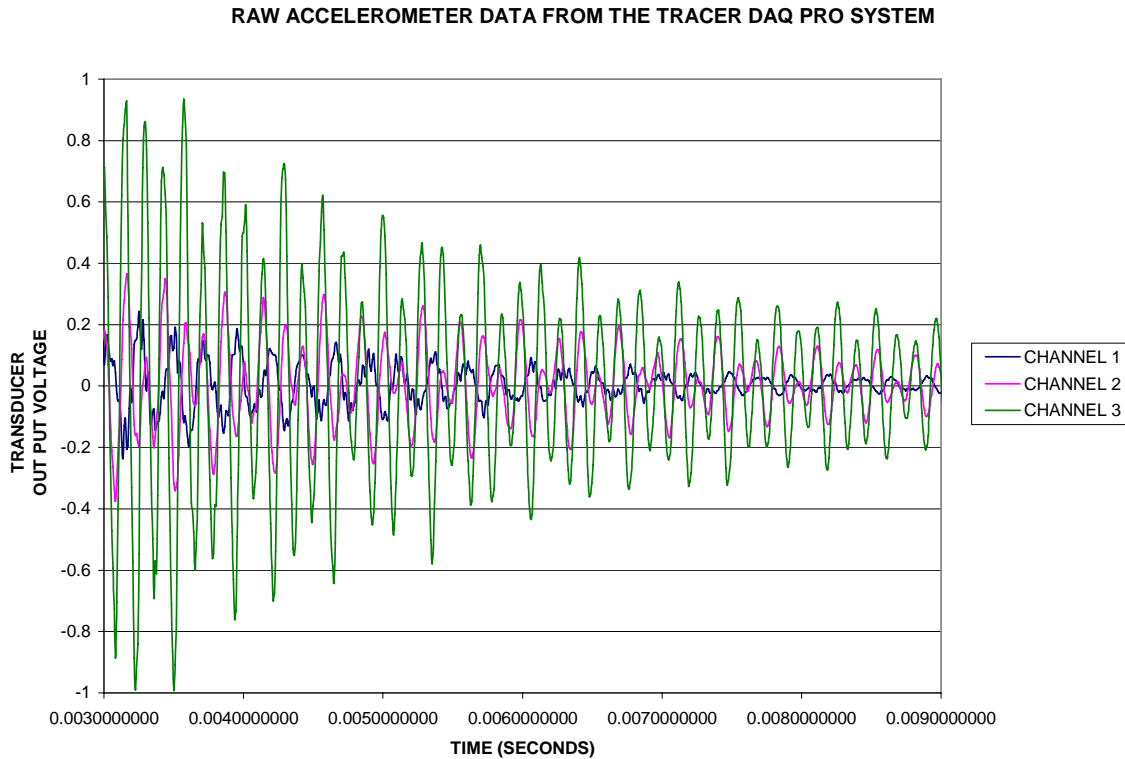**RAW ACCELEROMETER DATA FROM THE TRACER DAQ PRO SYSTEM**

Figure 4. A graphical example of the data collected from the small test cylinder shown in Figure 3 by Tracer DAQ Pro. Here only 3 channels are shown.

Pile Dynamics Inc. Pile Driving Analyzer

Like the Tracer DAQ Pro system, the Pile Driving Analyzer (PDA) by Pile Dynamics Inc (see Figure 5), includes 8 channels for data collection. Unlike the Tracer DAQ Pro system, it is specifically designed for collecting stress waves from piles during the driving process. The system has a higher degree of pre-processing which makes the data easier to interpret by the worker in the field. Specifically, the PDA uses raw strain gauge and accelerometer data to calculate both the velocity and force associated with the stress waves passing the point where the transducers are attached to the pile.

In addition, the project team constructed a testing station which consists of a horizontally suspended 6" × 6" × 8' concrete beam which approximated the free-end conditions of the full scale data acquisition trials (see Figure 6).

Figure 5. A Pile Dynamics Incorporated pile driving analyzer. Not shown are the reusable heavy-duty transducers and connection cables.

Figure 6. The PDA testing station of a horizontally suspended 6"×6"×8' concrete beam.

PHYSICAL TEST SET-UP

The data collected for this project was generated by stress waves induced in the horizontally suspended EDC pile. By laterally suspending the pile and letting it swing freely, a zero external resistance condition is created.

In order to achieve these conditions, metal stands capable of supporting the 5,000 pound EDC pile were fabricated. In addition, a driving hammer weighing approximately 1,500 pounds was also constructed.   The hammer was suspended as a pendulum from the laboratory's large heavy duty forklift (see Figures 7-9).

Figure 7. The EDC pile.

Figure 8. One of two stands constructed to support the horizontally suspended pile.

Figure 9. The heavy-duty forklift at University of Florida's Coastal Engineering Laboratory.

