SMART PILE

SmartPile Review Key Calculations

Summary Overview

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Introduction

Through sensors embedded in the pile, the SmartPIle® system obtains accurate information on stress levels in a concrete pile from the moment it is cast. This provides the system with the unique ability to measure residual stresses during installation and provide an accurate assessment of the true conditions in the pile. Multiple embedded sensors also collect accurate wave speed measurements, allowing a higher level of pile integrity monitoring. Consequently, accurate dynamic data on the shaft friction and tip resistance is available, so that an estimate of the ultimate static resistance (i.e. capacity of the pile) can be made. To enhance safety and ease of use, its patented design allows monitoring and recording of data from up to 500 feet from the pile, with no wires to connect. Powerful PC-based software generates DOT-formatted reports, provides multi-user access with password control, and allows data review from both current as well as past projects.

The system provides the user with the following benefits:

- It provides for a high level of confidence in achieving the required driving resistance
- It eliminates PDA installation pile preparation time at jobsite
- It eliminates climbing leads at the job site for gauge installation
- It provides constant monitoring of pile driving energy
- It records pile driving data history
- Instrumentation is calibrated before every installation
- It measures pile pre-stress and driving stresses (i.e, tip stresses, residual stresses, total stresses) and pile tip resistance
- It provides for high levels of pile integrity monitoring
- It provides for an efficient means for monitoring pile re-strikes
- Instrumented piles require no special handling by the contractor
- It provides additional features for pile manufacturing and installation quality control

This document provides an overview of the key transformations of Embedded Data Collector (EDC) sensor data to critical installation capacity and integrity reporting.

Contents

Common Units and Key Constants (Transformations)

The following are the units common to the calculations performed by the software:

Value	English	SI
Input Parameters		
Modulus of Elasticity	(5000) ksi	40000 MPa
Concrete Specific Weight	(.150) kips/ft^3 KIPS = 1000lbs	24 kN/m^3
Wave Speed (c) (both calculated and entered)	(13200) ft/sec	(4000) m/sec
Length, (of Pile, below top gages), Pile Marker Increment, etc.	Feet	meters
Cross Sectional Area (of Pile)	in^2	cm^2
Computed Values		
Maximum Compression	Ksi	MPa
Maximum Tension	Ksi	MPa
Maximum Energy	Ksi-ft	kN-m
Capacity (Force)	Kips	kN
Velocity	f/s	m/s
2L/c	msec	msec
Displacement	feet	meters

The following conversion factors are also applied to move from English to SI Unit:

Quantity		To Convert	To	Multiply by
Length / Displacement		Inches (in)	Meters (m)	0.0254
Length / Displacement		Feet (ft)	Meters (m)	0.3048
(Cross-Sectional) Area		Inches^2	Meters^2	6.45x10-4
(Cross-Sectional) Area		Feet^2	Meters^2	.0929
Volume		Feet^3	Meters^3	.028
Volume		Inches^3	Mm^3	16387

Quantity		To Convert	To	Multiply by
Mass		Pounds (lbm)	Kilograms (kg)	0.4536
Mass		Kilograms	Pounds (lb)	2.2046
Mass Density		Pounds/foot^3 [lbm/ft3]	Kilograms/meter^3[kg/m^3]	16.02
Wave Speed		Feet/sec	Meters/sec	.3048
Force		Pounds (lb)	Newtons (N)	4.448
Force		Kips (1000 lb)	Kilo Newtons (N)	4.448
Force per Unit Area (e.g. Compression, Tension, Pressure, Modulus of Elasticity)		Kips/ft^2	kPa	47.88
Force per Unit Area (e.g. Compression, Tension, Pressure, Modulus of Elasticity)		PSI (Pounds per Square Inch) pounds/in^2	Pascal (Pa)	6894
Force per Unit Area (e.g. Compression, Tension, Pressure, Modulus of Elasticity)		KSI (Kips per Square Inch) kips/in^2	MegaPascal (MPa)	6.894
Force per Unit Volume (e.g. Concrete Specific Weight)		Kips/Foot^3	kN/Meter^3	157.1
Energy		Foot-Pounds (lb-ft)	Netwon-Meters (N-m)	1.356
Energy		Foot-Pounds (ft-lbf)	Joules (J)	1.356
Energy		Foot-Kips (ft-kips)	Kilo Joules	1.356
Damping		Seconds / Feet	Seconds / Meter	3.2808
Blow Count		Blows/Foot	Blows / Meter	3.2808
		Tonne (1000 Kg). The METRIC unit of force. NOT to be confused with the English TON		
		G = 9.80665 m/s^2, 32.1741 ft/s^2		

Data Transformation

1 **Combined Session Configuration and Sensor Data**

SmartPile® Review Drive Capacity and Integrity reporting is the result of combining Embedded Data Collector (EDC) Sensor data with Pile Configuration details (Geometry, sensor locations, fixed wave speed, etc.) with the calculations presented in this document.

To generate a Pile Driving Report, the sensor data from the EDC (organized as samples/blows on the hard drive) are converted to Accel and Strain data associated with the Top, Tip or other (Mid) location in the pile. Each blow is individually processed, using a blow index based on either the data coming live into the system, or located on the hard drive.

When all blow data is processed, the Drive is considered complete and a pile drive report can be generated.

Raw Blow Data (Quantizations 12 bit AtoD Data)

- Directly from EDC through Acquisition (Live), 10 KSamples/sec
- From Files on the Hard Drive (.bdf)

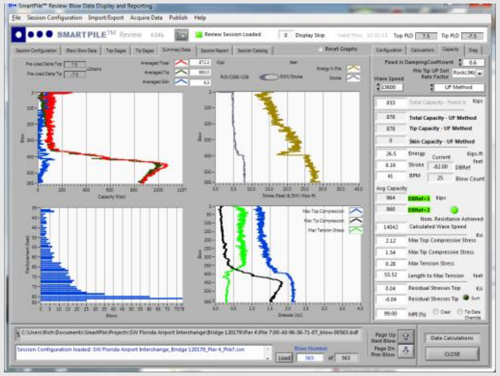
Session Configuration File (.ssn)

- User, Project, Location
- Pile Configuration (Diameter, Length, Sensor Placement)
- Calibration / Transformation Details
- Filtering / Processing Algorithm switches

Catalog Index built from found blow files

- RadioID-Blowxxx.bdf
- From Blow 1 → N

Blow Distribution, Pile Capacity and Integrity



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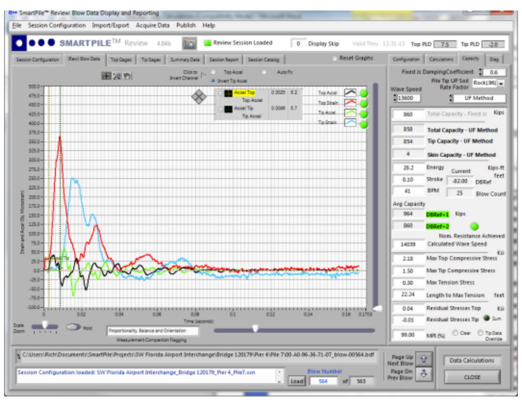
High Level Signal Processing

The Sensor data that is collected by the EDC consists of Digital Quantizations collected as samples based on a collection trigger (hammer impact). The sample data, typically 160 milliseconds at 10Ksamples/second are stored along with the sensor calibration data, timestamp, radio id, user input displacement, and radio diagnostics.

