Workshop and Electronic Workbook on Dynamic Pile Testing Fundamentals

Foundation QA Pty Ltd. 18 Mulgrave Way, Croydon VIC 3136 Australia
Tel: +61 3 9725 1901 Fax: +61 3 9725 1900 julian@foundationqa.com www.foundationqa.com

CONTENTS

PDA

J.P. Seidel

Company providing analysis

EX17; CL-SA > LIMESTONE

PDA OP:

Initials of PDA operator

Test identification information

PILE DRIVING ANALYZER ®
Version 2000.084

EX-17
VUL06 10.75x0.25"CEP

Time and date of test

Blow number

BN 64
08-Oct-96 2:27:33 PM

PDA output quantities

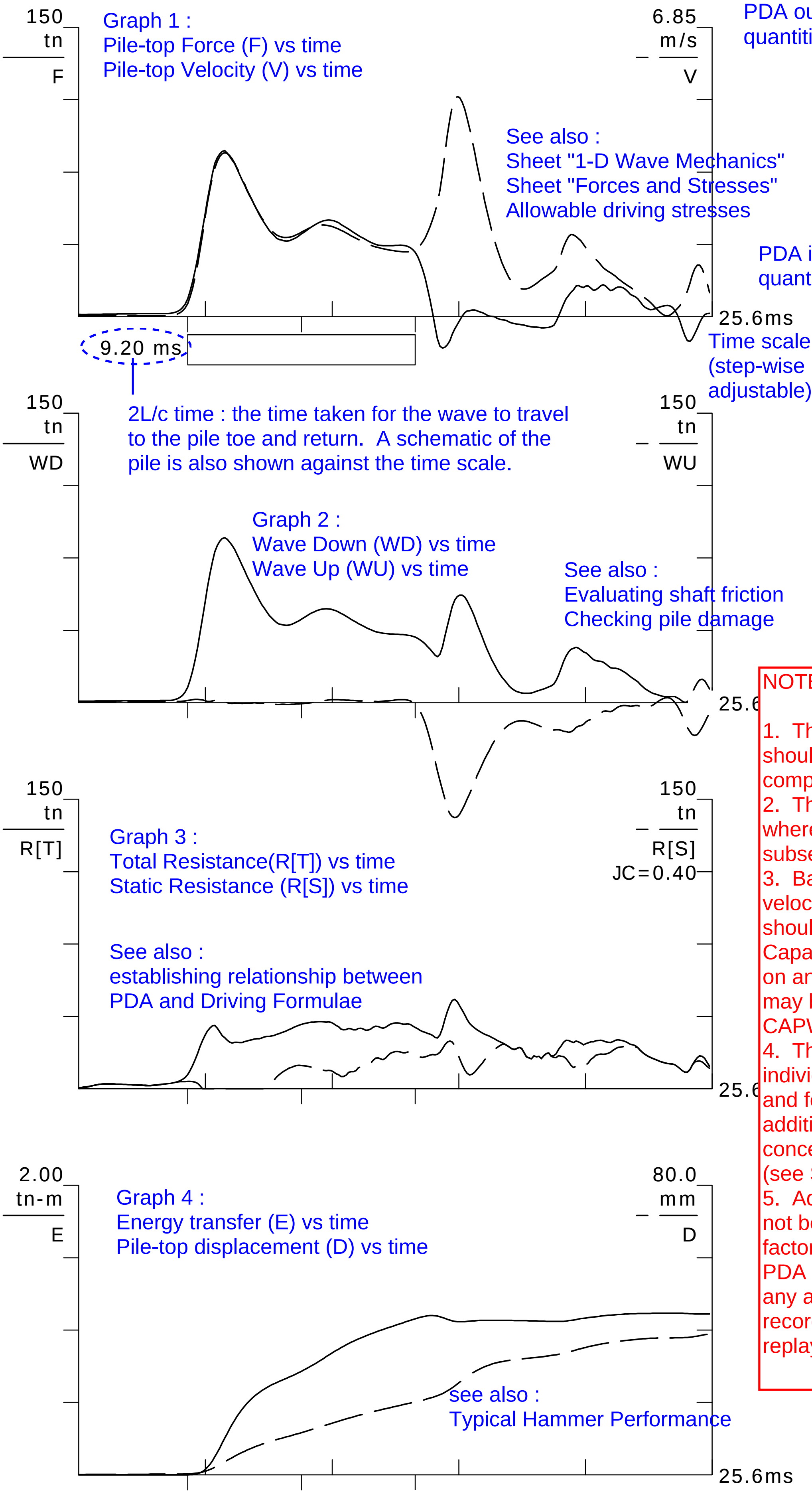
RMX	25 tn
FMX	86 tn
EMX	1.48 tn-m
RX0	46 tn
QUT	28 tn
TSX	65.7 MPa
CSB	79.4 MPa
DMX	53.6 mm
DFN	53.0 mm

PDA input quantities

LE	23.6 m
AR	53.20 cm^2
EM	2109 t/cm2
SP	7.88 t/m3
WS	5123.7 m/s
EA/C	21.9 tn-s/m

F34 A34

Active transducers



NOTES :

1. This standard 4-Graph print out should be required IMMEDIATELY at the completion of each individual test.
2. The blow chosen for print-out should where possible be the blow selected for subsequent CAPWAP analysis.
3. Basic output quantities such as force, velocity, displacement and stresses should not vary with later analysis. Capacity estimates (Rxx) are dependent on an assumed damping factor (JC), and may be changed after adjusted after CAPWAPanalysis.
4. The plot of individual forces and individual velocities for each transducer, and for the FULL data record should be additionally requested if there are any concerns about data quality. (see Sheet "Evaluating Data Quality").
5. Adjustment factors should generally not be applied to data. Any adjustment factors applied should be advised by the PDA Operator. A planned feature is that any adjustment to the force and velocity records will be indicated on this plot by replay factors.

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PDA

1 Dimensional Wave Mechanics
What do the graphs mean?
(1) : Easy driving

See also
Sheet (2) : Hard Driving

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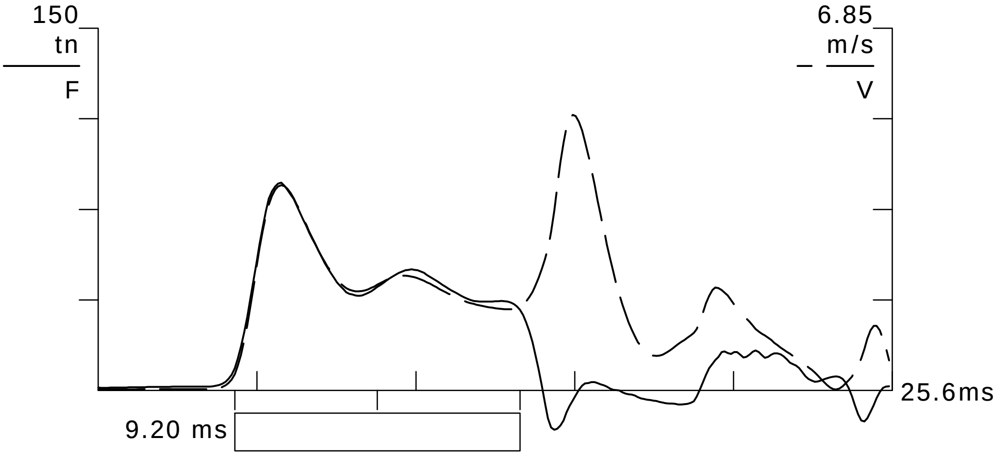

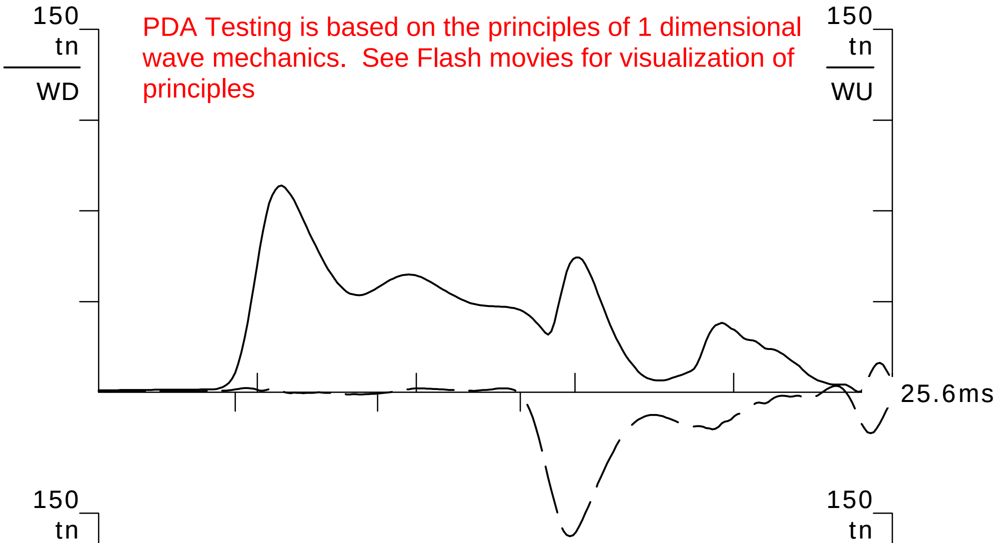

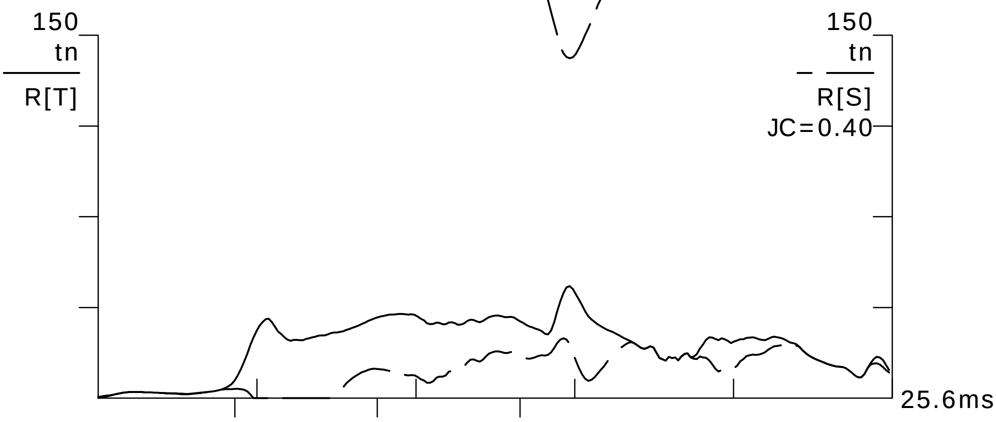

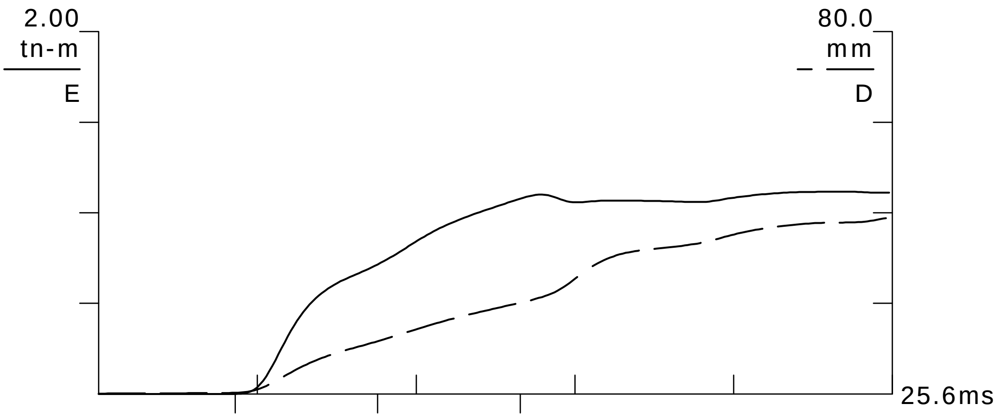

Flash Movies

Newton's balls

Add Springs

Add Wall

F and V (free)

