G&P GEOTECHNICS SDN BHD

OPERATING PROCEDURE FOR INTERPRETATION OF HIGH STRAIN DYNAMIC PILE TEST (HSDPT)

Section: OP- 027
Revision: 1
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WORK INSTRUCTIONS FOR ENGINEERS

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NHB / WSY

Checked by   : _____

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Approved by : _____

OP-027 . INTERPRETATION OF HIGH STRAIN DYNAMIC PILE TESTS (HSDPT)

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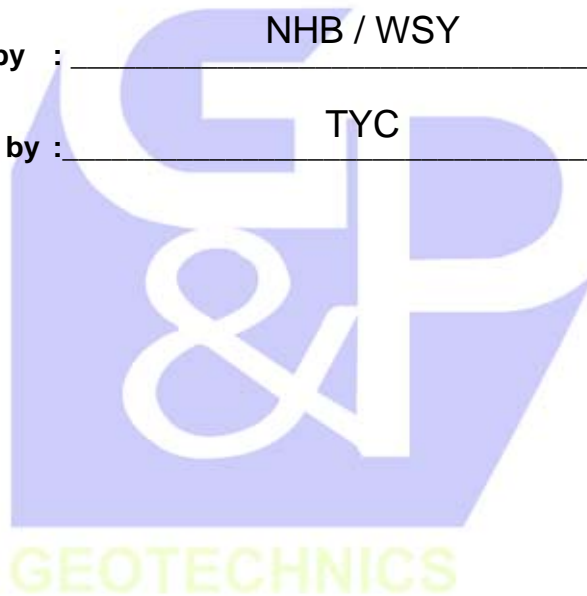
13.0   INTERPRETATION OF HIGH STRAIN DYNAMIC LOAD TESTS

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
    - $E = \rho.c^2 / k$ (in kPa)

        Where ρ is density of concrete (kN/m^3)

                c is the wavespeed (m/s)

                k is the gravity constant (9.81 m/s^2)

    - For Steel Pile, typical E = 2040 to 2140 t/ cm^2

    - For Concrete Pile, typical E = 300 t/cm^2 (weak or young) to 460 t/cm^2 (Strong or aged)

    - For composite sections, use area weighted average

        $E_{eq} = (E_{steel}.A_{steel} + E_{concrete}.A_{steel}) / A_{total}$

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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.
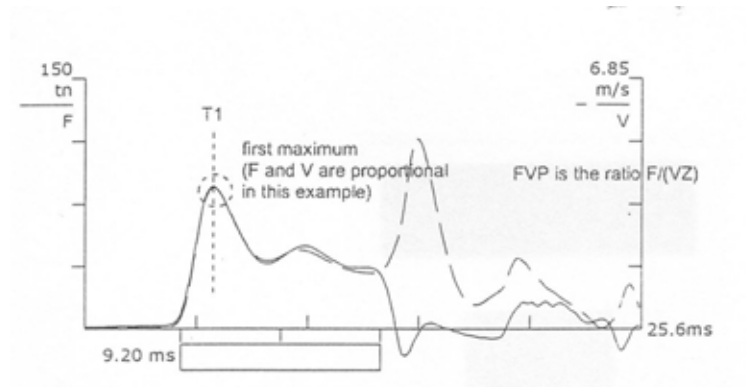

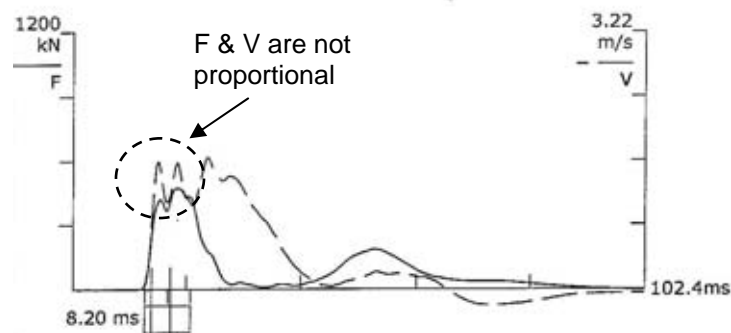**Figure 1: Good Proportionality between F and V**

Figure 2: Bad Proportionality between F and V

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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 ½ 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.