No transformations are made to this data when collected through SmartPile Acquisition. It is in SmartPile Review that these sensor Quantizations are converted to raw Strain and Acceleration using the calibration data in the session configuration and sample (blow).

The Raw Data is zero offset and filtered prior to being transformed to Force, Velocity, and Displacement. This filtered and offset is the foundation of all downstream calculations and is displayed in the Raw Data Tab of SmartPile® Review (below).



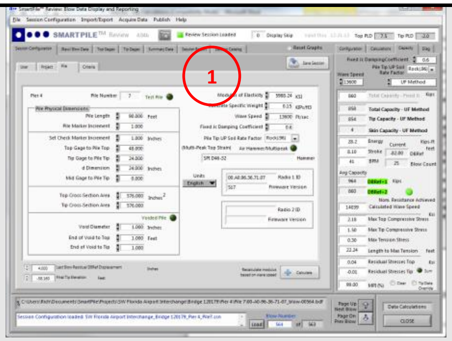
- Raw Data (Quantizations)
- Transformation (to Gs and uStrains)
  - Uses calibration data from the EDC
  - Embedded in each blow, in the session configuration
  - Based on the Radio ID (Unique)
- Mean Offset Adjust (Zero Set)
  - Looking at beginning or end of the buffer and selective mean determination
  - Varies by sensor type and location
- Filtering
  - IIR Butterworth, Low and High Pass
  - Applied to each channel based on channel configuration (Session Configuration)
- Strain to Force (E x Ɛ x A)
- Accel to Velocity, Displacement, Z(EA/c)Velocity, WaveUp, WaveDN
- Key Time points (T1, T2, 2L/C) (peak detect, basic calculations)
  - Based on User entered Wave Speed (Pile Configuration)
- Capacities, Jc, Tip-Skin Ratio
- Key Calculations (Stresses)
  - Compressive Stresses, Tension, MPI
- User input Displacements during data collection (Pile Drive) generates Blow Distribution
  - Display Updates based on Blow Count/Number and/or User input Displacement

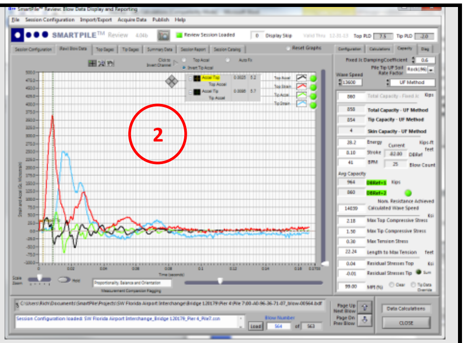
3

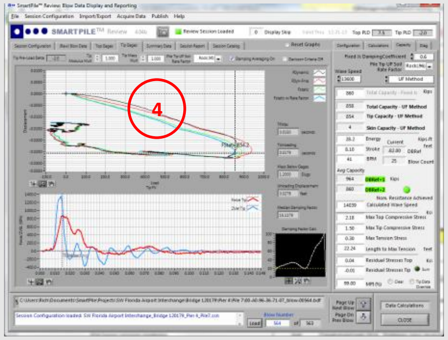
SmartPile Review tabs and Data Transformations

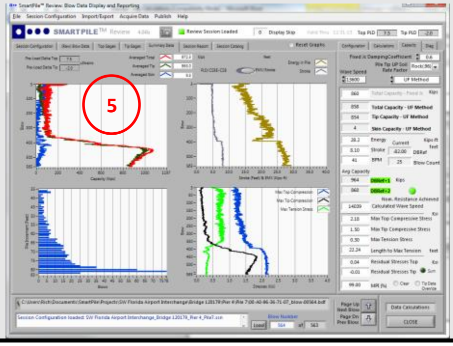
SmartPile Review was organized to logically present the data transformations and key time points that ultimately produce the capacity and integrity data presented in the Summary Tab:

1. The Session Configuration tab Details the Pile Configuration
2. The Raw Data Displays the Filtered and Offset Accelerometer and Strain Data used for the Top and Tip Calculations
3. The Top Gages tab displays the transformed Top Acceleration and Strain in terms of Force and ZVelocity, Wave Up and Wave Down. Key Time constants (in the form of display cursors are provided on the relevant displays)
4. The Tip Gages tab displays the Transformed Tip Acceleration and Strain in terms of Force and ZVelocity and Load versus Displacement. Key Time constants (in the form of display cursors are provided on the relevant displays)
5. The Summary Displays the Capacity Calculations (based on Top Wave Up/Wave Down, Tip Capacity), Energy/Stroke, User Input Displacement









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Raw Data

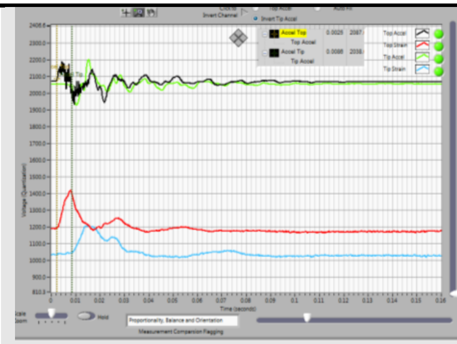
The Quantization Transformation includes converting the 12 Bit AtoD data to Raw Acceleration and Strain, then applying Polarity Adjustments (tip Accelerometer), (Noise) Filtering, and a Zero (Mean) Offset. This produces the Dynamic Strain and Acceleration data that is used for downstream transformations.

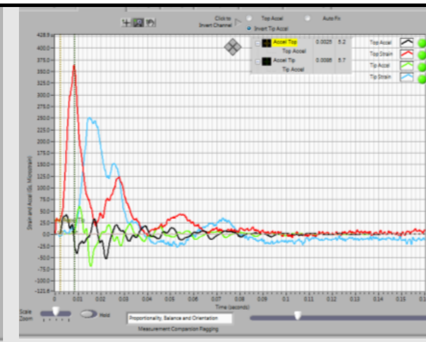
The transformations performed will be based on the sensor identifier:

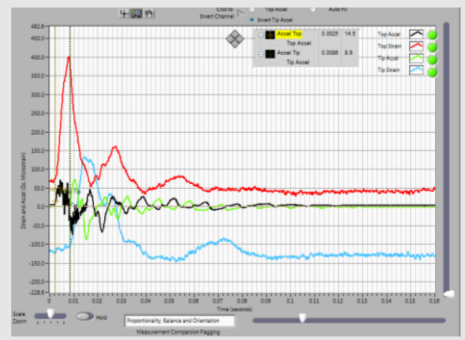
1. Top Accelerometer
2. Top Strain
3. Tip Accelerometer
4. Tip Strain

If multiple sensors are located at the Top or Tip, they will be averaged prior to any transformations and processing.