WU/WD (free)

F and V (fixed)

WU/WD (fixed)

Pile toe (free)

Pile toe (fixed)

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1 Dimensional Wave Mechanics
What do the graphs mean?
(2) : Hard Driving

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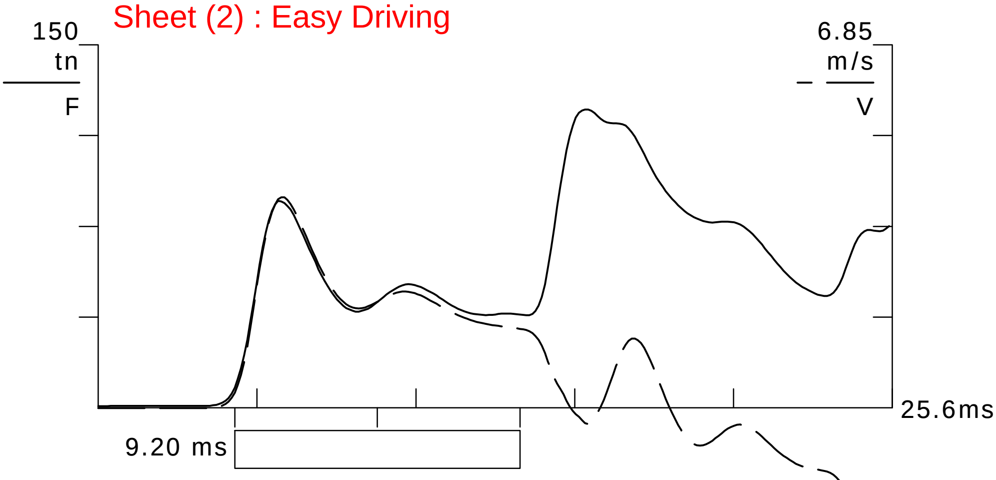
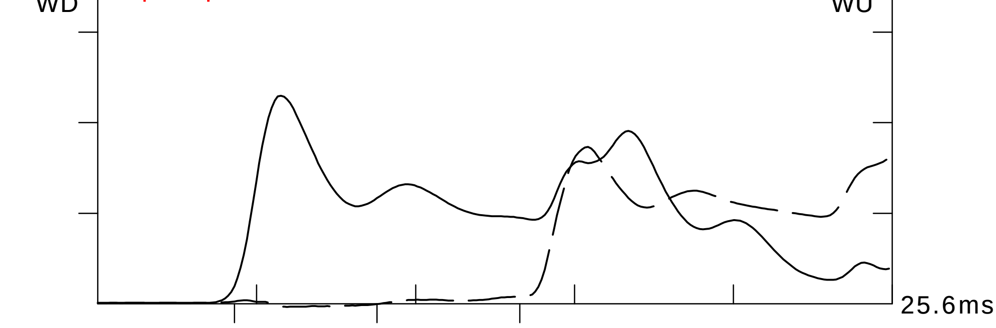
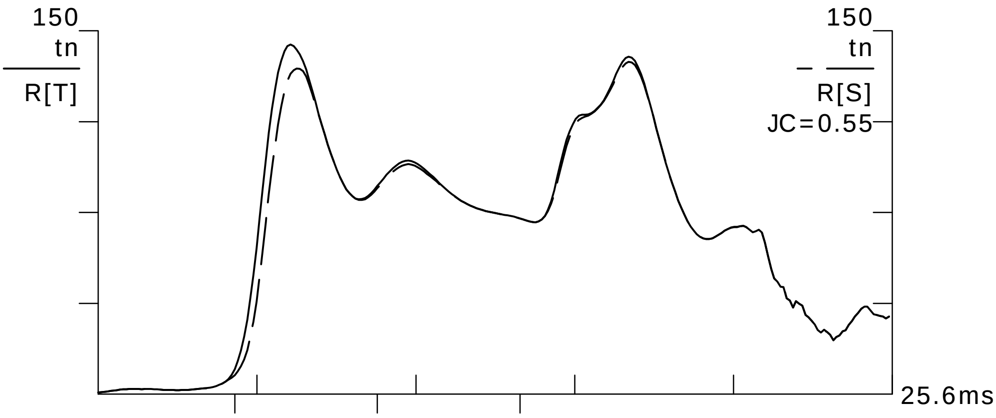
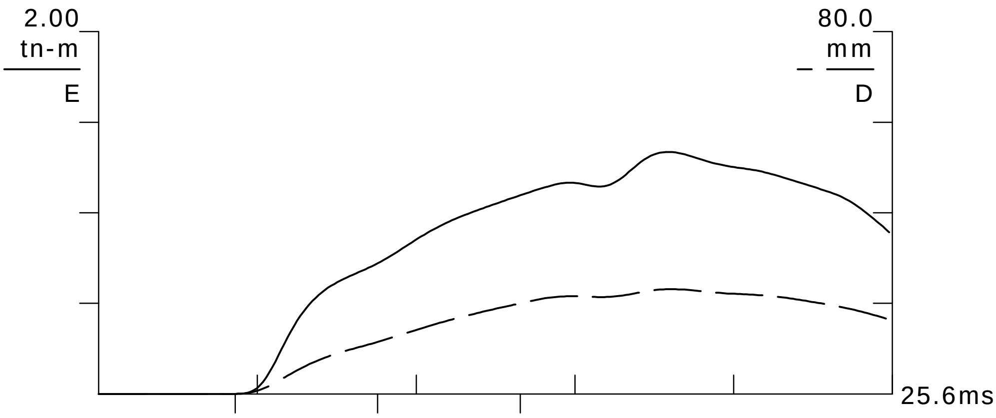
See also
Sheet (2) : Easy Driving



PDA Testing is based on the principles of 1 dimensional wave mechanics. See Flash movies for visualization of principles







BN	116
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RMX	137 tn
FMX	123 tn
EMX	1.34 tn-m
RX0	144 tn
QUT	111 tn
TSX	41.1 MPa
CSB	249.3 MPa
DMX	23.1 mm
DFN	0.8 mm
LE	23.6 m
AR	53.20 cm^2
EM	2109 t/cm2
SP	7.88 t/m3
WS	5123.7 m/s
EA/C	21.9 tn-s/m
F34	A34

Flash Movies

- Newton's balls
- Add Springs
- Add Wall
- F and V (free)
- WU/WD (free)
- F and V (fixed)
- WU/WD (fixed)
- Pile toe (free)
- Pile toe (fixed)

PDA INPUT QUANTITIES

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The saying "Rubbish In, Rubbish Out " applies. If the input values are not correct, all results can be in error.

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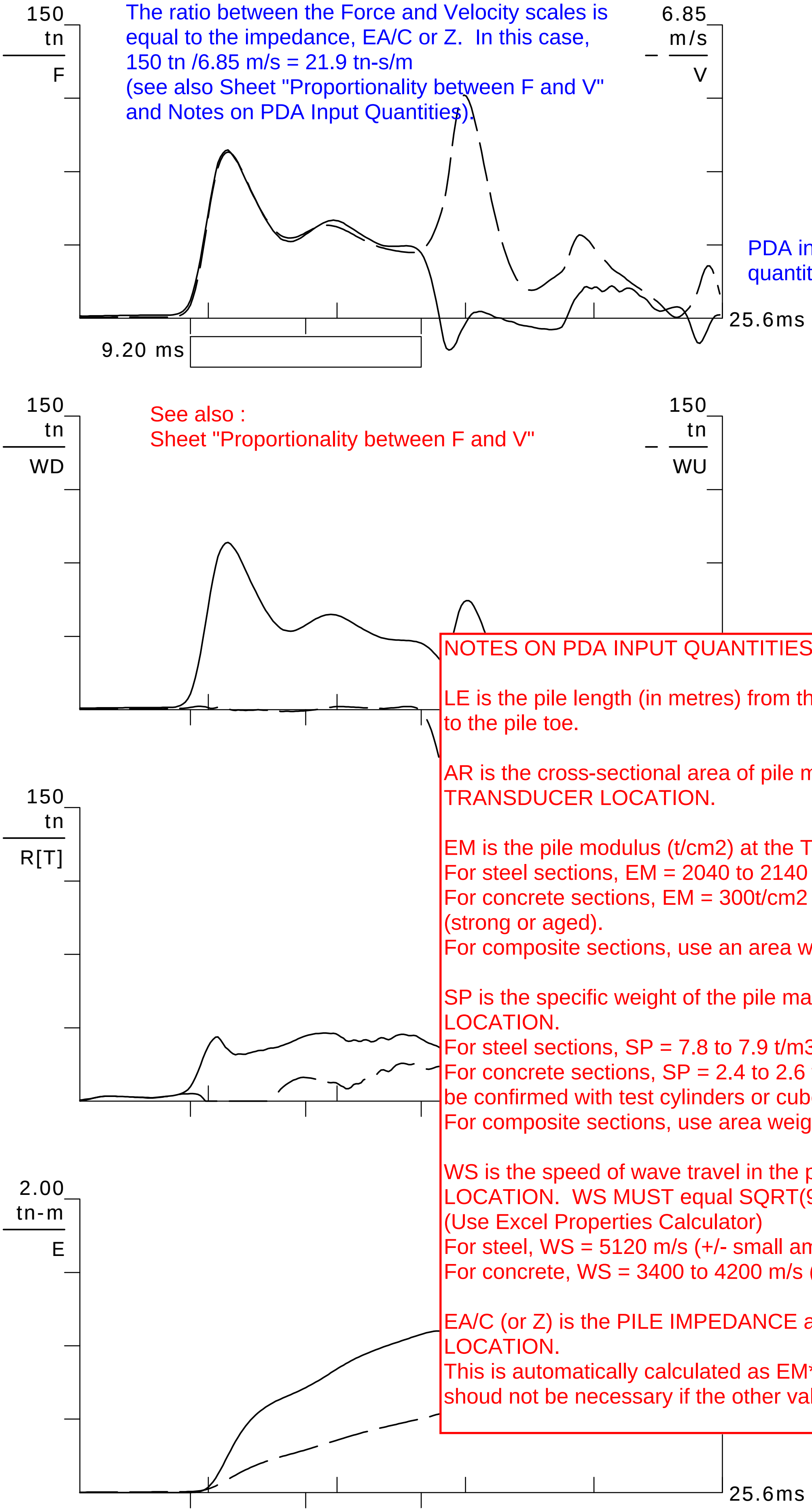
RMX	25 tn
FMX	86 tn
EMX	1.48 tn-m
RX0	46 tn
QUT	28 tn
TSX	65.7 MPa
CSB	79.4 MPa
DMX	53.6 mm
DFN	53.0 mm

The ratio between the Force and Velocity scales is equal to the impedance, EA/C or Z. In this case, 150 tn /6.85 m/s = 21.9 tn-s/m
(see also Sheet "Proportionality between F and V" and Notes on PDA Input Quantities).



PDA input quantities

LE	23.6 m
AR	53.20 cm^2
EM	2109 t/cm2
SP	7.88 t/m3
WS	5123.7 m/s
EA/C	21.9 tn-s/m

F34 A34

See also :
Sheet "Proportionality between F and V"

Excel properties spreadsheet

NOTES ON PDA INPUT QUANTITIES

LE is the pile length (in metres) from the TRANSDUCER LOCATION to the pile toe.

