Improving Design Phase Evaluations for High Pile Rebound Sites

By

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Problem Statement

**Definition:** >1/4” Rebound per Hammer Blow termed High Pile Rebound (HPR)

- HPR occurs throughout Florida
- HPR significantly increases hammer blows
- HPR may damage the piles & hammers
- HPR causes concerns about capacity loss
- HPR may produce liability claims by the contractors

**Typical Lab Testing** has shown limited trends with Fines Contents possibly being an indicator.

The lab testing **loading rate** is slow, but the pile driving is a fast dynamic loading rate.
PDA data

The test piles are instrumented with accelerometers and strain gages.

By double integrating accelerations, displacements versus time for each hammer blow are produced.

Rebound = DMX - SET = 0.725 in (> 0.25 in)

DMX = max displacement

Either the digital or inspector sets can be used.

Inspector sets = 1/ pile driving blows per ft.
Background

- Correlations Published
  - Rebound vs. N from SPT
  - Rebound vs. Fines Content
- Limited Data Available
- Can these be validated?
Objectives

- Re-evaluate published N & FC correlations
- Identify and evaluate the geotechnical engineering properties which may cause high pile rebound
- Develop correlations to predict pile rebound during the design phase from:
  - Cone Penetration Testing with Pore Pressures (CPTu)
  - SPT N values
  - Basic Engineering Properties from Grain Size & Atterberg Limits
  - Engineering Properties from Triaxial Tests including density, permeability and strength
  - Cyclic Triaxial Tests to evaluate any trends from faster loading
Selected Literature

- Large Displacement Piles Produced HPR

- HPR Encountered in Hawthorn Formation: *fine sands with silts and clays*

- Dash & Sitharam 2009 Cyclic Results
  - Excess Pore Pressure Ratio $R_u = \frac{\Delta u}{\sigma'_{3}} = 1$
  - Critical Stress Ratio 15.4 or 12.8 % of $\sigma_{\text{failure}}$
  - Initial Void Ratios $e_c = 0.44; 0.54$
  - *From 15 to 35 % silt the behavior changes*
  - *Rate of Loading Affects Response*

- Plasticity also affects cyclic behavior
  - *High PI* Reduces liquefaction or cyclic failure potential

![Graph showing cycles of loading for $R_u = 1$ vs. silt content.](image)

- $e_c = 0.44$
- $e_c = 0.54$
- CSR = 12.8 %
- $\sigma'_{c3} = 100 \text{ kPa}$
Methodology

Identify Test Sites - 3 Required More tested
- CAD Drawings
- Pile Driving Analyzing (PDA) Data from GRL

Perform Field Investigation
- Standard Penetration Test (SPT)
- CPTu (i.e. Piezocone)
- Shelby Tube Sampling

Reduce Data, Analyze and Develop Correlations

Conclusions & Recommendations that you’ll remember 😊
Identify Testing Sites

State of FLORIDA Map
# Testing Performed

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>SPT</th>
<th>CPTu</th>
<th>DMT</th>
<th>Undisturbed</th>
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<tbody>
<tr>
<td>1</td>
<td>I-4 / US-192 Interchange / Osceola County / Florida.</td>
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<td>✓</td>
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<td>✓</td>
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<tr>
<td>2</td>
<td>State Road 417 International Parkway / Osceola County / Florida.</td>
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<td>✓</td>
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<tr>
<td>3</td>
<td>I-4 / Osceola Parkway / Osceola County / Florida.</td>
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<td>✓</td>
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<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>State Road 50 and State Road 436 / Orange County / Florida.</td>
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<td>✓</td>
<td>☒</td>
<td>✓</td>
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<tr>
<td>5</td>
<td>I-4 / State Road 408 Ramp B / Orange County / Florida.</td>
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<td>✓</td>
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<td>✓</td>
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<tr>
<td>6</td>
<td>Anderson Street Overpass at I-4/SR-408 / Orange County / Florida.</td>
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<td>✓</td>
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<tr>
<td>7</td>
<td>I-4 Widening Daytona / Volusia County / Florida.</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>8</td>
<td>State Road 83 over Ramsey Branch Bridge / Walton County / Florida.</td>
<td>✓</td>
<td>✓</td>
<td>☒</td>
<td>✓</td>
</tr>
<tr>
<td>9</td>
<td>Saint Johns Heritage Parkway, Brevard County</td>
<td>✓</td>
<td>☒</td>
<td>☒</td>
<td>✓</td>
</tr>
<tr>
<td>10</td>
<td>I-10 Chaffee Road, Duval County Florida</td>
<td>✓</td>
<td>☒</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Standard Penetration Test (SPT)

