Optimizing the Use of Thermal Integrity System for Evaluating Auger-Cast Piles

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Problem Statement

- Thermal Integrity Profiling (TIP) has proven to be an effective method for evaluating the as-built integrity of drilled shafts.

- However, TIP is rarely used for evaluating auger-cast-in-place (ACIP) piles, as current practices do not require installation of standard integrity access tubes.

- Current integrity methods for ACIP piles is limited, thus their FDOT use has been limited to foundations for sound walls.

- GOAL: **Translate the use of thermal integrity technology to an effective method for evaluating ACIP piles.**
ACIP Piles
Construction

Source: Dan Brown et al., FHWA-HIF-07-03
ACIP Piles
Construction
Surface methods involving stress wave propagation analysis are the most common form of integrity testing for ACIP piles.
ACIP Piles
Quality Assurance

Single Center Wire Detects Anomaly

Inclination / alignment not quantifiable

Single thermal wire tied to center bar
TIP Methods
Infrared Probe

- Thermal Probe w/ Infrared Sensors
- Depth Encoder Assembly
- Data Collection System
TIP Methods
 Thermal Wire

Thermocouples

Data Loggers

Thermal Wire
New Thermal Wire

Thermal Wire:
- New version of Thermal Wire in production now is much stronger and requires far less cable ties, greatly reducing potential data loss and speeding installation.

*The new version of the wire has been deployed on numerous shafts with excellent results*
TIP Analysis – Concepts

• Integrity of a shaft can be affected by
  • reduced cross section,
  • cage offset resulting in decreased cover, and
  • inclusions of compromised or poor quality concrete,
  • all affect the heat production and temp of the shaft.

• Effective Radius – the radius of intact, uniform quality concrete that would produce the measured temperature.

• Temperature $\propto$ Effective Radius
Convection to air

Conduction to soil

Cage Diameter

Excavation Diameter

Temperature (F)

Depth (ft)
Convection to air

Conduction to soil

Cage Diameter

Excavation Diameter

Depth (ft)

Temperature (F)
Effects of Alignment and Shaft Radius

Temperature (F)

Radial Position (ft)

Shaft Radius (ft)
Level 1: Direct observation of the temperature profiles.

Level 2: Superimposed construction logs and concrete yield data. MOST COMMON

Level 3: Three dimensional thermal modeling.

Level 4: Signal matching numerical models to field data.
TIP Analysis - Direct Observation

Figure 2.14. Example thermal profiles with anomalies (Johnson, 2014).

- Bulge
- Cage Offset
- Normal End Conditions
TIP Analysis - Superimposed Construction Logs & Concrete Yield Data

Yield plots provide a record of concrete volume vs. change in height for each truck.
TIP Analysis

Yield plot converted to effective diameter vs. depth
TIP Analysis

Yield plot converted to effective diameter vs. depth

Measured temperature profile
TIP Analysis - Superimposed Construction Logs

[Graph showing temperature (deg F) vs. depth (ft) and radius (in) with marked points and annotations for theoretical and single-point T-R.]
Hyperbolic Temperature Corrections

\[ T_{fit} = \pm \left( \frac{T_{max} - T_{min}}{2} \right) \tanh \left( \frac{z - z_0}{\alpha} \right) + T_0 \]

\[ T_{max} = \text{Max. asymptotic temperature (℉)} \]
\[ T_{min} = \text{Min. asymptotic temperature (℉)} \]
\[ T_0 = \text{Inflection point temperature (℉)} \]
\[ z_0 = \text{Inflection point depth (ft)} \]
\[ \alpha = \text{Vertical stretch (ft)} \]

\[ T_{cor} = (T_{meas} - T_{fit}) \left( \frac{T_{norm}}{T_{fit}} \right) + T_{norm} \]

\[ T_{meas} = \text{Measured temperature (℉)} \]
\[ T_{norm} = \text{Normalizing temperature (℉)} \]
\[ (T_{max} \text{ for top & bottom, depends for transitions}) \]
# Summary of hyperbolic parameter selections

