Sixty Years of dynamic testing and analysis of piles

A retrospective

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What is "Capacity"?
A project in the early 1970s illustrating that, despite the diminishing return of the blow-count demonstrated by the dynamic formulae, then, as now, stupidity prevails.

To support the tower, the design required 23 steel H-piles driven to 85 ft depth.

Soil profile and SPT N-diagram at a piled foundation for a power line tower in the middle of Alaska.

The drop hammer height-of-fall was raised to more than 10 ft!
Another project at about the same time. Here the contractor had no problem getting the piles down to specified depth. The toe resistance was rather small toward the end, though.
Comparison of strain-waves from a pile driven with several different hammers.

Nos. 1 - 4 are drop hammers (0.6, 0.8, 1.8, and 2.8 tonne)
Nos. 5 - 6 are pneumatic hammers (Plt 290 K and M&H)
Nos. 7 - 8 are diesel hammers (D12 and D22)
Stress-waves (strain) measured at the head of a 260 mm diameter, 75 m long concrete pile before and after cushion change. Two blows recorded from each event.
Stress-waves measured both at the pile head and at the pile toe. (Different hammers, different pile lengths, and different cushions, but travel time is the same)
Some small steps toward theoretical analysis were indeed made by man, but the main result of the 1959 Gubbero tests was the realization of the complexity of pile driving.

Then, came the means to Analysis.

E.A.L. Smith (1960)
PILE-DRIVING ANALYSIS BY THE WAVE EQUATION

By E. A. L. Smith

\[ \frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \]
Tip-toeing through, missing the point

AN INTERESTING ASPECT OF THE TWO DAMPING FORMULATIONS FOR END RESISTANCE DEVELOPS WHEN THE STATIC POINT RESISTANCE IS ZERO: IN THE CASE FORMULATION, THE DYNAMIC TOE RESISTANCE IS FINITE (BECAUSE THE PILE TIP HAS VELOCITY), BUT IN THE SMITH FORMULATION IT IS ZERO.
EXAMPLE 7A: FULL FUEL, HIGH QUAKES

ID: 11

DELMA D 30

C.O.R = Coefficient of Restitution
Along with WEAP came the Pile Driving Analyzer, the PDA!

PDA set-up in 1977
The Case Method Estimate — CMES-RSP

**Dynamic and Static**

With the break-through use of both strain-gages and accelerometers.

Static Resistance includes adjustment by a damping factor.
THE
PIONEERS

George Goble 1975

Photo courtesy of Pete Bentley
A couple of wave-trace graphs from mid 1970s
A project in Salt Lake City in late 1980

Piles (similar to Pile 1, below) were driven well, but then, suddenly, they could not be driven deeper than about 15 m (e.g. Pile 2, below).

Did the pile driving hammer cease to work properly for the No. 2 piles? Or, was the difference in driving response between Piles 1 and 2 due to “changed conditions”? If the latter, the Contractor could recoup his costs.

Loose to compact silt and clay. Hydrostatic pore water pressure to 14 m depth

Large artesian pore pressures below 16 m depth

Very dense, 4 m thick layer capping pore pressures below

G.W.
The impact stress and stress-wave length were about the same for the piles, but the impact force is stress times area and the area was larger for Pile 1. Force is what moves a pile against the soil.
A project in Salt Lake City in late 1980

Piles (similar to Pile 1, below) were driven well, but then, suddenly, they could not be driven deeper than about 15 m (e.g. Pile 2, below).

12.75-in closed-toe pipe piles driven with Delmag D30-32
Pile 1 = 0.500 inch wall
Pile 2 = 0.375 inch wall

Large artesian pore pressures below 16 m depth

Loose to compact silt and clay. Hydrostatic pore water pressure to 14 m depth

Very dense, 4 m thick layer capping pore pressures below

G.W.
Example 1 of a CPTU sounding from a river estuary delta (Nakdong River, Pusan, Korea)

CPTU diagrams from a sounding in non-dilatant sand
The sand layer between 6 m and 8 m depth is potentially liquefiable.

The clay layer is very soft.

The sand below 34 m depth is very dense and dilatant, i.e., overconsolidated and providing sudden large penetration resistance to driven piles and relaxation problems.
Driving a 600 mm diameter, 45 m long, closed-toe, cylinder pile at the site

“The Pile that Ate Its Toe!”

Driving stopped because Termination Resistance had been reached. Ten minutes after EOD, the pile sunk 2 m! We continued driving.

Pile is broken and the resumed driving was essentially just crushing concrete. and driving the toe up into the cylinder void.

Portion of the CPTU U2-diagram

U0

U2
Wave Traces from the event

Three blows before the event occurred

Blow 216
Depth 32.6m

First blow after the event

Blow 219
Depth 34.2m

Wave Traces from the event

Three blows before the event occurred

Blow 216
Depth 32.6m

First blow after the event

Blow 219
Depth 34.2m

Wave Traces from the event

Three blows before the event occurred

Blow 216
Depth 32.6m

First blow after the event

Blow 219
Depth 34.2m
C A P W A P Analysis

Force-match and Velocity match

(Hannigan 1990)
Example of force-match iterations

(Hannigan 1990)
Back in the early days, we all wondered

(1) how true was the CAPWAP-determined capacity to that determined from a static loading test and
(2) how consistent would the capacities be between analyses performed by different operators?