- SPT tests performed as near as possible to the test pile.
- Disturbed samples retrieved every 5 ft and packaged for further lab testing.
- A soil profile for each SPT boring was developed using the Unified Soil Classification System (USCS).
Cone Penetration with Pore Water (CPTu)

CPTu Testing Near Test Pile

- Cone Tip Resistance ($q_t$)
- Sleeve Friction ($f_s$)
- Pore Water Pressure ($u_2$)

Soil Properties Estimated

- Saturated Density ($\gamma$)
- Permeability ($k$)
-Relative Density ($D_r$)
- Undrained Shear Strength ($S_u$)
- Fines Content (FC)
- Overconsolidation Ratio (OCR)
- State Parameter ($\psi$)
- Soil Behavior Type (SBT)

Brian Bloomfield
Thin Walled Tube Testing Near Test Pile @ Six Sites (1-3 & 8-10)

Conventional Testing

- Grain Size with Hydrometer & Limits
- Natural Moisture
- Density
- Triaxial Permeability
- CU Triaxial

Cyclic Triaxial Testing

- 1000 cycles
- Stress Levels
  - 20: 40: 60: 80 % of $\sigma_{dmax}$
- $\Delta u$; Load and Displacement recorded
- Confined based on $\sigma_{\varepsilon_{vo}}$ @ sample depth

Thank you SMO !!! Glenn Johnson, Jose Hernando and That Guy😊
Typical Field Testing (from 2 sites)

PDA Rebound (RED) between ½ and 1” from 70 to 90 ft.

Site 1: I-4 US 192 Ramp CA

Pier 6 / Pile 16
Pier 7 / Pile 10
Pier 8 / Pile 4
Typical Field Testing

SPT N-Values and Soil Profile

Site 1: I-4 / US-192 Interchange

Pier 6 / Pile 16

Pier 7 / Pile 10

CPTu for I-4 / US-192 Interchange

Pier 8 / Pile 4
Typical Field Testing

Rebound (RED) up to 1.5 inches throughout driving most critical at 60 ft.

SPT N-Values and Soil Profile

Site 2: SR 83 Ramsey Branch Bridge Over Choctawhatchee Bay

EB 5 / Pile 2
Field Testing Results
SR 83 Ramsey Branch Bridge CPTu
### Average Field Testing Data from Seven Sites with CPTu

<table>
<thead>
<tr>
<th>Site Type</th>
<th>Depth (ft.)</th>
<th>Driving Data</th>
<th>SPT Data</th>
<th>CPT Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rebound (in./blow)</td>
<td>Driving Blows (blow/ft.)</td>
<td>$N_{SPT}$ (blow/ft.)</td>
</tr>
<tr>
<td>Ave NonHPR</td>
<td>37-70</td>
<td>0.21-0.24</td>
<td>27-33</td>
<td>8-13</td>
</tr>
<tr>
<td>Ave HPR</td>
<td>61-77</td>
<td>0.36-0.81</td>
<td>50-172</td>
<td>20-23</td>
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</tbody>
</table>
Reevaluations of Rebound Vs. N & FC
Rebound vs. N

Shows some increase up to 1-inch; No real trends; Also evaluated various Fines Contents still no trends
Is Soil Dilation Occurring to Produce High $\Delta u$?

$N_{SPT}$ from Anderson Street Overpass & Seed 1985 correlations
Rebound > 0.50 inches shows more frequent dilation

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Percentage</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Rebound</td>
<td>Nonrebound</td>
</tr>
<tr>
<td>Contractive</td>
<td>53%</td>
<td>72%</td>
</tr>
<tr>
<td>Intermediate</td>
<td>27%</td>
<td>17%</td>
</tr>
<tr>
<td>Dilative</td>
<td>20%</td>
<td>11%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

125 samples 370 samples

Rebound < 0.50 inches
Rebound vs. Fines Content from SPT samples

\[ R^2 = 0.8215 \]

FC (% Below 35 %)
How Fines Content affect Rebound

<table>
<thead>
<tr>
<th>Fines Content % Range</th>
<th>Percentages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>Max</td>
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<tr>
<td>0</td>
<td>10</td>
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<tr>
<td>10</td>
<td>20</td>
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<td>80</td>
<td>90</td>
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<tr>
<td>90</td>
<td>100</td>
</tr>
</tbody>
</table>

