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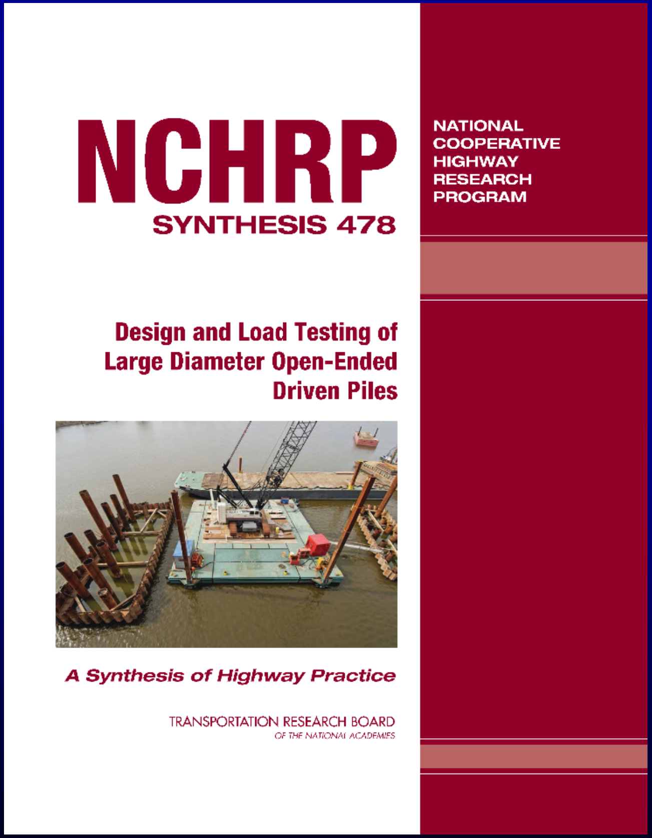
NCHRP Synthesis 478

Design and Load Testing of Large Diameter Open-Ended Driven Piles



Objectives

- Understand the key items learned from the synthesis process (literature review and interviews)
- Summarize practices being used by state DOTs, illustrated by case history examples

Objectives

- Key items learned
  - Development and influence of a soil plug in a pile
  - Static analysis methods
  - Drivability issues and criteria
  - Dynamic testing

Objectives

- Key items learned
  - Static testing
  - Lessons from outside the transportation sector

Definitions

and

Background

Large Diameter Open Ended Piles (LDOEPs)

- Driven pile
  - Tubular steel
  - Prestressed concrete cylinder
- 36 inches outside diameter or larger

Steel Pipe Piles

- <u>Spiralweld:</u> Continuously welded spiral from coiled sheet

- <u>Rolled and welded:</u> Plate steel rolled and welded

photos courtesy Skyline Steel

Concrete Pipe Piles

- Spun Cast or Bed Cast
- Prestressed
- Post-tensioned

photo courtesy Gulf Coast Prestress

Typical LDOEP Applications

- High lateral load demands (often due to extreme event loading)
- High axial demand
- Deep weak soils

Typical LDOEP Applications

- Eliminate the need for a footing by using a pile bent
- Marine construction - delivery, handling, and installation
- Significant unsupported length (scour, liquefaction, marine conditions)

Unique Challenges of LDOEPs

- Uncertainty of “plug” formation during installation

- Potential for installation difficulties and pile damage during driving is unlike other types of conventional bearing piles

Unique Challenges of LDOEPs

- Soil column within the pile may behave differently during driving or dynamic testing compared with static loading
- Axial resistance from internal friction
- Verification of nominal axial resistance is more challenging and expensive

Key Items Learned
From
Synthesis Process

Objectives

- Key items learned
  - ***Development and influence of a soil plug in a pile***
  - Static analysis methods
  - Drivability issues and criteria
  - Dynamic testing