FORK LIFT

GREEN BOXES DENOTE GENERAL
LOCATIONS OF TRANSDUCERS
FOR THE INDEPENDENT DATA
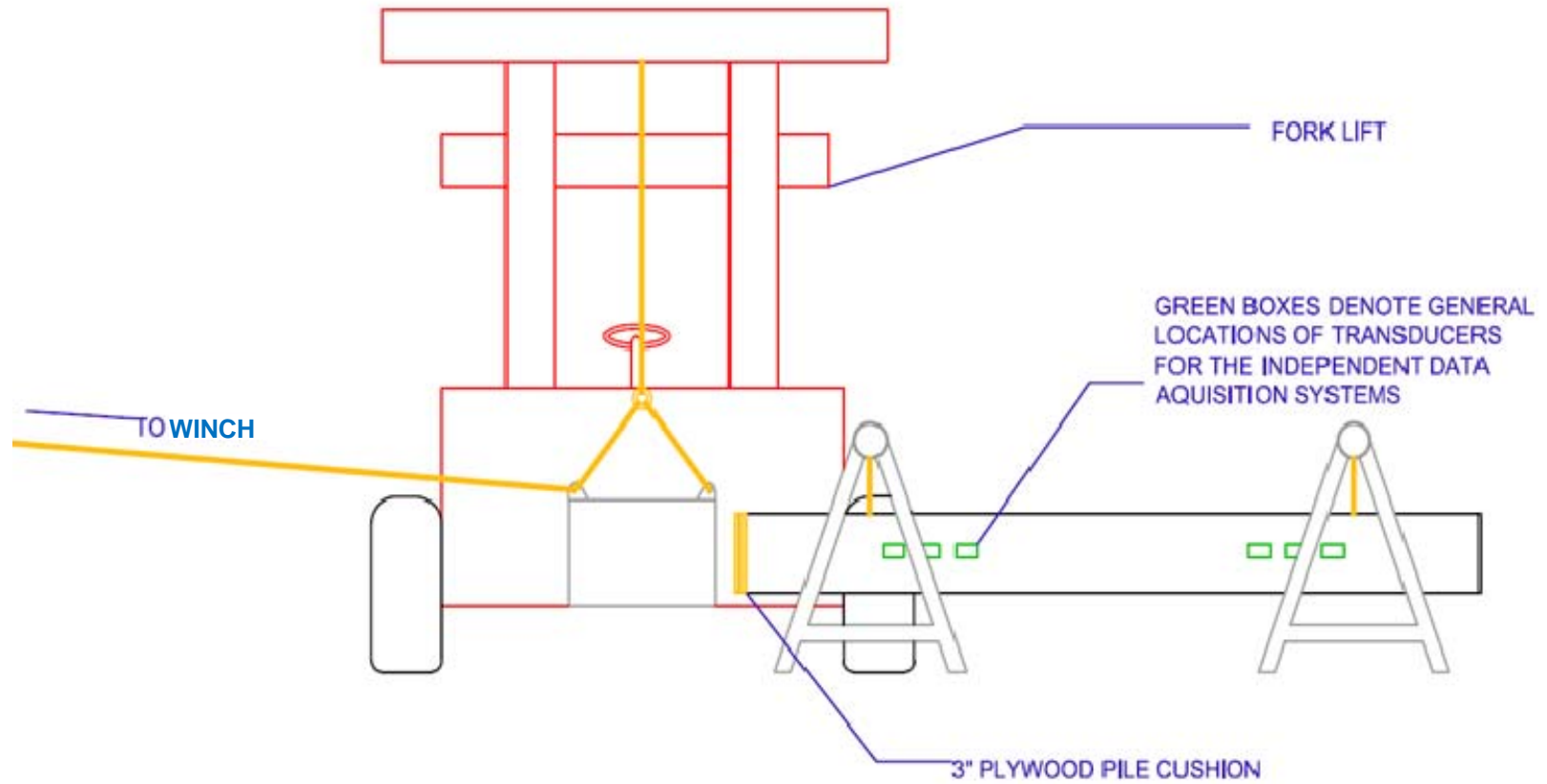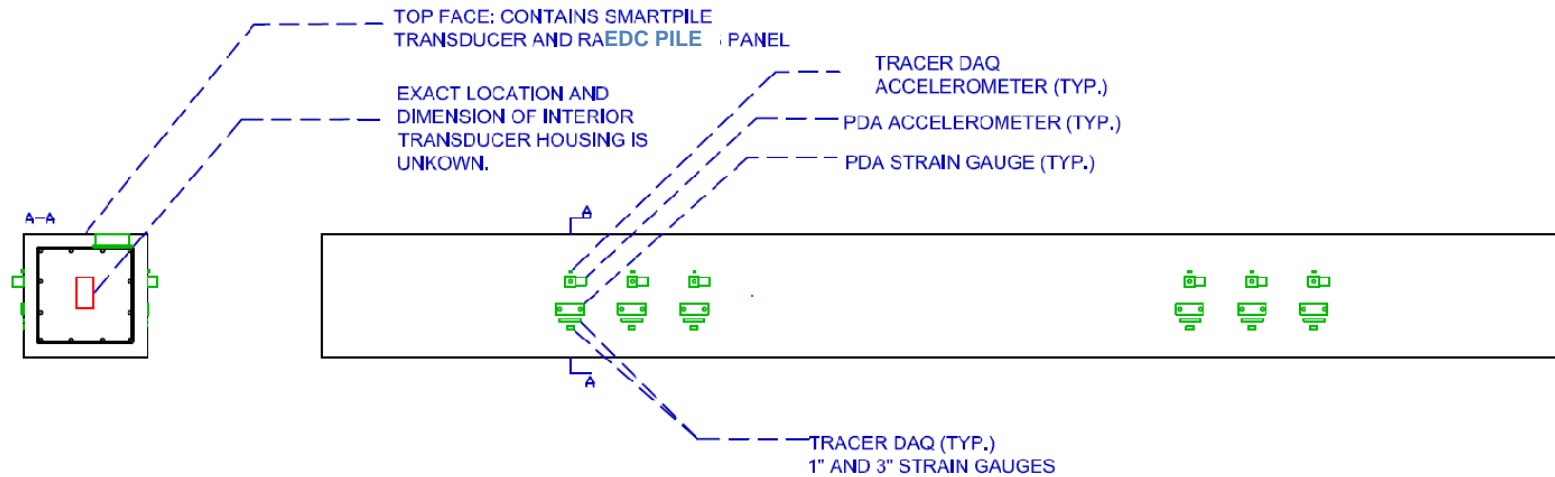AQUISITION SYSTEMS

TO WINCH

3" PLYWOOD PILE CUSHION

Figure 10. A diagram of the data acquisition layout. Shown above is the horizontally suspended EDC pile along with the pendulum-mounted impact hammer.

The research activities consisted of: 1) collecting the strain and acceleration data in both in the lab and "field" and transferring the data into excel sheets, filtering it for noise and surface waves; 3) reconstructing the wave down and wave up stresses in the pile at both the top and bottom of the pile; and 4) comparing the raw, and reduced strain, acceleration, and wave forces/stresses from PDA, EDC and UF data acquisition system. A discussion of each follows.

COMPARISON OF RAW DATA

Shown in Figure 11 is the layout of the instrumentation which includes: 1) EDC pile strain and accelerometers cast within the top and bottom of the pile, 2) PDA strain and accelerometers attached to the outside of the pile at the top and bottom; and 3) UF strain and accelerometers attached next to the PDA instruments. The PDA used piezo-resistance gages at the top of the pile and piezo-electric gages at the bottom of the pile. The UF strain gages were obtained from micro measurements and were attached to the pile through epoxy. The UF accelerometers were 500 g piezo-resistive gages obtained from the PCB Corporation. The eight gages (4 strain & 4 accelerometer at top and bottom) were read by a USB 1608 HS-2AO 8 channel, 16 bit, simultaneous 250,000 samples/channel/sec data acquisition system (DAQ).

For the impact testing, a special 1,000 lb hammer was constructed from a 2 ft ID × 3 ft long × ½" thick steel pipe filled with concrete. To prevent damage to the pile during impact, a 3" plywood cushion was placed between the hammer and the pile, Figure 12.

TOP FACE: CONTAINS SMARTPILE
TRANSDUCER AND RA **EDC PILE** PANEL

EXACT LOCATION AND
DIMENSION OF INTERIOR
TRANSDUCER HOUSING IS
UNKOWN.

TRACER DAQ
ACCELEROMETER (TYP.)

PDA ACCELEROMETER (TYP.)

PDA STRAIN GAUGE (TYP.)

A—A

A

A

TRACER DAQ (TYP.)
1" AND 3" STRAIN GAUGES

NOTES:

THIS MOUNTING PATTERN REPRESENTS THE EXTERNAL INSTRUMENTATION
LAYOUT THAT WILL BE ADDED ON BOTH SIDE FACES OF THE PILE. THE TOP FACE,
AS NOTED ON THE CROSS SECTION A-A, CONTAINS THE ACCESS PANELS FOR
THE INTERNAL SMARTPILE TRANSDUCER AND RADIO EQUIPMENT.

