Wave Equation Applications

PDCA 2015 Professor Driven Pile Institute

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GRL Engineers, Inc.
WAVE EQUATION APPLICATIONS

Develop Driving Criterion
  Blow Count for a Required Ultimate Capacity
  Blow Count for Capacity as a Function of Energy / Stroke

Check Driveability
  Blow Count vs. Penetration Depth
  Driving Stresses vs Penetration Depth

Determine Optimal Driving Equipment
  Driving Time

Refined Matching Analysis
  Adjust Input Parameters to Fit Dynamic Measurements
WHAT INFORMATION DO WE NEED FOR GRLWEAP ANALYSIS?
REQUIRED INFORMATION

• **Hammer**
  – Model
  – Stroke and Stroke Control
  – Any Modifications

• **Driving System**
  – Helmet Weight (Base, Insert, Striker Plate & Cushions)
  – Hammer Cushion Material \((E, A, t, e_r)\)
  – Pile Cushion Material \((E, A, t, e_r)\)
REQUIRED INFORMATION

• **Pile**
  - Length,
  - Cross Sectional Area
  - Taper or Other Non-uniformities
  - Specific Weight
  - Splice Details
  - Design Load
  - Ultimate Capacity
  - Pile Toe Protection
REQUIRED INFORMATION

- **Soil**
  - Boring Locations with Elevations
  - Soil Descriptions
  - N-values or Other Strength Parameters vs Depth
  - Elevation of Excavation
  - Elevation of Pile Cut-off
  - Elevation of Water Table
  - Scour Depth or Other Later Excavations
## Pile Driving and Equipment Data Form

<table>
<thead>
<tr>
<th><strong>Contract No.</strong></th>
<th><strong>Structure Name and/or No.</strong></th>
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<tbody>
<tr>
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<table>
<thead>
<tr>
<th><strong>Project</strong></th>
<th><strong>Pile Driving Contractor or Subcontractor:</strong></th>
</tr>
</thead>
<tbody>
<tr>
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<table>
<thead>
<tr>
<th><strong>County:</strong></th>
<th><strong>(Piles driven by):</strong></th>
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<table>
<thead>
<tr>
<th><strong>Manufacturer:</strong></th>
<th><strong>Model No.:</strong></th>
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<table>
<thead>
<tr>
<th><strong>Hammer Type:</strong></th>
<th><strong>Serial No.:</strong></th>
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<tbody>
<tr>
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<table>
<thead>
<tr>
<th><strong>Manufacturers Maximum Rated Energy:</strong></th>
<th><strong>(ft-lbs)</strong></th>
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<table>
<thead>
<tr>
<th><strong>Hammer Stroke at Maximum Rated Energy:</strong></th>
<th><strong>(ft)</strong></th>
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<tbody>
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<table>
<thead>
<tr>
<th><strong>Range in Operating Energy:</strong></th>
<th><strong>to</strong></th>
<th><strong>(ft-lbs)</strong></th>
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<table>
<thead>
<tr>
<th><strong>Range in Operating Stroke:</strong></th>
<th><strong>to</strong></th>
<th><strong>(ft)</strong></th>
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<tr>
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<table>
<thead>
<tr>
<th><strong>Ram Weight:</strong></th>
<th><strong>(kips)</strong></th>
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<table>
<thead>
<tr>
<th><strong>Striker Weight:</strong></th>
<th><strong>(kips)</strong></th>
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<table>
<thead>
<tr>
<th><strong>Diameter:</strong></th>
<th><strong>(in)</strong></th>
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<table>
<thead>
<tr>
<th><strong>Material #1:</strong></th>
<th><strong>Material #2:</strong> (for Composite Cushion)</th>
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<tbody>
<tr>
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<table>
<thead>
<tr>
<th><strong>Hammer Area:</strong></th>
<th><strong>Name:</strong></th>
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<table>
<thead>
<tr>
<th><strong>Cushion Thickness/Plate:</strong></th>
<th><strong>Name:</strong></th>
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<table>
<thead>
<tr>
<th><strong>No. of Plates:</strong></th>
<th><strong>Total Thickness of Hammer Cushion:</strong></th>
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<tbody>
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<table>
<thead>
<tr>
<th><strong>Helmet (Drive Head) Weight:</strong></th>
<th><strong>(kips)</strong></th>
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<table>
<thead>
<tr>
<th><strong>Material:</strong></th>
<th><strong>Cushion Area:</strong></th>
<th><strong>Thickness/Sheet:</strong></th>
<th><strong>(in)</strong></th>
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<tbody>
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<table>
<thead>
<tr>
<th><strong>No. of Sheets:</strong></th>
<th><strong>Total Thickness of Pile Cushion:</strong></th>
<th><strong>(in)</strong></th>
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<tbody>
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<table>
<thead>
<tr>
<th><strong>Pile Type:</strong></th>
<th><strong>Wall Thickness:</strong></th>
<th><strong>Taper:</strong></th>
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<table>
<thead>
<tr>
<th><strong>Cross Sectional Area:</strong></th>
<th><strong>Weight/Ft:</strong></th>
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<table>
<thead>
<tr>
<th><strong>Ordered Length:</strong></th>
<th><strong>(ft)</strong></th>
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<thead>
<tr>
<th><strong>Design Load:</strong></th>
<th><strong>(kips)</strong></th>
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<table>
<thead>
<tr>
<th><strong>Ultimate Pile Capacity:</strong></th>
<th><strong>(kips)</strong></th>
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<tbody>
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<table>
<thead>
<tr>
<th><strong>Description of Splice:</strong></th>
<th><strong>Driving Shoe/Closure Plate Description:</strong></th>
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<tbody>
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<thead>
<tr>
<th><strong>Submitted By:</strong></th>
<th><strong>Date:</strong></th>
<th><strong>Telephone No.:</strong></th>
<th><strong>Fax No.:</strong></th>
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### Notes