AR is the cross-sectional area of pile material (cm2) at the TRANSDUCER LOCATION.

EM is the pile modulus (t/cm2) at the TRANSDUCER LOCATION.
For steel sections, EM = 2040 to 2140 t/cm2.
For concrete sections, EM = 300t/cm2 (weak or young) to 460 t/cm2 (strong or aged).
For composite sections, use an area weighted average.

SP is the specific weight of the pile material at the TRANSDUCER LOCATION.
For steel sections, SP = 7.8 to 7.9 t/m3.
For concrete sections, SP = 2.4 to 2.6 t/m3 depending on quality, can be confirmed with test cylinders or cubes.
For composite sections, use area weighted average SP value.

WS is the speed of wave travel in the pile at the TRANSDUCER LOCATION. WS MUST equal SQRT(98100*EM/SP).
(Use Excel Properties Calculator)
For steel, WS = 5120 m/s (+/- small amount).
For concrete, WS = 3400 to 4200 m/s (not absolute limits)

EA/C (or Z) is the PILE IMPEDANCE at the TRANSDUCER LOCATION.
This is automatically calculated as EM*AR/WS. A check on this value shoud not be necessary if the other values are correct.

PROPORTIONALITY BETWEEN F AND V

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BN	64
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RMX	25 tn
FMX	86 tn
EMX	1.48 tn-m
FVP	1.00
QUT	28 tn
TSX	65.7 MPa
CSB	79.4 MPa
DMX	53.6 mm
DFN	53.0 mm
LE	23.6 m
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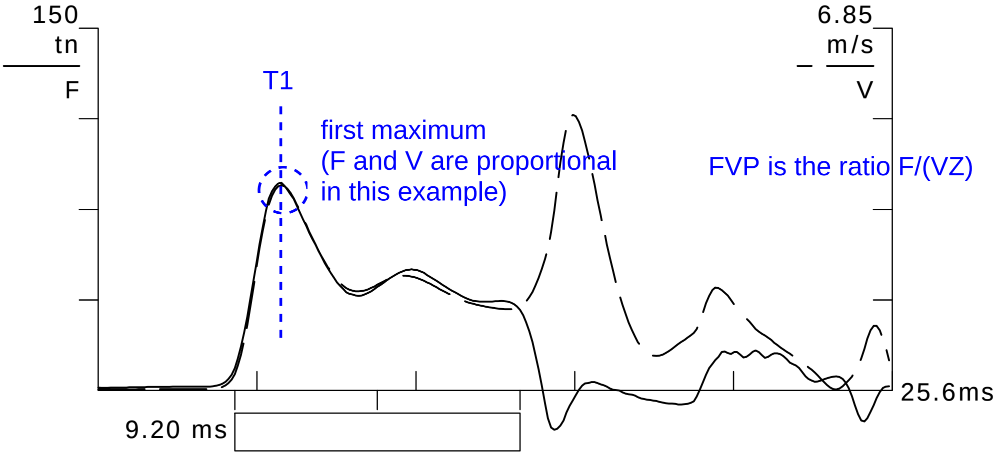

NOTES :

1. PDA testing is based on the principles of 1-Dimensional Wave Mechanics (1DWM).
2. 1DWM states that for a SINGLE wave travelling along UNIFORM rod, the FORCE and VELOCITY at any time and location will be related by F = V * EA/c or F = V *Z (See "Notes on PDA Input Quantities"). The Impedance is a constant of Proportionality.
3. The hammer input generates the first wave in a pile - a downward wave (WD).
4. When the downward (input) wave comes to either a change in pile impedance or any soil resistance, an upward (reflected) wave is generated.
5. As long as the reflected wave has not yet returned to the transducer location, the Force and Velocity will continue to be proportional. As the F and V scales are related by the impedance, the F and V plots should be identical until reflected waves return. F and V are said to be proportional.

REVIEW

1. If F and V are NOT proportional at the first maximum, and F is GREATER than V, possible reasons could be :
Reason 1) 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.
Check WS value against suggested range in Notes on PDA Input Quantities. WS should be DIVIDED by the ratio FVP, and EM will also reduce (to EM_old/FVP^2). Incorrect EM, WS will result in Forces, Energy and Capacity all being OVERESTIMATED by the ratio FVP.
Reason 2) there is significant shaft resistance close to the transducers. In this case there is a physical reason that proportionality DOES NOT EXIST, and no adjustment is necessary. The values of EM and WS should be compared against suggested ranges. WS can also be compared against WC which is the wavespeed used in checking 2L/c (see Sheet "Checking Pile Length and Wavepseed"). There should be reasonable agreement between WS and WC.
Reason 3) there is an increase of impedance close to the transducers. Check pile geometry and construction records, especially for cast-in-situ piles.
Iin the context of the above, "close" means within half the distance represented by the rise-peak time scaled against the pile schematic.

2. If F and V are NOT proportional at the first maximum, and F is LESS than V, possible reasons could be :
Reason 1) an underestimated 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. See above for procedure (WS, EM, Force, Energy and Capacity will increase in this case).
Reason 2) not possible due to shaft resistance, but possible due to tension response from pile bottom in very short piles.
Reason 3) there is a decrease in impedance close to the transducers. Check pile geometry and construction records, especially for cast-in-situ piles.
Reason 4) pile damage close to transducers (see Sheet "Checking Pile Damage").

PDA

KEY PDA OUTPUT QUANTITIES

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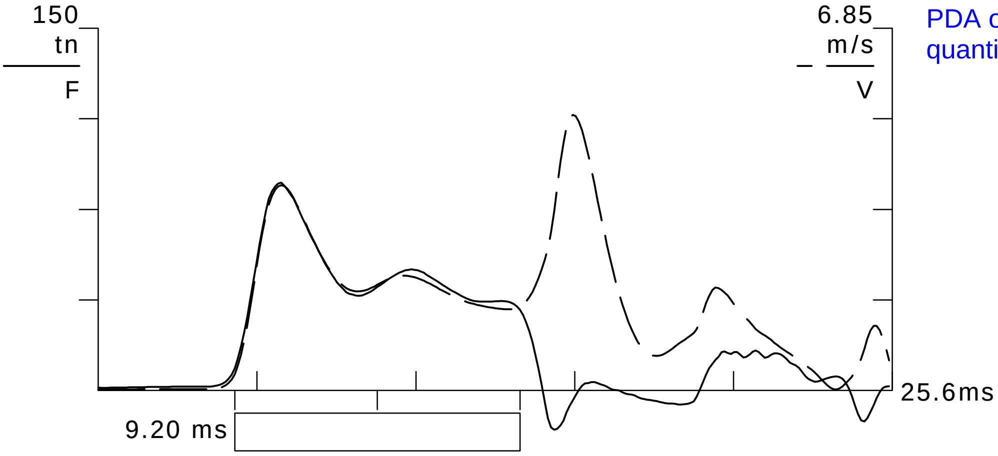

PDA output quantities

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FMX	86 tn
EMX	1.48 tn-m
RX0	46 tn
QUT	28 tn
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CSB	79.4 MPa
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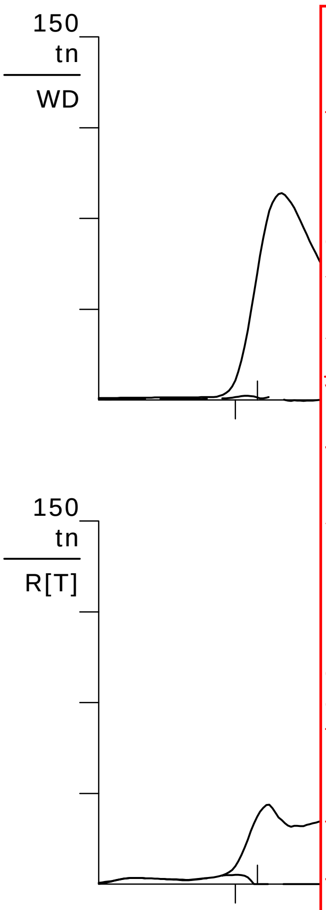


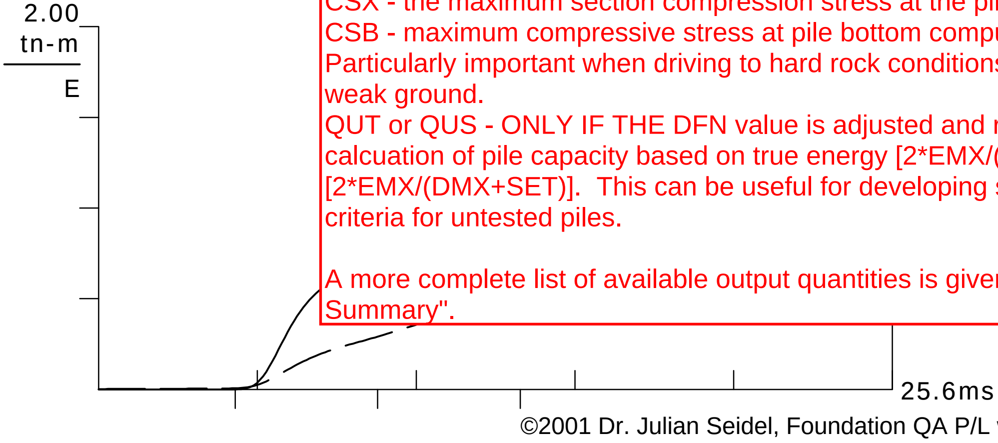
NOTES ON PDA OUTPUT QUANTITIES

1. There is a very large array of possible quantities which can be computed and printed by the PDA. Nine quantities can be selected for this standard printed output.
2. The quantities should generally include:

Basic measurement quantities that can be compared with the results of subsequent results to confirm that the same unadjusted data has been analyzed, or to highlight changes in subsequent analysis. In particular -
FMX - the maximum pile-top force. This will only vary if the assumed pile impedance is subsequently changed, or the strain measurements are scaled (either case should be justified).
VMX - the maximum pile-top velocity. This should not change in subsequent analysis.

The following quantities are also recommended :
DMX - the maximum pile-top displacement. This is a reasonably reliable measurment, and should be close to the sum of the pile set and temporary compression physically measured.
DFN - the final pile-top displacement. This is a measurement which can be reliable only if the PDA operator makes appropriate adjustments. In this case, DFN = pile set. If no adjustment is made, it can be extremely unreliable.
EMX - the maximum energy transferred from the hammer to the pile. This gives an indication of the hammer transfer efficiency. The efficiency of different classes of hammer varies considerably (see information sheet on energy plot). The energy transfer is also a function of the cushioning systems and the driving conditions.
RMX (or other of the available resistance quantities). This is the Case Method Maximum Resistance method. This should be used as a default resistance quantity, however, for long friction piles, RSU (Case Method with unloading correction) may be more appropriate. The Case Method will be a function of the assumed damping factor, JC.
TSX - maximum section tension stress computed by the Case Method at any location below the transducers. This assumes a uniform pile section. Particularly important for easy driving of concrete piles.
CSX - the maximum section compression stress at the pile-top (FMX/AR).
CSB - maximum compressive stress at pile bottom computed by the Case Method. Particularly important when driving to hard rock conditions, especially for short piles or piles in weak ground.
QUT or QUS - ONLY IF THE DFN value is adjusted and reliable, this is a Hiley formula calcuation of pile capacity based on true energy [2*EMX/(DMX+DFN)] or [2*EMX/(DMX+SET)]. This can be useful for developing site correlations and acceptance criteria for untested piles.