EACH TRANSDUCER GROUPING SHOWN ABOVE IS POSITIONED ON THE EXPECTED
CENTER LINE OF THE INTERIOR SMARTPILE TRANSDUCERS. THE POSITION OF
THE FIRST SET OF INTERNAL TRANSDUCERS IS EXPECTED TO BE 36" ON CENTER
FROM THE PILE TOP, WITH THE SECOND AND THIRD SET EACH SPACED 9" ON
CENTER FOLLOWING THE FIRST SET. THIS SPACING SCHEME IS ALSO EXPECTED
FOR THE PILE TIP WHERE THE LOWEST TRANSDUCER PAIR IS 36" ON CENTER
FROM THE PILE TIP.

BOTH EXTERNAL DATA AQUISITION SYSTEMS ARE CAPABLE OF COLLECTING DATA
FROM 8 CHANNELS AT ONCE. SINCE IT WILL REQUIRE 4 EXTERNAL CHANNELS TO
MONITOR ONE INTERNAL TRANSDUCER LOCATION THE EXTERNAL TRANSDUCERS
WILL BE ADJACENTLY MOUNTED TO ONLY TWO OF THE SIX INTERNAL LOCATIONS
AT ANY ONE TIME. THE DATA COLLECTION PROTOCOL WILL THEN CALL FOR THE
INTERMITTENT RELOCATION OF THE EXTERNAL TRANSDUCERS IN ORDER TO
COLLECT DATA AT ALL SIX **EDC PILE** TRANSDUCER LOCATIONS.

Figure 11. A side view and cross section of the EDC pile showing the layout of the independent, external transducers and their relative position to the interior EDC pile transducers.

FORK LIFT

GREEN BOXES DENOTE GENERAL
LOCATIONS OF TRANSDUCERS
FOR THE INDEPENDENT DATA
AQUISITION SYSTEMS

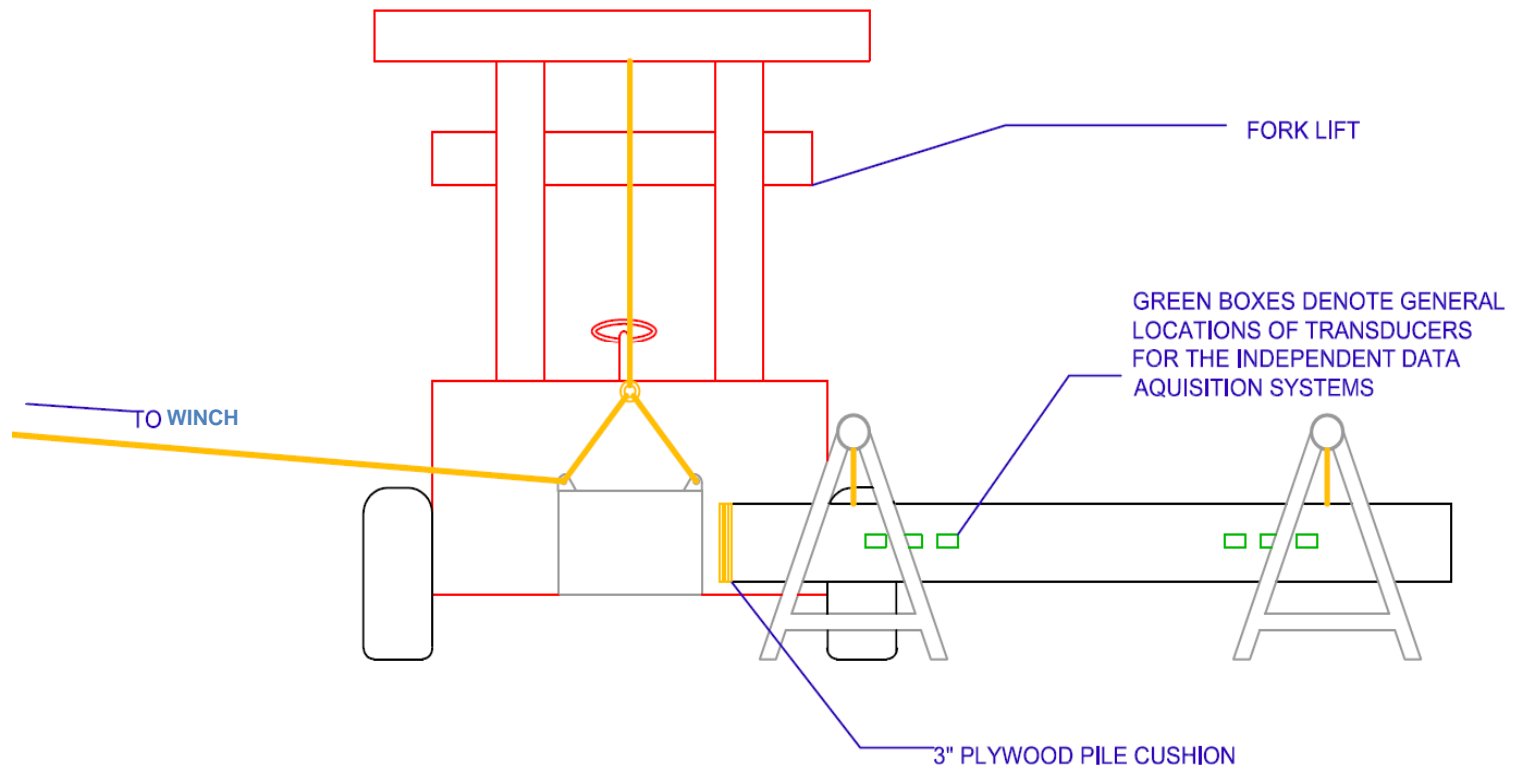TO WINCH

3" PLYWOOD PILE CUSHION

Figure 12. A 1,000-lb hammer striking the 15 ft EDC pile – Three to five foot drop heights.

For each blow, the hammer was pulled back to a specified vertical elevation (e.g., 3 ft or 4 ft), the hammer released and the instrumentation triggered.

Shown in Figures 13 and 14 are the raw data from the accelerometers (top of pile) and the strain gages (bottom of pile) from a 4 foot "drop height" hammer blow. In the case of the acceleration data, the period of the signals were approximately 0.0017 sec [2 × (15 ft – 3 ft)/14000 ft/sec] corresponding to the time for transmission of compression wave from top to the bottom of the pile and back. Also evident from the acceleration traces is the good comparison of particle motions between both sides of the pile. However not expected was the high frequency particle motion observed in the DAQ data. The DAQ system recorded particle motion 50 times faster than the other two systems. The latter high frequency motion is assumed to be attributed to lower wavelength surface waves (i.e., Rayleigh waves) which have elliptic particle motion which dampen out quickly. Also, it should be noted that the PDA trace has been integrated (velocity) within the PDA hardware (analog filter) and subsequently differentiated to obtain accelerations.