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Top Roll-off</th>
<th>Bottom Roll-off</th>
<th>Mid-shaft</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>Observed from TIP profile. Confidence: Strong</td>
<td>Observed from TIP profile. Confidence: Strong</td>
<td>Observed from TIP profile. Confidence: Strong</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td></td>
<td>Average annual temperature of region. Confidence: Strong</td>
<td>Observed from TIP profile. Confidence: Strong</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Average recent air temperature. Confidence: Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_0$</td>
<td>TOS +/- 1ft Confidence: Strong</td>
<td>BOS +/- 1ft Confidence: Strong</td>
<td>Observed from TIP profile/corroborated by boring logs Confidence: Medium</td>
</tr>
<tr>
<td>$a$</td>
<td>$= f(\sqrt{t})$ Typical range: 1-5 Confidence: Medium</td>
<td>$= f(\sqrt{t})$ Typical range: 1-5 Confidence: Medium</td>
<td>$= f(\sqrt{t})$ Typical range: 1-5 Confidence: Medium</td>
</tr>
</tbody>
</table>
Hyperbolic Abuse

• As with any signal matching approach, good matches can be found with physically impractical parameters.

• TOS & BOS corrections are almost always warranted, but parameters should be correctly selected based on actual air / soil temperatures and time of testing (e.g. $\alpha = 0.3\sqrt{t}$)

• Mid-shaft hyperbolic corrections should only be applied when justified (e.g. over-water shafts). Actual radius changes exhibit similar patterns and should not be mistakenly corrected.
Proper Selection of Hyperbolic Parameters

- Over 400 shafts tested and analyzed
- Top and bottom roll-offs fitted with hyperbolic function
- Hyperbolic parameters iterated by algorithm to achieve best fit
- Results analyzed to identify trends
$\alpha$ vs. time of testing

- **Bottom of Shaft**
- **Top of Shaft**

![Graph showing $\alpha$ vs. time of testing with data points for Bottom of Shaft in red squares and Top of Shaft in blue diamonds.](image-url)
\[ \alpha = c \sqrt{t} \]
\[ \alpha = 0.4 \sqrt{t} \]
Top Inflection Point Temperature

- Daily High Temp
- Daily Low Temp
- Best Fit Top Infl Temp
Inflection Point Depth Offset

Concrete Age (sqrt of time in hrs)

-5

-4

-3

-2

-1

0

1

2

3

4

5

Top

Bottom

y = -0.0964x

y = 0.1397x
Numerical Modeling

- Trends and patterns which give further insight and enhance traditional analysis
- Range of times for analysis/testing
- Best locations for placing sensors/tubes
- Minimum number of tubes/wire
- Size of anomaly that is detected with minimal sensors/tubes
- Effects of drastic changes in external environment (above ground in water or air)
The graph illustrates the temperature distribution along the radial position of different shaft diameters. The x-axis represents the radial position in inches (Radial Position), while the y-axis represents the temperature in degrees Fahrenheit (Temperature). The graph shows multiple curves for different shaft diameters: 2 ft, 4 ft, 6 ft, 8 ft, 10 ft, 12 ft, and 14 ft. Each curve is color-coded and indicates the acceptable measurement locations within the shaded area. The edge of the shaft is marked with a dotted line.
Temperature (degF) vs. Radial Position (in)

- Shaft Diameter
- Acceptable measurement area
- Typical cage location (6in cover)
Centerline measurements

Radial Distance

Temperature (degF)

Shaft Radius (in)

2ft Shaft

4ft Shaft

6ft Shaft

8ft Shaft

10ft Shaft

12ft Shaft

Center of Shaft Measurements
Number of Sensors
Effects of cage movement
Number of Sensors
Effects of cage movement

Depth (ft)

Temperature (degF)