A more complete list of available output quantities is given in the sheet "PDA Output Quantity Summary".



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PDA OUTPUT QUANTITY SUMMARY

Stress:

TSX	Max TENSION STRESS below transducers (CTX/AREA); TSN=CTN/AR
CSX	Max average axial COMPRESSION STRESS at transducer (FMX/AREA)
CSI	Max INDIVIDUAL COMPRESSION STRESS for any transducer
CSB	Max computed COMPRESSION STRESS AT TOE (CFB/AREA)

Hammer performance:

EMX	ENERGY TRANSFERRED to pile-EFV-(most important measure)
ETR	ENERGY TRANSFER RATIO (EMX/ER) (must input "ER" RATING)
BPM	BLOWS PER MINUTE
AMX	Max ACCELERATION
STK	STROKE [feet or metres] - use for OPEN END DIESEL HAMMERS only
VRI	Ram Impact Velocity (Steel piles only with ASHD Hammers; WR,WH)

Damage / Integrity: (user must always manually inspect "WU" to confirm PDA result):

BTA	[<60% BROKEN], [60% to 80% MAJOR DAMAGE], [>80% MINOR DAMAGE]
LTD	LENGTH TO DAMAGE (below sensors) (also BT2 & LT2)

Force:

FMX	Max COMPRESSIVE FORCE at transducers (MEX = Max STRAIN)
CTN	Max TENSION FORCE at or below transducers (first 2L/C only)
CTX	Max TENSION FORCE (from UP wave first 2L/C, or from DOWN wave after 2L/c)
CFB	Computed COMPRESSION FORCE at PILE BOTTOM (CFB=RX0 - SFT)
FT1	FORCE at operator-selected marker TIME ONE (FT2 at TIME TWO)

Velocity:

VMX	Max VELOCITY at transducers
VT1	VELOCITY at operator-selected marker TIME ONE (VT2 at TIME TWO)

Displacement:

DMX	Max DISPLACEMENT at transducers
DFN	DISPLACEMENT AT END of data record
DT1	DISPLACEMENT at operator-selected marker TIME ONE
DBX	Max DISPL AT TOE AT RMX (do NOT USE on FRICTION PILES!)

Others:

USR	USER INPUT (OBSERVATION OF STROKE, K.E., BCP, ETC.)
FVP	FORCE/VELOCITY PROPORTIONALITY
TRP	TIME RISE TO PEAK
WD1	WAVE DOWN at operator-selected marker TIME ONE
WU2	WAVE UP at operator-selected marker TIME TWO
WDX	WAVE DOWN @TMX

Capacity:

RSP	Original "Case Method" capacity result (depends on JC). JC guide: 0.1 - 0.3 SAND; 0.3 - 0.5 SILT; 0.5 - 1.0 CLAY. RP# is RSP with J = 0.# to get RSP with second J; i.e. RP4 is RSP(J=0.4)
RMX	Maximum "Case Method" capacity searches RSP at different T1 times for MAX result, (depends on JC; should probably NEVER use JC<0.4, unless with static correlation). NOT INTENDED for piles with bottom in CLAY: JC>0.8 UNUSUAL RMX(JC=.5) is often a good initial choice (confirm with CAPWAP). RX# is RMX with J=0.# to get RMX with second J; i.e. RX6 is RMX(J=0.6). WDX is WD1 at time (TMX) of RMX; DBX is MAX TOE DISPLACEMENT
RSU	RSP(JC) for high friction cases (early unloading with negative velocity prior to 2L/c). RU# is RSU with J=0.# to get RSU with second J; RU5 is RSU(J=0.5)
RAU, RA2	"Automatic" capacity methods independent of Case Damping factor, JC estimate. Generally only suitable for end-bearing piles with little or no shaft resistance.
SFT	SHAFT FRICTION TOTAL - no correction for damping. SFR has a CRUDE DAMPING CORRECTION which depends on JC).

PDA

CHECKING ACTIVE TRANSDUCERS

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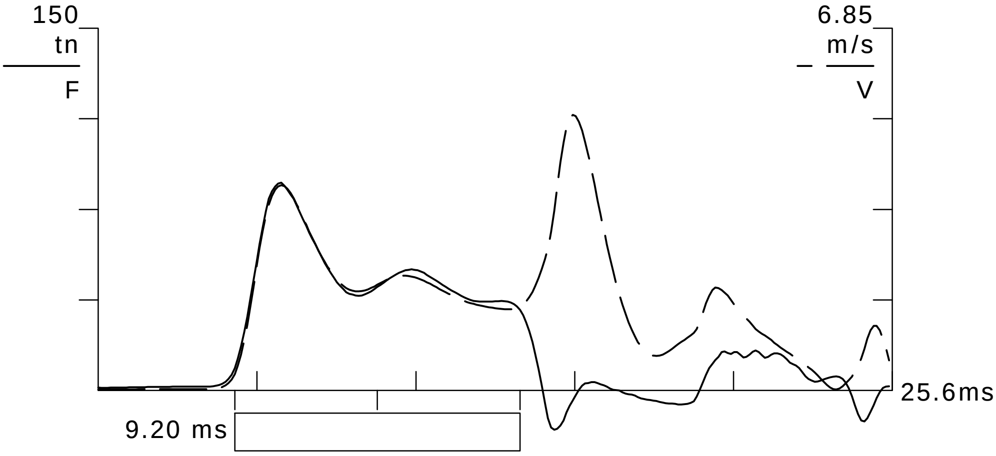

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EM 2109 t/cm2
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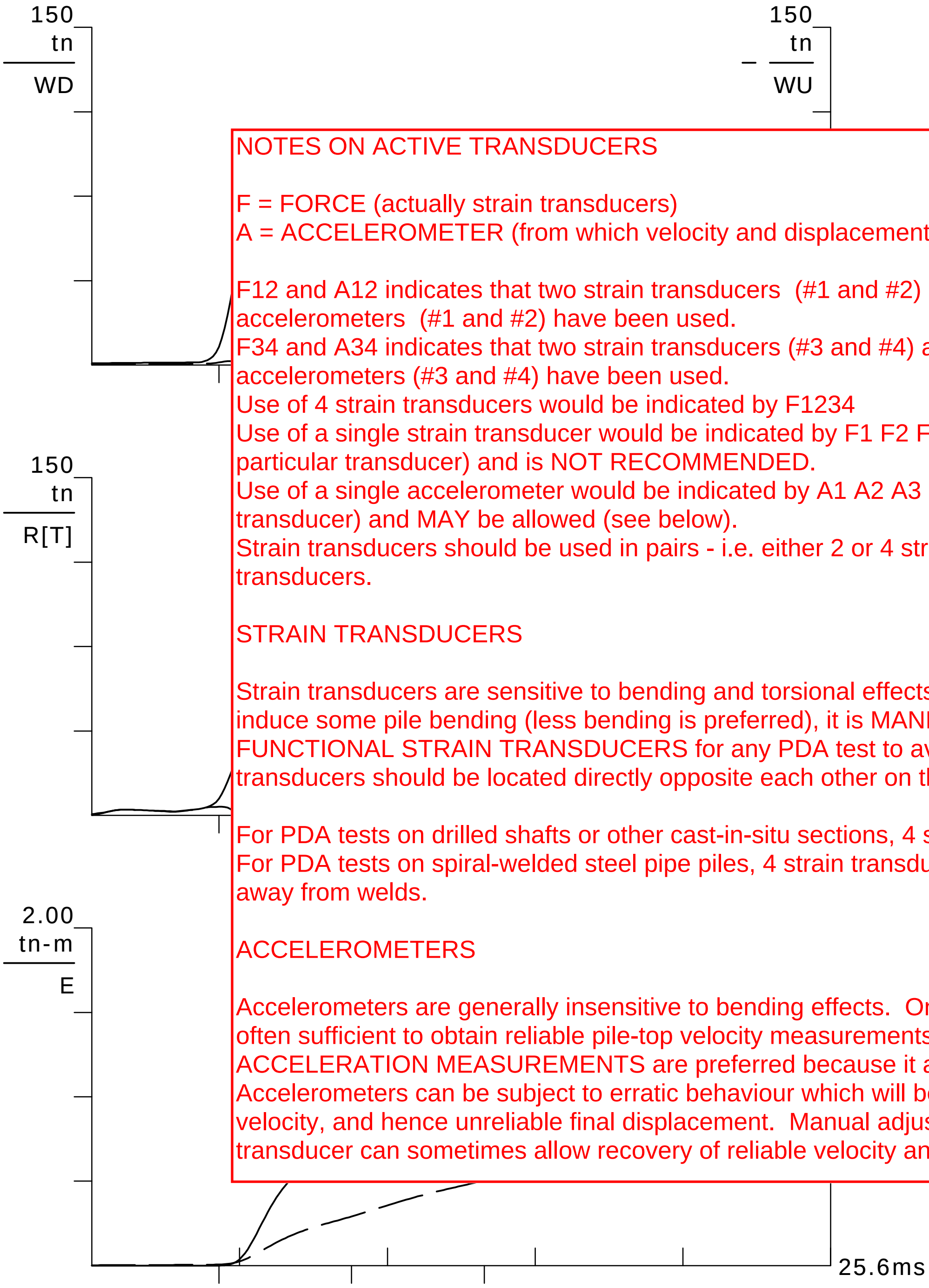
F34 A34

Active transducers



NOTES ON ACTIVE TRANSDUCERS

F = FORCE (actually strain transducers)
A = ACCELEROMETER (from which velocity and displacement are computed)

F12 and A12 indicates that two strain transducers (#1 and #2) and two piezo-electric accelerometers (#1 and #2) have been used.
F34 and A34 indicates that two strain transducers (#3 and #4) and two piezo-resistive accelerometers (#3 and #4) have been used.
Use of 4 strain transducers would be indicated by F1234
Use of a single strain transducer would be indicated by F1 F2 F3 or F4 (depending on the particular transducer) and is NOT RECOMMENDED.
Use of a single accelerometer would be indicated by A1 A2 A3 or A4 (depending on the particular transducer) and MAY be allowed (see below).
Strain transducers should be used in pairs - i.e. either 2 or 4 strain transducers NOT 1 or 3 strain transducers.

STRAIN TRANSDUCERS

Strain transducers are sensitive to bending and torsional effects. As hammer impacts generally induce some pile bending (less bending is preferred), it is MANDATORY to use AT LEAST TWO FUNCTIONAL STRAIN TRANSDUCERS for any PDA test to average any bending effects. The transducers should be located directly opposite each other on the pile section.

For PDA tests on drilled shafts or other cast-in-situ sections, 4 strain transducers should be used.
For PDA tests on spiral-welded steel pipe piles, 4 strain transducers should be used, and located away from welds.

ACCELEROMETERS

Accelerometers are generally insensitive to bending effects. One functional accelerometer is often sufficient to obtain reliable pile-top velocity measurements, although TWO ACCELERATION MEASUREMENTS are preferred because it allows checking consistency. Accelerometers can be subject to erratic behaviour which will be evident with a non-zero final velocity, and hence unreliable final displacement. Manual adjustments, or elimation of the erratic transducer can sometimes allow recovery of reliable velocity and displacement measurements.