A Simplified Examination of the Dynamic Behavior of a Soil Plug

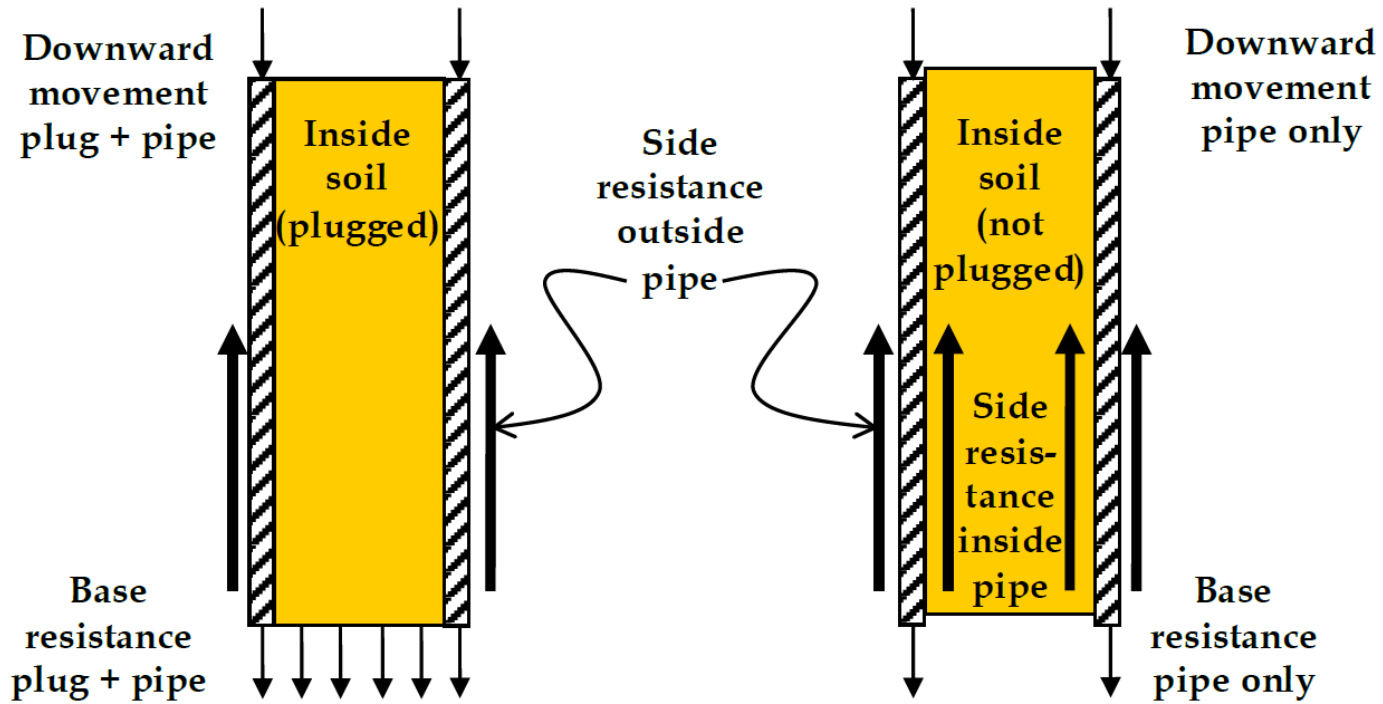


FIGURE 4 Schematic of a soil plug inside a pipe pile

A Simplified Examination of the Dynamic Behavior of a Soil Plug

- Pile often advances without plugging due to soil plug inertial resistance
- Acceleration of an LDOEP during driving >30g (Stevens, 1988)
- Inside unit side resistance too low to resist accelerations

Objectives

- Key items learned
  - Development and influence of a soil plug in a pile
  - ***Static analysis methods***
  - Drivability issues and criteria
  - Dynamic testing

Design for Axial Loading

- Nominal axial resistance determined from driving resistance

- Static computations serve as guide for estimating length

Design for Axial Loading

- Axial Resistance in Clay Soils (“alpha”)
- Axial Resistance in Sands (“beta”)
- Methods Utilizing CPT Data (API RP2 GEO 2011)
- Methods Specific to Prestressed Concrete LDOEPs (FDOT)

Design for Axial Loading

- API RP2 GEO 2011
  - Current state of practice for design for offshore industry
  - Long history of use
  - Slight differences from FHWA “alpha” and “beta” based on offshore experience
  - Several CPT-based methods
    - ICP-05, UWA-05, NGI05, Fugro05

Resistance Factor Selection

- Current (2013) AASHTO guidelines do not specifically represent LDOEPs.
- Based largely on NCHRP Report 507 (Paikowsky (2004))
  - A very small number of open ended pipe piles.
  - LDOEPs are not documented separately from smaller piles

Design for Lateral Loading and Serviceability

- Not different than for other deep foundations
- Consider contribution to lateral stiffness of concrete plug at top of pile (connection)
- Consider soil plug/column contribution to axial stiffness

Objectives

- Key items learned
  - Development and influence of a soil plug in a pile
  - Static analysis methods
  - ***Drivability issues and criteria***
  - ***Dynamic testing***

