Dynamic Pile Testing

ASTM D4945

Pile Driving Analyzer®

Garland Likins, Pile Dynamics, Inc.
2011 PDCA Professor’s Institute

Why test driven piles?

- Public assured of safe foundation (bridges, buildings, etc.)
- We spend lots of money - $4B. Remediation is very expensive!
- Reduce the risk
- Optimize foundation - reduce cost
- Driven piles are tested more often than any other foundation
- More safe, less risk, less cost

Static Analysis Methods

Residual (saprolitic) granite soils: fine to medium silty sand with low plasticity

International Prediction Event “Behaviour of Bored, CFA, and Driven Piles in Residual Soil”, ISC² Experimental Site, 2003, by Viana da Fonseca and Santos
QA Inspection:
Piles always have a “blow count” criteria

Wave Equation Analysis

But wave equation contains assumptions of hammer performance & dynamic soil behavior

Dynamic Pile Testing

Measurements are better than assumptions

Load is applied by impacting ram
Load is measured by strain transducers
Motion is measured by accelerometers
Dynamic testing on all driven pile types

Convert STRAIN ($\varepsilon$) to $F$

$$F(t) = EA\varepsilon(t)$$

Convert ACCELERATION to $V$

$$V(t) = \int a(t) \, dt$$

GRL 40 ton APPLE
Testing an 84" drilled shaft,
30" drop hydraulic release
Activated 4000+ tons

Convert strain to force
Integrate acc to velocity

Measure Strain and Acceleration
Strain to Force requires knowing Modulus
Elastic Modulus for concrete pile (length L) is determined from concrete wavespeed, c

Given: \( \frac{2L}{c} = 12 \text{ ms} = T \)
\( L = 75 \text{ ft} \)

Calculate E

\[
c = \frac{2L}{T} = (2)(75)/0.012 = 12,500 \text{ ft/s}
\]
\[
E = \frac{c^2}{\rho} = \frac{(12,500)^2}{0.15}/32.17 = 729,000 \text{ ksi}
\]
\[
E = \frac{729,000}{144} = 5,060 \text{ ksi}
\]
Attach sensors to pile prior to lofting pile
Rigid foam
“Sensor Protectors”

Concrete pile testing

Wireless sensors

wireless PDA
“smart sensors”
know their calibration
Experienced Engineer controls PDA as if on-site; monitors pile in real time with greatly reduced testing costs. Results available immediately to keep project on track.

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

Energy transferred to pile is equal to work done

\[ E = \int F \, du \]

\[ E(t) = \int F(t) \, v(t) \, dt \]

\[ \leftarrow \text{Max} \]

\[ \rightarrow \text{Rebound} \quad (\text{energy returned to hammer}) \]
**Hammer Performance is important....**

- Contractor productivity
- To install pile to design depth
- Confirms W.E. assumptions
- Test device, quality control

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**PDA Pile Stress Monitoring**

Assure dynamic stresses during driving remain below acceptable limits

- Average comp. stresses at sensor location
- Bending stresses at sensor location
- Tensile stresses in concrete piles
- Compressive stresses at pile bottom

To avoid pile damage –
   adjust driving system if needed
**FMX, CSX**

Force (Stress) Maximum at gage location

\[ \text{FMX} = \varepsilon_{av} EA \quad \text{CSX} = \varepsilon_{av} E \]

**Strain transducer**

FMX: Ensure that sufficient force is applied to mobilize resistance

CSX: Ensure safe pile top stress – compare with stress limits

*CSI is highest individual strain reading*

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**PDA testing - data acquisition**

Average force is proportional and reasonable; 2 sensors required to compensate bending

Local stress 352 MPa; >50 ksi

Average stress 224 MPa; ~32 ksi

Large bending present

Hammer-pile alignment issue
Compression force at toe

Any downward compression force before \( t=2L/c \)
will combine with the upward travelling wave
reflected at \( L/c \) and received at top at \( 2L/c \)

\[
t = 0 \quad L/c \quad 2L/c
\]

Resistance/Force at Bottom, CFB

Computed Force at Pile Bottom:

\[
CFB = R_{toe} = F_{d,1} + F_{u,2} - R_{shaft}
\]

- \( R_{shaft} \) - discussed later
- Search over time for max value
- For pure end bearing pile:
  \[
  CFB = F_{d,1} + F_{u,2} = RTL
  \]

Computed Stress at Pile Bottom

\[
CSB = CFB / A
\]

Assumes stress is uniform over section
Tension force at any location

Any downward compression force before \( t = 2L/c \)
will combine with the upward travelling tension
wave reflected at \( L/c \) and received at top at \( 2L/c \)

\[ t = 0 \quad L/c \quad 2L/c \]

Downward Wave  Upward Wave

toe  top

Maximum Net Tension force from superposition of
(a) maximum upward tension, and
(b) minimum downward compression

How do we calculate the maximum net tension force?