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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

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

Soil Type	Typical	Normal Range (DFI)
GRAVEL	0.3 – 0.4	-
SAND	0.4 – 0.5	0.05 – 0.20
SILT	0.5 – 0.7	0.20 – 0.45
CLAY	0.7 – 1.0	0.60 – 1.10

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|		
	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

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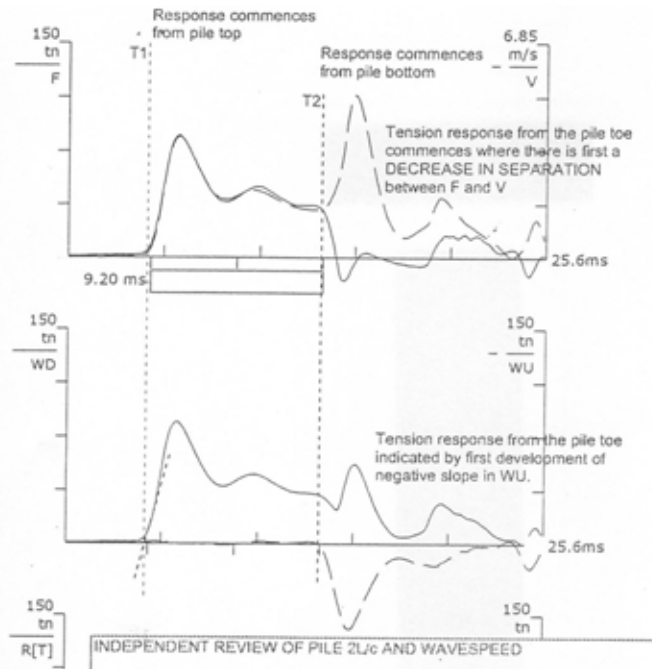
Figure 3: Location of T1 and T2

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)**

Stress Type	SI Unit Limit
Steel Compression	$0.9\ F_y$
Steel Tension	$0.9\ F_y$
Prestressed Concrete Compression (top)	$0.85\ f'_c - f_{pe}$
Prestressed Concrete Tension	$f_{pe} + 0.25\ (f'_c)^{1/2}$
Reg. Reinforced Concrete Compression (top)	$0.85\ f'_c$
Reg. Reinforced Concrete Tension	$0.70\ F_y\ (A_s/A_c)$
Timber	$3\ F_{at}$

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)

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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.

WORK = Force x Distance = Hammer Weight x 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 x Drop).

Table 3: Typical Transfer Efficiency of Various Types of Hammer

Hammer Class	Steel Piles	Concrete Piles
Diesel	25 – 50%	17 – 40%
Single Acting Air	40 – 65%	30 – 55%
Double Acting Air	22 to 45%	20 – 45%
Hydraulic / Drop (free)	> 75%	> 50%
Drop (Cable)	35 – 60%	25 – 50%

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

BTA (%)	Assessment
100	No Damage
80 – 99	Slight Damage
60 – 79	Damaged
< 60	Broken

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.

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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.
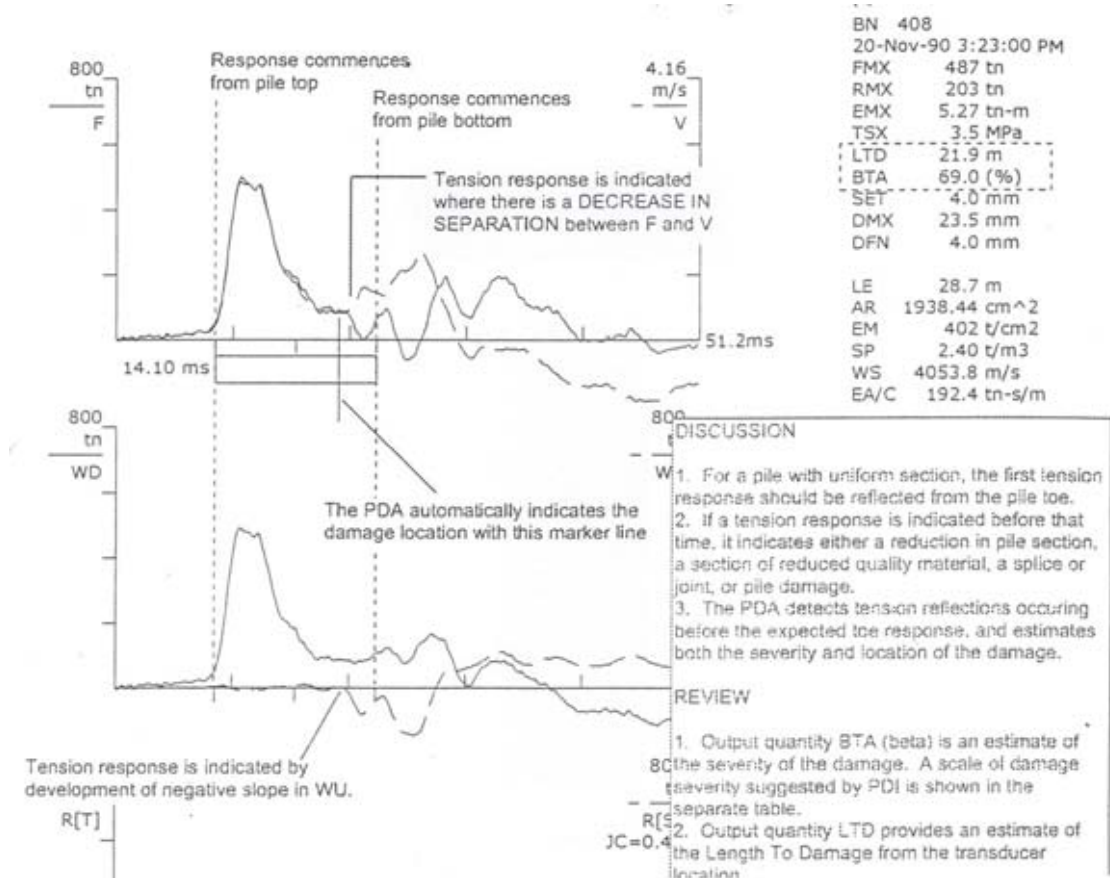