Considerations Affecting Behavior of Steel LDOEPS

- Base Resistance of Steel LDOEPs on Rock and Driving Shoes
  - Shoe increases diameter – inside vs. outside
  - Shoe height and buckling of toe
  - Sloping rock

Considerations Affecting Behavior of Steel LDOEPS

- Vibratory Driving and Splicing
- Effect of Pile Length on Behavior and Axial Resistance
  - Reduced side resistance (remolding, friction fatigue, etc.)
  - Elastic compression enduring driving
- Time-Dependency of Axial Resistance

Considerations Affecting Behavior of Steel LDOEPS

- Driving Resistance and Dynamic Load Testing
  - Modeling inertial resistance of the soil plug/column
  - Inserts to promote plugging
  - Residual stresses
  - Limitations of hammer mobilizing resistance
  - Detection and avoidance of pile damage during installation

Considerations Affecting Behavior of Concrete LDOEPS

- Pile volume and prestressed concrete LDOEPs
  - Area ratio vs. steel piles – frictional resistance
  - Potential for plugging
  - Soil “bulking” in void
  - Hoop stress / water hammer

Considerations Affecting Behavior of Concrete LDOEPS

- Base resistance of concrete LDOEPs
  - Plugging vs mobilizing cross-section

- Driving Resistance and Dynamic Load Testing
  - Management of driving stresses
  - Splices rare

Objectives

- Key items learned
  - ***Static testing***
  - Lessons from outside the transportation sector

Static Load Testing

- Can be difficult and costly to meet design load for larger piles
- Rapid load test methods (such as Statnamic) becoming common

Objectives

- Key items learned
  - Static testing
  - ***Lessons from outside the transportation sector***

Lessons Learned Outside Transportation

- Dr. D. Michael Holloway, P.E. – Consulting Engineer
- Mr. Mike Muchard, P.E. – Applied Foundation Testing, Inc.
- Mr. Steven Saye, P.E. – Kiewit
- Dr. Robert Stevens, P.E. – Fugro-McClelland Marine Geosciences, Inc
- Mr. Scott Webster, P.E. – GRL Engineers, Inc.

Lessons Learned Outside Transportation

Pile Plugging (or absence of plugging):

- Dominates pile driving behavior
- Difficult to predict
- Treated as choice of plugged or unplugged – actual behavior is in between the two
- General consensus is driving occurs unplugged for most piles

Lessons Learned Outside Transportation

Dynamic Testing Issues:

- Effect of plug behavior on dynamic testing and data interpretation
- Demonstrating full resistance for high loads
- Instrument location and quantity more critical
- Accounting for residual stress from manufacturing
- Pile durability due to trying to achieve high loads

Lessons Learned Outside Transportation

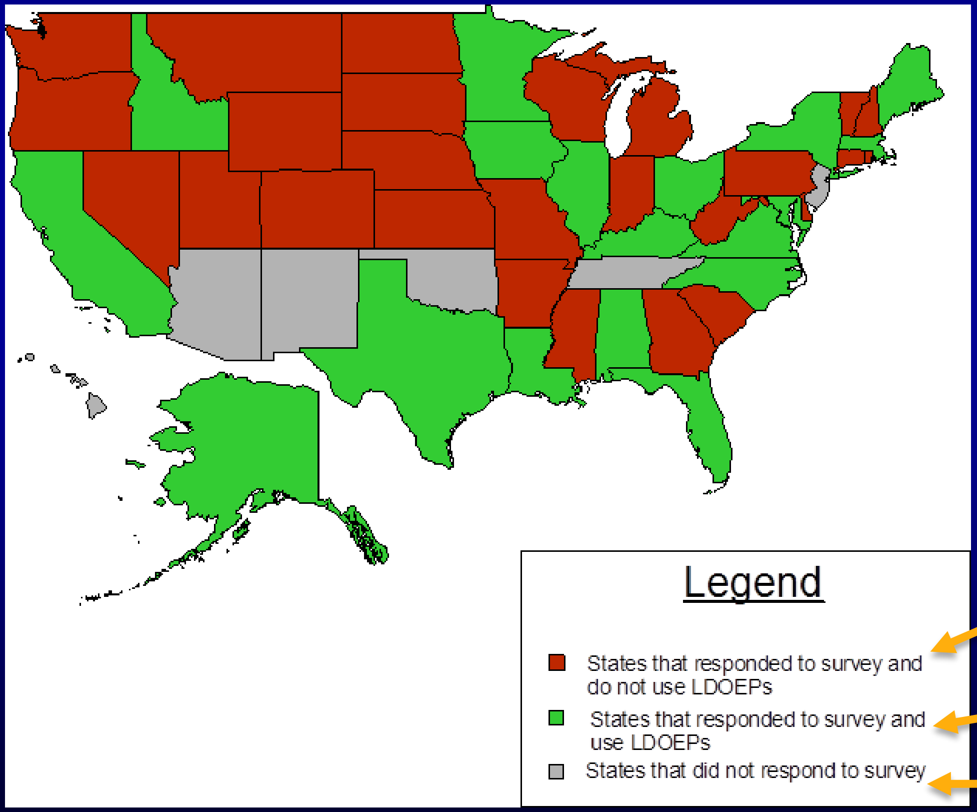
Static Axial Analysis:

- Most widely used methods significantly underestimate pile resistance
- API RP2 GEO from offshore industry consider good predictor of resistance
- Lack of accounting for residual stress

Summary of Current State DOT Practices

Summary of Current State DOT Practices

Survey of 50 State DOTs,
District of Columbia, Puerto Rico



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8

18 Agencies indicated LDOEP experience

NCDOT and MaineDOT are in design phase only (no construction nexperience)

Summary of Current State DOT Practices

- Report focused on responses of the 16 with design and installation experience.
- Telephone interviews with 7 agencies (Bold in red)
  - Most experience
  - Represent different geographic areas and geologic conditions

LDOEP Experience

Alabama (ALDOT)	***Louisiana (LADOTD)***
Alaska (ADOTPF)	*Massachusetts (MassDOT)*
California (Caltrans)	*Maryland DOT*
Florida (FDOT)	***Minnesota (MnDOT)***
Idaho (Idaho DOT)	***New York (NYSDOT)***
Illinois (Illinois DOT)	*Ohio (ODOT)*
Iowa (Iowa DOT)	*Texas (TXDOT)*
Kentucky (KYTC)	*Virginia DOT*

Summary of Current State DOT Practices

Reasons DOTs are NOT using LDOEPs:

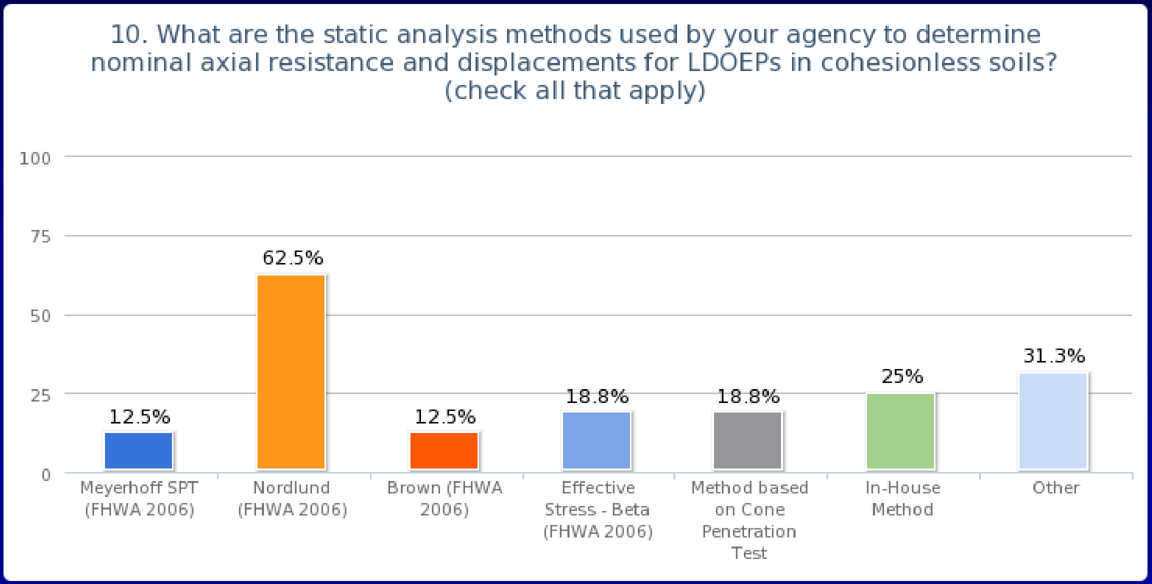
- Not cost-competitive
- Geologic and soil conditions more suited to other
- Lack of expertise and equipment among contractor pool
- Small typical structure size and loads.
- Design not specifically addressed in AASHTO