Min downward compression
\[ +786 \text{ kN} \]

Max upward tension
\[ -1377 \text{ kN} \]

\[ +786 \text{ kN} \]

\[ -591 \text{ kN} \]

Codes: Allowable Driving Stresses

USA (AASHTO)

- **Steel piles**
  - 90% of yield strength \( F_y \)

- **Timber piles**
  - Southern Pine 3.2 ksi
  - Douglas Fir 3.5 ksi

- **Concrete piles**
  - Compression:
    - \( (85\% \ f'_c) \) - prestress
  - Tension:
    - \( \text{prestress} + (50\% \ f'_c) \text{ prestress} + 3 \sqrt{f'_c} \)
    - \([f'_c \text{ in psi}]\)
**Pile Damage: BTA, LTD**

- Pile damage causes a tension reflection before 2L/c
- Time tension reflection arrives indicates depth to damage:
  \[ LTD = t_{damage} \times c / 2 \]
- Extent of damage is quantified by damage factor - BTA (β)

**Reflection at an Impedance Change**

<table>
<thead>
<tr>
<th>t = 0</th>
<th>L/c</th>
<th>2x/c</th>
<th>2L/c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Z1v1 + Z2v2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fd,1 + Fu,1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fd,2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Va</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Vd,1</td>
</tr>
</tbody>
</table>

2nd equation: \[ \beta = \frac{Z_d}{Z_1} \]

- \[ \beta = \frac{(Fd,1 - Fu,1)}{(Fd,1 - Fu,1)} \]

\[ \beta = \frac{(Fd,1 - 1.5Rx + Fu,1)}{(Fd,1 - 0.5Rx - Fu,1)} \]

(with shaft resistance)

\[ F_d,1 = 4816 \text{ kN} \]
\[ F_u,1 = -351 \text{ kN} \]
\[ Rx = 1237 \times 2 \]
\[ = 2474 \]

\[ \beta = \frac{4816-3711-351}{4816-1237+351} \]
\[ \beta = 0.192 \]
<table>
<thead>
<tr>
<th>$\beta$ (%)</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Uniform</td>
</tr>
<tr>
<td>80 - 100</td>
<td>Slight damage</td>
</tr>
<tr>
<td>60 - 80</td>
<td>Significant damage</td>
</tr>
<tr>
<td>&lt;60</td>
<td>Broken</td>
</tr>
</tbody>
</table>

**Broken Piles: $\beta < 60$**
- “End bearing” is unreliable in long term for broken piles - Only shaft capacity above break might be useful – usually minimal
- Capacity meaningless for “broken piles”
- BTA generally overestimates $Z_2 / Z_1$
  real lower section generally less

**Capacity**
- At time of testing
- vs depth during drive
- resistance distribution
  - CAPWAP®
  - iCAP®

The Case Method Equation

Upward traveling wave at time $2L/c$:
$$F_{u,2} = -F_{d,1} + \frac{1}{2}R + \frac{1}{2}R + R_B$$

or (rearranging)
$$R = F_{d,1} + F_{u,2}$$
The Case Method Equation

\[
R = \frac{1}{2}(F_1 + Zv_1 + F_2 - Zv_2)
\]

\(F_1\) and \(v_1\) are pile top force and velocity at time 1
\(F_2\) and \(v_2\) are pile top force and velocity at time 2

Time 2 is \(2L/c\) after Time 1: \(t_2 = t_1 + 2L/c\)

\(R\) is the total pile resistance present at the time of the test, and mobilized by the hammer impact.

