WORK INSTRUCTIONS FOR ENGINEERS

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OP-027 . INTERPRETATION OF HIGH STRAIN Dynamic Pile Tests (HSDPT)
13.0 INTERPRETATION OF HIGH STRAIN DYNAMIC LOAD TESTS

13.1. INTRODUCTION

The major considerations in the interpretation of high strain dynamic pile tests (HSDPT) can be categorised into four major sections as follows:

a) Data Input Checking

b) Data Quality Checking

c) Data Interpretation (CAPWAP)

d) Applications and Limitations

13.2. DATA INPUT CHECKING

Prior to the field test, more commonly known as PDA, the following should be checked:

- Wavespeed
  - For RC Driven Pile, typical wavespeed ~ 3800 – 4200 m/s, depending on concrete grade
  - For Spun Pile, typical wavespeed ~ 4400 m/s
  - For Steel Pile, typical wavespeed ~ 5120 m/s

- Area
  - Kindly check that the input area of pile is correct.

- Young’s Modulus
  - \[ E = \frac{\rho \cdot c^2}{k} \] (in kPa)
    - Where \( \rho \) is density of concrete (kN/m³)
    - \( c \) is the wavespeed (m/s)
    - \( k \) is the gravity constant (9.81 m/s²)
  - For Steel Pile, typical \( E \) = 2040 to 2140 t/cm²
  - For Concrete Pile, typical \( E \) = 300 t/cm² (weak or young) to 460 t/cm² (Strong or aged)
  - For composite sections, use area weighted average
    \[ E_{eq} = \frac{(E_{steel} \cdot A_{steel} + E_{concrete} \cdot A_{steel})}{A_{total}} \]
13.3. DATA QUALITY CHECKING

Prior to any attempt in interpreting the pile capacity using high strain dynamic load tests, the utmost important aspect to look at is the data quality. Therefore, we need to confirm that the data is of good quality, otherwise **RUBBISH IN → RUBBISH OUT.**

The following should be noted to check for the data quality:

a) The proportionality of the major *input rise* (the peaks do not have to match). Refer to Figure 1 for example of data with good and bad proportionality.

![Figure 1: Good Proportionality between F and V](image1)

![Figure 2: Bad Proportionality between F and V](image2)
NOTE: 1) If $F$ and $V$ are NOT proportional at the first maximum, and $F$ is GREATER than $V$, possible reasons could be:
   • An overestimated modulus (EM) and hence wavespeed (WS). This is possible for concrete and timber piles. THIS MUST BE CORRECTED. It is not possible for steel piles as they have a fixed modulus and wavespeed.
   • There is a significant shaft resistance close to the transducers. In this case, there is a physical reason that proportionality DOES NOT EXIST. No adjustment is necessary.
   • There is an increase of impedance close to the transducers. Check pile geometry and construction records, especially for cast-in-situ piles.

2) If $F$ and $V$ are NOT proportional at the first maximum, and $F$ is LESS than $V$, possible reasons could be:
   • An underestimated Modulus (EM) and hence wavespeed (WS). This is possible for concrete and timber piles. THIS MUST BE CORRECTED. Similarly, it is not possible for steel piles as they have a fixed modulus and wavespeed.
   • Not possible due to shaft resistance, but possible due to tension response from pile bottom in very short piles.
   • There is a decrease in impedance close to the transducers. Check pile geometry and construction records, especially for cast-in-situ piles.
   • Pile damage close to the transducers.

b) All Force ($F$) and Velocity ($V$) curves should be zero before the impact.
c) The velocities at the end of the record return to a relatively stable zero value (pile is at rest). If they do not return to zero, then this either indicates the transducer is malfunction or that the pile motion is not complete. If the pile motion is not complete, the estimates of final movement may be in error.
d) The difference of force responses measured from two strain gauges at any time should not vary by more than $1/3$ to $1/2$ of the maximum force value within the response. Variation generally indicates bending, which is usually greatest during or shortly after impact.
e) The force at the end of the record should return to a stable zero value.
13.4. PDA OUTPUT QUANTITIES

Basic measurement quantities are compared with the results of subsequent results to confirm that the same unadjusted data has been analysed, or to highlight changes in subsequent analysis. The PDA output quantities are summarised in Table 1.