Average
Number of Sensors
Effects of cage movement
2ft Diameter Pile

- 2" inclusion
- 6" inclusion
- 10" inclusion

Depth (ft)

Temperature (degF)
Field Testing

• 26 piles / small shafts tested and analyzed

• Various instrumentation schemes
  • Single center wire
  • Single center tube
  • 4 center wires
  • 4 cage wires
  • 2 cage wires

• Traditional as well as advanced analysis methods
Case Study: 22” shafts with 4 wires around single center bar

Observations

Thermal data shows top of shaft location and part of bottom roll-off (shaft deeper than last sensor)

Computed radius matches general shape of pile, but with less definition

Center bar eccentricity indicated by variations from sensors 2in with separation

Integrity assessment reasonably successful; pile is good
Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Hyperbolic T-R Relationship

![Graph showing Actual T-R and Pole-point solution relationship](image)
Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Hyperbolic T-R Relationship

\[ T = \left( \frac{T_{\text{max}} - T_{\text{min}}}{2} \right) \tanh \left( \frac{R - R_0}{\alpha} \right) + T_0 \]

\( T_{\text{max}} \) = Upper asymptotic temperature = Adiabatic temperature of concrete

*Modeling required*

\( T_{\text{min}} \) = Lower asymptotic temperature

\( T_0 \) = Inflection point temperature

\( R_0 \) = Inflection point radius = Radius at which measurements are taken

\( \alpha \) = Time factor
Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Hyperbolic T-R Relationship
Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Gradient Signal Matching

Lateral temp distributions for shafts 20-30”
Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Gradient Signal Matching
Case Study: 22” shafts with 4 wires around single center bar

Advanced Analysis: Gradient Signal Matching
Case Study: 14” ACIP piles with a single wire on single center bar

Of 14 piles instrumented, 3 experienced complete data loss and 4 produced only partial data, likely due to damage from internally protruding hooks on the upper reinforcing cage. All other piles yielded reasonably straight profiles with little to no indication of bar movement.
Case Study: 30” ACIP piles with full cage, comparison of 2 & 4 wire instrumentation
Case Study: 30” ACIP piles with full cage, comparison of 2 & 4 wire instrumentation

4 Wire System

Thermal data shows top but not bottom of pile. Pile extends deeper than reinforcing cage.

Straight / vertical average temperature profile, 16” effective radius throughout

1” cage movement in various directions over the depth of the pile

Integrity assessment reasonably successful; pile is good
**Case Study:** 30” ACIP piles with full cage, comparison of 2 & 4 wire instrumentation

Thermal data shows top but not bottom of pile. Pile extends deeper than reinforcing cage.

Average temperature profile exhibits an uncharacteristic slope over the entire length

Variation among wires indicates cage movement

Integrity assessment is inconclusive
Case Study: 30” ACIP piles with full cage, comparison of 2 & 4 wire instrumentation

Cage and wire locations are laid over an isothermal contour plot resulting from a signal matched model of the pile. Movement of the cage over the contours reveals two possible solutions which satisfy the thermal profile.
Inclination Measurements
Severe cage deformation during casing removal!
Tracking probe rotation from thermal gradient between IR sensors
Tracking probe rotation from thermal gradient between IR sensors
<table>
<thead>
<tr>
<th>InvenSense MPU-6000</th>
<th>Accelerometer</th>
<th>Gyroscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement range</td>
<td>±2g</td>
<td>250°/sec</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.06mg</td>
<td>0.0076°/sec</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>1kHz</td>
<td>8kHz</td>
</tr>
<tr>
<td>Communication</td>
<td>Serial (I²C or SPI)</td>
<td></td>
</tr>
<tr>
<td>Power source</td>
<td>2.375 – 3.46 Vdc</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-40°F to +221°F</td>
<td></td>
</tr>
<tr>
<td>Mechanical shock limit</td>
<td>10,000g for 0.2ms</td>
<td></td>
</tr>
</tbody>
</table>
Rotation Tracking