Case Method Static Resistance

Total Resistance = Static + Dynamic

To estimate dynamic resistance, a viscous damping parameter \(J_v\) is introduced for multiplication of computed toe velocity \(v_{toe}\)

\[
R_d = J_v v_{toe} \quad V_{toe} = \frac{(2 WD_1 - Rt)}{Z}
\]

Non-dimensionalization leads to the Case Damping Factor, \(J_c\)

\[
J_c = J_v + Z \implies R_d = J_c Z v
\]

Case Method Static Resistance

Static = Total Resistance – Dynamic

\[
R_{static} = R - R_{dynamic}
\]

\[
R_s = (1 - J_c)F_1 + Zv_1/2 + (1 + J_c)F_2 - Zv_2/2
\]

\[
R_s = (1 - J_c) WD_1 + (1 + J_c) WU_2
\]
Case Damping Factor Values for RMX

Gravel 0.3 0.4
Sand 0.4 0.5
Silt 0.5 0.7
Clay 0.7 1.0

Case Method Capacity

Easy driving

RS (t) = (1 - J) WD1 + (1 + J) WU2
RS (t) = (1 - J) (FT1 + Z VT1) /2 + (1 + J) (FT2 - Z VT2) /2

Hard driving
RMX method does a time search
RMX methods not as J sensitive

Most Sites Have “Set-up”
“capacity gain with time after installation”

- Caused by reduced effective stresses in soil due to pile driving (temporary)
  - Pore pressure (clay - drainage – log time)
  - Arching (sand - lateral motions)
  - Soil structure (cemented)
  - “Cookie cutters” (oversize “shoes”)

- Measure it by Dynamic Tests on Both End of Drive and Restrike (varied waits)
  - Pre-Design Tests
  - Early Production Piles
End of Drive

Restrike (8 days)

“Set-up”

End of Drive (EOD)
Temporary stop

Begin of Restrike (BOR)
35 minutes

No tension

Increase in lower 1/3

Reports - ASTM D4945

Stop 35 min
Pile Setup - Side Shear

18" PSC, O'Cell at bottom
Side in clay and silty clay in FL

\[ \Sigma = +90\% \text{ in 1 day} \]
(or 9x EOD capacity)

1-28d +43% about half of EOD-1d change

EOD Capacity plotted at ~1 min


....however,

first one caution...

In rare cases, the pile can lose capacity with time...

Identifying Soil Relaxation from Dynamic Testing

Morgano & White, GRL Engineers

Ohio Turnpike (I-80)

Piles drive in clayey silt (N=30) to weathered siltstone/shale (N=50/1")

Pre-Construction Wave Equation Analysis suggests:
20 blows per inch (1.3 mm set) at 9.3 ft (2.8m) stroke at 300 tons
<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Test Date</th>
<th>Blow Count (Blows/inch)</th>
<th>Transfer Energy (Kip-ft)</th>
<th>Hammer Stroke (ft)</th>
<th>Case Method Capacity (tons)</th>
<th>Test Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>2/15/02</td>
<td>20</td>
<td>16</td>
<td>9.2</td>
<td>290</td>
<td>EOID</td>
</tr>
<tr>
<td></td>
<td>2/16/02</td>
<td>15</td>
<td>12</td>
<td>8.5</td>
<td>200</td>
<td>BOR1</td>
</tr>
<tr>
<td></td>
<td>2/16/02</td>
<td>20</td>
<td>18</td>
<td>9.6</td>
<td>270</td>
<td>EOR1</td>
</tr>
<tr>
<td></td>
<td>2/23/02</td>
<td>10</td>
<td>14</td>
<td>8.5</td>
<td>170-200</td>
<td>BOR2</td>
</tr>
<tr>
<td>18</td>
<td>2/23/02</td>
<td>7</td>
<td>17</td>
<td>9.0</td>
<td>172</td>
<td>BOR1</td>
</tr>
<tr>
<td></td>
<td>2/23/02</td>
<td>27</td>
<td>18</td>
<td>9.7</td>
<td>330</td>
<td>EOR</td>
</tr>
</tbody>
</table>

Notes: 1. Pile 13 drove additional 5 inches during restrike sequences
2. Pile 18 drove additional 18 inches during restrike sequences

Testing detected capacity problem.
Prevented potentially major problem on major project

### Soils with relaxation potential

- **Weathered shale**
  - Rule of thumb: more weathered bedrock = more relaxation
  - Seeping water 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

### Static Load Test, Pile #20, Pier 14

![Static test on Undisturbed “sister” pile](image)

- Load vs. Displacement
- Foundation Force

198 tons Capacity

- Pile Top Displacement (inch)
….back to significantly more common SETUP…

and how we can benefit from it by testing…

North Section Intermodal Transit System Guideway
Orlando International Airport

Boring 8

Original Design Load 100 T for 24" pipe at 120 ft depth
Design/Build Proposal: save $18" pipe, shorter depth

Ref: Wayne Waters, Ed Waters & sons,
PDCA Winter Roundtable, Orlando 2004

Proving the point….