Summary of Current State DOT Practices

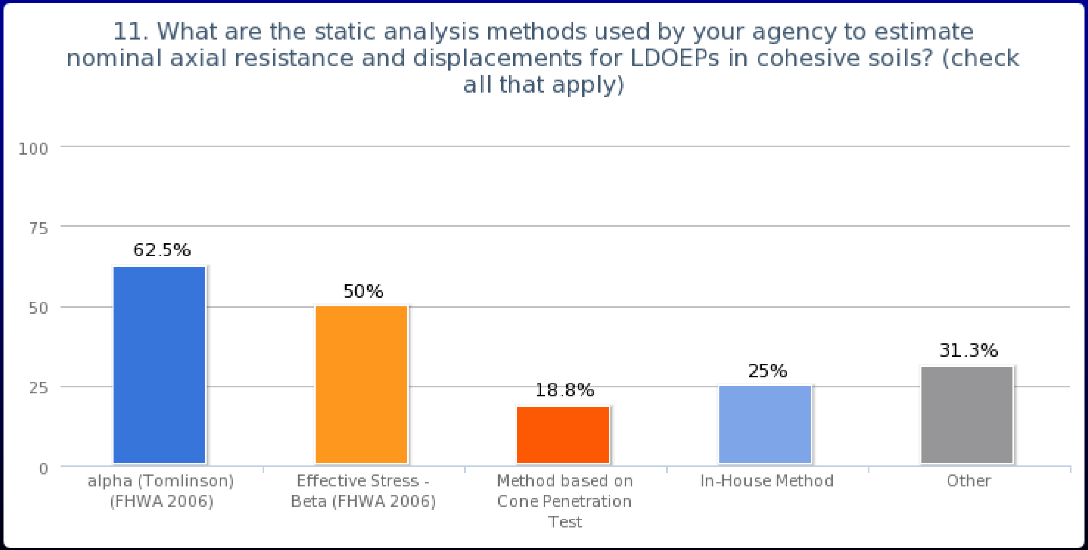
Reasons DOTs are NOT using LDOEPs:

- Specific design issues and questions:
  - Prediction and extent of plugging
  - Determining pile capacity/resistance
  - Length of concrete infill
  - Structural design of concrete-steel section
  - Resistance factor selection
- Concerns over vibrations to adjacent structures.

Summary of Current State DOT Practices



Static Analysis Methods



Summary of Current State DOT Practices

In-house or other methods:

- ADOTPF: modified Beta method from historic dynamic testing (Dickenson, 2012).
- ALDOT: Computer program from test pile data
- FDOT: Software FBDEEP developed by Univ. of Florida
- IDOT: Modified IDOT Static Method (correlations with SPT $N_{(1)60}$ and q_u)
- TXDOT: Texas Cone Penetrometer correlations
- Caltrans and KYTC: API Method

Summary of Current State DOT Practices

Resistance Factor Selection

Current AASHTO Specifications	50.0%	8
My Agency Developed Factors	12.5%	2
Combination of AASHTO and My Agency	31.3%	5
Other Agency or source	6.3%	1

Summary of Current State DOT Practices

Driving Criteria

Drive to a specified tip elevation	18.8%	3
Drive to a minimum tip elevation	56.3%	9
Drive to practical refusal	18.8%	3
Drive to a specified driving resistance (blow count) based on a driving formula	6.3%	1
Drive to a specified driving resistance (blow count) based on a wave equation analysis	43.8%	7
Drive to a specified driving resistance (blow count) based on high strain dynamic tests performed on indicator or test piles	75.0%	12
Drive to a specified driving resistance (blow count) based on static or rapid load tests performed on indicator or test piles, through signal match and wave equation.	43.8%	7
Verify resistance with restrikes	62.5%	10

Summary of Current State DOT Practices

Driving Criteria and Testing:

- Majority use wave equation analysis and/or high strain dynamic testing
- Static, Rapid, and Dynamic load tests very common
- Concerns with analysis of high strain dynamic data, particularly with treatment of soil plug/column
- Difficult to mobilize full resistance of large diameter steel piles on rock

Case Histories

- Hastings Bridge, Minnesota
- St. George Island Bridge, Florida

Case Histories – Hastings Bridge, MN

Key issues:

- Increased reliability through demonstrated pile resistance

- Vibrations on existing structures

Case Histories – Hastings Bridge, MN

Key issues:

- Limitations of dynamic tests to demonstrate fully mobilized pile resistance for piles driven to refusal on rock

