Load Testing

Static Load Testing
ASTM D1143

Deadload Testing

React. Piles/Anchors

Static Load Tests are the “standard”
Costly: Need 100% load + long time
Static Analysis Methods are not accurate

Figure 32 – Predictions from analytical methods to ultimate resistance of precast driven pile C1

International Prediction Event “Behaviour of Bored, CFA, and Driven Piles in Residual Soil”, ISC’2 Experimental Site, 2003, by Viana da Fonseca and Jamie Santos
International Prediction Event on the Behaviour of Bored, CFA and Driven Piles in CEFEUP/ISC’2 experimental site - 2003

A. Viana da Fonseca, President of ISC’2
Jaime Santos, Coordinator of the experimental site
Design Concepts - Factors of Safety

• Allowable Stress Design (ASD)
  \[ R_u > Q_d \times F.S. \]  \hspace{1cm} (F.S. = \text{Factor of Safety})
<table>
<thead>
<tr>
<th></th>
<th>ASD</th>
<th>F.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gates</td>
<td>3.50</td>
<td></td>
</tr>
<tr>
<td>Wave Eqn</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td>DLT</td>
<td>2.25</td>
<td></td>
</tr>
<tr>
<td>SLT</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>SLT + DLT</td>
<td>1.90</td>
<td></td>
</tr>
<tr>
<td>SLT or DLT</td>
<td>2.00</td>
<td>←IBC</td>
</tr>
</tbody>
</table>
Application: 2000 ton total structure load, 200 ton ultimate capacity piles

<table>
<thead>
<tr>
<th>F.S.</th>
<th>design load per pile</th>
<th>piles needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.50</td>
<td>200/3.50 = 57 t</td>
<td>35 dyn. formula</td>
</tr>
<tr>
<td>2.75</td>
<td>200/2.75 = 72 t</td>
<td>28 wave equation</td>
</tr>
<tr>
<td>2.25</td>
<td>200/2.25 = 89 t</td>
<td>23 dynamic test</td>
</tr>
<tr>
<td>2.00</td>
<td>200/2.00 = 100 t</td>
<td>20 Static (SLT)</td>
</tr>
<tr>
<td>1.90</td>
<td>200/1.90 = 105 t</td>
<td>19 SLT + dynamic</td>
</tr>
</tbody>
</table>

Lower F.S. → fewer piles → less cost
Design Concepts - Factors of Safety

• Allowable Stress Design (ASD)
  \[ R_u > Q_d \times F.S. \quad (F.S. = \text{Factor of Safety}) \]

• Load and Resistance Factor Design (LRFD)
  \[ \phi R_u > f_D L_D + f_L L_L + f_i L_i + \ldots \]

ASD “Factor of Safety” split into Load and Resistance factors \( \rightarrow \) F.S. \( \sim \frac{f_{avg}}{\phi} \)

\[ FS = \frac{(1.25D + 1.75L)}{\phi (D + L)} \]
Get resistance factors ($\phi$) from conversion of ASD “Factors of Safety”

Equate $Ru$ and solve for $FS$

\[
FS = \frac{(1.25D + 1.75L)}{\phi (D + L)}
\]

If $D/L = 2$ →

\[
\phi = \frac{(1.25 \times 2 + 1.75)}{FS (2 + 1)}
\]
\[
\phi = \frac{1.4167}{FS}
\]
<table>
<thead>
<tr>
<th>AASHTO:</th>
<th>ASD</th>
<th>LRFD</th>
<th>AASHTO</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F.S.</td>
<td>φ</td>
<td>F.S.</td>
<td></td>
</tr>
<tr>
<td>Gates</td>
<td>3.50</td>
<td>0.41</td>
<td>0.40</td>
<td>3.54</td>
</tr>
<tr>
<td>Wave Eqn</td>
<td>2.75</td>
<td>0.52</td>
<td>0.50</td>
<td>2.83</td>
</tr>
<tr>
<td>DLT (&gt;2%)</td>
<td>2.25</td>
<td>0.63</td>
<td>0.65</td>
<td>2.18</td>
</tr>
<tr>
<td>DLT (100%)</td>
<td></td>
<td></td>
<td>0.75</td>
<td>1.89</td>
</tr>
<tr>
<td>SLT</td>
<td>2.00</td>
<td>0.71</td>
<td>0.75</td>
<td>1.89</td>
</tr>
<tr>
<td>SLT + DLT</td>
<td>1.90</td>
<td>0.75</td>
<td>0.80</td>
<td>1.77</td>
</tr>
<tr>
<td>SLT or DLT</td>
<td>2.00</td>
<td>0.71</td>
<td></td>
<td>1.77</td>
</tr>
</tbody>
</table>