- The form is designed to document details of pile driving equipment and materials.
- It includes sections for hammer specifications, striker and plate data, hammer cushion, helmet (drive head) weight, pile type, and more.
- Each section of the form is to be filled in with the appropriate data for the project in question.

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### Technical Details

- **Hammer Area:** The area of the hammer is specified, which is crucial for understanding the impact of the hammer on the pile.
- **Cushion Thickness/Plate:** Details about the thickness of the cushion and the number of plates are important for the protection of the hammer and the pile.
- **Helmet (Drive Head) Weight:** The weight of the drive head is a critical factor in pile driving, affecting the energy transferred to the pile.
- **Pile Type:** Information on the type of pile, including wall thickness and cross-sectional area, is essential for the design and installation process.

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### Purpose

The purpose of this form is to ensure that all relevant data is recorded and available for future reference and analysis, aiding in the effective management of pile driving projects.
Example Problems

2006 FHWA Pile Manual – Chapter 16 (ASD)

#1 - General Bearing Graph
#2 – Constant Capacity / Variable Stroke
#3 – Tension and Compression Stress Control
#4 – Use of Soil Setup
#5 – Drivability Studies
#6 – Driving System Characteristics
#7 – Assessment of Pile Damage
#8 – Selection of Wall Thickness
#9 – Evaluation of Vibratory Driving

2015 FHWA Pile Manual – Chapter 12 (LRFD)

2010 GRLWEAP Program – 23 Examples
Example Problems

2015 FHWA Pile Manual – Chapter 12 (LRFD)

#1 - General Bearing Graph
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2010 GRLWEAP Program – 23 Examples

2010 GRLWEAP Program – 23 Examples
GRLWEAP Standard Examples

• Example 1: Generation of a Bearing Graph for an Open End Diesel Hammer
• Example 2: Closed End Hammer, Non Uniform Pile, Equipment Check
• Example 3: Concrete Pile, ECH, Tension Stress Check
• Example 4: Diesel Hammer Input
• Example 5: Pile Segment and Damping Input
• Example 6: Comparison of Damping Parameters
• Example 7: Reduced Diesel Fuel and Quake Variation
• Example 8: Effects of Splice/Slack on Pile Stress
• Example 9: Residual Stress Analysis (RSA)
• Example 10: Pile Damping, Long Piles, Diesel Hammer Performance
• Example 11: Drivability Analysis (Blow Count vs. Depth)
• Example 12: Inspector’s Chart or Constant Capacity Option
• Example 13: Composite Pile, Second Toe and Critical Stresses
• Example 14: Two Pile Analysis Considering Follower with Long Skirt
• Example 15: Mandrel Driven Pile
• Example 16: Drilled Shaft Test with No Helmet
• Example 17: Vibratory Hammer Analysis
• Example 18: Pile and Hammer Gravity Changes
• Example 19: Static Soil Analysis
• Example 20: Steel Follower on Concrete Pile
• Example 21: Using ST and Variable Pile Cushion Stiffness
• Example 22: Drivability Analysis for a large, non-uniform pipe pile – Offshore Wave 2010
• Example 23: CPT Based Static Analysis Input Example
GRLWEAP Example 1 & 2 Problem

