Thermal Integrity Testing of Drilled Shafts

AASHTO SOC Conference
August 4, 2009
Chicago, Illinois

Presented by: Gray Mullins, Ph.D., P.E.
Overview

- Background
- Case Studies
- Integrity Evaluation
- Conclusions
Background

- *Factors Affecting Anomaly Formation in Drilled Shafts*  
  (FDOT 2000-2004)

- *Thermal Integrity Testing of Drilled Shafts*  
  (FDOT 2004-2006)

- *Foundation Health Monitoring*  
  (FHWA 2007-2008)

- *Attenuating Mass Concrete Effects in Drilled Shafts*  
  (FDOT 2007-2009)
Mass concrete effects from hydration energy can be harmful in two ways:

- Differential temperature stresses / cracking
- High temperature curing errors

Hydration energy can be helpful as it produces a distinguishable heat signature.
Background

- Differential Temperature in mass concrete has immediate adverse effects in the form of cracking. . .(typically 35-40 deg F)
- Excessively high curing temperatures can affect long-term durability from Delayed Ettringite Formation, DEF (>160 deg F).
When’s Concrete Mass?

- Differential Temperature Limit
- Peak Temperature Cut-off
- Mass Concrete Geometry Limit
- Drilled Shaft Diameter Limit (pending)

- Performance-based Specification
  (Based on first two conditions)
Geometric Guidelines

- Mass Concrete Geometry Limit
  - When $\frac{\text{Volume (ft}^3\text{)}}{\text{Surface Area (ft}^2\text{)}} > 1$ ft
  - When minimum dimension > 3 ft

- Drilled Shaft Diameter Limit
  - When diameter > 6 ft (FDOT 2006)
Geometry Criterion Applied to Shafts

![Graph showing the relationship between shaft length and volume-to-area ratio for different shaft diameters. The graph illustrates how mass concrete varies with shaft length for different shaft diameters (3, 4, 5, 6, 7, 8). The Volume/Area Threshold is indicated on the graph.]
Case Studies: Hoover Dam

- Built 1932 - 1935
- More than 5 million yd$^3$ of concrete
- Equivalent to 2 lane road coast to coast (w/sidewalks)
- 600 miles of 1” steel cooling tubes
- 100 yr estimated cooling
Ringling Causeway Bridge

- Built 2001-2003
- 9 ft diameter shafts
- Standard FDOT shaft mix (4 ksi)
- Winter construction
- No cooling system
Ringling Causeway Bridge Shaft Curing Temperature

- Peak 156°F (69°C)
- Max Diff. 67°F (37°C)

Temperature (degrees F): 0, 20, 40, 60, 80, 100, 120, 140, 160, 180

Temperature (degrees C): -18, -8, 0, 2, 12, 22, 32, 42, 52, 62

- Center
- Edge
- Bay Water
- Air

Dates: 25-Feb-02, 27-Feb-02, 01-Mar-02, 03-Mar-02, 05-Mar-02, 07-Mar-02
Predicting Mass Concrete Conditions

- Must know mix design with detailed cement and flyash reports (can change monthly)
- Must know geometry of shaft or other concrete element in question
- Must know environmental conditions (e.g. air temp, soil type, soil temp, etc.)
Hydration Energy
(Schindler, 2005)

Cement Energy Production

\[ H_{cem} = 500p_{C_3S} + 260p_{C_2S} + 866p_{C_3A} + 420p_{C_4AF} + 624p_{SO_3} + 1186p_{\text{FreeCaO}} + 850p_{\text{MgO}} \]

Total Energy Production

\[ H_u = H_{cem} \cdot p_{cem} + 461 \cdot p_{SLAG} + h_{FA} \cdot p_{FA} \]
Hydration Energy
(Schindler, 2005)

Degree of Hydration

$$\alpha(t_e) = \alpha_u \cdot \exp\left(-\left[\frac{\tau}{t_e}\right]^\beta\right)$$