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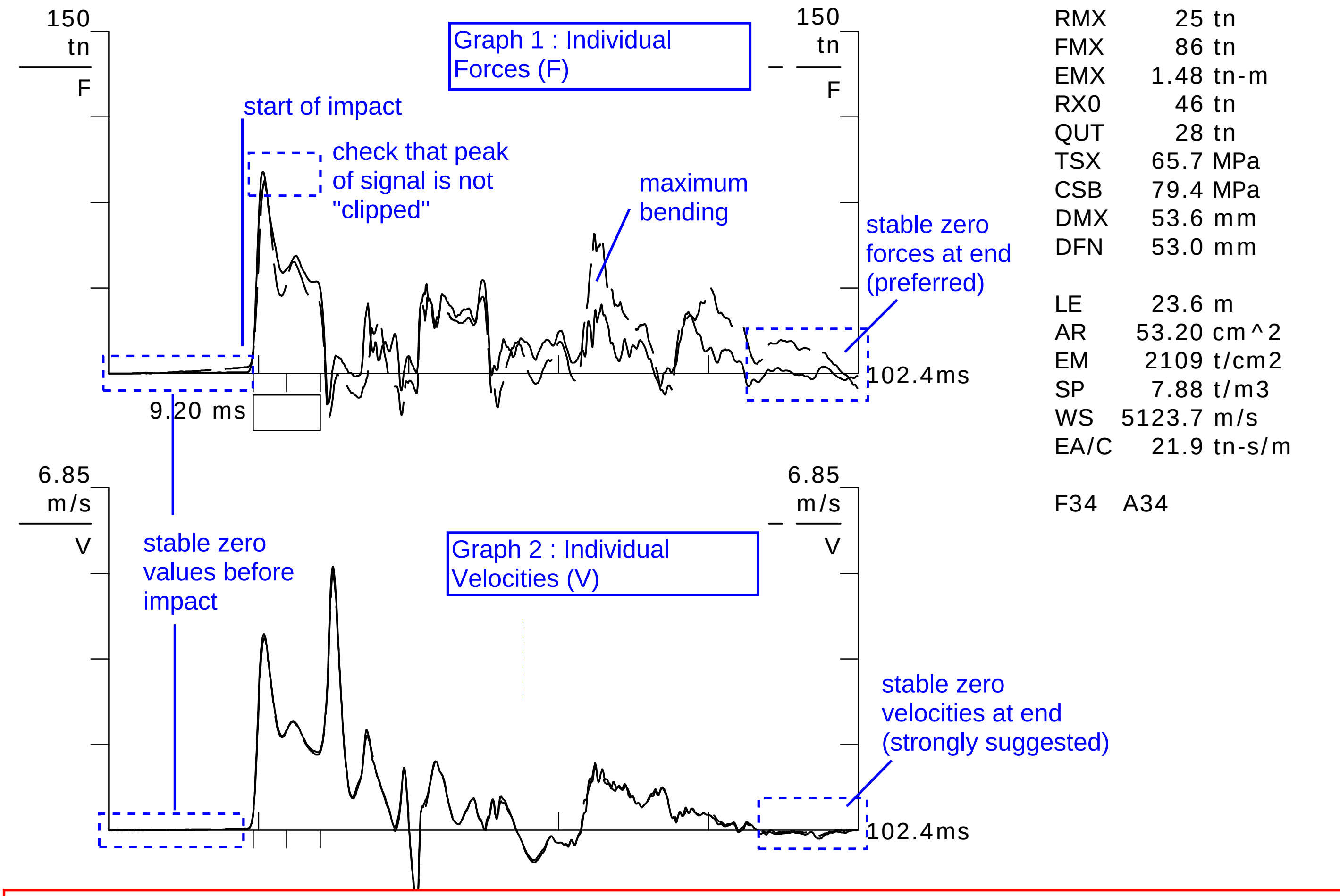
EVALUATING DATA QUALITY : (SUPPLEMENTARY HP PLOT "DPFV")

This is the same data from the previous page, but plotted at a different time scale. These plots show the complete data record of 102.4ms.



GOOD QUALITY DATA requires

1. A reasonably centralized hammer impact to minimize bending effects
2. All transducers operational and properly connected to the pile

If the data quality is in question, it may be advised to require a second plot (display plot command DPFV). This shows GRAPH 1 - the indvidual strain transducer responses (up to 4) plotted as equivalent Force (F) vs Time and GRAPH 2 - the individual accelerometer responses (up to 4) plotted as Velocity (V) vs Time

ITEMS TO CHECK :

1. All F and V curves should be zero before the impact (note dashed F curve rises slightly before impact)
2. The velocity responses are generally very similar (see Graph 2 where the responses are near identical).
3. The velocities at the end of the record return to a stable zero value (pile is at rest). If they do not return to zero, then this either indicates transducer malfunction or that pile motion is not complete. If the pile motion is not complete, the estimates of final movement may be in error. The PDA operator may choose to use a lower digitizing frequency so that a longer pile record is collected.
4. The force responses at any time do not vary by more than 1/3 to 1/2 of the maximum force value. Variation generally indicates bending, which is usually greatest during or shortly after impact. This may require realignment of the hammer, or replacement of the pile cushion to minimize bending.
5. The maximum force signal values are not clipped (indicated by a short section of uniform maximum force)
6. The forces at the end of the record return to a stable zero value. Non-stable non-zero values indicate that the effect of the impact is still generating stresses. As long as the values are small compared with the initial impact, this is not a concern.
7. Stable non-zero force values at the end of the record indicate transducer slippage. This will cause errors in measurement as well as potentially damage the transducers. The transducers should be repositioned.
8. The signals should be free of high frequency "noise" which may be due to electrical interference.

PDA

THE EQUIVALENCE OF Graph 1 (F and V) AND Graph 2 (WD and WU)

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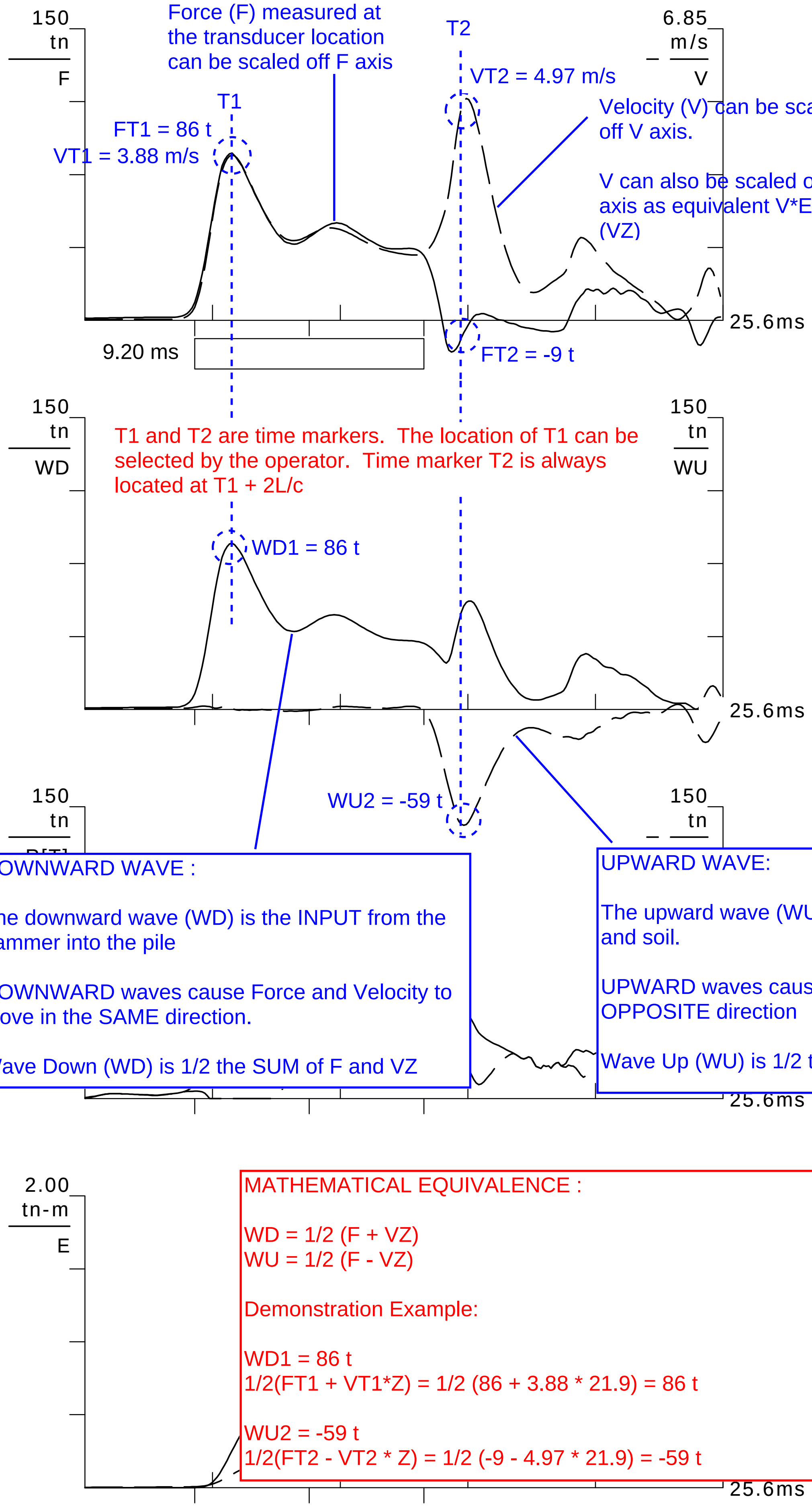
See also
Sheet "Proportionality of F and V"

BN	64	
08-Oct-96 2:27:33 PM		
FT1	86	tn
FT2	-9	tn
VT1	3.88	m/s
VT2	4.97	m/s
WD1	86	tn
WU2	-59	tn
CSB	79.4	MPa
DMX	53.6	mm
DFN	53.0	mm
LE	23.6	m
AR	53.20	cm^2
EM	2109	t/cm2
SP	7.88	t/m3
WS	5123.7	m/s
EA/C	21.9	tn-s/m

F34 A34



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 1/2 the SUM of F and VZ

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 1/2 the DIFFERENCE between F and VZ

MATHEMATICAL EQUIVALENCE :

WD = 1/2 (F + VZ)
WU = 1/2 (F - VZ)

Demonstration Example:

WD1 = 86 t
1/2(FT1 + VT1*Z) = 1/2 (86 + 3.88 * 21.9) = 86 t

WU2 = -59 t
1/2(FT2 - VT2 * Z) = 1/2 (-9 - 4.97 * 21.9) = -59 t

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PDA

CHECKING PILE LENGTH AND WAVESPEED

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EX-17
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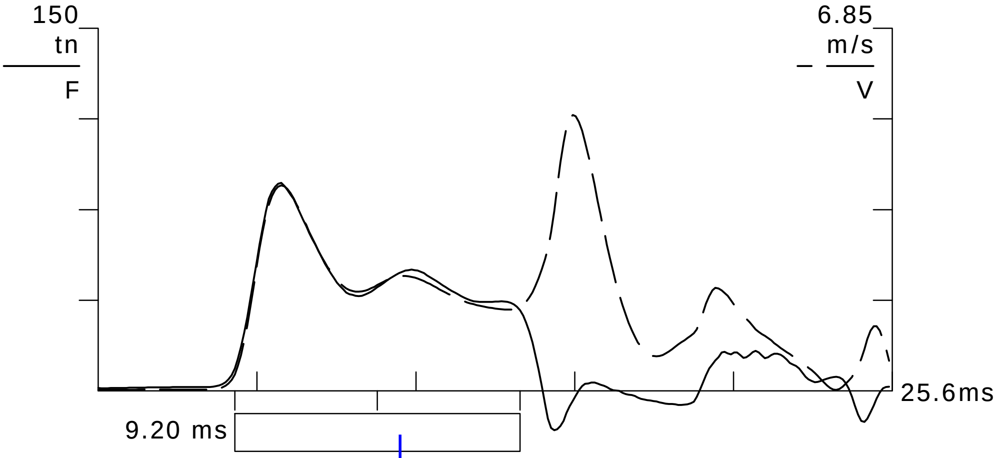
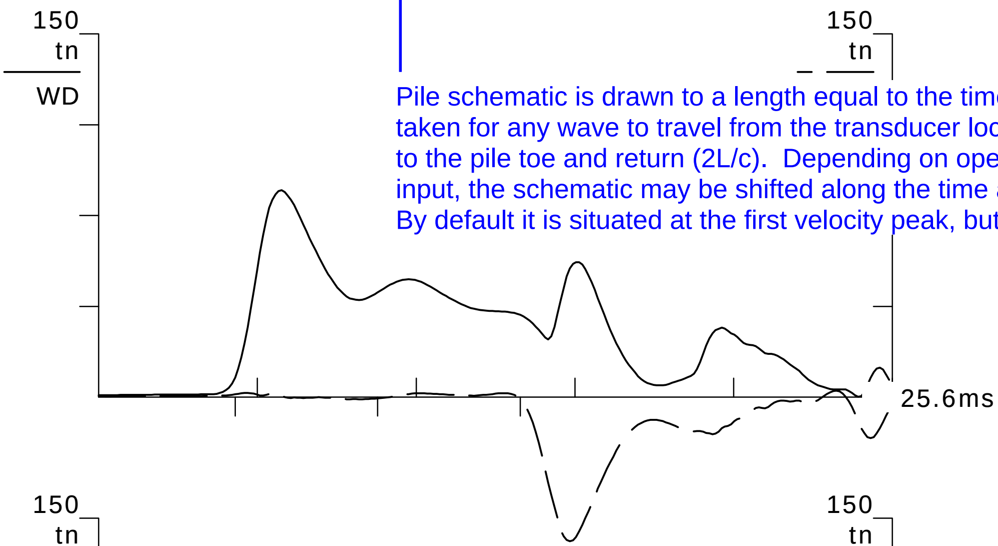
It is necessary to accurately establish the time 2L/c (see notes) in order to reliably apply the Case Method for capacity evaluation. This is also used for evaluation of the condition of the pile and for checking damage.

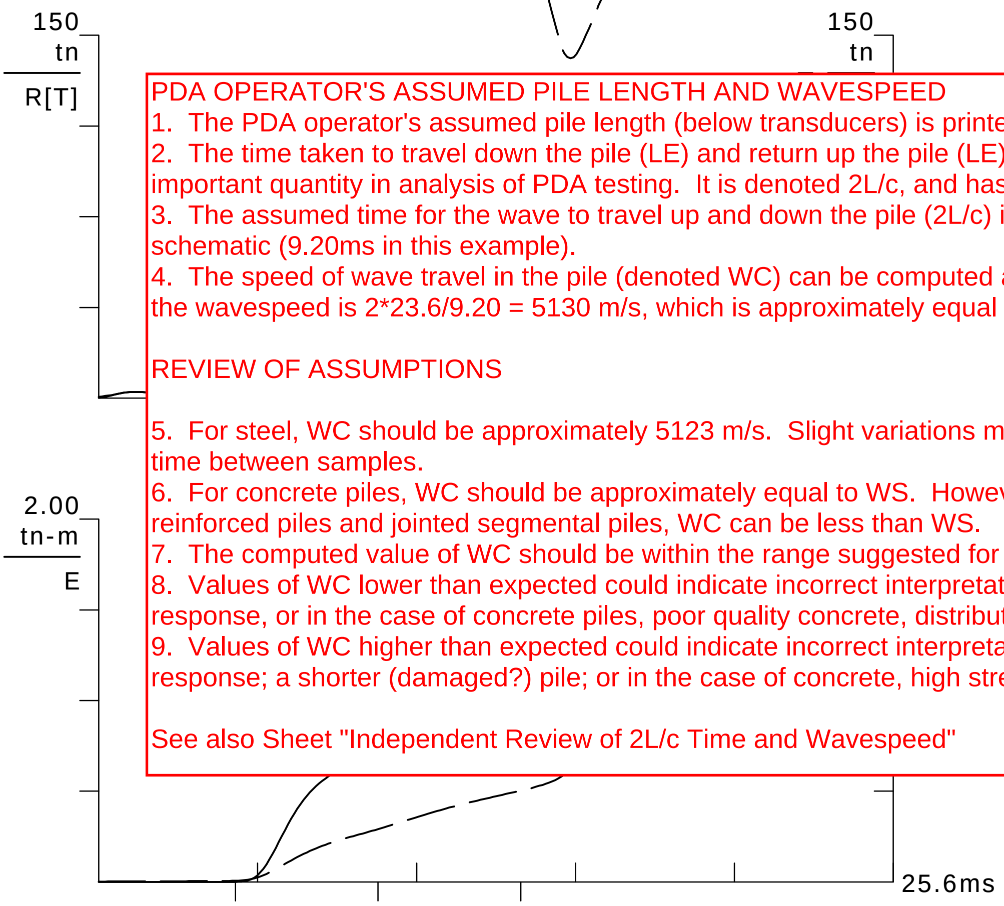
BN	64
08-Oct-96 2:27:33 PM	
RMX	25 tn
FMX	86 tn
EMX	1.48 tn-m
RX0	46 tn
QUT	28 tn
TSX	65.7 MPa
CSB	79.4 MPa
DMX	53.6 mm
DFN	53.0 mm
LE	23.6 m
AR	53.20 cm^2
EM	2109 t/cm2
SP	7.88 t/m3
WS	5123.7 m/s
EA/C	21.9 tn-s/m

F34 A34





Pile schematic is drawn to a length equal to the time taken for any wave to travel from the transducer location to the pile toe and return (2L/c). Depending on operator input, the schematic may be shifted along the time axis. By default it is situated at the first velocity peak, but it can



PDA OPERATOR'S ASSUMED PILE LENGTH AND WAVESPEED

1. The PDA operator's assumed pile length (below transducers) is printed as LE (23.6m in this example).
2. The time taken to travel down the pile (LE) and return up the pile (LE) at a wavespeed (WC) is an important quantity in analysis of PDA testing. It is denoted 2L/c, and has units of milliseconds (ms).
3. The assumed time for the wave to travel up and down the pile (2L/c) is printed to the left of the pile schematic (9.20ms in this example).
4. The speed of wave travel in the pile (denoted WC) can be computed as 2*LE/(2L/c). In this example the wavespeed is 2*23.6/9.20 = 5130 m/s, which is approximately equal to the pile-top wavespeed (WS).

REVIEW OF ASSUMPTIONS

5. For steel, WC should be approximately 5123 m/s. Slight variations may occur because of the finite time between samples.
6. For concrete piles, WC should be approximately equal to WS. However, especially in simply reinforced piles and jointed segmental piles, WC can be less than WS.
7. The computed value of WC should be within the range suggested for concrete piles.
8. Values of WC lower than expected could indicate incorrect interpretation of the time of pile toe response, or in the case of concrete piles, poor quality concrete, distributed cracking or open joints.
9. Values of WC higher than expected could indicate incorrect interpretation of the time of pile toe response; a shorter (damaged?) pile; or in the case of concrete, high strength concrete.

See also Sheet "Independent Review of 2L/c Time and Wavespeed"

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INDEPENDENT REVIEW OF 2L/c TIME AND WAVESPEED

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BN 64
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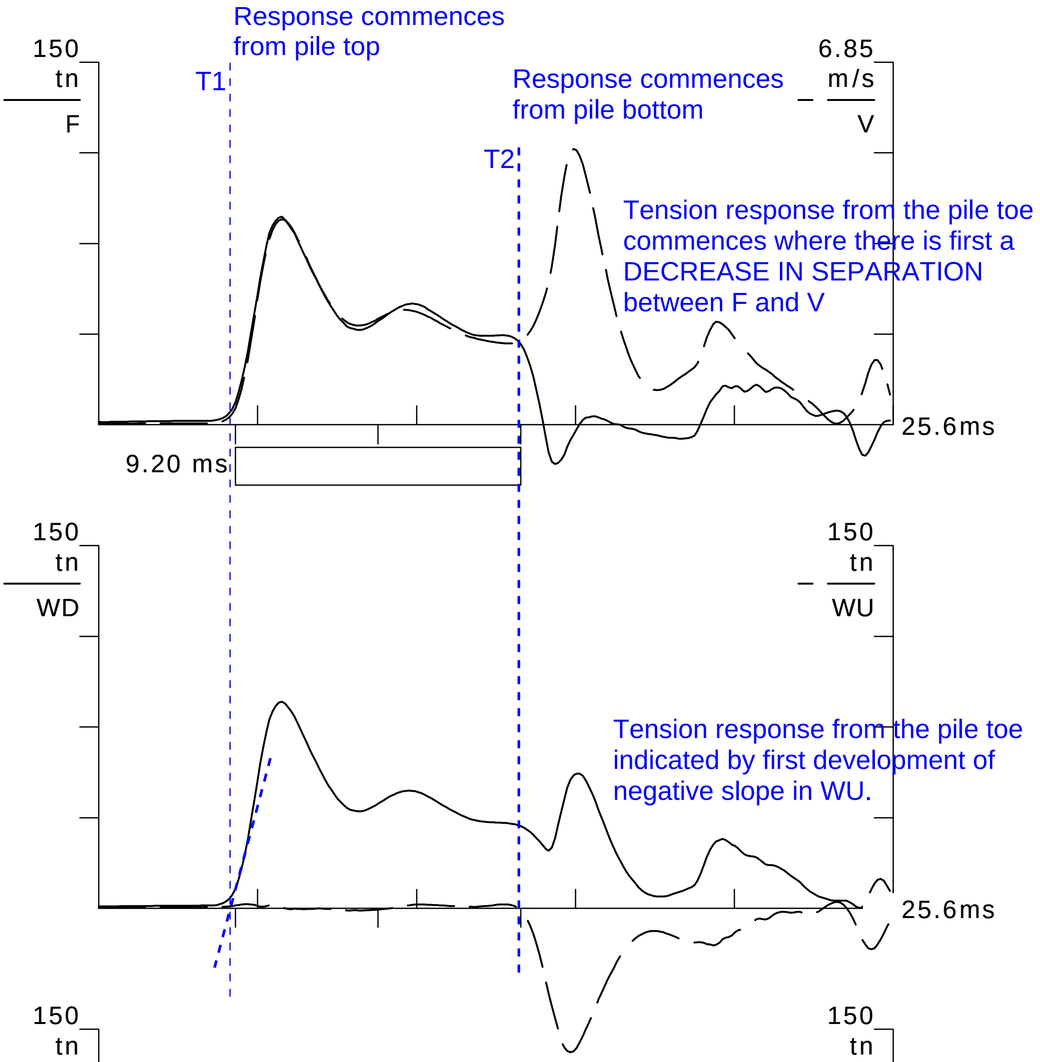
RMX	25 tn
FMX	86 tn
EMX	1.48 tn-m
RX0	46 tn
QUT	28 tn
TSX	65.7 MPa
CSB	79.4 MPa
DMX	53.6 mm
DFN	53.0 mm
LE	23.6 m
AR	53.20 cm^2
EM	2109 t/cm2
SP	7.88 t/m3
WS	5123.7 m/s
EA/C	21.9 tn-s/m