Shown in Figure 14 are measured strains at the tip of the pile for the accelerations shown in Figure 13. Evident from the figure the strains on both sides of the pile are not equal (e.g., PDA red vs. orange values) as observed with accelerations. However, the strains on both sides of the pile do exhibit the same periods and when averaged will compare favorably to the centerline values recorded by EDC pile. Also of interest is the reduction in high frequency surface waves observed in acceleration data. Evidently, the elliptic particle motions (i.e., accelerations) do not necessarily generate strains.
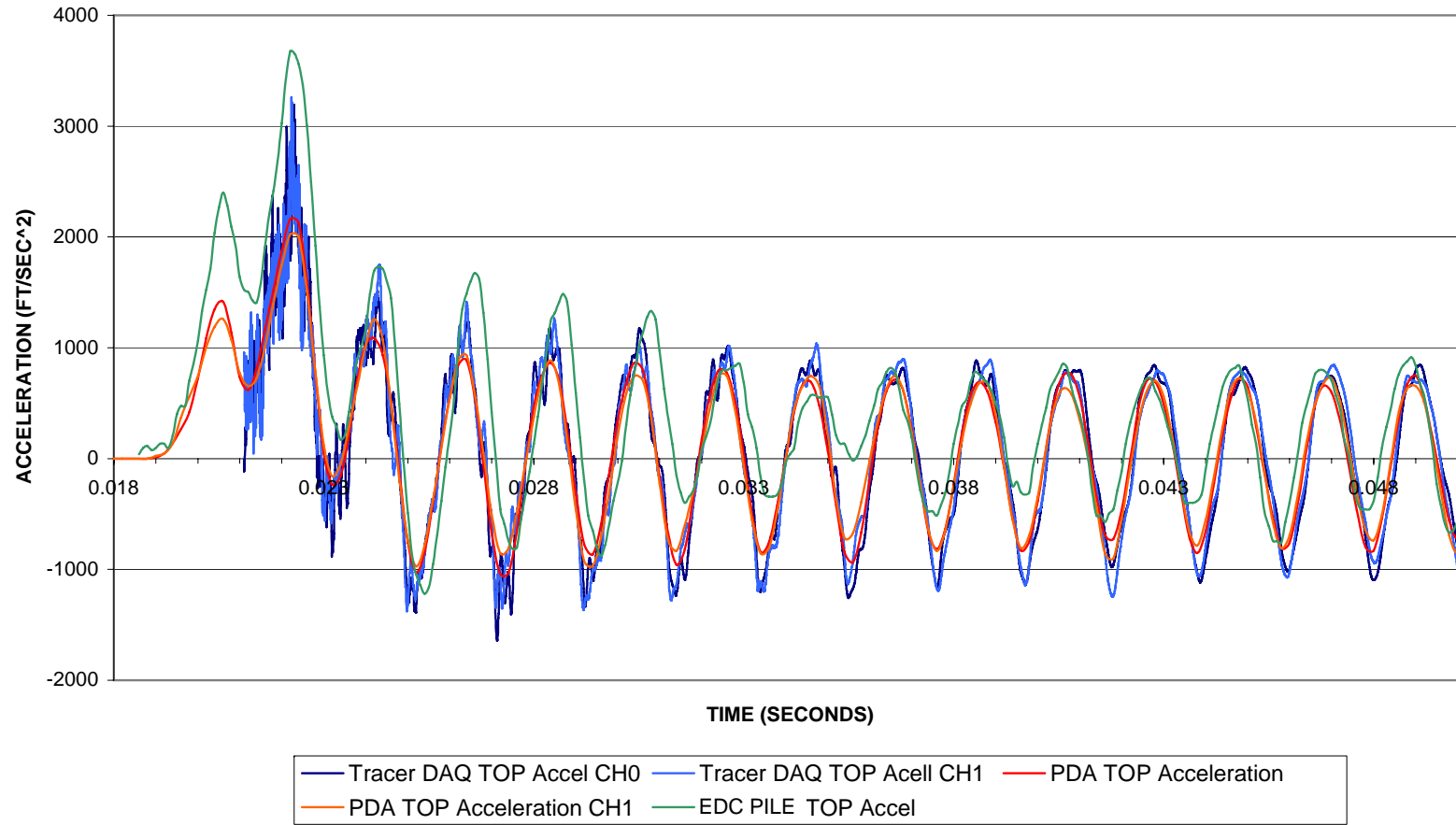
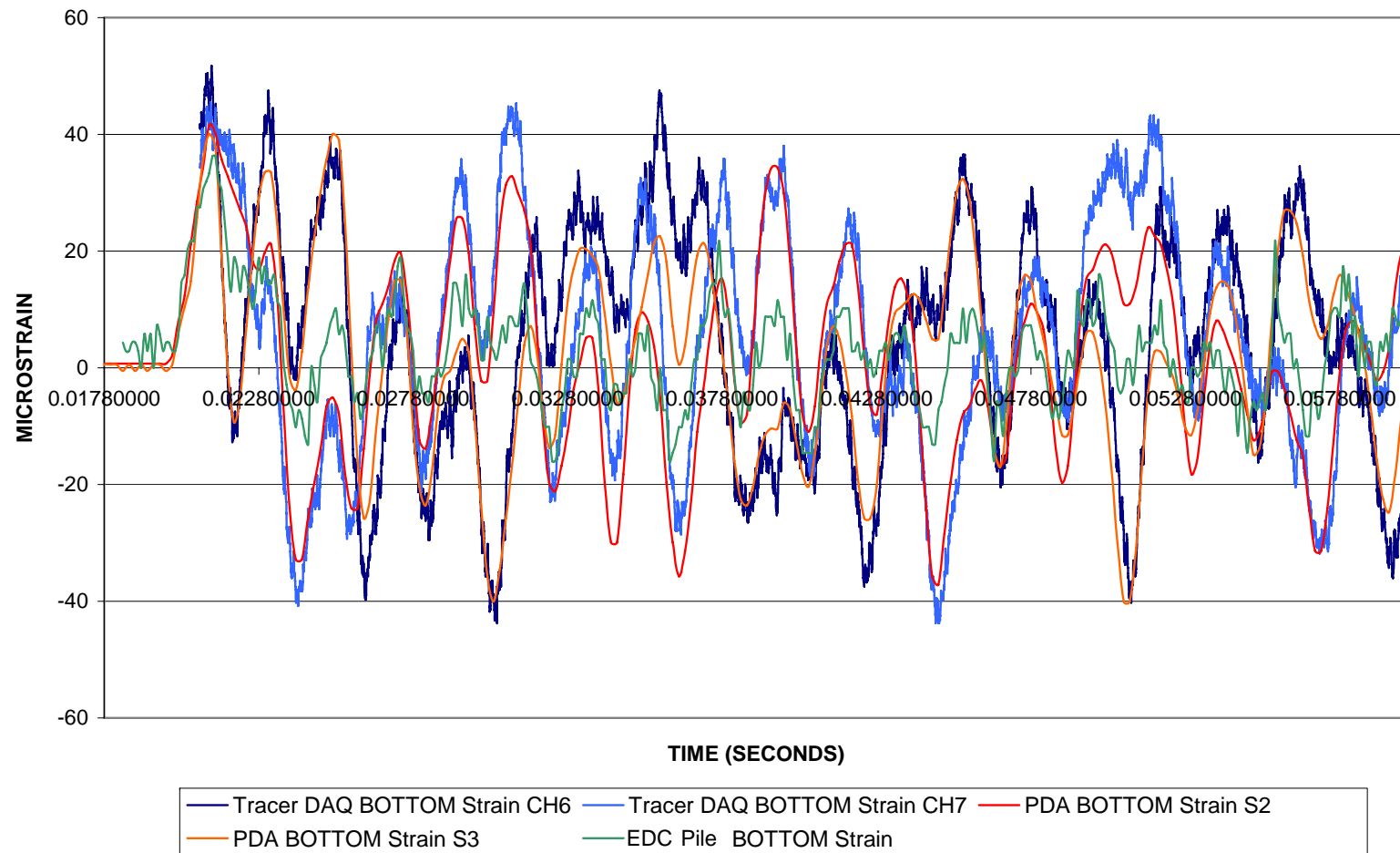Figure 13. Raw acceleration from PDA, EDC pile, and UF DAQ at top of pile.

