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<tr>
<th>Option</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
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<td>TRANSPO</td>
<td>14.581.201 Engineering Systems Analysis (Gartner) (see note below)</td>
<td>14.548.201 Traffic Management and Control (Xie)</td>
<td>14.505.201 Concrete Materials (Yu)</td>
<td>14.576.201 GIS Applications in Civil and Environmental Engineering (Xie)</td>
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<tr>
<td>GEOTECH</td>
<td>14.534.201 Soil Dynamics &amp; Earthquake Eng. (DeStefano)</td>
<td>14.532.201 Theoretical Soil Mechanics (Hajduk)</td>
<td>14.527.201 Geotechnical &amp; Environmental Site Characterization (Kurup)</td>
<td>14.530.201 Driven Deep Foundations (Palkowsky)</td>
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<td>ENVIRON</td>
<td>14.567.201 Environmental Aquatic Chemistry (Zhang)</td>
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<td>14.561.201 Physical and Chemical Treatment Processes (Zhang)</td>
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<td>18.502.001 Limnology (Mitchell)</td>
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<td></td>
<td>18.581.001 Understanding the MA Contingency Plan* (Fitzgerald)</td>
<td></td>
</tr>
</tbody>
</table>

**Great Theory Courses:**
- 14.530.201 Driven Deep Foundations (Palkowsky)
- 14.534.201 Soil Dynamics & Earthquake Eng. (DeStefano)

**Structural/Geotech:**
- 14.581.201 Engineering Systems Analysis (Gartner) (see note below)
- 14.567.201 Environmental Aquatic Chemistry (Zhang)

**Structural/CMT:**
- 14.505.201 Concrete Materials (Yu)
- 14.548.201 Traffic Management and Control (Xie)

**Geotechnical Design:**
- 14.532.201 Theoretical Soil Mechanics (Hajduk)
- 14.527.201 Geotechnical & Environmental Site Characterization (Kurup)
14.532 THEORETICAL SOIL MECH.

Course Outline

- Introduction & Review
- Linear Elasticity
- Rigid Plasticity
- Soil-Structure Interaction
- Steady-State Flow
- Unsteady State Flow

Course Grading

- Weekly Assignments (50%)
- Mid-Term (25%)
- Final Exam (25%)
WHY PERFORM DEEP FOUNDATION NDT?

NDT Accomplishes 3 Major Tasks

• Verifies Construction
  – Integrity (PDA/CSL/PIT)
• Verifies Design
  – Capacity (SLT/PDA)
• Streamlines Design & Installation

“One test result is worth 1000 expert opinions.” - Werner von Braun
WHY PERFORM DEEP FOUNDATION NDT?

Driven Pile Overstressing

Photographs courtesy of
FHWA NHI-132069 Driven Pile Foundation Inspection Course &
FHWA NHI-132070 Drilled Shaft Foundation Inspection Course

Poor Drilled Shaft Construction
WHY PERFORM DEEP FOUNDATION NDT?

Photograph courtesy of Bengt Fellenius
Common Deep Foundation NDT

High Strain Dynamic Load Testing
(commonly called PDA)

Static Load Testing (SLT)
14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

**COMMON DEEP FOUNDATION NDT**

**Crosshole Sonic Logging (CSL)**
Variations: Singlehole Sonic Logging (SSL), Crosshole Tomography (CT)

**Low Strain Testing**
(a.k.a Pulse Echo, Sonic Echo, Impulse Echo, PIT)

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Deep Foundation NDT

N OT S O C O M M O N D E E P F O U N D A T I O N N D T

Rapid Load Testing
(e.g. STATNAMIC)

Gamma-Gamma Logging
(GGL)

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Figures courtesy of Berminghammer & WPC Inc.

