Pile Driving Formulae: Dead End or are Still Useful?

Leo Rothenburg

$W H = R s$

Hammer Energy = Work of Soil Resistance

$R = \frac{W H}{S}$

FORMULA

$R = \frac{W H}{S+c}$
Outline

- Applications of Pile driving formulae
- Current practices and accuracy issues
- Wave equation analysis and monitoring
- Comparison of different methods
- Current research (mainly USA)
- Conclusions and research needs
Main application of dynamic formulae: pile driving acceptance criteria

From Standard Specifications:

The nominal resistance for driven piles shall be determined from the following formula:

\[
R_s = \frac{2E_r}{s + 0.1} \quad \text{[safe load, lb, with } FS = 6 \text{ built-in]}
\]

\[E_r - \text{ rated energy, } ft \cdot lb ; \]
\[s - \text{ penetration per blow, in} \]

\[
R_u = 1.75 \sqrt{E_r \log(10N) - 100} \quad \text{[ultimate load, ton]}
\]

Used by at least 20 agencies according to 2004 survey

Recommended by FHWA, used by at least 7 agencies according to 2004 survey
Pile loading tests
Accuracy of ENR formula

Original formula:

US practice (FS=6):

\[ R_u = \frac{E_r \eta}{s+c} \]

Lost set “c” is fixed at a wrong level
All energy is transferred to pile

Other formulae deal with these parameters in more realistic ways
# Performance of pile driving formulae

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Pile Length</th>
<th>Delmag 30</th>
<th>Ultimate Pile Capacities according to different formulae, tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ram 6,600 lb</td>
<td>Set 0.84 in</td>
<td>Empirical</td>
<td>Mechanistic</td>
</tr>
<tr>
<td>12&quot; PC/PS</td>
<td>80'</td>
<td>420</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td>40'</td>
<td>381</td>
<td>153 127 112</td>
</tr>
<tr>
<td>12&quot; BP53</td>
<td>80'</td>
<td></td>
<td>231 292 244</td>
</tr>
<tr>
<td></td>
<td>40'</td>
<td>231 292 176</td>
<td></td>
</tr>
</tbody>
</table>

Range: 112 tons to 420 tons

### Traditional FS

<table>
<thead>
<tr>
<th>Formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENR</td>
<td>6.0</td>
</tr>
<tr>
<td>Gates</td>
<td>3.5</td>
</tr>
<tr>
<td>WSDOT</td>
<td>3.0</td>
</tr>
<tr>
<td>Hiley</td>
<td>3.0</td>
</tr>
<tr>
<td>Pacific Coast</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Dynamic testing

\[ V(t) = \int_0^t a(\tau) d\tau \]

\[ F(t) = AE \int_0^t \varepsilon(\tau) d\tau \]

Frequently used code: CAPWAP (Case Pile Wave Analysis Program)
US Survey – 45 respondents

- Static load test – 77%
- Wave Equation – 80%
- ENR – 45%
- Gates – 16%
- Dynamic test – 84% (1 to 10% of piles)

Conditions
- EOD – 82%
- EOR – 56%
- Not specified – 36%
“Dynamic testing”

Illinois Department of Transportation

Memorandum

To: ALL BRIDGE DESIGNERS
From: Ralph E. Anderson
Subject: Pile Data Guidelines for 2007 Standard Specifications
Date: September 13, 2006

The new specification utilizes the FHWA Modified Gates formula, in place of the ENR formula, along with new terminology and several pay item changes related to piling. In addition, the Gates formula requires the design capacities be unfactored ultimate or nominal values.
Comparison of different methods

(Paikowsky database, 2004)

<table>
<thead>
<tr>
<th>Method</th>
<th>Performance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPWAP</td>
<td>( \lambda = 0.73 )</td>
</tr>
<tr>
<td>ENR (c=1)</td>
<td>( \lambda = 1.01 )</td>
</tr>
<tr>
<td>GATES</td>
<td>( \lambda = 1.010 )</td>
</tr>
<tr>
<td>WSDOT</td>
<td>( \lambda = 0.99 )</td>
</tr>
</tbody>
</table>

\( \lambda = \frac{\text{Predicted capacity}}{\text{Measured capacity}} \)

\( \sigma/\lambda = \text{Measure of scatter} \)
Safety factors practice

- DYNAMIC FORMULA, FS = 3.0 to 3.5
- WAVE EQUATION, FS = 2.5
- DYNAMIC TESTING, FS = 2.25
- STATIC TESTING, FS = 1.8 TO 2.0
Time effects in clayey soils

![Graph showing pile capacity (kN) vs. time after end of initial driving (days). The graph compares static and dynamic (restrike) pile capacities.]

After Svinkin and Woods (www.vulkanhammenr.net)
Conclusions

- Global databases of pile load tests give no preference to any existing method
- Efforts to integrate local experience and practices into pile driving formulae continues in a number of countries
- Several US DOTs utilize local databases of pile loading tests and pile driving records
Ontario database

Published in 1993

Pile driving records not included
Research needs

- Create a comprehensive pile database for Ontario by supplementing “Pile Load and Extraction Tests 1954-1992” with driving records from MTO and adding new tests carried out after 1992.
- Calibrate various pile driving formulae against the Ontario database in order to establish the most suitable formula/method.