Proof test > 250 tons

303 piles - 10% tested by restrike
use set-up
$1 million saved vs original design

Bent #9
• Req. Cap. = 250 tons
• EOD PDA = 135 tons (9 bl/ft)
• 5 day BOR = 256 tons (64 b/ft)
St. John's River Bridge – test program

Aug 11 EOD
25 bpf
Sept 16 150 bpf

150 bpf @ twice the Energy
24 x 0.5 inch c.e.pipe, ICE 120S

ST Johns River Bridge
PDA test program $650,000 extra soil borings $750,000
increased loads by 33% with substantially shorter piles (set-up considered)
Total project:
• $130 million (estimate)
• $110 million (actual)
• $20 million savings savings in pile costs

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

Allowable Compression Capacities (tons) using IBC max allowable stresses (PPC Piles)

<table>
<thead>
<tr>
<th>20th Cent. loads</th>
<th>Pile size</th>
<th>f’c (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>
</tr>
<tr>
<td>75</td>
<td>12</td>
<td>105</td>
<td>129</td>
</tr>
<tr>
<td>90</td>
<td>14</td>
<td>143</td>
<td>176</td>
</tr>
<tr>
<td>115</td>
<td>16</td>
<td>187</td>
<td>229</td>
</tr>
</tbody>
</table>

Karl Higgins “Competitive Advantages of High Capacity, Prestressed Precast Concrete Piles” PDCA/REIP conference, Sept. 2007

Ref: Scales & Wolcott, FDOT, presentation at PDCA Roundtable Orlando 2004
Driven piles and dynamic testing are well suited for marine and near shore applications.
Testing eliminates the uncertainty of bearing capacity.

- Static testing
- Dynamic Testing
- Wave Equation
- Dynamic Formula
- Static Analysis

Better verification methods, and more testing, results in lower SF and therefore less cost.

AASHTO standard specifications (pre 2007)

Application: 2000 ton column load, 200 ton ultimate capacity piles

<table>
<thead>
<tr>
<th>F.S.</th>
<th>design load per pile</th>
<th>piles needed</th>
<th>method</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.50</td>
<td>200/3.50 = 57.1 t</td>
<td>35</td>
<td>dyn. formula</td>
</tr>
<tr>
<td>2.75</td>
<td>200/2.75 = 72.7 t</td>
<td>28</td>
<td>wave equation</td>
</tr>
<tr>
<td>2.25</td>
<td>200/2.25 = 86.9 t</td>
<td>23</td>
<td>dynamic test</td>
</tr>
<tr>
<td>2.00</td>
<td>200/2.00 = 100 t</td>
<td>20</td>
<td>Static (SLT)</td>
</tr>
<tr>
<td>1.90</td>
<td>200/1.90 = 105.3 t</td>
<td>19</td>
<td>SLT + dynamic</td>
</tr>
</tbody>
</table>

lower F.S. → fewer piles → less cost
**LRDF (Load & Resistance Factor Design)**

\[(\phi) \text{Ru} > f_D L_D + f_L L_L + f_i L_i + \ldots\]

**LRFD - Different Loading Factors** ...

- ACI, AISC: \(1.2D + 1.6L\)
- AASHTO: \(1.25D + 1.75L\)
- Eurocode: \(1.35D + 1.5L\)
- Australia: \(1.20D + 1.5L\)

need different “\(\phi\)” factors
for same equivalent F.S.

---

**AASHTO (2010) 1.25D + 1.75L**

look at \(D/L = 3\)

\[D = 1500; \quad L = 500\]

\[1500 \times 1.25 + 500 \times 1.75 = 2750\]

Application:

- 2000 ton column load → 2750 ton “factored load”
- 200 ton ult capacity piles ("nominal resistance")

<table>
<thead>
<tr>
<th>“factored resistance” piles</th>
<th>per pile</th>
<th>needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\phi = 0.40) [200 \times 0.40 = 80 t \rightarrow 35] Gates formula</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>(\phi = 0.50) [200 \times 0.50 = 100 t \rightarrow 28] wave equation</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>(\phi = 0.65) [200 \times 0.65 = 130 t \rightarrow 22] 2%, # dynamic</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>(\phi = 0.70) [200 \times 0.70 = 140 t \rightarrow 20] 25% (?) dynamic</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>(\phi = 0.75) [200 \times 0.75 = 150 t \rightarrow 19] SLT or 100% dyn</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>(\phi = 0.80) [200 \times 0.80 = 160 t \rightarrow 18] SLT and 2%, # dyn</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