Figure courtesy of FHWA NHI-10-016
“New” Deep Foundation NDT

Thermal Integrity Testing (TIT)

Photograph and data from Mullins (2009)
STATIC LOAD TESTING (SLT)

Common Testing Standards

- Axial Compressive (ASTM D1143-07ε1)
- Axial Tension (ASTM D3689-07)
- Lateral (ASTM D3966-07)
- Osterberg Cell (None)

Applicable Foundations

- Driven Piles
- ACIP
- Drilled Shafts
- Micropiles

Basic Premise
Load Pile, Measure
Load & Displacement

Lateral Load Test
Southern LNG Plant, Savannah GA
**STATIC LOAD TESTING (SLT)**

**What It Provides:**
- Load-Displacement Relationship
- Foundation Capacity (open to interpretation)
- Skin & Toe Distributions (if instrumented)
- Creep Characteristics (dependent on test)

**What It Doesn’t Provide:**
- Foundation Capacity (if not loaded to failure)
- Skin & Toe Distributions (if not instrumented)
- Integrity Evaluation

---

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Deep Foundation NDT

STATIC LOAD TESTING (SLT)

Kentledge (Dead Wt.) System

Reaction Piles

Figures courtesy of Dr. Kyle Rollins and Dr. Dan Brown, PDCA Professors Driven Pile Course (2007).
AXIAL COMP. STATIC LOAD TESTING SETUP

- Reaction beam
- Stiffeners
- Load cell
- Spherical bearing
- Ram
- Bourdon Gage
- Dial Gage
- Bracket attached to pile
- Wire
- Scale
- Mirror
- LVDT
- Stem reaction plate
- Test Pile

Figure courtesy of FHWA NHI-132069 Driven Pile Foundation Inspection Course
AXIAL COMP. STATIC LOAD TESTING SETUP

See also NYS DOT Static Load Test Manual.

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Deep Foundation NDT

STATIC LOAD TESTING (SLT) RESULTS

Figure 7.17: Effects of Multiple Load Cycles on a CFA Pile (FHWA GEC 8).

Figure 1 – The Offset Method (Fellenius 2001).
14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

STATIC LOAD TESTING (SLT) RESULTS

STATIC LOAD TEST DATA
Test File: TP#2
Test: TP#2 SLT7
Date(s): 10/22/97 to 10/24/97
Time: 1 Year
Type: Slow Maintained
Remarks: None
Capacity: 685 kN

Results from Hajduk (2006)
AXIAL COMPRESSION SLT
LOADING RATE

ASTM D1143 Procedures
A. Quick Test (5% Load Incr., 4-15 min Load Held)
B. Maintained Test (25% Load Incr., Creep Dependent)
C. Loading in Excess of Maintained (Reload Procedure B)
D. Constant Time Interval (20% Load Incr., 1 hr Load Held)
E. Constant Rate of Penetration (see ASTM)
F. Constant Movement Increment (see ASTM)
G. Cyclic Loading Test (see ASTM)
AXIAL COMPRESSION SLT
LOADING RATE

Time (hours)

Time (sec)

Load (kN)

Figure derived from data from Hajduk (2006).
Static Load Test Results, 12inch SQ PSC Pile (from Hajduk et al. 1999).
AXIAL COMPRESSION SLT

EFFECT OF LOADING RATE

Figure courtesy of Dr. Kyle Rollins and Dr. Dan Brown, PDCA Professors Driven Pile Course (2007).
Common Gauges

- Strain Gauges
  - Vibrating Wire
  - Electrical Resistance
  - Fiber Optic

- Tell-Tales
  - Dial Gauges
  - Extensometers
  - LVDT's

Figures from ASTM D1143 and Rollins and Brown (2007).
SLT INSTRUMENTATION

Other Gauges

- Piezometers
- Accelerometers
- Total Pressure Cells
- Inclinometers
  - MEMS

Figures from Hajduk (2006)
14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

STATIC LOAD TESTING (SLT) RESULTS

Results from Hajduk (2006)
Axial SLT Interpretation

Davisson Failure Criteria (Offset Method)

Load = $\varepsilon(\text{AE})$

- What is area?
- What is concrete modulus?
- What is precision of strain measurement?
- Residual Stresses?