Total %: 58% vs 31%

Rebound < 0.50 inches
Analysis of CPTu Data

- Robertson Software CPET-IT with Correlations
- Geotechnical soil properties estimated from CPTu data were used to evaluate HPR soil behavior

- Soil Stratigraphy Using CPT Data
- Location I-4 / US-192 Interchange
CPTu Estimated Permeability

Typical Results: I-4 / US-192 Interchange

- Rebound soils: $3 \times 10^{-3}$ cm/s to $1.5 \times 10^{-6}$ cm/s
- Non-rebound soils: $3 \times 10^{-2}$ cm/s to $3 \times 10^{-4}$ cm/s
CPTu Overconsolidation Ratio (OCR)

- Soils with high OCR can also be classified as cemented soils.
  - Cemented soils behave like overconsolidated soils.
- HPR soils: OCR ranges from 5 to 10.
- NonHPR soils: OCR ranges from 0.5 to 3.
Evaluation Existing Correlation between HPR and CPT Pore Water Pressure

Published Correlations

Rebound = 0.0221u₂ (tsf) + 0.0447
R² = 0.76

Six Sites

y = 0.0006x + 0.2807
R² = 0.12

Re-evaluation
Digital vs Inspector Comparison

Digital Rebound (DMX-Digital SET) produces slightly higher $R^2$ - Less Scatter at low $\Delta u$
$\frac{1}{2} \text{ inch Rebound Six Sites } R^2 \text{ improves}$

![Graph of Digital Rebound vs. CPTu Pore Pressure](image)

- Equation: $y = 0.0014x + 0.3324$
- $R^2 = 0.48$

![Graph of Inspector Rebound vs. CPTu Pore Pressure](image)

- Equation: $y = 0.0008x + 0.5986$
- $R^2 = 0.38$
Soil Behavior Type Charts

- Based on CPT output, engineers can classify soils and Rebound Soil Stress Trends.
  - Robertson (1998)
  - Robertson (2012)
  - Schneider (2008)
  - Islami and Fellenius (1997)

Caution: Regenerating the following trends is complex & time-consuming and is presented for research purposes only.
Soil Behavior Type (SBT) Tip and Sleeve Data

Robertson (1990)

Rebound

Non-rebound
Soil Behavior Type (SBT) Tip and Pore Pressure (1990)
Soil Behavior Type (SBT) Tip and Sleeve (1997) by Eslami and Fellenius

- **Rebound**
  - Effective Cone Resistance, $q_e$ (MPa) vs. Sleeve Friction, $f_s$ (KPa)

- **Non-rebound**
  - Effective Cone Resistance, $q_e$ (MPa) vs. Sleeve Friction, $f_s$ (KPa)
Soil Behavior Type (SBT) Tip and Sleeve (2012)

Rebound

- Fine Dilative (FD) Soils Rebound

Non-rebound

- Coarse Dilative (FD) Coarse Contractive (CC)
- Fine Contractive (FC) Soils Do Not Rebound
Soil Behavior Type (SBT) Tip and Pore Pressure

Schneider (2008)

Rebound

Non-rebound
SBT Findings

- Conventional CPT Soundings can be used
  - HPR soils fall in Zones 3-5
  - There seems to be a pore pressure threshold
  - Based on a very limited number of soundings
Shelby Tube -- Grain Size Results

- Classification with Hydrometer
  - All cohesionless soils SM regardless of rebound or no rebound behavior
  - Cohesive rebound soils all CH
  - Cohesive nonrebound soils predominately CL one SC

- Conclusion: only cohesive rebound soils showed a grain size trend
Shelby Tube -- Silt Content Results

**Cohesionless Soils**

- Above 20% Silt ALL
- Rebound > 0.5”

**Cohesive Soils**

- Between 20 & 35% Silt ALL
- Rebound > 0.5”
Shelby Tube – Clay Content Results

- Only Cohesive soils show trend
- Cohesionless not shown
- All clay contents above 30% rebound
Shelby Tube -- Atterberg Limits on Clays Results

- Nonrebound Soils that are Clays all CL
- Rebound Soils that are Clays all CH
- Plot Above A-Line
- Matches Literature (Slide 6)
Shelby Tube – Triaxial Permeability Results

Cohesionless

- Clay % (5% - 12%)
- Sand % (35% - 88%)
- Silt % (4% - 55%)
- Fine % (12% - 65%)
- Unit Weight (104 pcf - 124 pcf)
- Cc > 1, Cu > 2
- Rebound > 0.5 in