F34 A34

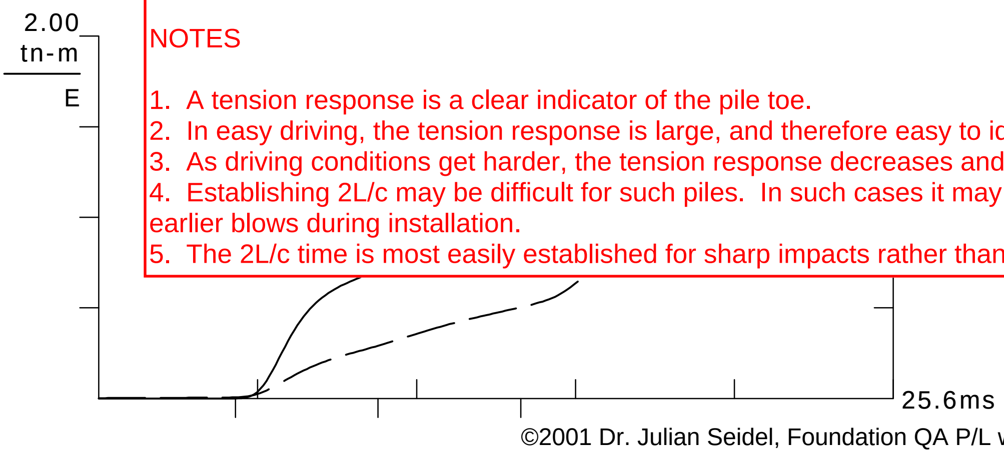


INDEPENDENT REVIEW OF PILE 2L/c AND WAVESPEED

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) (see dashed lines above).
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 WD curve).
3. Marker T2 should be positioned where the velocity (V) starts to rise RELATIVE TO the Force (F), or more simply where the Upward Wave (WU) first starts to reduce.
4. The distance between T1 and T2 can be measured and the 2L/c time determined by scaling on the time axis. In this example, T2 - T1 = 3.55cm, and the full time axis is 9.89cm for 25.6ms. A 2L/c time of 9.19ms is estimated, similar to the PDA Operator's selection (9.20ms).
5. The wavespeed WC is estimated as 5136 m/s.

NOTES

1. A tension response is a clear indicator of the pile toe.
2. In easy driving, the tension response is large, and therefore easy to identify.
3. As driving conditions get harder, the tension response decreases and may not exist in hard driving.
4. Establishing 2L/c may be difficult for such piles. In such cases it may be necessary to examine earlier blows during installation.
5. The 2L/c time is most easily established for sharp impacts rather than heavily cushioned blows.



PDA

FORCES AND STRESSES

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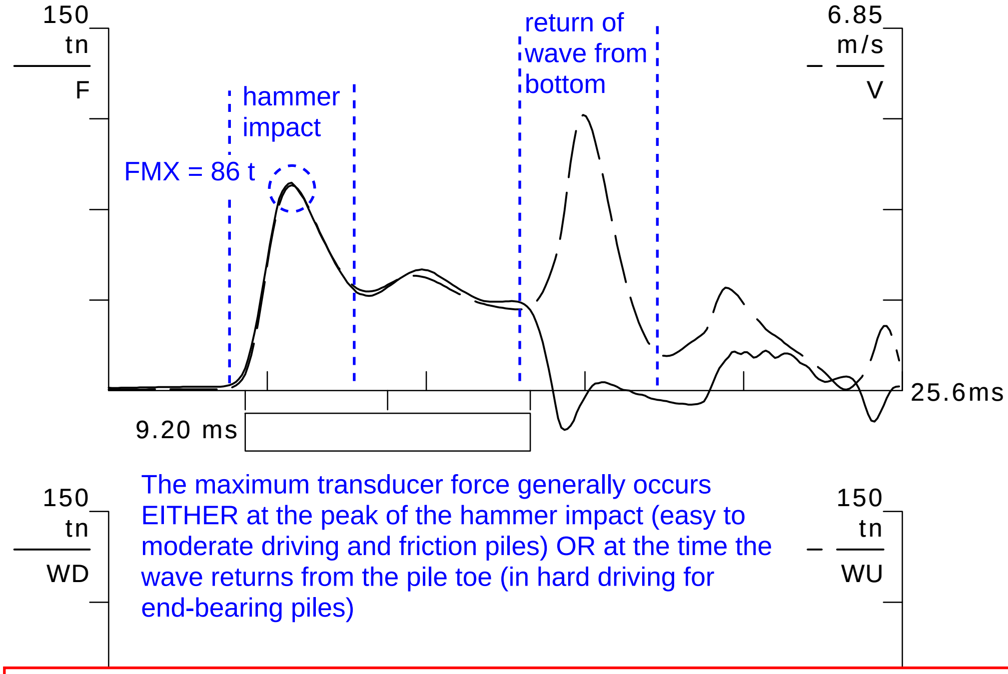
Graph 1 (solid) is FORCE at the transducer location.



BN 64
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RMX	25 tn
FMX	86 tn
EMX	1.48 tn-m
RX0	46 tn
QUT	28 tn
TSX	65.7 MPa
CSB	79.4 MPa
DMX	53.6 mm
DFN	53.0 mm
LE	23.6 m
AR	53.20 cm^2
EM	2109 t/cm2
SP	7.88 t/m3
WS	5123.7 m/s
EA/C	21.9 tn-s/m

F34 A34

NOTES ON PILE STRESSES

1. All pile STRESS computations are based on the equivalent FORCE quantity divided by area (AR).
2. Compression stresses at the transducer location are computed DIRECTLY from the MEASURED average strains x modulus (EM).
3. An error in modulus will affect ALL interpreted stresses.
4. Output quantity CSX is the maximum average pile stress.
5. Bending causes higher local stresses. Quantity CSI is the maximum local stress.

6. Estimates of stresses below transducer assume a uniform pile section (uniform AR).
7. All stresses estimated at locations below the transducer location are ONLY ESTIMATED based on Case Method analysis and the principles of 1-dimensional wave mechanics.
8. Output quantity CSB is the maximum estimated average compressive stress at the pile bottom. This can be critical for piles driven to hard strata.
9. Output quantity TSX is the maximum estimated average tension stress in the pile shaft. This is generally critical for concrete piles in easy driving, but can also be critical for end-bearing piles in hard driving.

ALLOWABLE DRIVING STRESSES IN PILES (AFTER PDI)

Note : National Codes or Project Specifications may take precedence

Stress Type	SI unit limit	English unit limit
Steel Compression	0.90 Fy	0.90 Fy
Steel Tension (may be limited by weld)	0.90 Fy	0.90 Fy
Prestressed Concrete Compression (top)	0.85 f'c - fpe	0.85 f'c - fpe
Prestressed Concrete Tension	fpe + 0.25 (f'c)$^{1/2}$	fpe + 3.0 (f'c)$^{1/2}$
Reg. Reinforced Concrete Compression (top)	0.85 f'c	0.85 f'c
Reg. Reinforced Concrete Tension	0.70 Fy (As/Ac)	0.70 Fy (As/Ac)
Timber	3Fat	3Fat

Key :
Fy = Steel yield strength (in MPa or psi)
f'c = Concrete 28 day strength (in MPa or psi)
fpe = Effective prestress (in MPa or psi)
As = Steel reinforcement area
Ac = Concrete area
Fat = Allowable static timber stress (in MPa or psi)

25.6ms

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PDA

PILE CAPACITY :
Graph 3 (RESISTANCE vs TIME)

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BN 64
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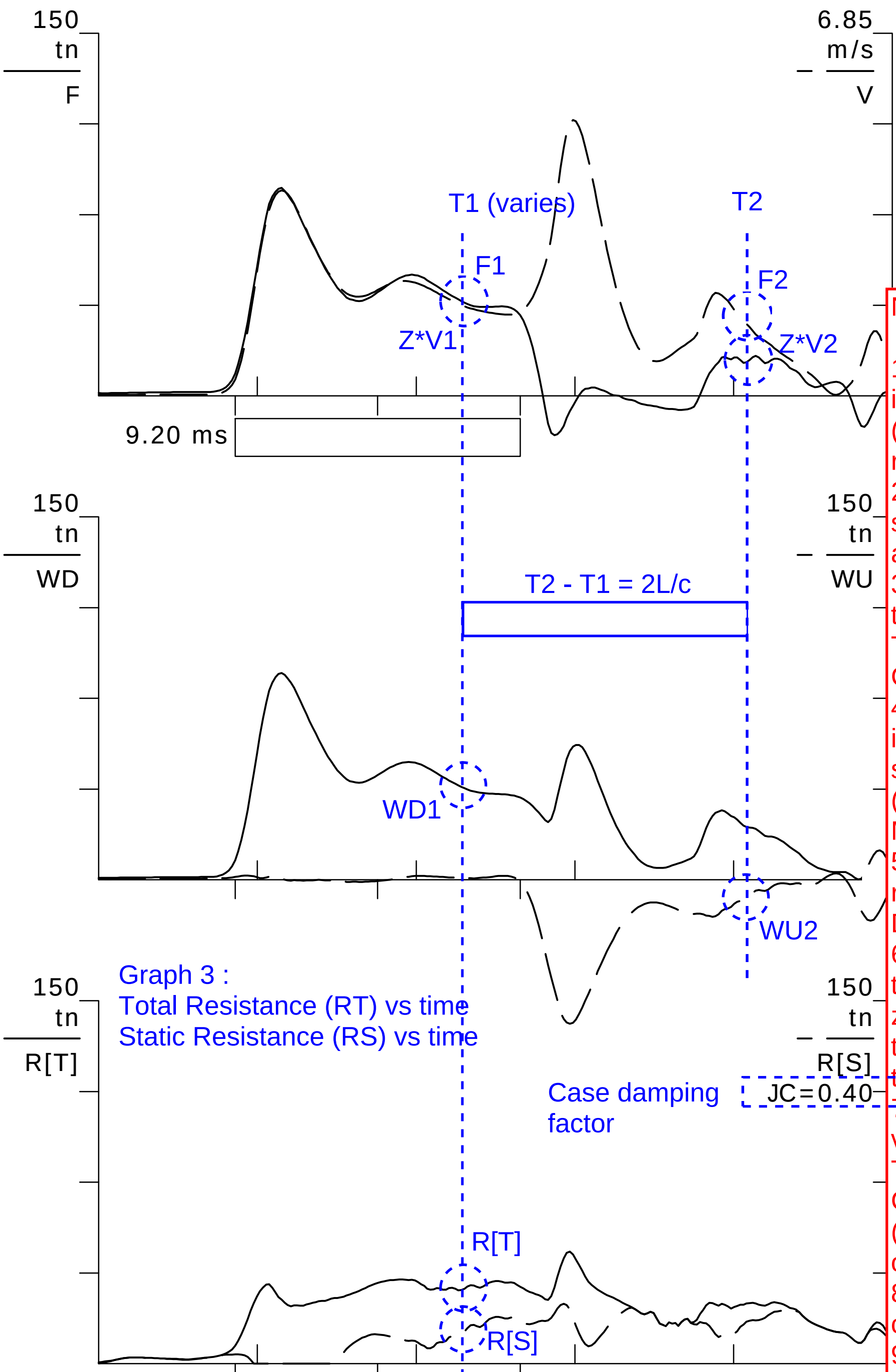
RMX	25	tn
FMX	86	tn
EMX	1.48	tn-m
RX0	46	tn
QUT	28	tn
TSX	65.7	MPa
CSB	79.4	MPa
DMX	53.6	mm
DFN	53.0	mm



NOTES ON PDA CAPACITY ESTIMATION

1. The resistance during installation and testing is composed of (long-term) static resistance and (short-term) dynamic resistance (damping resistance).
2. In general, engineers wish to isolate the static capacity. This is used to confirm design assumptions and to compare with static tests.
3. The PDA uses the Case Method to estimate the total driving capacity (static and dynamic). This is the quantity R[T] ("Resistance Total") in Graph 3. See Case Method Equations below.
4. An assumed Case Damping factor, JC, is introduced into the Case Method to estimate the static resistance. This is the quantity R[S] ("Resistance Static") in Graph 3. See Case Method Equations below.
5. See sheet "Case Damping Factor, JC" for recommendations on choice of the Case Damping Factor.
6. The MOBILIZED resistance starts at zero at the beginning of the test when the movement is zero; reaches a maximum (generally about the time of maximum movement) and then returns to zero at the completion of the blow.
7. The PDA automatically computes the variation of R[T] and R[S] with change of time T1.
Graph 3 shows the variation of Total Resistance (R[T]) and Static Resistance (R[S]) as a function of time.
8. The difference between the R[T] and R[S] curves is the dynamic (damping) resistance.
9. If the permanent movement (set) measured for each blow is less than 2-3mm, it is probable that the MOBILIZED (i.e. measured) capacity is less than the ultimate pile capacity. In this case, the mobilized capacity is equivalent to a PROOF load.
10. For large diameter piles, and particularly drilled shafts, capacity may be underestimated even with a larger permanent set (up to 1% or more of pile diameter).
11. The PDA computes a number of capacity estimates, all with a 3-letter output code starting with the letter R (e.g. RSP, RMX, RAU). See sheet "PDA Output Quantity Summary".