Rate of Energy Production

$$Q_H(t) = H_u \cdot C_c \cdot \left(\frac{\tau}{t_e}\right)^\beta \cdot \left(\frac{\beta}{t_e}\right) \cdot \alpha(t_e) \cdot \frac{E}{R}\left(\frac{1}{273 + T_r} - \frac{1}{273 + T_c}\right)$$
Input Parameters
(from concrete supplier)

\[ \alpha_u = \frac{1.031 \cdot w/cm}{0.194 + w/cm} + 0.50 \cdot p_{FA} + 0.30 \cdot p_{SLAG} \leq 1.0 \]

\[ \beta = 181.4 \cdot p_{C_3A}^{0.146} \cdot p_{C_3S}^{0.227} \cdot Blaine^{-0.535} \cdot p_{SO_3}^{0.558} \cdot \exp(-0.647 \cdot p_{SLAG}) \]

\[ \tau = 66.78 \cdot p_{C_3A}^{-0.154} \cdot p_{C_3S}^{-0.401} \cdot Blaine^{-0.804} \cdot p_{SO_3}^{-0.758} \cdot \exp(2.187 \cdot p_{SLAG} + 9.50 \cdot p_{FA} \cdot p_{FA-CaO}) \]
Ringling Causeway Bridge
(Modeled and Measured)
Shaft Core Temperature
Single Shaft Heat Signature
Thermal Integrity Evaluation

- Drilled shafts lack reliable means of assuring good quality construction outside reinforcing cage.
- Temperature generation in concrete provides a useful mechanism to detect anomalies in shafts.
Why Test Shaft Integrity?
Why Test Shaft Integrity?
Why Test Shaft Integrity?
Why Test Shaft Integrity?

- Quality Assurance of drilled shafts relies heavily on good construction practices.
- The most popular method of post construction evaluation is Cross Hole Sonic Logging which cannot detect anomalies outside the cage.
- New thermal integrity method uses Infra-red Thermal Imaging of the entire shaft length.
Cross-hole Sonic Logging

- Drilled Shaft
- Reinforcement Cage
- CSL Logging Tubes
- Anomaly
Sonic Echo Testing

Drilled Shaft

Anomaly Formation

Anomaly Reflection

Signal

Toe Reflection

Signal
Thermal Integrity Evaluation

- Drilled Shaft
- Reinforcement Cage
- Logging Tubes
Thermal Integrity Evaluation

- Drilled Shaft
- Reinforcement Cage
- Logging Tubes
- Normal Heat Signature
Thermal Integrity Evaluation

- Drilled Shaft
- Reinforcement Cage
- Logging Tubes
- Anomaly
Thermal Integrity Evaluation

Anomaly

Drilled Shaft

Reinforcement Cage

Logging Tubes

Interrupted Heat Signature
Thermal Integrity System

- Depth encoder
- Access Tubes
- Lead Wire to Infrared Probe
Field Trials – RW Harris Site

- Site Layout & Construction
- Instrumentation
- Infrared Integrity Testing
- Cross-hole Sonic Logging
- Pile Integrity Testing
Site Layout

- 4 Thermal Monitoring Access Tubes
- 1 Water Table Well (W.T. 20 inches Below Surface)
Drilled Shaft Construction

- 48 in. diam.; 25 ft deep
- Polymer Slurry
- 54 in. Temporary Casing (6 ft Depth)
- Concrete Parameters
  - $F'c = 4000 \text{ psi}$
  - Slump = 6 to 9 inches
  - $w/c$ ratio = 0.43
  - Coarse Aggregate = #57 Stone
Reinforcement Cage

- 36 in Diameter
- 16 – No. 11 Reinforcement
- No. 4 Shear Reinforcement @ 12 in O.C.
- 6 Logging Tubes (3 PVC & 3 Steel)
- 2 Levels of Sand Bag Anomalies
Instrumentation