From ASD conversion (D/L = 2)
AASHTO (LRFD 2010)  
1.25D + 1.75L

**look at D/L = 3**  
D = 1500:  
L = 500

**Application:**  
$1500 \times 1.25 + 500 \times 1.75 = 2750$

2000 ton structure load $\rightarrow$ 2750 ton “factored load”

200 ton ult capacity piles ( “nominal resistance” )

<table>
<thead>
<tr>
<th>phi</th>
<th>per pile</th>
<th>needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>200*0.40</td>
<td>80 t</td>
</tr>
<tr>
<td>0.50</td>
<td>200*0.50</td>
<td>100 t</td>
</tr>
<tr>
<td>0.65</td>
<td>200*0.65</td>
<td>130 t</td>
</tr>
<tr>
<td>0.70</td>
<td>200*0.70</td>
<td>140 t</td>
</tr>
<tr>
<td>0.75</td>
<td>200*0.75</td>
<td>150 t</td>
</tr>
<tr>
<td>0.80</td>
<td>200*0.80</td>
<td>160 t</td>
</tr>
<tr>
<td></td>
<td>ASD</td>
<td>LRFD</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----</td>
<td>------</td>
</tr>
<tr>
<td>Gates</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Wave Equation</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Dynamic testing</td>
<td>23</td>
<td>22 (20 ODOT)</td>
</tr>
<tr>
<td>Static testing</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>100% Dyn testing</td>
<td>x</td>
<td>19</td>
</tr>
<tr>
<td>Static + Dynamic</td>
<td>19</td>
<td>18</td>
</tr>
</tbody>
</table>
Statistical analysis methods

Mean (bias) = $\lambda$
Average of results

Standard Deviation = $\sigma$
68% of data fall within one $\sigma$ of mean
95% of data fall within two $\sigma$ of mean

Coefficient of Variation (COV) = $\frac{\sigma}{\lambda}$
LRFD is based on Reliability

Reliability Index $\beta$  |  Probability of failure $p_f$
---|---
$\beta = 2.00$  |  $2.28\%$
$\beta = 2.33$  |  $1.00\%$
$\beta = 2.50$  |  $0.62\%$
$\beta = 3.00$  |  $0.10\%$

Probability density of $g$

Reliability index $\beta$

$$\beta = \frac{\lambda}{\sigma}$$

Probability of failure $P_f$

= shaded area

$g = R - Q$

$g > 0$ is satisfactory
$g < 0$ is unsatisfactory

Geotechnical use for piles ($\beta = 2.33$) because failure of group is 1 to 4 orders of magnitude smaller than for single pile
First Order Second Moment – Live and Dead loads only

\[
\phi = \frac{\lambda_R \left( \frac{\gamma_D Q_D}{Q_L} + \gamma_L \right)}{\left( \frac{\lambda_{Q_D} Q_D}{Q_L} + \lambda_{Q_L} \right) \exp\left\{ \beta_T \sqrt{\ln\left[ \left( 1 + COV_R^2 \right) \left( 1 + COV_{Q_D}^2 + COV_{Q_L}^2 \right) \right]} \right\}}
\]

\(\lambda_R\) = resistance bias factor

\(COV_Q\) = coefficient of variation (the ratio of the standard deviation to the mean) of the load

\(COV_R\) = coefficient of variation of the resistance

\(\beta_T\) = target reliability index

\(\gamma_D, \gamma_L\) = dead and live load factors

\(Q_D/Q_L\) = dead to live load ratio

\(\lambda_{Q_D}, \lambda_{Q_L}\) = dead and live load bias factors
\[ \lambda_R = \text{resistance bias factor} \]

\[ \text{COV}_Q = \text{coefficient of variation (the ratio of the standard deviation to the mean) of the load} \]

\[ \text{COV}_R = \text{coefficient of variation of the resistance} \]

\[ \beta_T = \text{target reliability index} \]

\[ \gamma_D, \gamma_L = \text{dead and live load factors} \]

\[ \frac{Q_D}{Q_L} = \text{dead to live load ratio} \]

\[ \lambda_{QD}, \lambda_{QL} = \text{dead and live load bias factors} \]