Figure 4: Example plot of a pile with damage

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 ½ the SUM of F and VZ at the time T1, which is the time where the peak of the impact is located.

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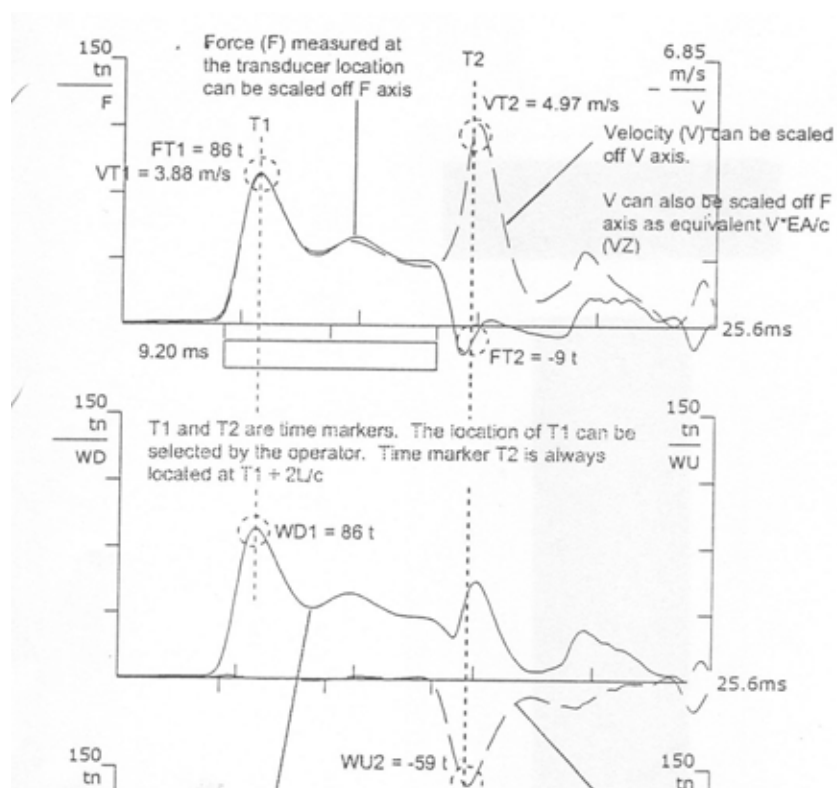*Page 10 of 10*

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

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 + ZV) at time T1
    WU = Upward Wave = ½ (F – ZV) 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

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Static Resistance, R(S) = (1 – JC) WD1 + (1 + JC) WU2