Programmable stepper motor assembly from Anaheim Automation
Rotation Tracking – Probe Based System

- Digital communication timed out after short periods of time
- Accuracy lost due to output drift.
- Drift not able to be corrected as all calculations are performed onboard the sensor.
**LORD Microstrain 3DM-GX4**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Accelerometer</th>
<th>Gyroscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement range</td>
<td>±5g</td>
<td>300°/sec</td>
</tr>
<tr>
<td>Resolution</td>
<td>&lt;0.1mg</td>
<td>&lt;0.008°/sec</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>4kHz</td>
<td>4kHz</td>
</tr>
<tr>
<td>Communication</td>
<td>USB 2.0</td>
<td></td>
</tr>
<tr>
<td>Power source</td>
<td>+3.2 to +36 Vdc</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-40°F to +185°F</td>
<td></td>
</tr>
<tr>
<td>Mechanical shock limit</td>
<td>500g (calibration unaffected)</td>
<td>1000g (bias may change)</td>
</tr>
<tr>
<td></td>
<td>5000g (un-powered survivability)</td>
<td></td>
</tr>
</tbody>
</table>
Rotation Tracking – IMU Sensor

- Experienced drift at low sampling frequencies and high rotational rates

180° oscillations at 17 deg/sec
Some drift at 100kHz
No drift at 500kHz

180° oscillations at 450 deg/sec
Some drift at 100 and 500kHz
45° oscillations at 17 deg/sec

Some drift at 100kHz

Negligible drift at 500kHz

45° oscillations at 450 deg/sec

Some drift at 100 and 500kHz
Rotation Tracking – IMU Sensor

- Experienced drift at low sampling frequencies and high rotational rates

5 revolutions CW and CCW at 20 deg/sec

Drift at 100kHz yielding ~90° error over 5 revolutions

No drift at 500kHz
3-D Position Tracking – IMU Sensor

Specially fabricated probe body to house IMU sensor

30ft 1.5in PVC pipe with prescribed lateral deflections
3-D Position Tracking – IMU Sensor

Lateral Position, X (in)

Actual

Measured

Lateral Position, Y (in)

Actual

Measured

Vertical Position, Z (ft)

Vertical Position, Z (in)
3-D Position Tracking – IMU Sensor

![Graph showing actual and measured lateral positions]

- Actual
- Measured
3-D Position Tracking – IMU Sensor

Error due to diameter tolerance between tube and probe which allows sensor to be oriented and an inclination misaligned with the that of the tube.

0.09in diameter tolerance yields ~+/−1.25° angle difference, which equates to 4in error over 15ft. Results showed similar error.
3-D Position Tracking – IMU Sensor

New Probe Design
3-D Position Tracking – IMU Sensor

New Probe Design
USB to CAT6 converter

IMU sensor
Tracking probe rotation from thermal gradient between IR sensors
Summary

- TIP can work for ACIP, but advanced analysis methods must be used when instrumentation is minimal.

- Qualitative analysis works well, but present drilled shaft analysis methods do not work with small piles and near center measurements.

- Simplified T-soil method could solve problems.

- The addition of inclination measurement could greatly enhance TIP analysis for ACIP piles.
Case Study:

Dry Clay

Permanent Casing (54" ID)

Saturated Sand

Uncased (48")

Depth (ft)

Temperature (F)

Top Roll-off

Needs correction

Transition due to boundary change

Needs correction

BOC (i.e. expected change in diameter)

Do not correct!

Bottom Roll-off

Needs correction
Case Study:
Model Analysis

TOS = GSE = 0ft

BOC = 22.4ft
(54” cased, 48” uncased)

BOS = 35.4ft

Convective air cooling w/ diurnal temperatures 66-83 °F

Low diffusivity overlying high diffusivity at 12ft

Ambient soil temperature = 60 °F
Case Study: Model Results

- Low Diffusivity Boundary
- Permanent Casing (54'' ID)
- Uncased (48'')
- High Diffusivity Boundary

Top Roll-off Needs correction

Transition due to boundary change Needs correction

BOC (i.e. expected change in diameter) Do not correct!