\[
\begin{align*}
\gamma_L &= 1.75 \\
\lambda_{QL} &= 1.15 \\
\text{COV}_{QL} &= 0.2 \\
\gamma_D &= 1.25 \\
\lambda_{QD} &= 1.05 \\
\text{COV}_{QD} &= 0.1
\end{align*}
\]
First Order Second Moment – Live and Dead loads only

\[ \phi = \frac{\lambda_R \left( \frac{\gamma_D Q_D}{Q_L} + \gamma_L \right) \sqrt{\left( \frac{1 + COV_{Q_d}^2 + COV_{Q_L}^2}{(1 + COV_R^2)} \right)}}{ \left( \frac{\lambda_{Q_d} Q_D}{Q_L} + \lambda_{Q_L} \right) \exp\left\{ \beta_T \sqrt{\ln\left( (1 + COV_R^2)(1 + COV_{Q_d}^2 + COV_{Q_L}^2) \right)} \right\}} \]

- **\( \lambda_R \)** = resistance bias factor
- **\( COV_Q \)** = coefficient of variation (the ratio of the standard deviation to the mean) of the load
- **\( COV_R \)** = coefficient of variation of the resistance
- **\( \beta_T \)** = target reliability index
- **\( \gamma_D, \gamma_L \)** = dead and live load factors
- **\( Q_D/Q_L \)** = dead to live load factors
- **\( \lambda_{Q_d}, \lambda_{Q_L} \)** = dead and live load bias factors

Two factors from correlation of measured vs predicted.
( measured / predicted )
Every point has ratio Measured / Predicted = 1.00

\[ \beta = 2.33 \]
\[ D/L = 2 \]

Measured/Predicted

Bias (\( \lambda \)) = 1.000

STD = 0.000

COV = 0.000

\[ \Phi = 0.801 \]

F.S. = 1.77

For “perfect”
“Perfect Agreement”

Example: DL = 1000; LL = 500
- Total load = 1500
- Measured $R_U = 2656$
- Predicted $R_U = 1328$
- Predicted $R_U$ is half real $R_U$

Measured/Predicted Bias ($\lambda$) = 2.000
- STD = 0.000
- COV = 0.000
- $\Phi = 1.602$
- F.S. = 0.88
- F.S. * $\lambda$ = 1.77

Example (D/L = 2):
- Factored resistance $\geq$ factored load
  - (Predicted $R_U \cdot \Phi$) $\geq$ (1.25D + 1.75L)
  - (1328 * 1.6) $\geq$ (1000 * 1.25 + 500 * 1.75)
  - 2125 $\geq$ 2125

In application, Bias $\lambda$ is already accounted for in $\phi$

ASD: FS = 1.77

YES
Overpredict →  Underpredict →
Obviously, **low COV** is highly beneficial

\[ \beta = 2.33 \]

\[ D/L = 2 \]

Measured/Predicted Bias (\( \lambda \)) = 1.0278

STD = 0.170

COV = 0.165

\[ \Phi = 0.715 \]

F.S. = 2.04

N = 303
Another statistics approach....

- **Monte Carlo Simulation (MCS)**
  - Monte Carlo Simulation is a more “rigorous” method for the calculation of the resistance factors, in terms of providing an exact solution (to any degree of precision, given sufficient simulation size/time).
  
  - MCS method can be applied to random samples with distributions that are *neither normal nor lognormal* or when the limit state equation is not linear.
Monte Carlo Simulation (MCS) overview:

- Describe a performance function \( g(x) \) (e.g. \( g = R - Q \)).

- Compute \( g(x) \) for very large number of sets of randomly generated independent parameters (from mean \( \lambda \) and standard deviation \( \sigma \)) and trial \( \phi \).

- Number of events when \( g(x) \) is unsatisfactory divided by number of simulation sets is Probability of Failure \( p(f) \).

- Compare \( p(f) \) to a Target Probability of Failure \( P(f) \).