Hammer:
Delmag D 12-42; 46 kJ (34 ft kips)

Hammer Cushion:
50 mm (2 inch) Aluminum + Conbest

Helmet: 7.6 kN (1.7 kips)

Pile: Closed End Pipe
OD 356 mm (14 inch)
Wall 8 mm (0.314 inch)

Shaft Resistance, 84%:
Triangular Distribution
1240 kN (280 kips)

Toe Resistance, 16%:
240 kN (54 kips)

Medium Sand
N’ = 20
GRLWEAP Example 1 Solution

**Delmag D12-42**

- **Ram Weight**: 2.82 kips
- **Efficiency**: 0.800
- **Pressure**: 1640 (100%) psi
- **Helmet Weight**: 1.70 kips
- **Hammer Cushion**: 60155 kips/in
- **COR of H.C.**: 0.800
- **Skin Quake**: 0.100 in
- **Toe Quake**: 0.234 in
- **Skin Damping**: 0.050 sec/ft
- **Toe Damping**: 0.150 sec/ft
- **Pile Length**: 66.00 ft
- **Pile Penetration**: 62.00 ft
- **Pile Top Area**: 13.41 in²

**Graphs**:

- **Compressive Stress (ksi)** vs. **Blow Count (bl/ft)**: 27.9 ksi at 85 blows/ft.
- **Tension Stress (ksi)** vs. **Blow Count (bl/ft)**.
- **Ultimate Capacity (kips)** vs. **Blow Count (bl/ft)**: 330 kips at 85 blows/ft.
- **Stroke (ft)** vs. **Blow Count (bl/ft)**: 8.4 ft at 85 blows/ft.

**Pile Model Skin Friction Distribution**

- **Res. Shaft = 84% (Proportional)
GRLWEAP Example 2 Solution

FHWA #2: Delmag D12-42, 14" x 0.312" CEP

DELMA D 12-42
Capacity 330.0 kips
Ram Weight 2.82 kips
Efficiency 0.800
Pressure 1640 (100%) psi
Helmet Weight 1.70 kips
Hammer Cushion 60155 kips/in
COR of H.C. 0.800
Skin Quake 0.100 in
Toe Quake 0.234 in
Skin Damping 0.050 sec/ft
Toe Damping 0.150 sec/ft
Pile Length 66.00 ft
Pile Penetration 62.00 ft
Pile Top Area 13.41 in²

Pile Model
Skin Friction
Distribution
Res. Shaft = 84 %
(Proportional)
GRLWEAP Example 3 Problem

Penetration Depth for Tension Evaluation

Hammer:
- JUNTTAN HHK 3

Hammer Cushion:
- 200 mm (7.9 inch) Monocast MC 901

Helmet: 9.6 kN (2.16 kips)

Pile Cushion: 114 mm (4.5 inch) Plywood

Pile:
- Square Prestressed Concrete
- Pile Length 12 m (39 ft)
- 356 mm (14 inch)
- Ultimate Capacity: 1807 kN (406 kips)

Shaft Resistance, 10%:
- 180 kN (40 kips)

Shaft Resistance, 33%:
- 597 kN (134 kips)

Shaft Resistance, 5%:
- 97 kN (22 kips)

Toe Resistance, 52%:
- 933 kN (210 kips)
Example 3 Solution - Shallow Depth

- Compressive Stress (MPa)
- Tension Stress (MPa)
- Blow Count (blows/.25m)
- Ultimate Capacity (kN)

- Stroke
- Efficiency
- Helmet
- Hammer Cushion
- Pile Cushion
- Skin Quake
- Toe Quake
- Skin Damping
- Toe Damping
- Pile Length
- Pile Penetration
- Pile Top Area

- Res. Shaft = 48 % (Proportional)

- JUNTTAN HHK 3
  Stroke 1.00 m
  Efficiency 0.800
  Helmet 9.60 kN
  Hammer Cushion 1989 kN/mm
  Pile Cushion 229 kN/mm
  Skin Quake 2.500 mm
  Toe Quake 5.994 mm
  Skin Damping 0.161 sec/m
  Toe Damping 0.500 sec/m
  Pile Length 12.00 m
  Pile Penetration 3.50 m
  Pile Top Area 1267.35 cm²