Bottom Roll-off Needs correction
Top Roll-off

- $Z_0 = 0$ ft
- $T_{\text{max}} = 141.6$ °F
- $T_0 = 66.3$ °F
- $\alpha = 1.28$

Soil Transition

- $Z_0 = 11.9$ ft
- $T_{\text{max}} = 141.6$ °F
- $T_{0\text{min}} = 120.2$ °F
- $\alpha = 1.25$

Bottom Roll-off

- $Z_0 = 35.4$ ft
- $T_{\text{max}} = 110$ °F
- $T_{\text{min}} = 60$ °F
- $\alpha = 1.4$
Selection of TOS Inflection Point

Inflection point influenced by air temperatures
Selection of $\alpha$ time factor

\[ \alpha \approx 0.3\sqrt{t} \]
**Top Roll-off**

\[
\begin{align*}
Z_0 &= -1.0 \text{ ft} \\
T_{max} &= 144 \degree F \\
T_0 &= 77 \degree F \\
\alpha &= 3.0
\end{align*}
\]

**Soil Transition**

\[
\begin{align*}
Z_0 &= 11.4 \text{ ft} \\
T_{max} &= 144 \degree F \\
T_{min} &= 126.5 \degree F \\
\alpha &= 1.25
\end{align*}
\]

**Bottom Roll-off**

\[
\begin{align*}
Z_0 &= 35.7 \text{ ft} \\
T_{max} &= 117.5 \degree F \\
T_{min} &= 55 \degree F \\
\alpha &= 1.33
\end{align*}
\]
How does time of testing affect analysis results?
Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar

- Thermal data shows both top and bottom of pile
- Only subtle variations in temperature versus depth; no bar inclination evident
- Pump stroke computed radius generally agrees with predicted radius
- Integrity assessment reasonably successful; pile is good
Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar

- Thermal data shows both top and bottom of pile
- Some variation in temperature with depth; bar inclination may be present
- Pump stroke computed radius generally agree with predicted radius
- Integrity assessment was reasonably successful; pile is good based on 7in nominal design radius and predicted effective radius exceeds that value throughout.
Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar

- Thermal data only shows top of pile which appears normal
- Only subtle variations in temperature versus depth for first 25ft (left) and 45ft (right); no bar inclination evident
- Pump stroke computed radius generally agrees with predicted radius
- Integrity assessment unsuccessful; broken wire prevented full analysis
Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar

- Thermal data shows both top and bottom of pile
- Straight / vertical temperature profile; no bar inclination evident
- Small step in pile at 45ft; profile straight thereafter
- Pump stroke computed radius generally agrees with predicted radius
- Assessment reasonably successful; pile is good

- Thermal data shows top but not the bottom of pile
- Pile extends deeper than reinforcing bar (bottom most thermal sensor)
- Straight / vertical temperature profile; no bar inclination evident
- Pump stroke computed radius generally agrees with predicted radius
- Assessment reasonably successful; pile is good
Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar

- Thermal data only shows top of pile which appears normal
- Variations in temperature versus depth for first 25ft; may indicate bar inclination
- Pump stroke computed radius versus predicted radius inconclusive
- Integrity assessment unsuccessful; broken wire prevented full analysis

- Thermal data only shows top of pile which appears normal
- Only subtle variations in temp vs depth for first 20ft; no apparent bar inclination over that depth
- Pump stroke computed radius versus predicted radius inconclusive
- Integrity assessment unsuccessful; broken wire prevented full analysis
Case Study 3: 14” ACIP piles with a single wire on single center reinforcing bar

- Thermal data shows both top and bottom of pile
- Straight / vertical temperature profile; no bar inclination evident
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