- Adjust \( \phi \) and repeat until \( p(f) < P(f) \).
## Monte Carlo Simulation (MCS) results

<table>
<thead>
<tr>
<th>Monte Carlo Method</th>
<th>B=2.33</th>
<th>B=3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias</td>
<td>p(f)=1.0%</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>COV-R</td>
<td>max ( \phi )</td>
</tr>
<tr>
<td>CAPWAP N=303</td>
<td>1.028</td>
<td>0.165</td>
</tr>
<tr>
<td>60,000 simulations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAPWAP N=303</td>
<td>1.028</td>
<td>0.165</td>
</tr>
<tr>
<td>1,000,000 simulations</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Compare FOSM with Monte Carlo with AASHTO

<table>
<thead>
<tr>
<th>Monte Carlo</th>
<th>Method</th>
<th>Bias</th>
<th>COV</th>
<th>(\lambda)</th>
<th>(\phi)</th>
<th>Max (\phi)</th>
<th>F.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOSM</td>
<td>CAPWAP</td>
<td>303</td>
<td>1.028</td>
<td>0.165</td>
<td>0.715</td>
<td>2.04</td>
<td></td>
</tr>
</tbody>
</table>

### AASHTO

- **testing 2%**: \(\phi = 0.65\), F.S. = 2.18
- **testing 100%**: \(\phi = 0.75\), F.S. = 1.89
- **testing 2% plus a SLT**: \(\phi = 0.80\), F.S. = 1.77

### IBC

F.S. = 2.00

*from 2004 published correlation paper*
Dynamic Pile Testing

For each blow determine

- Capacity at time of testing
Current Situation:
Inefficient use of materials (design < 20% Fy)
Proof Tests to \{ 2x Design \} $\rightarrow$ F.S. = 2 "Tradition"

Conditions Favorable to Higher Capacities:
- Soft Rock, Till
- Hard Rock
- Soil Setup
<table>
<thead>
<tr>
<th>20th Cent. loads</th>
<th>Pile size</th>
<th>$f'c$ (psi)</th>
<th>Assume prestress 700 psi</th>
<th>Increase factor over 20th Century loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inch</td>
<td>5000</td>
<td>6000</td>
<td>7000</td>
<td>5000</td>
</tr>
<tr>
<td></td>
<td>6000</td>
<td>7000</td>
<td></td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>7000</td>
<td></td>
<td></td>
<td>7000</td>
</tr>
</tbody>
</table>

| 90               | 14       | 143        | 176                      | 208                                    |

IBC safety factor is 2.0 for either static or dynamic test.

Final Design by IBC.

Savings: 50%

Driven piles are least cost.

Karl Higgins “Competitive Advantages of High Capacity, Prestressed Precast Concrete Piles” PDCA DICEP conference, Sept. 2007.
Most Sites Have “Set-up” (defined as capacity gain with time)

• **Caused by reduced effective stresses in soil during pile driving** *(temporary)*
  – Pore pressure effects - clay
  – Arching (lateral motions) - sand
  – Soil structure (e.g. chemical bonds)
  – “Cookie cutters”

• **Measure it by Dynamic Tests on Both End of Drive and Restrike**
<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>0.492</td>
<td>WS</td>
<td>16810.0</td>
<td>WC</td>
<td>16818.2</td>
<td>JC</td>
</tr>
<tr>
<td>Q1CSX</td>
<td>23.39</td>
<td>Q2CSI</td>
<td>25.90</td>
<td>Q3CSB</td>
<td>8.05</td>
<td>Q4EMX</td>
</tr>
<tr>
<td>Q5BPM</td>
<td>48.3</td>
<td>Q6RX5</td>
<td>392</td>
<td>Q7RX7</td>
<td>355</td>
<td>Q8RX9</td>
</tr>
</tbody>
</table>

**St. John’s River Bridge – test program**

**Aug 11, 1999**

- F (1500)
- V (22.8)
- TS: 51.2
- TB: 10.2

**24 x 0.5 inch c.e.pipe, ICE 120S**

**Sept 16**

- F (1500)
- V (22.8)
- TS: 51.2
- TB: 10.2

**25 bpf**

**152 bpf @ twice the Energy**
ST Johns River Bridge
PDA test program $650,000
increased loads by 33%
with substantially shorter piles
(set-up considered)

Total project (6 bridges):
• $130 million (estimate)
• $110 million (actual)
• $20 million (savings)

Ref: Scales & Wolcott, FDOT, presentation at PDCA Roundtable Orlando 2004
Caution...