Figure 14. Raw strain data from PDA, EDC pile, and UF DAQ at bottom of pile.

FILTERING THE RAW DATA

Since the focus of the research is the assessment of stresses at a point (i.e., tip), as well as the propagation of stresses along the pile, the estimation of particle velocities from accelerations are critical. The PDA data is already filtered (i.e., analog filter), EDC pile software offers both filtered and unfiltered data, whereas the Tracer DAQ was only available unfiltered. Consequently, the Tracer DAQ and EDC pile data was filtered using Fast Fourier Transform as discussed.

Fourier Analysis Background

In general, a *Fourier Transform* provides the means of transforming a signal defined in the time domain into one defined in the frequency domain. In the case where both the time and the frequency variables are discrete (i.e., data acquisition, e.g., samples/sec), the process is referred to discrete Fourier transform, DFT. Let $x(nT)$ represent the discrete time signal, and let $X(mF)$ represent the discrete frequency transform function. The forward transform to frequency domain given by

$$X(mF) = \sum_n x(nT) e^{-inm2\pi FT} \qquad \text{Eq. 1}$$

And the inverse transform to the time domain is given

$$x(nT) = \frac{1}{N} \sum_m X(mF) e^{inm2\pi FT} \qquad \text{Eq. 2}$$

Where T = time increment

F = frequency

There are several ways to calculate the Discrete Fourier Transform (DFT), a typical approach is the Fast Fourier Transform (FFT) available in Microsoft Excel spreadsheets. Shown in Figure 15 is the DFT (Eq. 1) for one of the Trace DAQ acceleration signals. The x axis identifies the frequency within the data signal and the y axis gives the amplitude of the specific frequency.
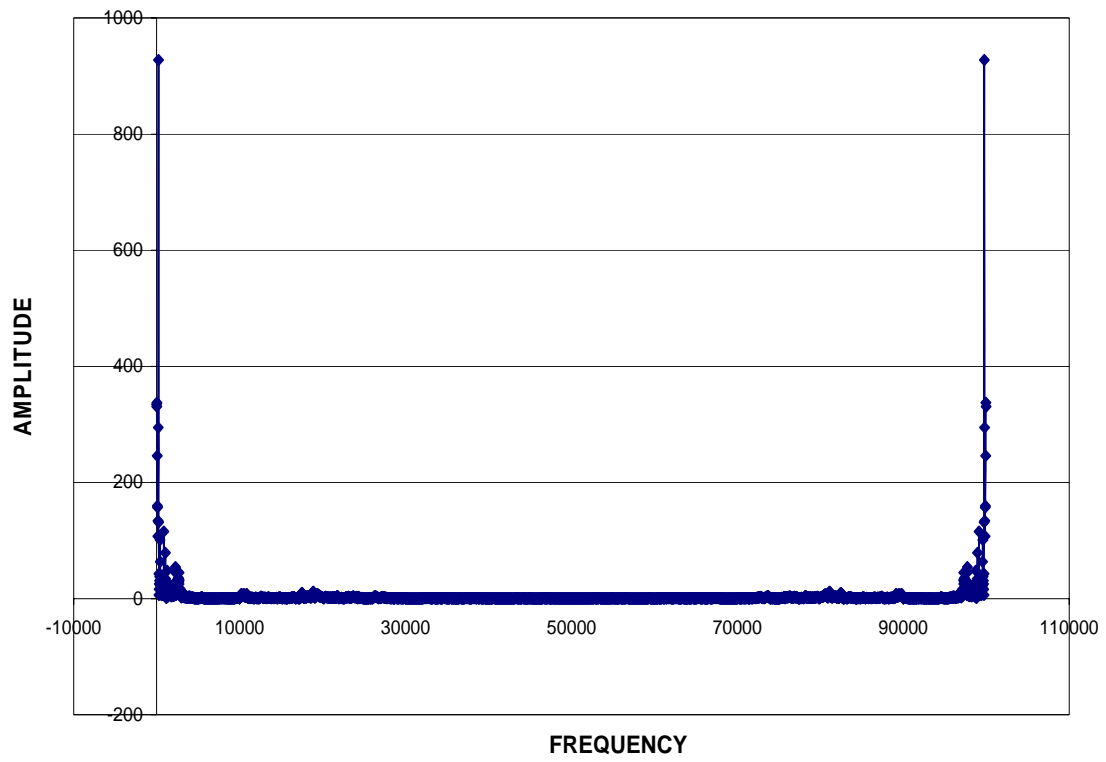
Figure 15. Frequency and amplitude content of Tracer DAQ acceleration record.

Figure 16. Impact hammer ready for release.

17

Figure 17. Pile imbedded in compacted soil.

Figure 18. End restraining blocks.

Figure 19. Close-up of pile imbedded in compacted soil.

Figure 20. Zoned compacted soil.

Figure 21. Pile imbedded in compacted soil and instrumentation set-up.