Any gages identified as Mid-Gages are displayed in the Raw Data Tab, but are not used in any Capacity and Integrity reporting. *Mid-Gage Preload data is exported and can be used to monitor/graph Mid Preload Changes.*





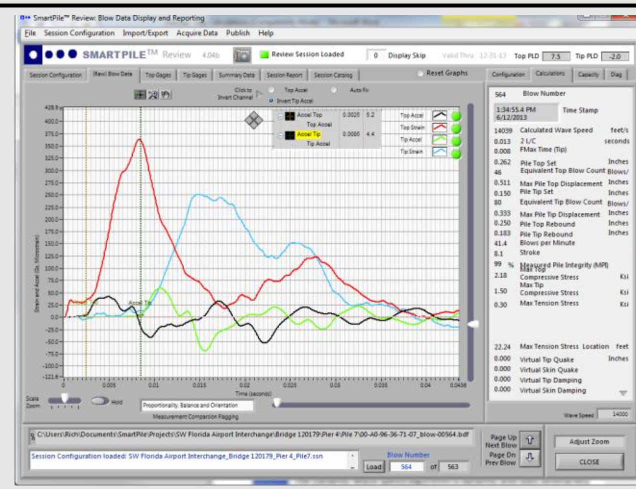


5

Dynamic Wave Speed

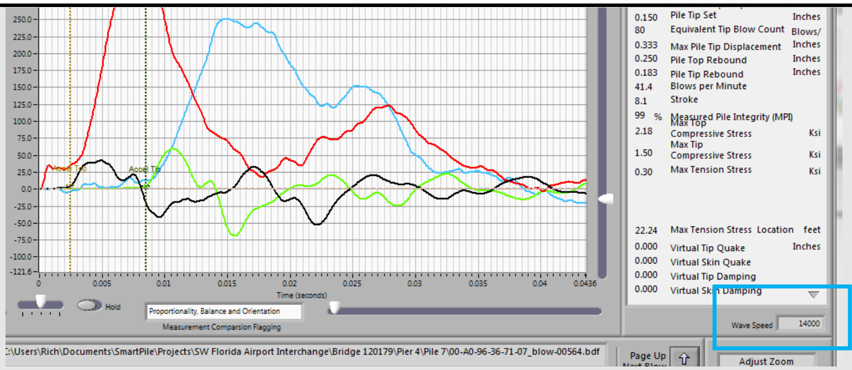
The Top and Tip accelerometers in the pile provide the ability to determine the wave speed. This is accomplished by having the distance between the top and tip gages (as calculated from the Pile configuration) and the time of flight between a key signal point on the Top and Tip accelerometer readings: First Peak, First Zero Crossing, etc.

The Dynamic Wave speed algorithm is dynamic and uses several key time points to establish the best wave speed estimate.



It is also possible to manually determine the wave speed by using the Top and Tip Cursors on the Raw Data tab. Moving these cursors automatically results in a wave speed calculation displayed for the operator (**BLUE BOX**). Please note that this manual calculation is not stored or used as any part of the calculations.

Manual wave speed calculations (above) at the end of the drive can/should be performed if automatic calculations are in question.



6

Top and Tip Gages – Force, Velocity, and Displacement

Both the top and tip Accel and Strain are converted to:

Force(t) =

Raw Strain(t) * Ɛ (kips/in^2) * A (in^2) / 100000**

*** Note 100000 represents the microstrain output of the Strain Gage*

Velocity(t) =

$$V(t) = \frac{\underline{(RawAccel_{t-1}+RawAccel_t)/2}}{2} + V_{t-1}$$

ZVelocity(t) =

Z = E (kips/in^2) * A (in^2) / C (ft/sec) → kips sec / ft

2L/c =

2 * L (Length Below the Top Gages) / C (Wave Speed)
Where: L is entered by the User (Pile Configuration)
C is entered by the User (Pile Configuration)

	Description	Units
Force(t)	Instantaneous Axial Force. Calculated by multiplying the Strain Value (in Microstrain) by Youngs Modulus (E) and the cross sectional area.	Kips (1000s lbs), kN
VEL(t)	The Particle velocity is derived (Integrated) from the Accelerometer Data.	Feet/sec Meters/sec
Z	Pile Impedance. Modulus times area divided by wave speed.	Kips-sec/ft
ZVEL(t)	Pile Impedance times the Particle Velocity. The Particle velocity must be obtained from the Accelerometer. Provides a similar representative Kips / Tonnes representation	Kips (1000s lbs), kN
2L/c	The 2L/c time interval is the time it takes for the stress wave to travel from the location of the tip instrumentation to the pile tip and back.	Seconds

7	**Wave Up and Wave Down** The Pile Total Capacity is based on Wave Up and Wave Down while the ratio of measured tip to skin forces is used to determine the Dynamic Damping value. The Impedance (Z) is calculated using the Top cross-section area, Tip cross-section area, and fixed wave speed from the pile configuration.	Wave Down_{top} = [Force_{top}(t) + ZVelocity_{top}(t)]/2 Wave Up_{top} = [Force_{top}(t) – ZVelocity_{top}(t)]/2 Z_{top}=Modulus* Top Cross Section Area/Wave speed Wave Down_{tip} = [Force_{tip}(t) + ZVelocity_{tip}(t)]/2 Wave Up_{tip} = [Force_{tip}(t) – ZVelocity_{tip}(t)]/2 Z_{tip}=Modulus* Tip Cross Section Area/Wave speed
8	**Key Time Constants** Several Key Time Constants are also established in support of calculating the Pile Capacity, Dynamic Damping and Tip Unloading Point. These are identified in the table (Right). The process of identifying several of these time points is based on scanning the sensor waveforms. The identified values are displayed on the cursors on the requisites Top and Tip displays.	(see table below)

Time Sample	Description	Equation	Relevance to Capacity Calcs
t1, t_1	The Sample at which the top Force curve initially peaks	Find first max in F_{Top} array	Top Gages
t2, t_2		$T_2 = T_1 + 2L/c$	Case Method
$T_{TWaveDN}$	Time required for the stress wave to travel from the Top to Tip instrumentation	$T_{TTWaveDN}$ = T1 + Length Between Gages / (Wave Speed)	Tip-Skin Ratio for Dynamic Jc
T_{FMAX}	This is the time sample in the blow when the Tip maximum force is registered	T_{FMAX} = Sample (Time) where TipF is maximum	Unloading Point Tip Capacity
$T_{Unloading}$	This is the time sample where the velocity goes to Zero on the Tip Gages	TUnloading = Sample (Time) where the Tip V(t) goes to zero	Unloading Point Tip Capacity

9 **Dynamic Damping**

Dynamic Damping is calculated using the WaveUp and Wave Down at the Top and Tip of the Pile at key time points (previously outlined).