Ohio DOT uses 0.70 for dynamic testing

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**Ru \(\geq\) (F.S.) Qd PDCA 2001**

also has LRFD code

Application:

- 2000 ton column load,
- 200 ton ult capacity driven piles

<table>
<thead>
<tr>
<th>SF</th>
<th>design load per pile</th>
<th>needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>200/3.50 = 57 t</td>
<td>35 dyn form</td>
</tr>
<tr>
<td>2.5</td>
<td>200/2.50 = 80 t</td>
<td>25 w.e.</td>
</tr>
<tr>
<td>2.1</td>
<td>200/2.10 = 95 t</td>
<td>21 2% dyn</td>
</tr>
<tr>
<td>1.9</td>
<td>200/1.90 = 105 t</td>
<td>19 1% SLT</td>
</tr>
<tr>
<td>1.65</td>
<td>200/1.65 = 121 t</td>
<td>17 15% dyn +1 SLT</td>
</tr>
</tbody>
</table>
**Number of piles required for example case**

<table>
<thead>
<tr>
<th></th>
<th>AASHTO ASD</th>
<th>AASHTO LRFD</th>
<th>Eurocode 2159</th>
<th>Australia AS 2159</th>
<th>PDCA 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dynamic formula</strong></td>
<td>35</td>
<td>35</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wave equation</strong></td>
<td>28</td>
<td>28</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dynamic test</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max (28 or 2%)</td>
<td>22</td>
<td>20</td>
<td>22</td>
<td>19 or 20 (high or low redundancy)</td>
<td>21</td>
</tr>
<tr>
<td><strong>Dynamic test 100%</strong></td>
<td>19</td>
<td>17</td>
<td>10%</td>
<td>19</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Static test</strong></td>
<td>19</td>
<td>19</td>
<td>23 to 16</td>
<td>18 to 58</td>
<td>19</td>
</tr>
<tr>
<td><strong>Static test (1%)</strong></td>
<td>19</td>
<td>19</td>
<td>23 to 16</td>
<td>18 to 58</td>
<td>19</td>
</tr>
<tr>
<td><strong>Dynamic test and Static test</strong></td>
<td>18</td>
<td>18</td>
<td>18 to 20</td>
<td>18 to 20 (high or low redundancy)</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2% dyn</td>
<td>1 static</td>
<td>18 to 20</td>
<td>18 to 20 (high or low redundancy)</td>
<td>17</td>
</tr>
</tbody>
</table>

**AASHTO LRFD Example - 18” sq PSC**

2,750 tons total factored load
10 piles each with 275 kips factored Resistance

<table>
<thead>
<tr>
<th>PHI</th>
<th>R_{req}</th>
<th>EB (100 ksf)</th>
<th>F_s (1 ksf)</th>
<th>Req. L_{pen}</th>
<th>$</th>
<th>$$$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td>367</td>
<td>225</td>
<td>142</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>0.65</td>
<td>423</td>
<td>225</td>
<td>198</td>
<td>33</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>0.50</td>
<td>550</td>
<td>225</td>
<td>325</td>
<td>54</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>0.35</td>
<td>786</td>
<td>225</td>
<td>561</td>
<td>94</td>
<td>94</td>
<td>94</td>
</tr>
</tbody>
</table>

**What are the consequences of insufficient testing?**

- Tampa Expressway – April 2004
- failed structure (loss of use) more than one year delay
- high remediation costs (more than $120 million)
**Dynamic Testing Benefits**

- More information in less time (reduces delays):
  - Confirms pile capacity design
  - Tests integrity, stresses, hammer energy
- Improves quality control
  - (test more piles; tests “problem piles”)
- Rational means to reduce pile costs
  - Shorter piles or fewer piles (lower S.F.)
  - Significantly less cost than static test

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**Why test driven piles?**

- Public assured of safe foundation (bridges, buildings, etc.)
- We spend lots of money - $4B. Remediation is very expensive!
- Reduce the risk
  - Optimize foundation - reduce cost
- Dynamic testing allows driven piles to have more testing than other foundations
  - More safety, less risk, less cost

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**More Information**

- PDA test program “Viewer” with PDA sample data (no cost for universities) available on request
- Student “notes” with sample problems (and solutions) available upon request
- Brochures available on [www.pile.com/brochure/](http://www.pile.com/brochure/)
- Contact: info@pile.com for requests
“One test result is worth a thousand expert opinions”

Werner Von Braun
Father of the Saturn V rocket

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