Applied Load, $Q$

Settlement

$D/120 + 0.15\text{ in}$

$QL/\text{AE}$

$L/\text{AE}$
AXIAL SLT INTERPRETATION

OTHER METHODS (FELLENIUS 2001)

Other Methods
- Mazurkiewicz
- Norlund and Hoy’s
- Fuller and Hoy’s
- Vander Veen’s
- $\Delta = 1$ inch
- Static-Cyclic
HIGH STRAIN DYNAMIC LOAD TESTING (PDA)

ASTM D4945-08

Basic Premise
Every Hammer Blow with Set
= Load Test to Failure

Applicable Foundations:
- Driven Piles
- ACIP
- Drilled Shafts (Small Diameter)
- Micropiles
- SPT Energy Calibration

PSC Pile Installation
CofC Addlestone Library,
Charleston, SC

Micropile PDA testing with Drop
Weight Hammer
(Hajduk et al., 2005)
14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

HIGH STRAIN DYNAMIC LOAD TESTING (PDA)

What It Provides:
• Hammer Performance
• Pile Installation Stresses
• Pile Integrity
• Pile Capacity @ Time of Test
  – Case Method ($J_c$) (Site Specific)
  – CAPWAP
  – Skin/Toe Distribution
  – Simulated Static Load-Displacement

What It Doesn’t Provide:
• Actual Pile Capacity (for low sets)
• Creep Characteristics
• Pile Setup Characteristics
  (without additional Tests)
HIGH STRAIN DYNAMIC LOAD TESTING (PDA)
14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

HIGH STRAIN DYNAMIC LOAD TESTING (PDA)

- Project Data
- Pile Information
- Output Quantities
- Pile Information
- Force & Velocity Traces
- Pile Stresses
- Integrity
- Energy Delivered
- Capacity (Case Method)
HIGH STRAIN DYNAMIC LOAD TESTING (PDA)

Typical Results (using PDI Plot)

1 - 16 min Stop, Restrike, (10/1.25\textdegree), 3\textdegree Stroke
2 - 1450 min Stop, Restrike, (10/0.63\textdegree), (7/0.38\textdegree), (6/0.75\textdegree)
3 - Static Load Test

4 - 15 day Stop, Restrike, (7/0.03\textdegree), 1.5\textdegree Stroke
5 - 2 min Stop, (10/0.09\textdegree), 3\textdegree Stroke
6 - 2 min Stop, (10/0.09\textdegree), (14/0.31\textdegree), (18/0.56\textdegree), (19/14,16,18/1\textdegree), (19/1.25\textdegree)
HIGH STRAIN DYNAMIC LOAD TESTING (PDA)

Figure B. Pile 6N PDA Measurements relative to Depth during Pile Installation.
14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

SIGNAL MATCHING ANALYSIS (CAPWAP)

Computed and Measured Traces

Skin Friction Distribution

Soil/Pile Properties

BC/Match Data

Model

Figure courtesy of GRL Engineers
14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

Signal Matching Analysis (CAPWAP)

Measured/Computed Match

Simulated Static Load-Displacement Relationship

Measured PDA Data

Force in Pile

Skin Distribution

Revised 11/2012
### SLT/PDA COMPARISON

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dynamic Load Test (DLT)</strong></td>
<td>• Pile is tested during driving - real time</td>
<td>• Not as accurate as SLT (Maybe. Dependant on many factors)</td>
</tr>
<tr>
<td>(ASTM D4945)</td>
<td>• Results immediately available</td>
<td>• Requires experienced operator in field/engineer for analysis</td>
</tr>
<tr>
<td></td>
<td>• Economical versus SLT</td>
<td>• Relies on sensors (and maybe cables) that can slow work</td>
</tr>
<tr>
<td></td>
<td>• Reduces time for testing piles (multiple tests/day possible)</td>
<td>• No lateral loading</td>
</tr>
<tr>
<td></td>
<td>• Provides integrity evaluation, driving stresses, can detect installation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>problems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Repeatable</td>
<td></td>
</tr>
<tr>
<td><strong>Static Load Test (SLT)</strong></td>
<td>• Pile is tested w/load similar to that imposed by structure</td>
<td>• Cost</td>
</tr>
<tr>
<td>(ASTM D1143, D3689)</td>
<td>• Extensive instrumentation possible</td>
<td>• Time consuming</td>
</tr>
<tr>
<td></td>
<td>• Repeatable</td>
<td>• Extensive setup &amp; teardown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Extensive manpower and equipment</td>
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</table>
# Load Testing (SLT/PDA) ASD Design

<table>
<thead>
<tr>
<th>Construction Control Method</th>
<th>PDCA 2001</th>
<th>AASHTO 1992</th>
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<td>ASCE 20-96&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>16 to 40 tons</td>
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<td>3.0</td>
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<td>3.0</td>
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<tr>
<td>PDA</td>
<td>1.9 to 2.1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.25</td>
<td>≥ 2</td>
<td>SCDOT (1991)</td>
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<td></td>
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<td>2.25&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>SLT</td>
<td>1.65 to 1.9</td>
<td>2</td>
<td>≥ 2</td>
<td></td>
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<td>1.5 to 1.9</td>
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<td>1.6 to 1.9</td>
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<td>1.6 to 1.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>

<sup>a</sup> Depends on pile type, site variability, loading conditions, etc. See Standard for further details.