Once the Tip / Skin ratio is determined, the Dynamic Damping, Jc, is calculated using the formula established by the University of Florida and FDOT research.

$$\text{Tip/Skin (unitless)} = R_{D,tip} / R_{D,skin}$$

$$\frac{\text{Wave Down}_{tip}(T_{TWaveDN}) + \text{Wave Up}_{tip}(T_{TWaveDN})}{2^{*}(\text{Wave Down}_{top}(t_1) - \text{Wave Down}_{tip}(T_{TWaveDN}))}$$

$$\text{Dynamic Damping} = J_c = -0.09744 * \ln(\text{Tip/Skin}) + .2686$$

10 **Total Capacity using Fixed and Dynamic Damping**

Having established the Wave Up, Wave Down, the Key Constants, and the Dynamic Damping, the Total Capacity of the pile can be calculated using the following basic formula (Likens and Hussein, 1988) :

$$\text{Total Capacity} = (1-J_c)^{*}\text{WaveDown}_{Top} + (1+J_c)^{*}\ \text{WaveUp}_{Top}$$

Given sampling jitter, the Maximum capacity is determined in a region around the t1 and t2 intervals.

Maximum Case Capacity (RMX) using the Dynamically calculated J_c

Total Static Capacity (RMX) (Kips/kN)=

$$MAX_{T1+200}\left\{ (1-Jc)*\frac{F(t1)+ZV(t1)}{2} + (1+Jc)*\frac{F(t2)-ZV(t2)}{2} \right\}$$

Where t is each sample

Where t2 is 2L/c from the first peak (t1)

We “hunt” the range from t1,T1+200 samples to find the local maximum

Where Jc is dynamically calculated using TOP AND TIP Gages

Maximum Case Capacity (RMAX) using a Fixed Jc

Same Capacity Calculation

Same calculation, EXCEPT Jc is the fixed value entered in the pile configuration or Review Control

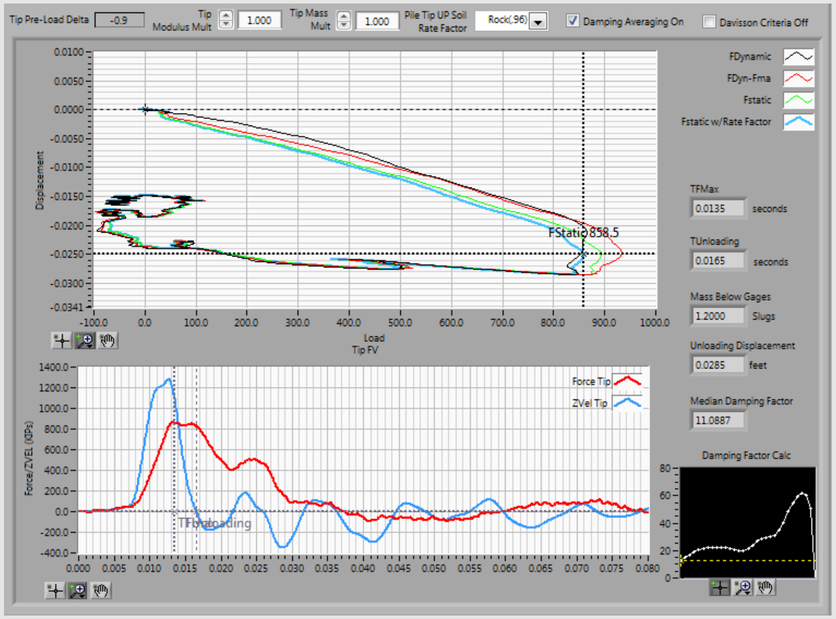
Uses TOP GAGES ONLY

11

Tip Capacity: Unloading Point Method (Middendorp, et al., 1992)

1. Using the Tip Force and Velocity curves, we determine the first significant force peak and then the first point at which the velocity is zero beyond that force point, where V(t)=0, the displacement is maximum and damping is zero (prior to springing back) → $T_{unloading}$
2. From this index we calculate the Static Resistance, $F_{unloading}$ = $F_{Tip}(T_{unloading})$ – Mass of Pile Below the Sensors * $A(T_{unloading})$
3. We can calculate the Mean Damping Factor, C across that range, where:
    a. C(t) = (FTip(t) – $F_{unloading}$ – Fa (Mass of Pile Below the Sensors) * Accel(t))/v(t)
    b. C_{median} = Median [C(t)] through the above range (T_{fmax} to $T_{unloading}$)
4. The Median Damping Factor is averaged against the previous blow (previous Median Damping Factor)
5. We use this then to calculate the Static Resistance through the blow:

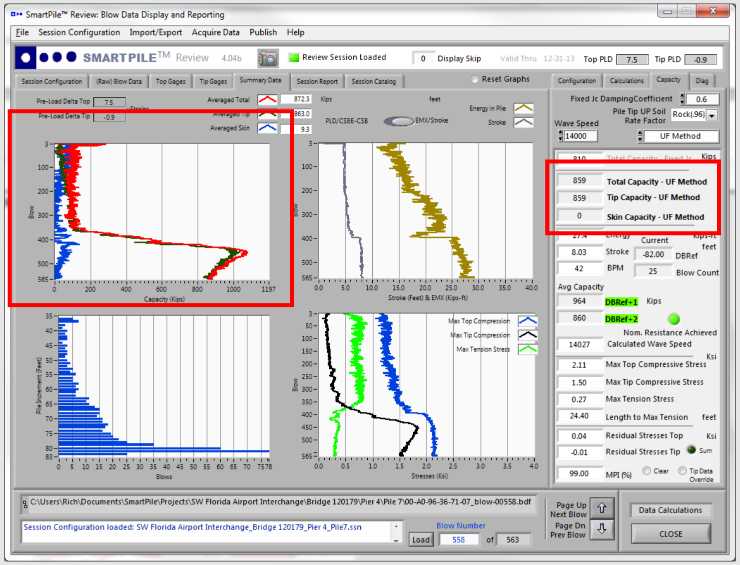
    FStatic(t) = FTip(t) – C_{media}*Velocity(t) – MxaUnloading Point, $V(T_{unloading}) = 0$
6. Once the F_{static} Capacity Curve is derived, the Tip Capacity is calculated as the Force at the unloading point times the applicable soil rate factor (Mullins, 2002)



12 University of Florida Capacity

The University of Florida Capacity method uses the Total Capacity calculated using the Dynamic Jc and the Tip Dynamic Unloading Capacity. The Skin Capacity is calculated as the Total Capacity – Tip Capacity.