Sometimes the pile can lose capacity with time...
Soils with relaxation potential

- **Weathered bedrock formations**
  - Weathered shale is most susceptible
  - Rule of thumb: more weathered bedrock = more relaxation
  - Seeping water effectively softens bedrock surface
  - High normal force after driving plastically creeps away with time; reduces friction
  - Rock fracturing from driving adjacent piles

- **Saturated dense to v.dense sands & sandy silts**
  - Due to negative pore water pressure during driving increases effective stresses of end bearing
  - Pore water pressure equalizes after wait causing reduced soil strength
Dynamic Pile Monitoring

For each blow determine

- Capacity
  at time of testing
- Pile integrity
- Pile stresses
- Hammer performance

Last three items detect or prevent problems for driven piles
Consequences of no redundancy, site variability, and only minimal testing, caused disastrous sudden failure.

TAMPA Tribune – Nov 23, 2004 – “Almost half of the foundations supporting the new elevated portion of the Lee Roy Selmon Expressway need major repairs, and the cost of fixing them has grown to $78 million.”

(eventual total cost was $120 M)
Dynamic Testing – save $$, reduce risk

Large Projects

• Pre-bid special test program optimizes design
  • Pile length and size, pile type
  • Establish design load (ultimate capacity)
  • Evaluate set-up or relaxation
    (multi-day restrikes)
• Early production pile tests (different hammer?)
  • Establish driving criteria
  • Evaluate hammer and procedures
  • Confirm set-up or relaxation trends
• Periodic production pile tests
  • Monitors hammer consistency
  • Evaluate site variability
• Evaluate “problem piles”
Dynamic Testing – save $$, reduce risk

Small Projects

- Test early production piles
  - Confirm design capacity achieved
    - Evaluate set-up or relaxation
      - Multi-hour restikes
      - Restrike pile driven day before?
  - Evaluate hammer and procedures
  - Evaluate site variability
- Establish driving criteria
- Evaluate “problem piles”
To be presented at IFCEE 2018, Orlando, March 2018

Authors:
Van Komurka, & Adam Theiss,

soils - silty sands to silt with sand, some lean clay in upper layers

16 inch x 0.5 inch x 61 ft steel pipes - concrete filled. Costs include cap
### SAVINGS FROM TESTING THE DRIVEN-PILE FOUNDATION FOR A HIGH-RISE BUILDING

<table>
<thead>
<tr>
<th>Construction Control Method (CCM)</th>
<th>Safety Factor</th>
<th>Design Load (kips)</th>
<th># piles</th>
<th>Total Cost</th>
<th>Foundation Cost</th>
<th>Testing Cost</th>
<th>Cost Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>WE, DLT, SLT</td>
<td>2.0</td>
<td>600</td>
<td>456</td>
<td>2,513,762</td>
<td>2,277,502</td>
<td>236,260</td>
<td>0</td>
</tr>
<tr>
<td>WE &amp; DLT</td>
<td>2.5</td>
<td>480</td>
<td>572</td>
<td>2,983,308</td>
<td>2,795,349</td>
<td>187,959</td>
<td>469,546</td>
</tr>
<tr>
<td>WE</td>
<td>3.0</td>
<td>400</td>
<td>684</td>
<td>3,307,287</td>
<td>3,305,287</td>
<td>2,000</td>
<td>793,525</td>
</tr>
<tr>
<td>formula</td>
<td>3.5</td>
<td>343</td>
<td>806</td>
<td>3,835,023</td>
<td>3,834,523</td>
<td>500</td>
<td>1,321,261</td>
</tr>
</tbody>
</table>

Above: Taking advantage of Set-up

<table>
<thead>
<tr>
<th>Below: Ignoring Set-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>WE, DLT, SLT</td>
</tr>
<tr>
<td>WE &amp; DLT</td>
</tr>
<tr>
<td>WE</td>
</tr>
<tr>
<td>formula</td>
</tr>
<tr>
<td>Construction Control Method (CCM)</td>
</tr>
<tr>
<td>----------------------------------</td>
</tr>
<tr>
<td>WE, DLT, SLT</td>
</tr>
<tr>
<td>WE &amp; DLT</td>
</tr>
<tr>
<td>WE</td>
</tr>
<tr>
<td>formula</td>
</tr>
</tbody>
</table>