- Pile Model Distribution
- Skin Friction

- Skin Friction Distribution

- Res. Shaft = 48 % (Proportional)
Example 3 Solution - Final Depth

**Compressive Stress (MPa)**

- 0
- 4
- 8
- 12
- 16
- 20

**Tension Stress (MPa)**

- 0
- 4
- 8
- 12
- 16
- 20

**Blow Count (blows/.25m)**

- 0
- 25
- 50
- 75
- 100
- 125
- 150

**Ultimate Capacity (kN)**

- 0
- 250
- 500
- 750
- 1000
- 1250
- 1500
- 2000
- 2500

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**JUUTTAN HHK 3**

- **Stroke**: 1.00 m
- **Efficiency**: 0.800
- **Helmet**: 9.60 kN
- **Hammer Cushion**: 1989 kN/mm
- **Pile Cushion**: 376 kN/mm
- **Skin Quake**: 2.500 mm
- **Toe Quake**: 6.000 mm
- **Skin Damping**: 0.160 sec/m
- **Toe Damping**: 0.500 sec/m
- **Pile Length**: 12.00 m
- **Pile Penetration**: 11.50 m
- **Pile Top Area**: 1267.35 cm²

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**Pile Model**

**Skin Friction Distribution**

- Res. Shaft = 48 % (Proportional)
Pile: Square Precast Concrete

Pile Length 16 m (52.5 ft)
Pile Penetration 15 m (49.2 ft)
305 mm (12 inch)
Ultimate Capacity 1340 kN (300 kips)

Shaft Resistance, 92%
Uniform Distribution
1233 kN (276 kips)

Toe Resistance, 8%
107 kN (24 kips)

Stiff Clay

c_u = 70 kPa (1.5 ksf)
Setup Factor = 1.33

Hammer: Vulcan 08: 35.3 kJ (26 ft-kips)
Hammer Cushion: 216 mm (8.5 inch) Hamortex
Helmet: 11.6 kN (2.6 kips)
Pile Cushion: 152 mm (6 inch) Plywood
Example 4 Solution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Stroke</td>
<td>3.25 ft</td>
</tr>
<tr>
<td>Ram Weight</td>
<td>8.00 kips</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.670</td>
</tr>
<tr>
<td>Helmet Weight</td>
<td>2.60 kips</td>
</tr>
<tr>
<td>Hammer Cushion</td>
<td>2176 kips/in</td>
</tr>
<tr>
<td>Pile Cushion</td>
<td>1800 kips/in</td>
</tr>
<tr>
<td>COR of P.C.</td>
<td>0.500</td>
</tr>
<tr>
<td>Skin Quake</td>
<td>0.100 in</td>
</tr>
<tr>
<td>Toe Quake</td>
<td>0.100 in</td>
</tr>
<tr>
<td>Skin Damping</td>
<td>0.200 sec/ft</td>
</tr>
<tr>
<td>Toe Damping</td>
<td>0.150 sec/ft</td>
</tr>
<tr>
<td>Pile Length</td>
<td>52.50 ft</td>
</tr>
<tr>
<td>Pile Penetration</td>
<td>49.20 ft</td>
</tr>
<tr>
<td>Pile Top Area</td>
<td>144.00 in²</td>
</tr>
</tbody>
</table>

Pile Model
- Skin Friction Distribution
  - Res. Shaft = 92%
    - (Proportional)

81 blows / ft without anticipated soil set-up (300 kips)
42 blows / ft with anticipated soil set-up (225 kips)
GRLWEAP Example 6 Problem

Hammer:
- ICE 42-S: 56.9 kJ (42 ft-kips)
  or
- Vulcan 014: 56.9 kJ (42 ft-kips)

Hammer Cushion: Varies

Helmet: Varies

Pile: Closed End Pipe
- Pile Length 20 m (66 ft)
- Pile Penetration 16 m (52.5 ft)
- 355 mm (14 inch) x 9.5 mm (3/8 inch)
- Ultimate Capacity 1800 kN (405 kips)

Shaft Resistance, 30%
- Triangular Distribution
  540 kN (121 kips)

Toe Resistance, 70%
- 1260 kN (284 kips)

Loose Silty Fine Sand

Very Dense Silty Fine Sand

Depth (m)      (ft)

0      0
10     33
20     66
30     99
40     132
50     165
60     198
70     231
80     264
90     297
100    330
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GRLWEAP Example 6

Solution

99 bl/ft

228 bl/ft

Pile Model
Skin Friction Distribution

Res. Shaft = 30 %
(Proportional)

Pile Model
Skin Friction Distribution

Res. Shaft = 30 %
(Proportional)
Questions ? ? ?