- Total Capacity = Total Static Capacity, Case equation with Dynamic Jc from TOP and TIP gages
- Tip Capacity = Tip static capacity from Unloading Point based on TIP GAGES
- Skin Capacity = Total Capacity – Tip Capacity



13 Pile Integrity: Maximum Compressive Stress

The Top and Tip Maximum compressive stresses are a simple calculation that is based on the Maximum force as reported by the sensor at the Top or Tip. If there is no Tip Sensor, then the Tip Compressive stresses are estimated using the Top Gages and a new time constant, $T_{Inflection}$, which is T_1 minus the Top Strain rise time

$T_{Inflection} = t_1 -$ Top Strain rise time

Maximum Top Compressive Stress (Ksi/MPa):

Max (Top Force)/Top Cross-Section Area

Maximum Tip Compressive Stress (Ksi/MPa):

Max (Tip Force)/Tip Cross-Section Area

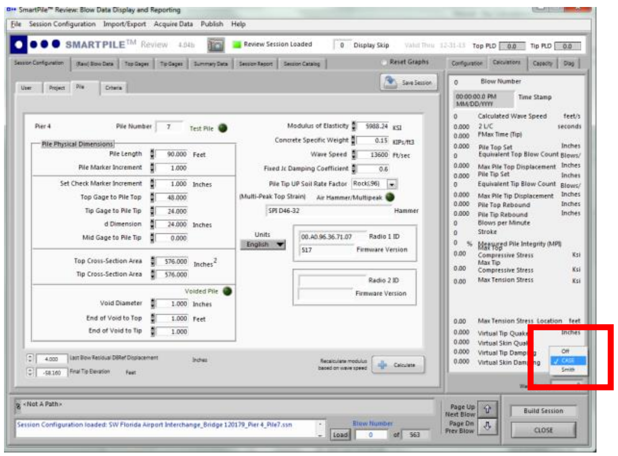
Maximum Tip Compressive Stress (Estimated, No Tip) (Ksi/MPa):

$WaveDown_{Top}(t1) + WaveUp_{Top}(t2) -$ Shaft Resistance

Where Shaft Resistance =

$2 * WaveUp_{Top}(T_{Inflection} + 2L/c)$

14	**Pile Integrity: Maximum Tension Stress** Pile Maximum Tension stresses are based on Top Wave Up and Wave Down waveforms and local maximums/minimums in specific sampling periods, from T1 until the end of the blow.	Maximum Tension Stress (Through Pile) (Ksi/MPa): Find the maximum of 1. Local Minimum of Wave Down(t1 → t2) + Wave Up (t2) 2. Wave Down(t2) + Local Minimum of Wave Up(t2 → End) 3. Local Minimum of (Wave Up (t2→End) + Wave Down(inside Local Min Range)) And divide by the cross sectional area of the pile top.
15	**Pile Energy** The maximum energy transferred at the top of the Pile by the hammer is as based on the Top Sensors, Force and Velocity. The maximum of the FV area is the maximum energy (as illustrated in the equation, Right).	(Kips-ft / kN-m) $Energy = \int_0^t F(t) * V(t)$ On TOP Gages
16	**Measured Pile Integrity** MPI is a composite function that uses two parallel and independent analysis methods: The first based on the traditional detection of change in pile impedance (Z2/Z1) using a Wave Up analysis method (similar to the PDI BTA method). The second method is based on changes in the pre-load stresses in the concrete pile as measured by the embedded instrumentation (specifically the top and tip strain gauges) See also Appendix 1.	Beta Component: $\text{Beta} = \dfrac{\text{Wave Down (t1) - 1.5Rx + Wave Up (t4)}}{\text{Wave Down (t1) - .5 Rx - Wave Up (t4)}}$ Where t1 = Max WaveDN t4 = Pickpoint: Find a valley between WaveDN Max (t1) and 2LC (Looking for an M signature representing a reflection) Rx = The peak prior to the WaveUP(t4) Min (t1 → t4)

17	**Blows per Minute (BPM)**	Blows per minute is based on the average time between the last 3 blows. Time differences are based on the timestamps between each of the blows. This value will reset when the interval between blows exceeds 10 seconds.
18	**Stroke** This is the height of the hammer stroke and is based on the time between blows (and the timestamp embedded in each blow sample). ***This formula is only good for diesel hammers.***	stroke height (feet) = $4.01(60/BPM)^2 – 0.3$ stroke height (meters) = $1.22\ (60/BPM)^2 – 0.3$
19	**Virtual Quake and Damping (Optional)** Quake and Damping (Smith OR Case) on a per-blow basis can be optionally displayed and exported. The calculations applied are based on the Tip Unloading and Top / Tip Displacements (Right). Output is enabled by selecting the output in the right hand calculations tab (shown below): 	**Quake** Tip Quake = Tip Displacement at Unloading (Inches/cm) Skin Quake = Max Top Displacement – Final Top Displacement (Inches/cm) **Tip/Skin Damping** Note EA/c = Modulus * Cross Section Area / Wave Speed Case Tip Damping = (Dynamic) Unloading Point Median Damping Factor / EA/c (unitless) Smith Tip Damping = (Case Tip Damping * EA/c)/ (Unloading Point) Tip Capacity (s/ft / s/m) Case Skin Damping = Calculated (Case) Dynamic Jc Damping – Case Tip Damping (unitless) Smith Skin Damping = (Case Skin Damping * EA/c)/(Dynamic Jc) Skin Capacity (s/ft / s/m)

Appendix 1 – Interpretation of SmartPile™ EDC Measured Pile Integrity (MPI) Results

Introducing Measured Pile Integrity (MPI)

The SmartPile™ EDC system uses the output value MPI (Measured Pile Integrity) to report on the concrete pile integrity. MPI is a composite function that uses two parallel and independent analysis methods:

- The first based on the traditional detection of change in pile impedance (Z2/Z1) using a Wave Up analysis method (similar to the PDI BTA method)
- The second based on changes in the pre-load stresses in the concrete pile as measured by the embedded instrumentation (specifically the top and tip strain gauges)

Pile Impedance Based Damage Analysis

The change in pile impedance interpretation (Z2/Z1) is based on a signal analysis technique of the Wave Up signal involving a search for abruptly occurring waveform artifacts during the time that the stress wave travels from the top of the pile to the tip and back up to the top ($0 \leq T \leq 2L/c$, with L the length of the pile and c the wave speed). The magnitude of any detected anomalies is appropriately weighted and the impedance ratio (Znew/Zold) is reported as a percentage, albeit that any values less than 51are reported as 0. This is based on the fact that any values below 60% already indicate significant issues with the pile, with the actual value providing little to no additional insight.