Table 1: Summary of PDA Output Quantities

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantities</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress</td>
<td>TSX</td>
<td>The maximum section tension stress computed by the Case method at any location below the transducers. <strong>Particularly important</strong> for easy driving of concrete piles.</td>
</tr>
<tr>
<td></td>
<td>CSX</td>
<td>The maximum section compression stress at the pile top (FMX / AR).</td>
</tr>
<tr>
<td></td>
<td>CSI</td>
<td>The maximum INDIVIDUAL COMPRESSION STRESS for any transducer.</td>
</tr>
<tr>
<td></td>
<td>CSB</td>
<td>The maximum compressive stress at the pile bottom computed by the Case method.</td>
</tr>
<tr>
<td>Hammer</td>
<td>EMX</td>
<td>The maximum energy transferred from the hammer to the pile. This gives an indication of the hammer transfer efficiency.</td>
</tr>
<tr>
<td>Performance</td>
<td>BPM</td>
<td>Blows per Minute</td>
</tr>
<tr>
<td>Damage</td>
<td>BTA</td>
<td>&lt; 60% : BROKEN</td>
</tr>
<tr>
<td>/Integrity</td>
<td></td>
<td>60 – 80 : MAJOR DAMAGE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 80% : MINOR DAMAGE</td>
</tr>
<tr>
<td></td>
<td>LTD</td>
<td>Length to Damage (Below Sensors)</td>
</tr>
<tr>
<td>Force</td>
<td>FMX</td>
<td>The maximum pile top force.</td>
</tr>
<tr>
<td></td>
<td>CTN</td>
<td>The maximum tension force at or below transducers (first 2L/c only)</td>
</tr>
<tr>
<td></td>
<td>CTX</td>
<td>The maximum tension force (from UP wave first 2L/c or from DOWN wave after 2L/c)</td>
</tr>
<tr>
<td></td>
<td>CFB</td>
<td>Computed compression force at PILE BOTTOM.</td>
</tr>
<tr>
<td>Velocity</td>
<td>VMX</td>
<td>The maximum pile top velocity.</td>
</tr>
<tr>
<td>Displacement</td>
<td>DMX</td>
<td>The maximum pile top displacement.</td>
</tr>
<tr>
<td></td>
<td>DFN</td>
<td>The final pile top displacement.</td>
</tr>
<tr>
<td>Capacity</td>
<td>RMX</td>
<td>Maximum resistance calculated using Case method. * NEVER use JC &lt; 0.4 unless with static correlation). * NOT INTENDED for piles with bottom in CLAY.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Typical damping factors JC for use with RMX method:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Typical</th>
<th>Normal Range (DFI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRAVEL</td>
<td>0.3 – 0.4</td>
<td>-</td>
</tr>
<tr>
<td>SAND</td>
<td>0.4 – 0.5</td>
<td>0.05 – 0.20</td>
</tr>
<tr>
<td>SILT</td>
<td>0.5 – 0.7</td>
<td>0.20 – 0.45</td>
</tr>
<tr>
<td>CLAY</td>
<td>0.7 – 1.0</td>
<td>0.60 – 1.10</td>
</tr>
</tbody>
</table>
### RSP (seldom used)
Original "Case Method" capacity result (depends on JC).
- 0.1 – 0.15 : Clean Sands
- 0.15 – 0.25 : Silty Sands
- 0.25 – 0.40 : Silts
- 0.40 – 0.70 : Silty Clays
- 0.70 or higher for clays

* RP# is RSP with J = 0.#. For e.g., RP4 is RSP (J=0.4)

### RSU
Used for high friction cases (early unloading with negative velocity prior to 2L/c).

### RAU, RA2
"Automatic" capacity methods independent of Case Damping Factor, JC estimate.
* Only suitable for end-bearing piles with little or no shaft resistance.

### QUT / QUS
ONLY IF THE DFN value is adjusted and reliable, this is a Hiley formula calculation of pile capacity based on true energy \(2*EMX/(DMX+DFN)\) or \(2*EMX/(DMX + SET)\). This is useful for developing site correlations and acceptance criteria for untested piles.

### 13.5. DATA INTERPRETATION

#### 13.5.1. Independent Review of 2L/c Time and Wavespeed

The following procedure shall be followed to review the 2L/c time and wavespeed:

1. The time for the wave to travel up and down the pile (2L/c) can be checked by drawing time markers at the commencement of the impact (T1) and at the commencement of the response from the toe (T2).