<sup>b</sup> Requires signal matching analysis.

<sup>c</sup> With WEAP.

---

**after Likins (2003)**
CROSSHOLE SONIC LOGGING (CSL)

What It Provides:

- Integrity Evaluation (Initial and Repairs)
  - Along entire Shaft length
  - Size and location of anomalies (2D and 3D)

What It Doesn’t Provide:

- Foundation Capacity

Basic Premise
Send & receive UPV signals across concrete to detect irregularities

FHWA NHI-10-016
(Drilled Shaft Manual)
“Of the available test methods, Cross-hole Sonic Logging (CSL) is the preferred method (for Drilled Shaft Integrity Testing)"

Applicable Foundations:

- CIP Piles (ACIP, DSDP, etc.)
- Drilled Shafts

West Tower Drilled Shaft Foundations
Arthur Ravenel Jr. Bridge, Charleston SC
CROSSHOLE SONIC LOGGING (CSL)

Typical Setup

Field Operations

Access Tubes (PVC)

Pulley/Depth Wheels

Drilled Shaft

DAS

Yours Truly

Typical Setup
CROSSHOLE SONIC LOGGING (CSL) VARIATIONS

Crosshole Sonic Logging (CSL)

Singlehole Sonic Logging (SSL)

Crosshole Tomography (CT)

Needs PVC Access Tubes
CROSSHOLE SONIC LOGGING (CSL) ANALYSIS

FAT = First Arrival Time

Apparent Wavespeed
(c or \( V_c \))

\[ V_c = \frac{\alpha E}{\sqrt{\rho}} \]

\[ \alpha = \frac{1-v}{(1+v)(1-2v)} \]

Low density, voids, soil intrusions or other anomalies result in a delayed/absent and reduced strength signal.

Results with Depth
# Crosshole Sonic Logging (CSL) Analysis

**FHWA NHI-10-016 Table 20-2**

Concrete Condition Rating Criteria (CCRC)

<table>
<thead>
<tr>
<th>Rating</th>
<th>Symbol</th>
<th>Apparent Wavespeed Reduction</th>
<th>Signal Distortion/Strength</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>G</td>
<td>&lt;10%</td>
<td>≤ 6 dB</td>
<td>Good quality concrete</td>
</tr>
<tr>
<td>Questionable</td>
<td>Q</td>
<td>10% - 20%</td>
<td>6.1 to 9 dB</td>
<td>Minor contamination or intrusion and/or questionable concrete quality.</td>
</tr>
<tr>
<td>Poor/Defect</td>
<td>P/D</td>
<td>&gt; 20%</td>
<td>&gt; 9 dB</td>
<td>Results indicative of water slurry contamination or soil intrusion and/or poor quality concrete</td>
</tr>
<tr>
<td>No Signal</td>
<td>NS</td>
<td>No Signal</td>
<td>None</td>
<td>Highly probable that a soil intrusion or other severe defect has absorbed the signal</td>
</tr>
<tr>
<td>Water</td>
<td>W</td>
<td>≈ 60%</td>
<td>≥ 12 dB</td>
<td>Indicative of a water intrusion or of water filled gravel intrusion with few or no fines present</td>
</tr>
</tbody>
</table>

**Results with Depth**

- **Debonding**: First Arrived Time (FAT) (Microseconds)
- **Defect**: Relative Energy
- **Soft Bottom**: ENERGY (VOLT-MICROSECOND)

---

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14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