It is important to note that the change in pile impedance damage analysis approach is most effective in detecting horizontally oriented defects that affect the pile cross section (such as in the case of tension cracks), and is NOT meant to provide any insight into vertically oriented material damage unless or until the damage results in a reduction in cross sectional area.

The method of pile impedance based damage detection is most effective during “softer” driving (which creates higher tension stresses in the pile) because during “harder” driving damage is more likely near the pile tip due to the increase in the compressive stresses in the pile (to basically double the original value when driving into very hard material).

While the interpretation of these values is subjective, it is obvious that as the reported MPI values deviate further from 100% the likelihood of pile damage increases. Generally speaking, results interpretation of the pile impedance based damage analysis is recommended as follows:

100% - No issues detected regarding a change in pile impedance
99% - 80% - Minor signal issues detected possibly indicating slight pile damage
79% - 60% - More significant issues detected indicating possible pile damage
Less than 60 % - Major issues detected, seek qualified professional assessment

Pre-Stress Based Damage Analysis

Significant effort is currently applied to ensure the integrity of the pile top during driving through the use of adequate pile cushions, and constant visual monitoring and inspection techniques. With EDC, similar levels of oversight are now applied independent of accessibility.

An alternate material integrity analysis method involving the monitoring of static pre-stress levels (specifically changes) within the core of the concrete material yields a different level of insight regarding the structural integrity of the pile. Because the embedded strain instrumentation is positioned in the pile core prior to pile casting and subsequent pre-stressing, the instrumentation can monitor the pre-stress levels, even at the pile tip, which for obvious reasons cannot be monitored once pile driving has started. But it is at this very location where the pile is subject to the greatest compressive stresses, shear stresses, and stress gradients within the foundation element during installation.

The pre-stress levels in a pre-tensioned pre-stressed concrete pile are established as the result of two directly opposing forces reaching equilibrium. The first being the tensile stress in the steel strands multiplied by the total cross sectional area of these strands; and the second the compressive stress in the concrete multiplied by the total cross sectional area of the concrete. Once this equilibrium condition and corresponding pre-stress level is established, any change in either force will upset this balance and result in a new equilibrium (and therefore new pre-stress level).

For example, a vertically oriented crack extending up from the pile tip is very likely to upset this balance. When viewed looking into the pile end (see Figure 1), separate concrete sections will result, with the resulting pre-stress level in each section determined by the section's cross sectional area and the number of steel strands in that section.
Consequently any vertical crack resulting in non-symmetric volumes will result in some sort of pre-stress shift, with a complete loss of pre-stress potentially indicating the complete loss of bonding between the steel and the concrete from the pile tip up to the location of the strain gauge. It should be noted, however, that any change in the static pre-stress levels, especially a reduction or relaxation inthe concrete compressive static stress levels during pile driving, especially a reduction in the concrete compressive stress levels, should be considered a possible leading indicator high stresses near the pile tip.

Figure 1: Orientation of vertical cracking

Please note that an increased compressive residual force could be the result of the pile weight of the pile plus any below grade soil shaft friction forces preventing tip rebound from a hammer blow.

The monitoring of the changes in pile internal pre-stress levels is accomplished by measuring and tracking the static pre-stress equilibrium levels for every hammer blow measured after the dynamic strain events have dissipated or settled out. With the raw offset strain values available for display in the Raw Data analysis tab of SmartPile™ Review, any reported change in the measured static pre-stress values are clearly evident in the strain signal presentation during data playback.

If the recorded change in pre-stress level drops the equivalent of more than 50 microstrain for 10 consecutive blows, than is it assumed and reported that pile damage has occurred. In all other cases, it is assumed that the pile is intact.

Interpreting Measured Pile Integrity values

The reported MPI value is basically the calculated change in impedance output, reduced by 50 if the pre-stress based damage analysis indicates pile damage. So for example, if the detected change in pile impedance is calculated to be worth 12 points, MPI can report either an 88% (100-12) or a 38% (100-12-50) depending on whether the pre-stress based damage analysis indicates any damage to the pile.

The reported “Measured Pile Integrity” (MPI) values can then be described as follows:

MPI	Pile Impedance based damage analysis	Pre-stress based damage analysis
100 %	No issues detected	No Issues detected
99 – 80 %	Minor signal issues detected possibly indicating slight pile damage	No Issues detected
79 – 60 %	More significant issues detected indicating possible pile damage	No Issues detected
59 -51 %	Major issues detected indicating likely pile damage; seek qualified professional assessment	No Issues detected
50 %	No issues detected	Issues detected indicating likely pile damage; seek qualified professional assessment
49-30 %	Minor signal issues detected possibly indicating slight pile damage	Issues detected indicating likely pile damage; seek qualified professional assessment
29 – 10 %	More significant issues detected indicating possible pile damage	Issues detected indicating likely pile damage; seek qualified professional assessment
9 – 0 %	Major issues detected indicating likely pile damage; seek qualified professional assessment	Issues detected indicating likely pile damage; seek qualified professional assessment

Interpretation Examples

A measured shift in the reported static pre-load value if detected is a composite of three potential sources:

1. Residual compressive stresses
2. Compromised or relaxed pre-stress (tension)
3. Any unsettled dynamic wave propagation (error)

The system software accounts for the third as described below, with any resultant reported measurement shift being a summation of the remaining two. The specific error condition being monitored for is a relaxation of the static compressive pre-load.

To help prevent large negative reported pre-load delta values, the SmartPile™ algorithm takes a baseline measurement at the beginning of a blow at the pile tip and determines if any residual negative movement was present and detected at the end of the previous blow. Any reported delta measurement is then adjusted accordingly. ***For this very reason, stepping through blows backwards vs. forwards in SmartPile™ Review will affect the reported pre-load delta values and must be avoided.*** Before acting on large negative reported static pre-load delta shifts, move to the Raw Data analysis tab and look for unsettled wave propagation on the tip strain at the end of recorded blows. Check and confirm that the dynamic strain events have settled out, as it is easier to assess reported conditions when all dynamic events have settled out to zero by the end of the blow.

In softer driving, which is common during the initial part of the pile driving, tip strain readings don't always return to zero by the end of the blow as shown in Figure 2 below (red arrow). When soil conditions tighten up, the dynamic tip strain measurements settle out to zero by the end of the blow, as seen in Figure 3.