- Use of lateral load test for design

Case Histories – Hastings Bridge, MN

- 42-in open-end pipe piles
  - t_w = 1 inch (for impact loads) or 7/8-in
  - Driven to bear on rock
- Axial Statnamic tests
  - 4,600 kips (1 in); 4,200 kips (7/8 in)
  - Maximum deflection about 2-½ inches; permanent sets of around ¼ in.
- Dynamic tests
  - 3,000 to 3,500 kips (Maximum hammer could mobilize)

Case Histories – Hastings Bridge, MN

- Statnamic tests used as basis of design
- Dynamic tests utilized on production piles to demonstrate:
  - that the piles were driven to a good seating on rock
  - that the piles were not damaged
  - that the hammer was performing as intended.

Case Histories – St. George Island, FL

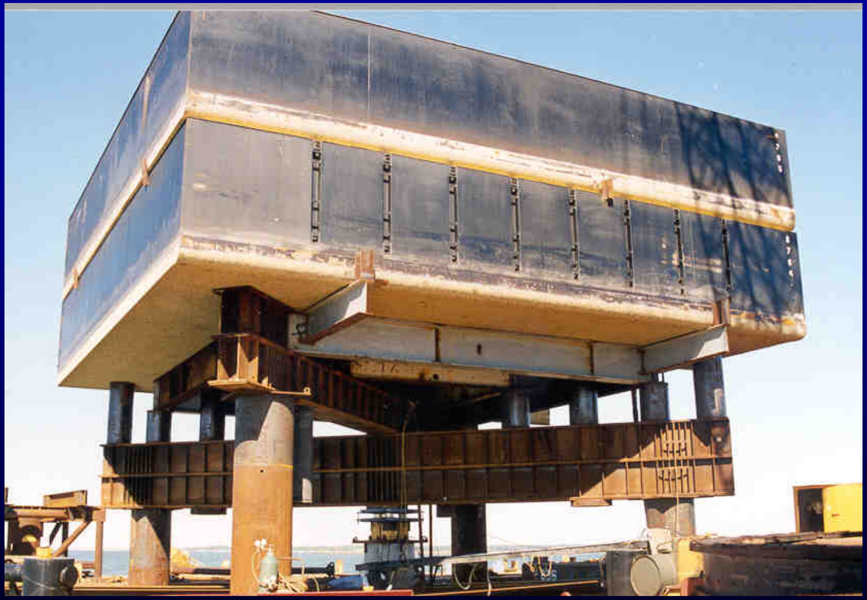
Key issues:

- Assess nominal resistance of underlying Florida limestone
- Determining pile order lengths to meet schedule
- Comparison of axial load testing methods
- Control of longitudinal cracking

Case Histories – St. George Island, FL

Testing Program:

- 4 static load tests
- 6 Statnamic load tests
- 50 dynamic tests on production piles



Case Histories – St. George Island, FL

Summary of test results for St. George Island Bridge (Kemp and Muchard, 2007)

Pile No.	Static Load Test Maximum Capacity (kN/tons)	STATNAMIC Load Test Maximum Capacity (kN/tons)	CAPWAP Restrike Maximum Capacity (kN/tons)
LT-1	9,493 / 1,068	9,627 / 1,083	8,667 / 975
LT-2	13,813 / 1,554	13,564 / 1,526	8,960 / 1,008
LT-3	13,600 / 1,530	13,831 / 1,556	8,089 / 910
LT-5	12,836 / 1,444	11,689 / 1,315	9,013 / 1,014

- Reasonable agreement between static and Statnamic
- Dynamic tests slightly under-predict vs. static

Case Histories – St. George Island, FL

- Longitudinal cracks were observed in 7% of piles, usually within three to four weeks after driving
- Determined to be “water hammer” from build-up of fluid soil inside the pile annulus
- Excess “hoop stresses” resulted in cracking
- Contractor elected to monitor and clean out plug/soil column - no further cracking

Research Needs

- Develop new methods or improve existing methods for calculating static resistance by accounting for the large pile sizes.
- Develop appropriate resistance factors.
- Better understanding of the mechanism of pile plugging, including effectiveness of forcing a pile to plug.

Research Needs

- Determining the most appropriate or applicable failure criteria/mechanism.
- Calibration of resistance factors and static analyses methods to dynamic testing.
- Guidance on how to adequately perform signal matching and wave equation analysis for LDOEPS as compared to smaller piles.

Questions?

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