Above: Taking advantage of Set-up

Below: Ignoring Set-up

<table>
<thead>
<tr>
<th>Construction Control Method (CCM)</th>
<th>Safety Factor</th>
<th>Design Load (kips)</th>
<th># piles</th>
<th>Total Cost</th>
<th>Cost Penalty</th>
<th>Construction days</th>
<th>Time Penalty (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WE, DLT, SLT</td>
<td>2.0</td>
<td>400</td>
<td>684</td>
<td>3,477,927</td>
<td>964,165</td>
<td>127</td>
<td>42</td>
</tr>
<tr>
<td>WE &amp; DLT</td>
<td>2.5</td>
<td>320</td>
<td>885</td>
<td>4,361,508</td>
<td>1,847,746</td>
<td>165</td>
<td>80</td>
</tr>
<tr>
<td>WE</td>
<td>3.0</td>
<td>267</td>
<td>1050</td>
<td>4,992,764</td>
<td>2,479,002</td>
<td>196</td>
<td>111</td>
</tr>
<tr>
<td>formula</td>
<td>3.5</td>
<td>229</td>
<td>1222</td>
<td>5,814,673</td>
<td>3,300,911</td>
<td><strong>228</strong></td>
<td><strong>143</strong></td>
</tr>
</tbody>
</table>

SAVINGS FROM TESTING THE DRIVEN-PILE FOUNDATION FOR A HIGH-RISE BUILDING
South Carolina Ports Authority
Wando Terminal Improvements
By Cape Romain Contractors

“In-situ dynamic testing carried an initial cost of $275,000, only 0.4 percent of the overall program budget. Ultimately, spending this 0.4 percent initially ended up saving SCPA 15 percent in construction costs.”
## Driven Pile Cost and Testing Cost

<table>
<thead>
<tr>
<th>Year</th>
<th>Driven Pile Cost</th>
<th>Testing Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>$10,705,041</td>
<td>$305,921</td>
</tr>
<tr>
<td>2006</td>
<td>$18,836,927</td>
<td>$313,315</td>
</tr>
<tr>
<td>2007</td>
<td>$15,948,151</td>
<td>$379,750</td>
</tr>
<tr>
<td>2008</td>
<td>$26,591,945</td>
<td>$587,882</td>
</tr>
<tr>
<td>2009</td>
<td>$25,308,605</td>
<td>$450,863</td>
</tr>
<tr>
<td>2010</td>
<td>$26,211,622</td>
<td>$518,557</td>
</tr>
<tr>
<td>Total</td>
<td>$123,602,290</td>
<td>$2,556,288</td>
</tr>
</tbody>
</table>

\[ \frac{\$2.5M}{\$123.6 \text{ M}} = 2\% \]

Test / driven pile cost

---

### Method Selection

<table>
<thead>
<tr>
<th>Method</th>
<th>AASHTO PHI (LRFD)</th>
<th>Relative cost of piles</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula (Gates)</td>
<td>0.40</td>
<td>1.00</td>
<td>0%</td>
</tr>
<tr>
<td>Wave Equation</td>
<td>0.50</td>
<td>0.80</td>
<td>20%</td>
</tr>
<tr>
<td>2% PDA</td>
<td>0.65</td>
<td>0.62</td>
<td>38%</td>
</tr>
<tr>
<td>2% PDA Ohio DOT</td>
<td>0.70</td>
<td>0.57</td>
<td><strong>43%</strong></td>
</tr>
<tr>
<td>100% PDA or SLT</td>
<td>0.75</td>
<td>0.53</td>
<td>47%</td>
</tr>
<tr>
<td>PDA + SLT</td>
<td>0.80</td>
<td>0.50</td>
<td>50%</td>
</tr>
</tbody>
</table>

**Savings $92,700,000**
Advantages of Dynamic Testing

- More information faster and at lower cost
  - Supplement or replace static tests
  - Optimize foundation design
  - Capacity & distribution from CAPWAP
  - 40 years experience; large database
- Detect bad hammers
- Know driving stresses (compression-tension)
  - Develop better installation procedures
  - Detect pile damage
  - Lowers risk of foundation failures
- Lower overall foundation costs
Main cost is the foundation and its installation, not the testing cost. The benefit to cost ratio for dynamic testing is very favorable for the contractor, engineer, and the owner.

Testing needed to get most benefit (low F.S. or high PHI), Significant set-up allows significant savings

Dynamic Testing is highly beneficial (lowers total costs), particularly to design build or value engineering. Lowest project cost results from more testing

Need to guard against relaxation in some soils fortunately fairly rare and soils generally known.

Lack of adequate testing can cause failures, and the remediation can be very expensive. Testing reduces risk
Unknowns = Risk = Liability

Actual testing removes unknowns and therefore reduces risks and liability

State-of-Practice includes testing
“One test result is worth a thousand expert opinions”

Werner Von Braun
Father of the Saturn V rocket

Measurements are better than Guesses