2. Marker T1 should be positioned where an extension of the rising Force (F), Velocity (V) or Downward Wave (WD) curves meet the time axis. (see Figure 3)

3. Marker T2 should be positioned where the velocity (V) starts to rise relative to the force (F), or where the Upward Wave (WU) first starts to reduce. (see Figure 3)

4. The distance between T1 and T2 can be measured and the 2L/c time determined by scaling on the time axis.
13.5.2. Stresses

The PDA output quantities, CSX and TSX are used to check against the limiting compressive and tensile stress in the pile. The recommended compressive and tensile stress in the pile by Pile Dynamics Inc. (PDI) is presented in Table 2.

Table 2: Summary of Allowable Compression and Tension Forces (US and AS Practice)

<table>
<thead>
<tr>
<th>Stress Type</th>
<th>SI Unit Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Compression</td>
<td>0.9 $F_y$</td>
</tr>
<tr>
<td>Steel Tension</td>
<td>0.9 $F_y$</td>
</tr>
<tr>
<td>Prestressed Concrete</td>
<td></td>
</tr>
<tr>
<td>Compression (top)</td>
<td>0.85 $f'<em>c - f</em>{pe}$</td>
</tr>
<tr>
<td>Prestressed Concrete</td>
<td></td>
</tr>
<tr>
<td>Tension</td>
<td>$f_{pe} + 0.25 (f'_c)^{1/2}$</td>
</tr>
<tr>
<td>Reg. Reinforced Concrete</td>
<td></td>
</tr>
<tr>
<td>Compression (top)</td>
<td>0.85 $f'_c$</td>
</tr>
<tr>
<td>Reg. Reinforced Concrete</td>
<td></td>
</tr>
<tr>
<td>Tension</td>
<td>0.70 $F_y$ ($A_s/A_c$)</td>
</tr>
<tr>
<td>Timber</td>
<td>3 $F_{at}$</td>
</tr>
</tbody>
</table>

Where $F_y$ = Steel Yield Strength (MPa)

$f'_c$ = Concrete 28 day Strength (MPa)

$f_{pe}$ = Effective prestress (MPa)

$A_s$ = Steel Reinforcement Area

$A_c$ = Concrete Area

$F_{at}$ = Allowable Static Timber Stress (MPa)
Compare the CSX (Maximum Compressive Stress) and TSX (Maximum Tensile Stress) values from PDA with the allowable compressive and tensile stress.

The tension force is generally of interest for concrete piles and usually only during easy driving although for large quake soils, high tensile stresses can be a problem for refusal driving. If the CSX or TSX is higher than the allowable compressive stress or tensile stress, it is most likely that the pile is **OVERSTRESSED**.

### 13.5.3. Energy Transfer

The pile hammer delivers energy to the pile. The energy transferred results in work which allows the pile to move a distance against the force of soil resistance.

\[
\text{WORK} = \text{Force} \times \text{Distance} = \text{Hammer Weight} \times \text{Drop Height}
\]

Typical transfer efficiency ranges (suggested by PDI) are tabulated below. The transfer efficiency is based on the ratio of measured energy, $EMX$ to hammer potential energy (Weight $\times$ Drop).

**Table 3: Typical Transfer Efficiency of Various Types of Hammer**

<table>
<thead>
<tr>
<th>Hammer Class</th>
<th>Steel Piles</th>
<th>Concrete Piles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>25 – 50%</td>
<td>17 – 40%</td>
</tr>
<tr>
<td>Single Acting Air</td>
<td>40 – 65%</td>
<td>30 – 55%</td>
</tr>
<tr>
<td>Double Acting Air</td>
<td>22 to 45%</td>
<td>20 – 45%</td>
</tr>
<tr>
<td>Hydraulic / Drop (free)</td>
<td>&gt; 75%</td>
<td>&gt; 50%</td>
</tr>
<tr>
<td>Drop (Cable)</td>
<td>35 – 60%</td>
<td>25 – 50%</td>
</tr>
</tbody>
</table>

### 13.5.4. Pile Damage

Output quantity BTA (beta) is an estimate of the severity of the damage. A scale of damage severity suggested by PDI is shown in Table 4.