- 16 Thermal Couples
- 2 Levels of 4 Strain Gages
Logging tube 1ft from edge

Logging tube 8ft from edge

Test Shaft

Logging Tubes

183F Peak Core

Reinforcement Cage
Signal Matched Results
Cross-hole Sonic Logging Results

Tubes 4 - 6

Tubes 2 - 4

Tubes 2 - 6

Cross-section A
Top Anomaly

Cross-section B
Bottom Anomaly

Steel Logging Tubes

Known Anomaly

PVC Logging Tubes

CSL Logging Tubes

Thermal Logging Tubes

2 6 4

A

B
Pile Integrity Testing
Pile Integrity Test Results

Known Anomaly (approx. 8 ft down)

Second anomaly (16 ft) not detected
Thermal Integrity Evaluation

- Field Measurements
- Model Soil / Shaft System
- Compare Predicted and Measured
- Signal Match Model Results

Modeled shape determines amount/degree of anomalous conditions
St. Augustine Bridge of Lions
Bridge of Lions
Pier 25 – Shaft 3
3ft diameter
Concreting Curve

Depth (ft/m)

Concrete Volume Placed (cy/m³)

Theoretical Volume
Cage Alignment
Cage Alignment
WSDOT Nalley Valley I-5/SR16
Modeled and Measured Core and Tube Temps
Cage Alignment

Temperature (deg F)

Depth (ft)

T1_1
T2_2
T3_2
T4_2
T5_2
T6_2
T7_2
T8_2
T9_2
T10_2
Average

TUBE 1

Increasing Tube Nos.

N

40 ft

125F

150F

175F
Cage Alignment

Temperature (deg F)

Depth (ft)

T1_1
T2_2
T3_2
T4_2
T5_2
T6_2
T7_2
T8_2
T9_2
T10_2
Average

45 ft

Increasing Tube Nos.

N

TUBE 1

125F
150F
175F

45 ft
Cage Alignment

Temperature (deg F)

Depth (ft)

T1_1
T2_2
T3_2
T4_2
T5_2
T6_2
T7_2
T8_2
T9_2
T10_2
Average

TUBE 1

Increasing Tube Nos.

N

125F
150F
175F

50 ft
Cage Alignment

Temperature (deg F)

Depth (ft)

- T1_1
- T2_2
- T3_2
- T4_2
- T5_2
- T6_2
- T7_2
- T8_2
- T9_2
- T10_2

Average

55 ft

Increasing Tube Nos.

TUBE 1

N

125F
150F
175F

55 ft
Cage Alignment

Temperature (deg F)

Depth (ft)

T1_1
T2_2
T3_2
T4_2
T5_2
T6_2
T7_2
T8_2
T9_2
T10_2
Average

Increasing Tube Nos.

N

TUBE 1

125F
150F
175F

60 ft
Cage Alignment

Temperature (deg F) vs. Depth (ft)

- TUBE 1
- Increasing Tube Nos.

65 ft
Cage Alignment
(at 40 ft)

- Highest Measured Temp
- Lowest Measured Temp
- Lateral Temp Dist (model)
- Cage Diameter at tubes
- Excavation Diameter
- Worst Case Cover (7.5in)

Depth 40 ft

Temperature (F)

Horizontal Position
Thermal Testing Timeframe
4000-P Mix Design

Temperature (deg F)

Diameter
- 4ft Diameter
- 6ft Diameter
- 8ft Diameter

Optimal Testing Window
Acceptable Testing Window

Time (hrs)
Conclusions

- Infra-red Thermal Integrity testing shows remarkable capabilities to detect anomalies outside the reinforcing cage (bulges and necks).
- Cross-hole Sonic Logging showed no problems with the shaft integrity in spite serious cross sectional reduction.
- Pile Integrity Testing showed an irregularity of unknown proportion at one of the two anomaly locations but not the second.
Conclusions

- Cage alignment is easily identified and can confirm minimum cover / cage alignment
- Thermal modeling provides insight into a normal shaft signature as well as mass concrete conditions
- Thermal models can be signal matched field measurements to ascertain location and size of anomalies.
Infrared Integrity Services available at http://foundations.cc/