Compilation of CAPWAPs by different operators — AM site  
(Fellenius 1988)
Compilation of CAPWAPs by different operators — JI site (Fellenius 1988)
Compilation of CAPWAPs by different operators — JI site (Fellenius 1988)
Wave traces from one of twenty-four 305 mm square, precast concrete piles were driven through about 11 m of clay deposit into dense clayey silty glacial till.

1st Stress-wave Conference; Authier and Fellenius (1980), reporting analysis produced by Frank Rausche, GRL.
CAPWAP  Matches

Easy Driving at 11.3 m depth

End of Driving at 12.5 m depth

1st Stress-wave Conference; Authier and Fellenius (1980), reporting analysis produced by Frank Rausche, GRL.
Bearing Graphs from WEAP Simulations assuming different quake magnitudes

1st Stress-wave Conference; Fellenius and Authier (1980)
Stress-wave Conferences 1980 - 2008

Not shown: the 9th Kanazawa 2012.
Dynamic and static tests on a 20-inch diameter, 41 m long prestressed pile driven for Alesea Bay Bridge foundations

CAPWAP-determined capacity was 3,600 kN, but static loading test gave 8,000+ kN. Yet, I consider the two tests to agree perfectly.

Load distribution Toe load-movement response
Design of a piled foundation LNG facility involving ≈1,000, 120 ft long, 24-inch prestressed piles

At End-of-Driving, EOD, the construction piles had been ‘hammered’ in excess of 100 bl/ft for several feet!
Of course, “set-up” was considered to be just an additional “conservative benefit”.

You can lead the horse to water ... !
Also the best field work can get messed up if the analysis and conclusion effort loses sight of the history of the data.

The dynamic test (CAPWAP) was performed after the static test. The redriving (ten blows) forced the pile down additionally about 45 mm.
“Plugging” of an Open-toe Pipe Pile

In Driving, the pipe and core are fully mobilized. In a Static Test the core is only partially mobilized.

The core consists of soil and its response is that of a very soft pile ("loaded" upward). The core stiffness, EA, is a thousand times softer than that of a concrete core.

Therefore, CAPWAP-determined capacity is not likely the same as the capacity evaluated from the static loading test.
View on October 4, 2011, taken from the south-east end of CFS building showing some of the about 1,680 piles driven for the CFS.
Photos from the driving of piles with extension
CAPWAP "Match" by a pirated copy.
Here, a properly performed CAPWAP
Oliveira et al. (2008) reported a case history from Sao Paolo, Brazil, where dynamic tests were combined with a static loading test performed on a 700-mm diameter, 12 m long, CFA pile. The dynamic test and static loading tests were carried out 66 days and 97 days, respectively, after constructing the pile.

The dynamic tests followed the procedure of Aoki (2000) called “Dynamic Increasing Energy Test, DIET”, consisting of a succession of blows from a special free-falling drop hammer, while monitoring the induced acceleration and strain with the Pile Driving Analyzer. Five blows were given with an 8,000-kg hammer and heights-of-fall of 200, 400, 600, 800, and 1,000 mm, respectively. Each blow was analyzed by means of the CAPWAP program.

<table>
<thead>
<tr>
<th>N (blows/0.3m)</th>
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<tbody>
<tr>
<td>0 10 20 30 40 50</td>
</tr>
<tr>
<td>Alluvial Soil</td>
</tr>
<tr>
<td>Gray silty clay</td>
</tr>
<tr>
<td>trace sand</td>
</tr>
<tr>
<td>GW</td>
</tr>
<tr>
<td>Alluvial Soil</td>
</tr>
<tr>
<td>Black organic soft silty clay</td>
</tr>
<tr>
<td>Alluvial soil</td>
</tr>
<tr>
<td>Sand</td>
</tr>
<tr>
<td>Residual soil</td>
</tr>
<tr>
<td>Sand with gravel pieces</td>
</tr>
<tr>
<td>PILE</td>
</tr>
</tbody>
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### Load-Movement Curves from CAPWAP Analysis on Five Successive Blows

- **HEAD**
- **SHAFT**
- **TOE**

<table>
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<tr>
<th>LOAD (kN)</th>
</tr>
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<tbody>
<tr>
<td>0 10 20 30 40 50 60</td>
</tr>
<tr>
<td>MOVEMENT (mm)</td>
</tr>
<tr>
<td>0 10 20 30 40 50 60</td>
</tr>
</tbody>
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Now, with the load-movement curve from the static tests

These results were used to state that the capacity determined in the dynamic test did not agree with that from the static test!
Now, with the load-movement curve from the static tests

On closer examination, the records do agree and the quality of the agreement is unusually good.
Now, with the load-movement curve from the static tests

On closer examination, the records do agree and the quality of the agreement is unusually good.

As no surprise at all, the dynamic testing introduced residual load in the pile which made the pile response in the static test a little stiffer than would have been the case in the absence of a prior dynamic test (as shown by the curve “Modeling without residual load”).
Range of definitions of "Capacity" (Fellenius 1975!)

You can always define a "capacity" and then determine it from the pile-head load-movement curve. So, what pile "capacity" would you assess from this static test?

Capacities assessed in a survey of 94 professionals and specialists (Fellenius 2017)
Thank you for your attention

Hal Hunt’s “Pointless” Collection