Note: For set >4mm, 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 4mm 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:
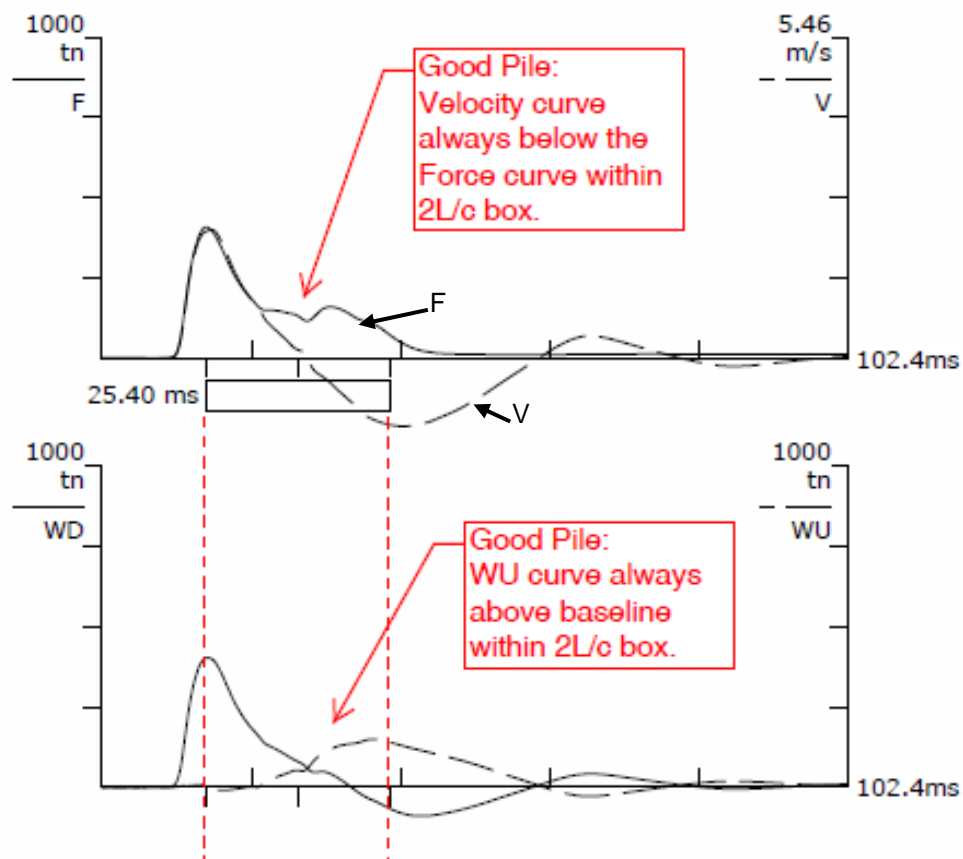

Figure 6: Example of Intact Pile (CASE)

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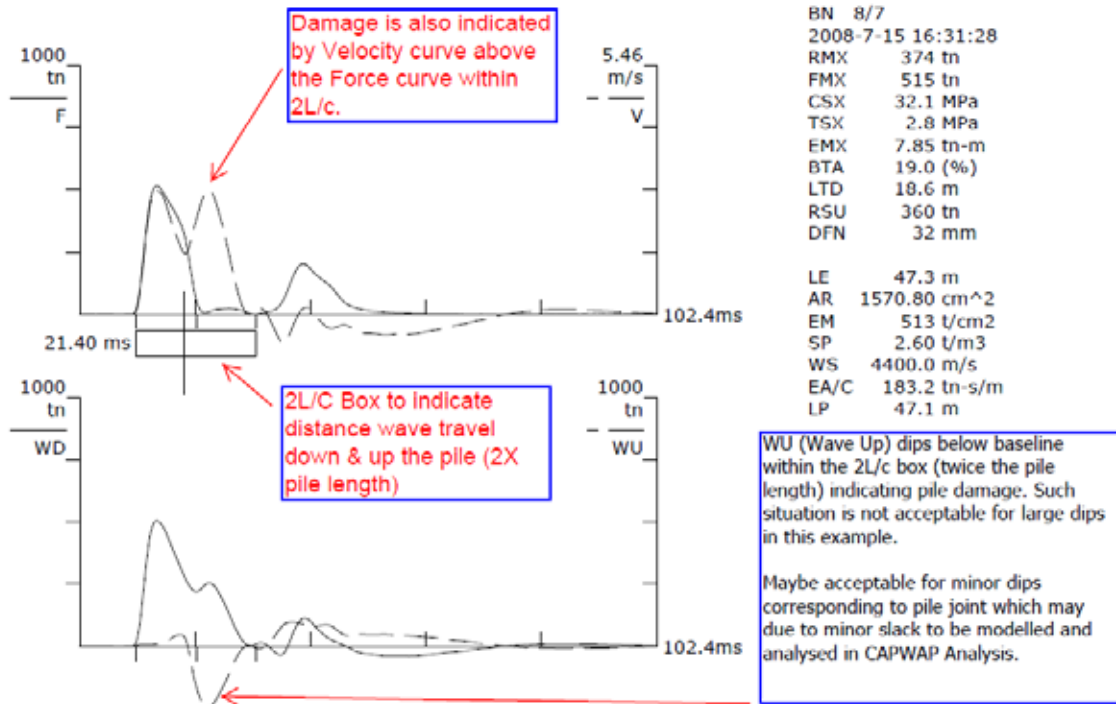*Revision: 1*
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Figure 7: Example of Broken Pile (CASE)