Most k values below 10^-6 cm/sec rebound > 0.5

Cohesive

- Clay % (6% - 10%)
- Sand % (35% - 88%)
- Silt % (3% - 54%)
- Density (96 pcf - 123 pcf)
- Cohesionless Cohesive

Most k values below 10^-7 cm/sec rebound > 0.5
Triaxial and CPT Cone Resistance Comparison

\[ qt = 23.81 \Delta \delta - 216.55 \]
\[ R^2 = 0.47 \]
SBT Plot

- Shelby Tube sample depths and locations matched to nearest CPTu data.
- Rebound and nonrebound data on Robertson 2012 SBT chart
Shelby Tube – Cyclic Triaxial Results

Stress Ratio could also be % failure stress
10% 20% 40% 60% 80%

HPR Soils More Resilient: Many more cycles to produce the same strain!!!!
Up to 4 times more just like the piles
Some of the Conclusions 😊

1. There is no clear Rebound versus N value Correlation when sufficient data is available

2. The Rebound versus FC correlation is weak based on a larger number of data points

3. SPT N values showed some dilative trends for HPR soils at one of the sites

4. There was no clear USCS classification difference for cohesionless HPR and NonHPR soils

5. Rebound seems to be a function of silt content greater than 20 % and less than 40% for SM soils

6. Cohesive HPR soils classified as CH, while the NonHPR cohesive soils classified as CL

7. The CPTu pore water pressures of HPR soils are very high as long as the layer is thick enough.
Some of the Conclusions (Cont.) 😊

8. Most SBT charts give some indication of type and behavior of rebound and non-rebound soils.
   a. Robertson (1990) Tip and Sleeve ☹
   b. Robertson (1990) Tip and Pore Pressure ☹ ☹
   c. Islami and Fellenius (1997) Tip and Sleeve ☹
   d. Robertson (2012) Tip and Sleeve (Dilative vs Contractive) ☹ ☹ ☹
   e. Schneider (2008) Tip and Pore Pressure ☹ ☹

9. Permeability of HPR soils is 1-2 orders of magnitude lower than NonHPR soils ($10^{-7}$ to $10^{-8}$ to $10^{-3}$ or $10^{-4}$ cm/s)

10. HPR soils are rate of loading dependent and two to three times more resilient (i.e., do not deflect as much during rapid loadings as NonHPR soils)
Recommended Decision Tree - Level I

Note: Displacement piles driven with single acting diesel hammers were evaluated and are the basis for this decision tree.
Level II: Supplemental Laboratory Testing Design Phase Investigation

FROM LEVEL I

Grain Size Analysis with Hydrometer & Atterberg Limits

Cohesionless SM-Soils

Silt Content > 20%
& Fines Content > 30%

YES

Sand Content < 70%

YES

Concern about Exceeding Specification 455-5.10.3 Rebound Criteria

NO

Low Concern for Rebound with Excessive Pile Hammer Blows

NO

Proceed to Level III Supplemental Field Testing Investigation

YES

Conduce Limit > 50%
& Plastic Index > 30%

Liquid Limit > 50%

YES

Clay Content > 35%

YES

Concern about Exceeding Specification 455-5.10.3 Rebound Criteria

NO

Non-plastic

Plastic

LL & PI above A line
Recommended Decision Tree **Level III**

**Level III: Supplemental Field Testing Design Phase Investigation**

- **Cone Penetrometer with Pore Water Pressure Test Data**
- **Pore Pressure Exceeds Approximately 100 psi over a Relatively Thick Layer**
  - YES: Concern about Exceeding Specification 455-5.10.3 Rebound Criteria
  - NO: Low Concern for Rebound with Excessive Pile Hammer Blows
    - NO: Flexible Wall Permeability Testing
      - **SM-Permeability < 10E-06 cm/sec**
        - NO: Concern about Exceeding Specification 455-5.10.3 Rebound Criteria
        - YES: CH & CL-Permeability < 10E-07 cm/sec
          - YES: Final Decision
          - NO: Final Decision

*Note* that stress-level cyclic triaxial testing with 1000 cycles each at stress levels at 20, 40, 60, and 80% of the failure stress from triaxial tests conducted in accordance with ASTM D4767 indicated that HRP soils required two to three times more cycles to attain 2.5, 5, 10, and 15% strain levels than non-HPR soils and are termed more resilient, which matches the phenomenon that occurs during driving in theses soils.
Thank You

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