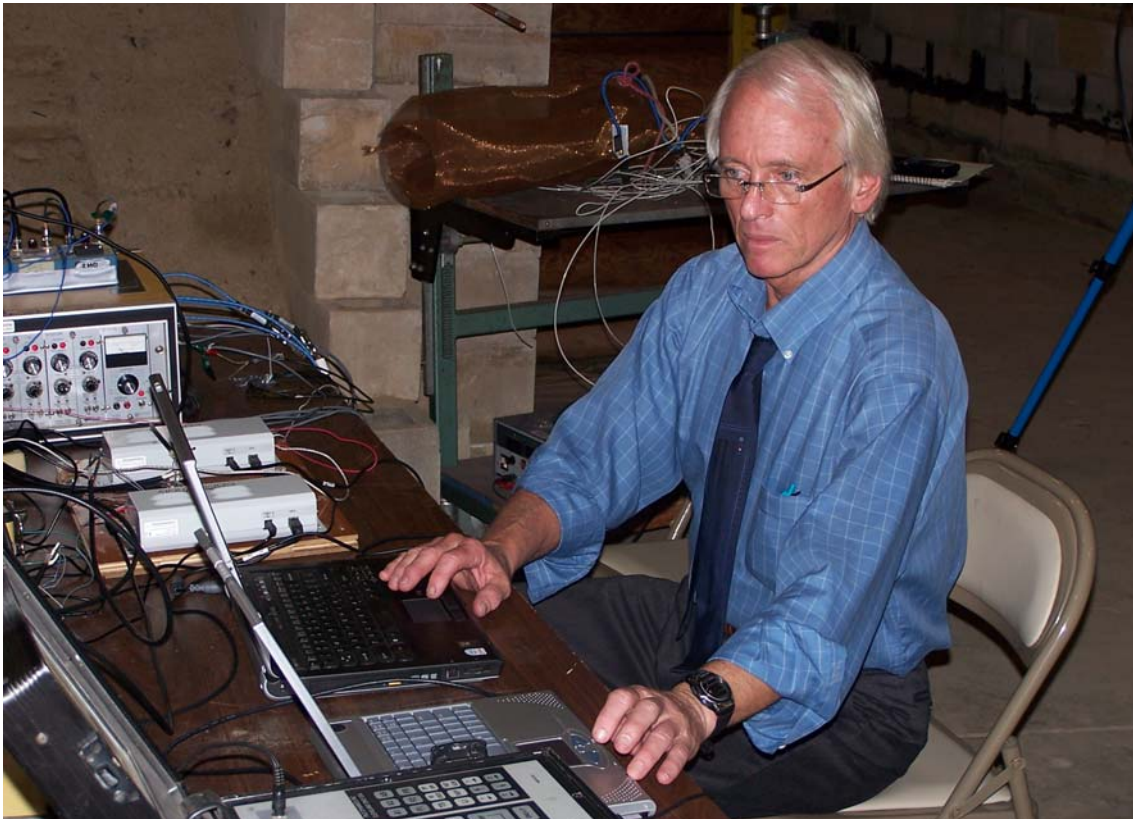Figure 22. Pile imbedded in compacted soil with attached sensors.

Figure 23. EDC pile wireless data collection set-up.

Figure 24. Co-PI running data acquisition system.

Figure 25. Pile impact hammer prior to release.

Fourier Analysis Process

Using the Excel sheet filtering, all the DAQ and EDC pile acceleration traces were filtered to eliminate frequencies higher than 1kHz. This threshold was used since all relevant wave velocities (and hence periods) were lower. For instance, shown in Figures 26 and 27 are top acceleration signals from the top left and right side gages. Evident from the plots, the surface waves identified in the raw DAQ systems were definitely filtered (<1000 Hz) out. Also shown in each plot are the signals filtered with the EDC pile software, as well as the FFT method.

The rationale for setting the filter threshold of 1kHz (or 1kS/s - kilosamples per second) was computed as follows.
Since the roundtrip travel time after impact for the 30 foot long pile was 11,000 feet per second, the period for one cycle would be 60/11,000 or 0.005 seconds. Any time increments smaller than this (or conversely higher frequencies) simply complicates the analysis. For example, through a FFT analysis, the raw unfiltered data showed high surface wave harmonics at approximately 680 Hz. These are artifacts of the spectral response to impact and not of the generated particle and pressure waves of interest. Thus, the cutoff frequency was set slightly above the 680 Hz.

Similar to the top of the pile, the acceleration data at the bottom of the pile was filtered for the DAQ and EDC pile systems as shown in Figures 28 and 29. As expected, the bottom raw DAQ data showed lower surface wave acceleration at the pile tip. Also, the filtered EDC signals had different initial amplitudes than the FFT filtered results. All of the measured gages gave very similar frequency of primary signal.