<u>**Unsettled Tip Strain**</u>

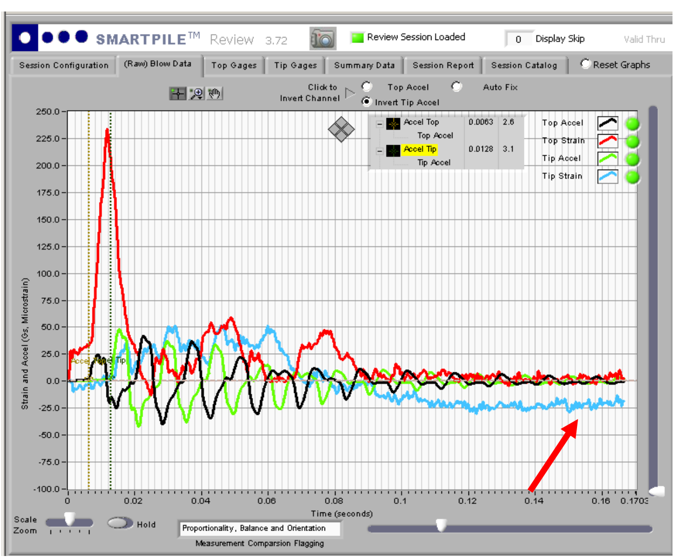


Figure 2: Unsettled tip strain (blue) wave propagation at the end of blow

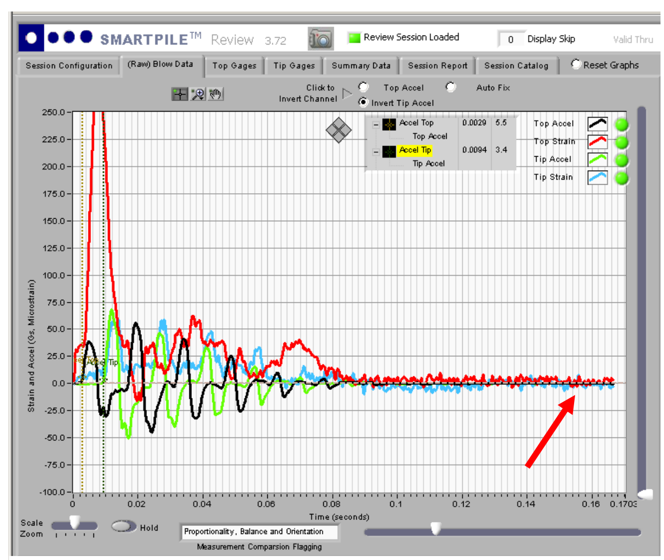


Figure 3: Settled tip strain (blue) wave propagation at the end

Use of Tip Stresses as a leading indicator of pile damage

In Figure 4 the change in static strain (pre-stress) reading at the top and the tip of the pile are shown (left vertical axis in microstrain) as well as the compressive stresses (CSB) at the tip (right vertical axis in ksi), all as a function of the blow count (horizontal axis).

As can be seen from a report generated with SmartPile™ Review, around blow count 1500 the pile penetrates a hard soil layer, causing the compressive stresses measured at a point in the tip core to increase to approx. 1.6 ksi. At the same time the static tip strain (pre-stress) begins to fall and eventually drops some 50 microstrain, indicating likely damage to the pile tip.

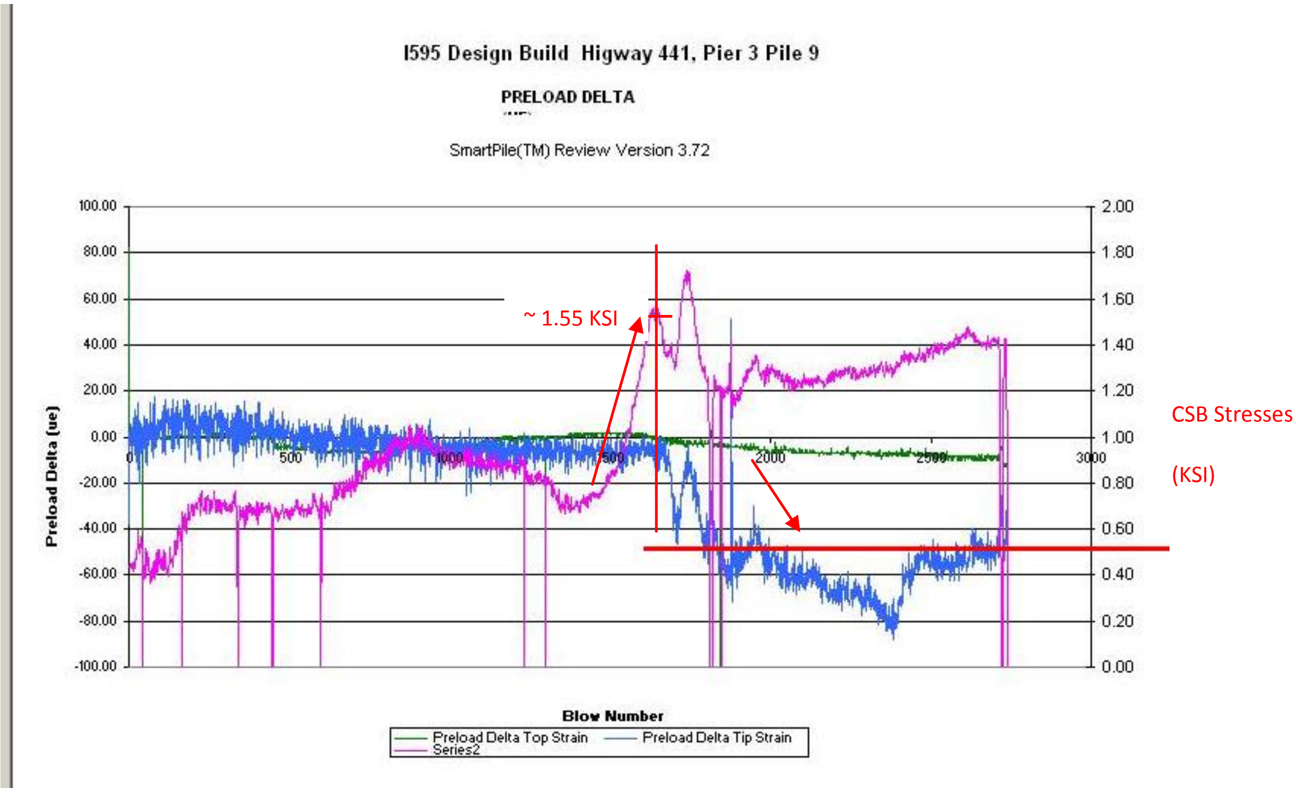


Figure 4: Measured CSB (magenta) plotted with top (green) and tip (blue) pre-load deltas. Note the loss of pre-stress occurring right after punching through a hard layer (~ 1.55 KSI) resulting in an eventual pre-stress relaxation of approximately 50 microstrains (red line)

It should be noted that the pile tip compressive stresses are NOT necessarily uniformly distributed, and may contain VERY large localized shear stress gradients distributed anywhere across the pile tip cross sectional area. Although the gauge mounted in the center of the pile may not actually record the maximum compressive stress experienced by the pile tip, the gauge IS adequately positioned to measure any localized changes in compressive material pre-load.