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

```
Soil Model Parameters/Extensions                        Skin      Toe

Case Damping Factor                                     1.717    0.458
Reloading Level            (% of Ru)                      100      100
Unloading Level            (% of Ru)                       42
```

```
CAPWAP match quality:       2.68(Wave Up Match)
Observed: final set =     1.000 mm; blow count =      1000 b/m
Computed: final set =     0.851 mm; blow count =      1175 b/m
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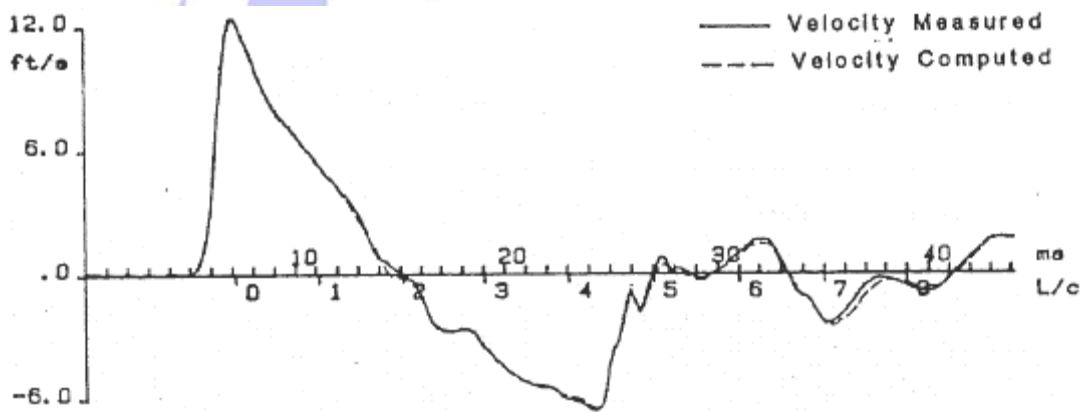
Match quality of 5 or less indicates good matching and therefore good estimate of mobilised pile capacity.

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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
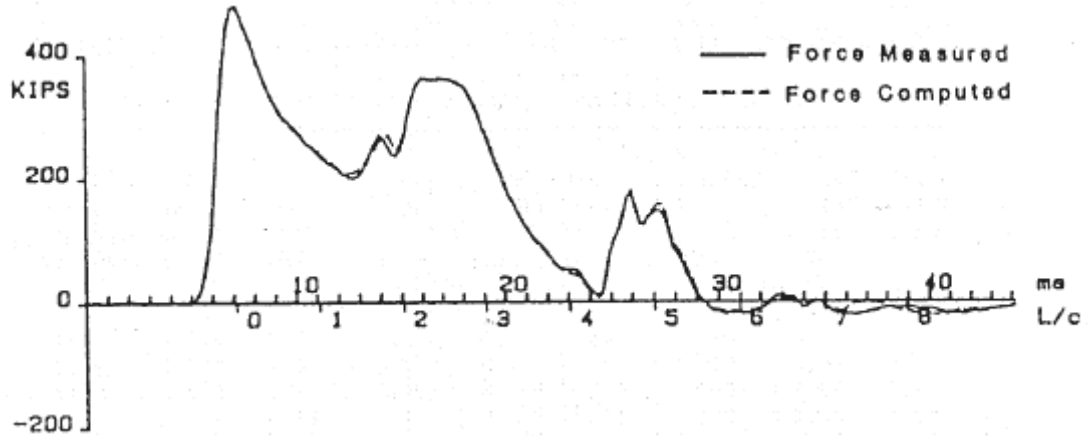
3)   Comparing the Measured Velocity and Computed Velocity traces

13.8.   References

1)   P.J. Hannigan (1990) Dynamic Monitoring and Analysis of Pile Foundations Installations, Deep Foundations Institute.

2)   F. Rausche, B. Robinson & L. Liang (2000) Automatic Signal Matching with CAPWAP, Application of Stress-Wave Theory to Piles, Niyama & Belm (eds), Balkema, Rotterdam.