Shown in Figures 30 and 31 are the average top and bottom acceleration signals from the PDA, and Tracer DAQ compared to the EDC pile signals located at the center of the pile cross-section. Again all had similar frequency content, with slightly different signal amplitudes. The latter signals will be used in generating the up and down waves traveling within the pile.
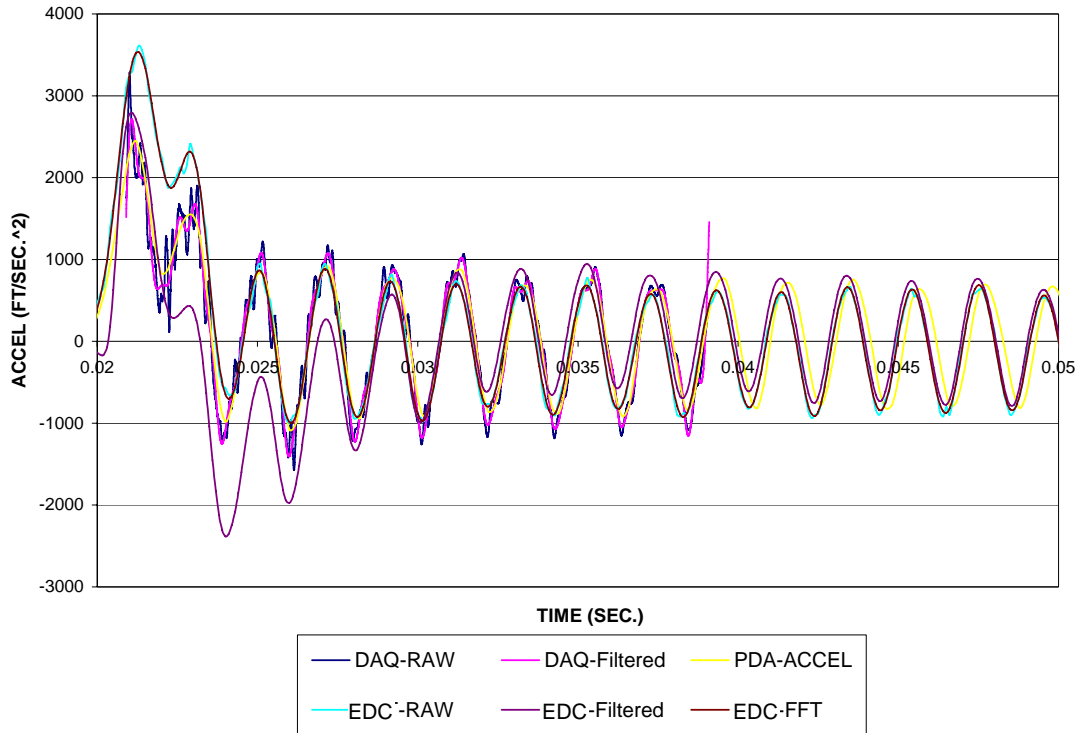
Figure 26. Filtered and unfiltered data from top accelerometer (left side of pile).
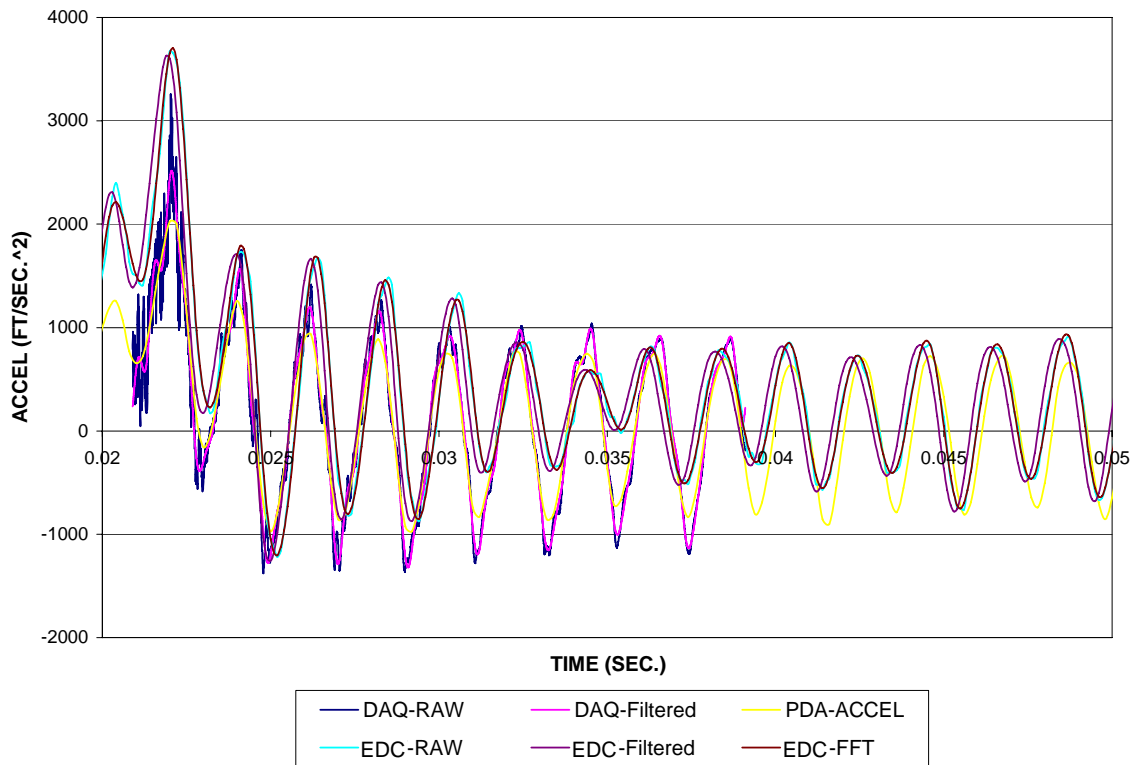

Figure 27. Filtered and unfiltered data from top accelerometer (right side of pile).
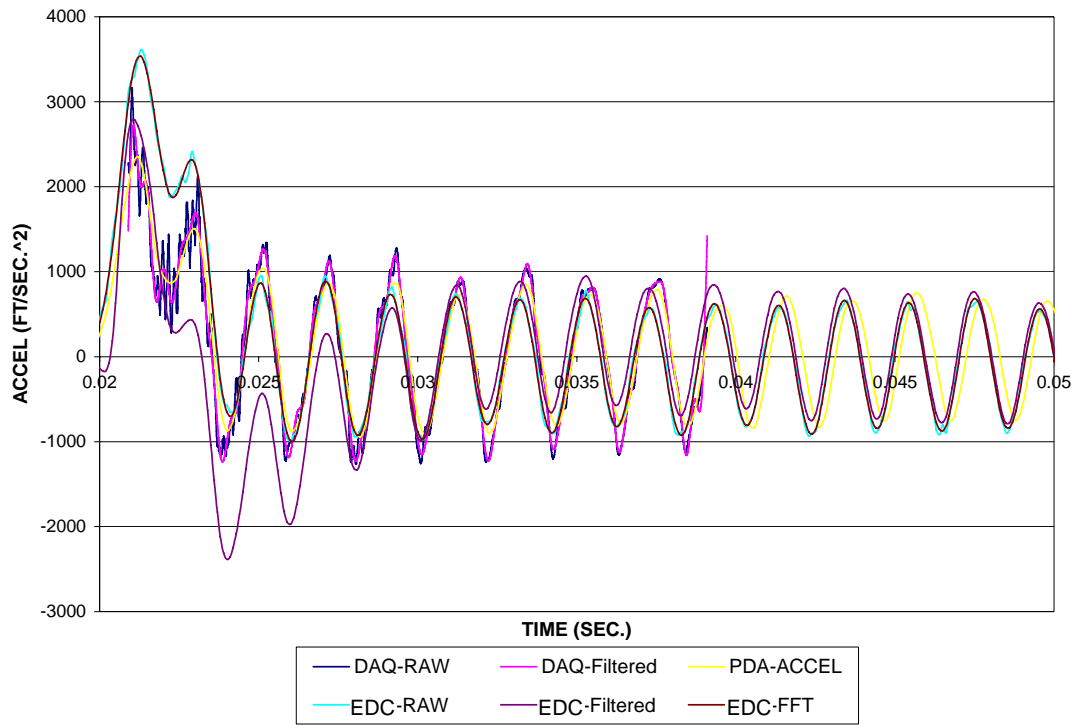
Figure 28. Filtered and unfiltered data from bottom accelerometer (left side of pile).
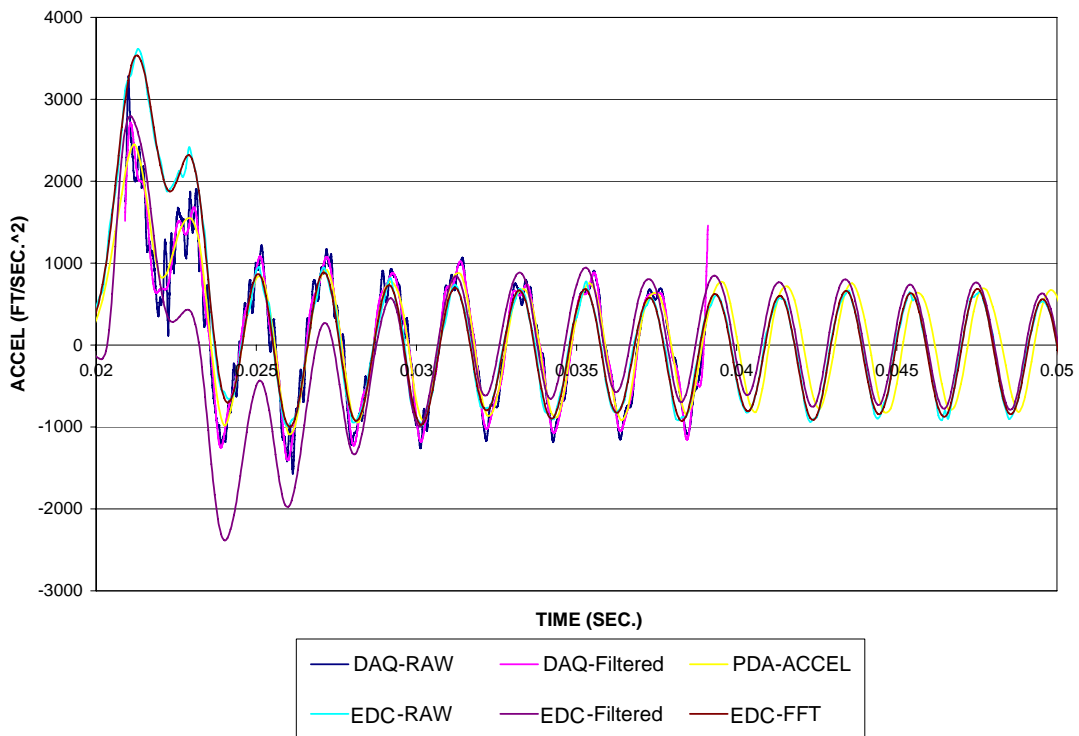