**Table 4: Scale of Damage**

<table>
<thead>
<tr>
<th>BTA (%)</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>No Damage</td>
</tr>
<tr>
<td>80 – 99</td>
<td>Slight Damage</td>
</tr>
<tr>
<td>60 – 79</td>
<td>Damaged</td>
</tr>
<tr>
<td>&lt; 60</td>
<td>Broken</td>
</tr>
</tbody>
</table>

In general, pile damage is indicated by the BTA value less than 100. If the pile is short or the rise time is very long, the PDA cannot check for damage and the value 200 is allocated for this condition.

Comment from tester should also be referred on whether it is an air gap discontinuity or sever pile body damage/broken/crushing.

Output quantity LTD provides an estimate of the Length to Damage from the transducer location. Refer to Figure 4 for an example plot of pile with damage.

The consequences of pile damage depend on the structure and its function, loading conditions, environmental conditions, pile manufacture and damage location. Therefore, a careful assessment should be made of any damage indication.
**NOTE:**

1) It is important that the 2L/c time be correct or false indications of damage could occur.

2) PDA may have difficulty in detecting damage very close to the transducer location or close to the pile toe.

3) Soil resistance effects may reduce or completely hide the effects of pile damage, especially if the soil resistance is high and the damage is minor.

4) Due to set up effects, a more accurate assessment of damage can often be made during installation rather than on restrike.

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**13.5.5. Capacity Determination**

In order to determine the pile capacity, it is essential to understand the relationship between (Force, Velocity) and (Downward Wave, Upward Wave).

**13.5.6. Downward Wave:**

The downward wave (WD) is the INPUT from the hammer into the pile. Downward waves cause Force and Velocity to move in the same direction. Wave Down (WD) is $\frac{1}{2}$ the SUM of F and VZ at the time T1, which is the time where the peak of the impact is located.
WD = ½ \[ F + Zv \]

13.5.7. Upward Wave:

The upward wave (WU) is the REFLECTION from the pile and soil. Upward waves cause Force and Velocity to move in the opposite direction.
Wave Up (WU) is ½ the F and VZ, which is at the time T2 (2L/c from time T1).

WU = ½ \[ F - Zv \]

Refer to Figure 5 for an example of pile capacity determination.

![Figure 5: Example of Pile Capacity Determination](image)

**NOTE:** Suffix 1 indicates any time after impact. Suffix 2 indicates at time 2L/c after time 1.

- F = Force
- V = Velocity
- Z = Impedance (EA/c)
- WD = Downward Wave = ½ (F + VZ) at time T1
- WU = Upward Wave = ½ (F – VZ) at time T2
- JC = Case Method Damping Factor

Having known the upward and downward wave, the pile capacity can be determined from the following relationships:

Total Driving Resistance, \( R(T) = WD1 + WU2 \)
Static Resistance, \( R(S) = (1 - JC) WD1 + (1 + JC) WU2 \)

**Note:** For set \( >4\text{mm} \), RMX tends to be higher (and hence not representative) as compared to the CAPWAP results. Therefore, it shall be ensure that the set is less than \( 4\text{mm} \) per blow during testing to obtain representative capacity using CASE method (in other words, RMX~ CAPWAP capacity).

### 13.6. CASE Analyses

CASE wavetraces are useful to check for pile defects/damage. Examples of Intact and Damaged piles are shown below:

![Figure 6: Example of Intact Pile (CASE)](image)
13.7. **CAPWAP Analyses**

CAPWAP is the matching of computed force wave trace at pile head with the measured force wave trace in the field. The computed force wave trace is generated from static analysis of an assumed soil model with variable skin resistance distribution along the pile.

It is an iterative process and the quality of matching can be checked by:

1) **Match Quality**

<table>
<thead>
<tr>
<th>Soil Model Parameters/Extensions</th>
<th>Skin</th>
<th>Toe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Damping Factor</td>
<td>1.717</td>
<td>0.458</td>
</tr>
<tr>
<td>Reloading Level (% of Ru)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Unloading Level (% of Ru)</td>
<td>42</td>
<td></td>
</tr>
</tbody>
</table>

CAPWAP match quality: 2.68 (Wave Up Match)

- Observed: final set = 1.000 mm; blow count = 1000 b/m
- Computed: final set = 0.951 mm; blow count = 1175 b/m

Match quality of 5 or less indicates good matching and therefore good estimate of mobilised pile capacity.
Results with match quality of greater than 5 should be evaluated closely and taken into consideration conservatively.

2) Comparing the Measured Force and Computed Force traces

3) Comparing the Measured Velocity and Computed Velocity traces

13.8. References