CROSSHOLE SONIC LOGGING (CSL) EXAMPLE

CSL Results
Date Tested: 10/14/02
Diameter: 125 in O.D. Steel Casing

Remarks: Date Concrete Poured: 10/22/2002
WPC CSL Engineer(s): MRL/BLH

<table>
<thead>
<tr>
<th>Filter 1</th>
<th>Filter 1</th>
<th>Filter 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORE 1</td>
<td>CORE 2</td>
<td>CORE 3</td>
</tr>
<tr>
<td>Design f'c</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Elevation (ft)

Compressive Strength (ksi)

KEY:
- CSL ANOMALY ZONE
- HONEYCOMBING
- SAND
- AIR VOIDS
- DETECTED VOID
- GRAVEL

Subsequent Analysis
Inspection Coring
CROSSHOLE SONIC LOGGING (CSL) EXAMPLE

The Use of Crosshole Tomography to Evaluate Drilled Shaft Repairs
(Chernauskas and Hajduk, 2009)
CROSSHOLE SONIC LOGGING (CSL)

Key Terms (after Amir 2002)

- **Anomaly**: Any irregular feature identified in the NDT results.
- **Flaw**: Any deviation from the planned shape and/or material of the shaft.
- **Defect**: A flaw that, because of either size or location, may detract from the shaft’s intended performance.
Most Anomalies linked to Construction (especially tremie removal)
LOW STRAIN INTEGRITY TESTING (PIT)  
ASTM 5882-07

What It Provides:
• Integrity Evaluation
• Length Evaluation

What It Doesn’t Provide:
• Foundation Capacity
• Detailed Anomaly Analysis

Basic Premise
Send low strain pulse down foundation to detect irregularities from wave reflections

Applicable Foundations:
• Timber Piles
• CIP Piles (ACIP, DSDP, etc.)
• Drilled Shafts
• Concrete Structures
LOW STRAIN INTEGRITY TESTING (PIT)

Typical Setup

Field Testing
LOW STRAIN INTEGRITY TESTING (PIT)

Dependant on Wavespeed (c)

\[ c = \sqrt{\frac{E}{\rho}} \]

Factors Affecting Wavespeed:
- Moisture Content (timber)
- Strength (\(f'_{c}\))
- Voids/Inclusions

Typical Setup
FHWA NHI-10-016

REMEMBER:
- PIT is one part of inspection process.
- Good PIT testing links results to inspection records.

Results

Hammer Strike
Reflection from Bottom of Shaft
Second Reflection from Bottom of Shaft

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LOW STRAIN INTEGRITY TESTING (PIT)

LIMITATIONS (after DFI 2004 and FHWA NHI-10-016):

• Clean undamaged concrete must be accessible.
• Multiple reflections from shaft cross-section and soil stiffness variations can complicate responses and mask detail, increasing the risk of misinterpretation.
• Unlikely to detect base response where length/diameter ratio of shaft exceeds 10:1 (rock), 20:1 (stiff/hard soils), 40:1 (medium stiff soils, 60:1 (soft soils).
• Unable to determine geometry, length (thickness) or lateral position of any anomaly.
• Accuracy of shaft depth interpretation is plus or minus 10%.
• Requires experience to interpret the data.

Most ACIP Contractors DO NOT like/trust this test method
14.528 DRILLED DEEP FOUNDATIONS
Deep Foundation NDT

Thermal Integrity Testing (TIT)
No ASTM

What It Provides:
• Integrity Evaluation
  – Along entire shaft length
  – Outside of reinforcing cage
  – Size and location of anomalies
• Cage Alignment Evaluation

What It Doesn’t Provide:
• Foundation Capacity

Basic Premise
Monitor thermal signature of concrete for deviations.

Applicable Foundations:
• CIP Piles (ACIP, DSDP, etc.)
• Drilled Shafts

From Mullins (2009)
REQUIREMENTS FOR ALL SUCCESSFUL DEEP FOUNDATION PROJECTS

1st Leg: Design (Geotechnical)

2nd Leg: Construction

3rd Leg: Inspection (CMET)

NDT is only one part of 3rd Leg (Inspection). Needs to be used in conjunction with all available data (e.g. installation records)

Revised 11/2012
DEEP FOUNDATION NDT SUMMARY

- Verifies Construction Techniques (PDA/CSL/PIT)
- Produces Confidence in Construction Process
- Confirms Foundation Design and Capacity (SLT/PDA)