Case Study – US19 over Barge Canal, Pier3 Pile2; anatomy of a failure

This case study illustrates a scenario whereby the measured pre-stress was completely lost at the tip of the pile. A subsequent extraction of that same pile confirmed the damage to the tip as detected and reported through MPI. It should be noted that, except for a few individual blows, the pile impedance based damage analysis did not indicate any damage to the pile.

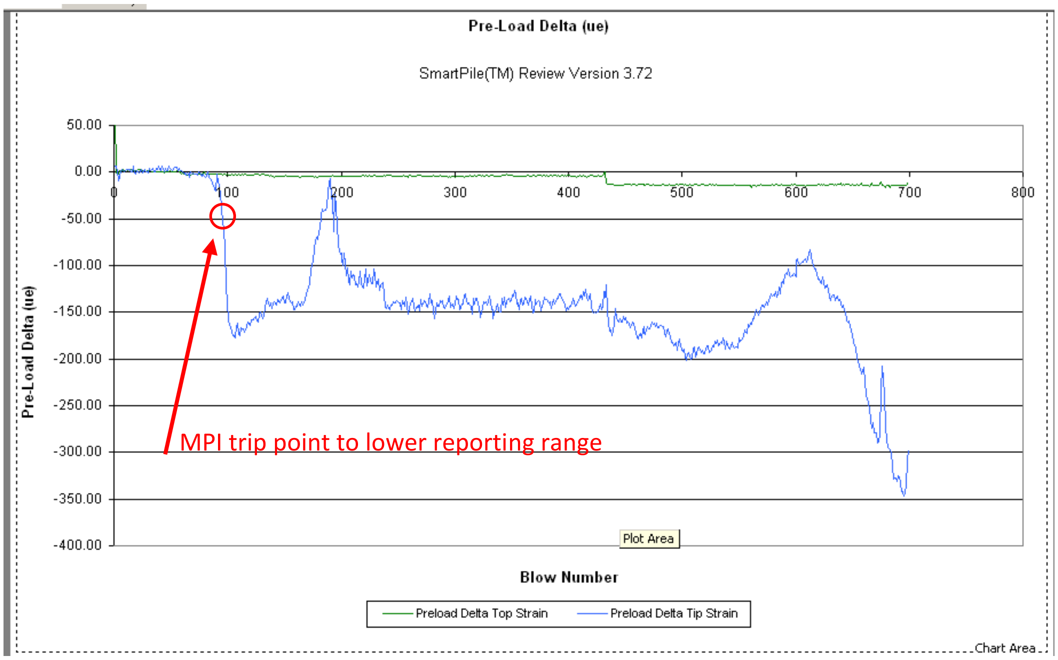


Figure 5: Tip (blue) and Top (green) measured pre-load deltas (above), and corresponding reported MPI values (below)

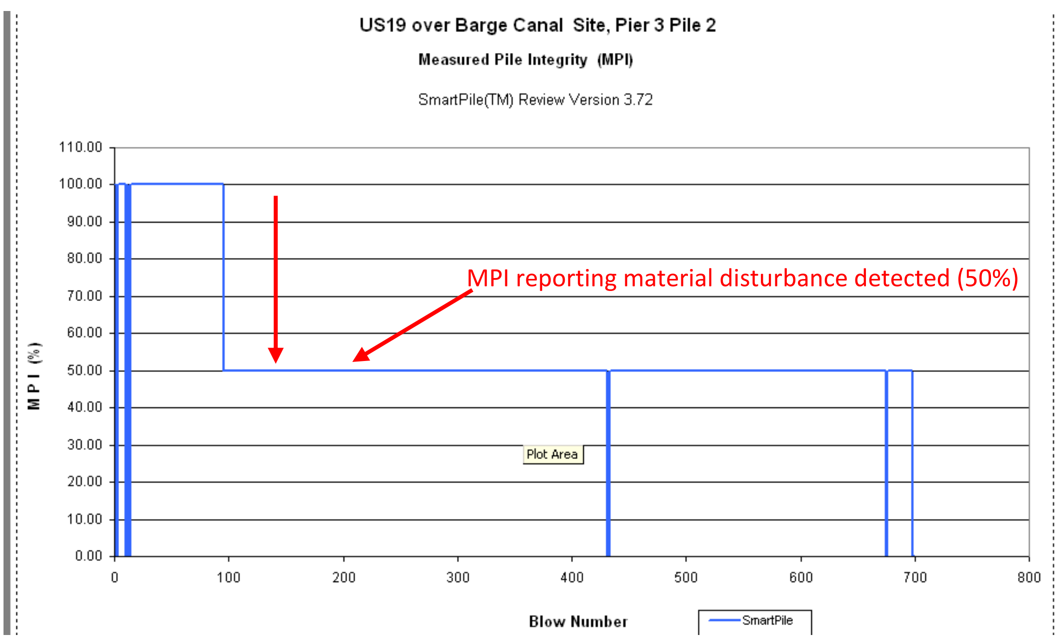


Figure 6: Example of material disturbance. Driven pile referenced from data above after extraction. Vertical cracks extend 10 feet up from the pile tip as noted by the visible ends of the tape measure. The tip instrumentation located in a segmented mass within pile core remained operational.

The SmartPile™ Measurement System - Components and Design

Regarding any data analysis approach, it is important to note that the quality of the measured data is only as good as the design and implementation of the measurement system. The SmartPile™ EDC foil-based embedment gauge is manufactured and sealed in a controlled environment to address the bonding and sealing concerns that are common for gauges embedded in concrete. The external package is of a special contoured design to ensure that proper bonding is established and maintained with the material under test. To optimize measurement precision, the EDC embedment gauge utilizes the latest foil resistor technology; leveraging the latest state of the art resistor grade metal alloys for better long term stability. The foil resistor design also provides for precise thermal compensation using a proprietary approach to negate any gauge thermal output effects throughout the normal operating temperature range of the sensor.

To address the front end signal conditioning design requirements; the SmartPile™ EDC system utilizes the latest state-of-the-art, low power, high performance instrumentation design, layout, and military standard fabrication practices. Instrumentation grade components are carefully selected to ensure both precision and stability. The result is an active strain sensing and measurement system with built-in thermal compensation that can withstand the rigors of concrete casting, curing, and deep foundation installation process.

Figure 7: Embedment strain gauge manually chiseled out of solid 24” PSC pile end to show encapsulation effectiveness and material bonding. Note the lack of any visible material voids in surrounding concrete

Figure 8: Another embedment strain gauge extraction, now showing close-up of bonding effectiveness of waffle pattern. Note the negative image of the pattern visible in loose piece of concrete above (rotated)

Conclusion

During pile driving it is important to continually consider the pile integrity, especially during hard driving conditions. Quite often this is done based on a pile impedance based damage analysis, but the SmartPile™ EDC system includes a second and completely independent analysis method: the pre-stress based damage analysis. If either of these analysis methods indicates that damage of the pile tip is likely, it is strongly suggested to seek a qualified professional assessment to determine how to proceed.