Figure 29. Filtered and unfiltered data from bottom accelerometer (right side of pile).
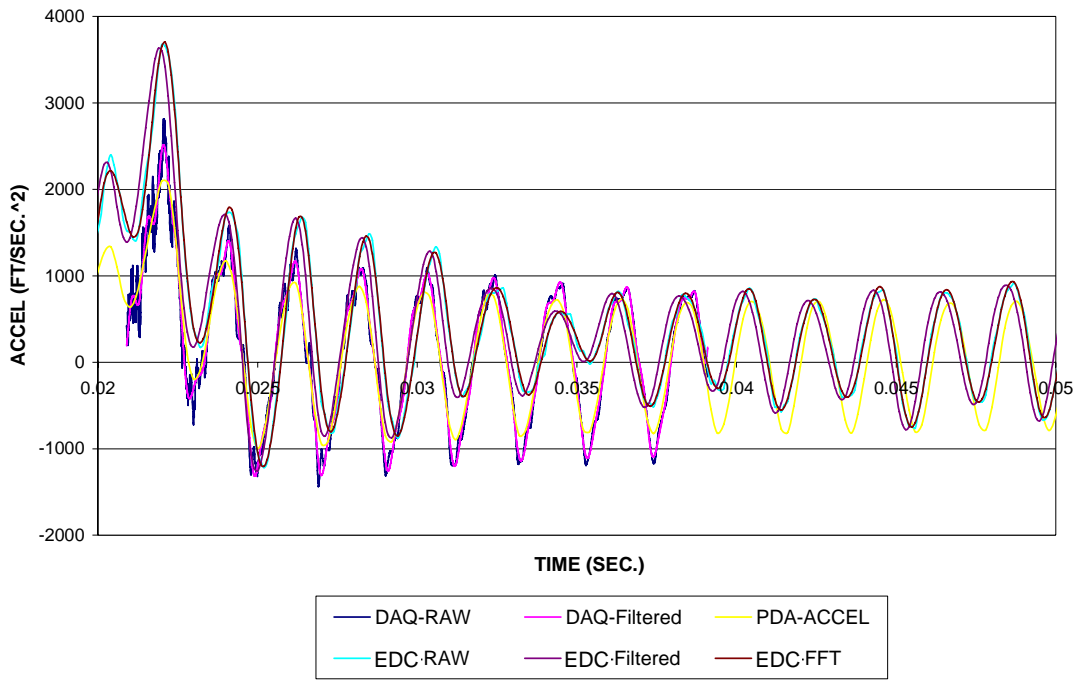
Figure 30. Average filtered and unfiltered acceleration data from top of pile.
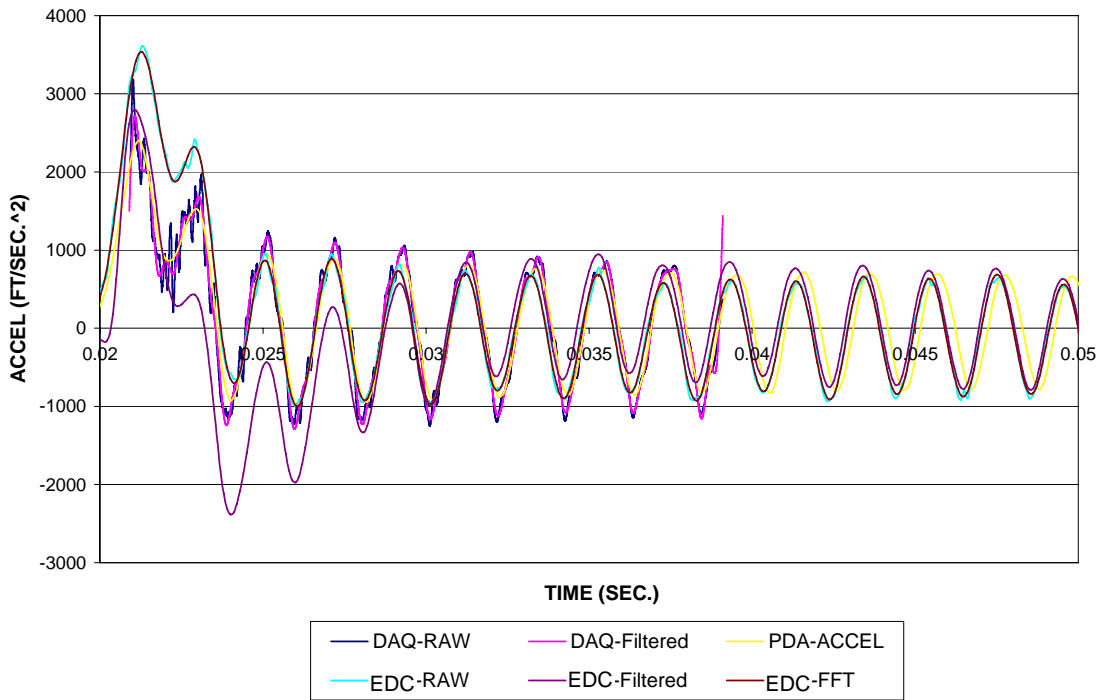

Figure 31. Average filtered and unfiltered acceleration data from bottom of the pile.

While the objective of this research project was to investigate, purchase, install and test a variety of sensors on an impacted EDC pile, the next phase is to analyze the resulting data. However, based on the test results, the project objectives were clearly met and the Project was a complete success.

The attached Appendices provide the reader with the operational specs sheets for the purchased instrumentation.