CASE METHOD EQUATIONS
Note suffix 1 indicates any time after impact. Suffix 2 indicates at time 2L/c after time 1. F = Force; V = Velocity; Z = Impedance (EM*AR/WS); WD = Downward wave; WU = Upward Wave

Total (driving) Resistance (R[T]) :
R[T] = 0.5 * (F1 + Z*V1) + 0.5 * (F2 - Z*V2) or alternatively
R[T] = WD1 + WU2
Static Resistance (R[S]) :
R[S] = 0.5*(1 - JC) * (F1 + Z*V1) + 0.5* (1 + JC) * (F2 - Z*V2) or alternatively
R[S] = (1 - JC) * WD1 + (1 + JC) * WU2

Above example : F1 = 38.8t; Z*V1 = 36.5t; F2 = 10.3t; Z*V2 = 29.5t; WD1 = 37.6t; WU2 = -4.5t; JC = 0.40. From which R[T] = 33.1t and R[S] = 12.3t

25.6ms

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PDA

CASE METHOD DAMPING FACTOR, JC

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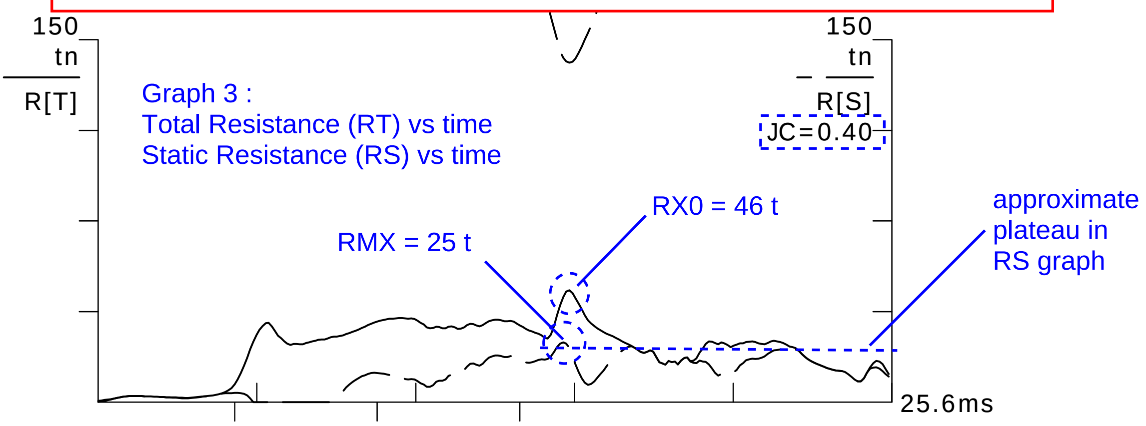
BN	64
08-Oct-96 2:27:33 PM	
RMX	25 tn
FMX	86 tn
EMX	1.48 tn-m
RX0	46 tn
QUT	28 tn
TSX	65.7 MPa
CSB	79.4 MPa
DMX	53.6 mm
DFN	53.0 mm
LE	23.6 m
AR	53.20 cm^2
EM	2109 t/cm2
SP	7.88 t/m3
WS	5123.7 m/s
EA/C	21.9 tn-s/m
F34	A34

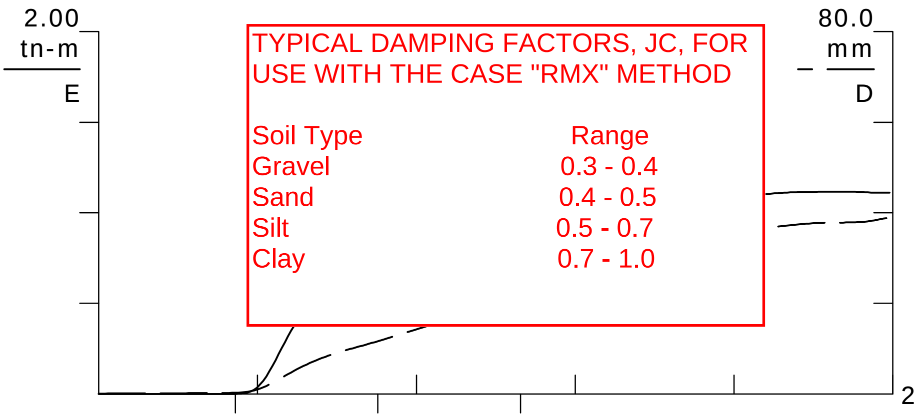
INTERPRETATION

1. The purpose of the Case Method damping factor, JC, is to determine how much of the total driving resistance results from static resistance. The Case Method Equation for capacity is given in the sheet "Pile Capacity : Graph 3 (Resistance vs Time)".
2. The value of JC must be estimated on site, or can be computed by correlation against another method (e.g. CAPWAP analysis).
3. The value of JC depends on many factors including hammer and pile type, pile geometry, and cushioning, all of which affect the pile velocities. This is because damping resistance is a function of pile velocity.
4. The value of JC is most dependent on soil conditions, and whether the pile is tested during driving or some time after installation (restrike).
5. In general, the value of JC increases with decreasing grain size.
6. In general, the value of JC increases with duration of delay after driving.
7. The value of JC is dependent on which PDA resistance method is used.
8. The author's personal preference is to generally use the "Maximum Resistance Method" - output quantity RMX.
9. For long friction piles (with shaft resistance) it may be better to use the "Unloading Method" - output quantity RSU.
10. Local conditions or experience with other Case Method Resistance methods (see sheet "PDA Output Quantity Summary") can be accepted with demonstration of correlations.

REVIEW

1. See Table "Typical Damping Factors, JC, for use with the Case RMX Method" for values that may apply for different soil conditions. The ranges are not absolute.
2. Values for all Case Resistance Methods should be confirmed by correlation.
3. When the pile set is large enough to suggest that the ultimate pile capacity has been measured, the RS vs time graph often demonstrates an upper plateau which is the ultimate static resistance if the correct JC value is used. This is a technique which can be used to estimate JC in the field on a pile-by-pile basis.





TYPICAL DAMPING FACTORS, JC, FOR USE WITH THE CASE "RMX" METHOD

Soil Type	Range
Gravel	0.3 - 0.4
Sand	0.4 - 0.5
Silt	0.5 - 0.7
Clay	0.7 - 1.0

foundation Q a

ENERGY TRANSFER AND HAMMER PERFORMANCE

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EX-17
VUL06 10.75x0.25"CEP

This is the same data from the previous page, but plotted at a different time scale. These plots show the complete data record of 102.4ms.

BN	64
08-Oct-96 2:27:33 PM	
RMX	23 tn
FMX	86 tn
EMX	1.48 tn-m
RX0	46 tn
QUT	28 tn
TSX	65.7 MPa
CSB	79.4 MPa
DMX	53.6 mm
DFN	53.0 mm
LE	23.6 m
AR	53.20 cm^2
EM	2109 t/cm2
SP	7.88 t/m3
WS	5123.7 m/s
EA/C	21.9 tn-s/m
F34	A34

150 tn F — 6.85 m/s V

INTERPRETATION :

1. 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)
2. FORCE = Modulus (EM) * Area (AR) * strain (measured)
3. DISTANCE = Double integration of acceleration (measured)
4. WORK = ENERGY IN = Integral (Force x distance)
5. Graph 4 shows the variation of Energy transferred from the hammer to the pile (E) on Left Axis as a function of time.
6. The maximum energy transfer can be printed in the output quantity list as the value EMX.

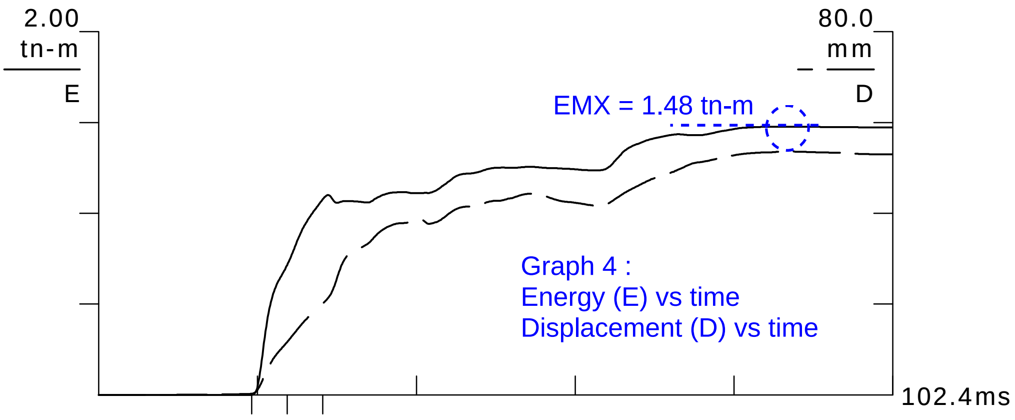
REVIEW :

1. Hammer energy can be monitored during a contract to investigate any deterioration or improvement in performance.
2. Different classes of hammer may be more or less efficient.
3. Typical transfer efficiency ranges (suggested by PDI) are tabulated below. The transfer efficiency is based on the ratio of measured energy to hammer potential energy (weight x drop).
4. Hydraulic hammers generally demonstrate the highest transfer efficiency, with efficiency often between 80% and 95%.
5. The transfer efficiency (EMX / hammer potential energy) should be checked against the suggested range. Transfer efficiency should not exceed 100%. Drop should be estimated as closely as possible.
6. Transfer efficiency is affected by hammer and pile cushions, pile type, pile length.
7. Transfer efficiency is also affected by soil conditions - it is greater in easy driving and reduces in hard driving conditions.

R[T] — R[S] JC=0.55

Suggested typical hammer transfer efficiencies (after PDI)

Hammer Class	Steel Piles	Concrete Piles
Diesel	25 to 50%	17 to 40%
Single acting Air	40 to 65%	30 to 55%
Double acting Air	22 to 45%	20 to 45%
Hydraulic, or Drop (free)	>75%	>50%
Drop (cable)	35 to 60%	25 to 50%



PDA

DISPLACEMENT, SET AND TEMPORARY COMPRESSION

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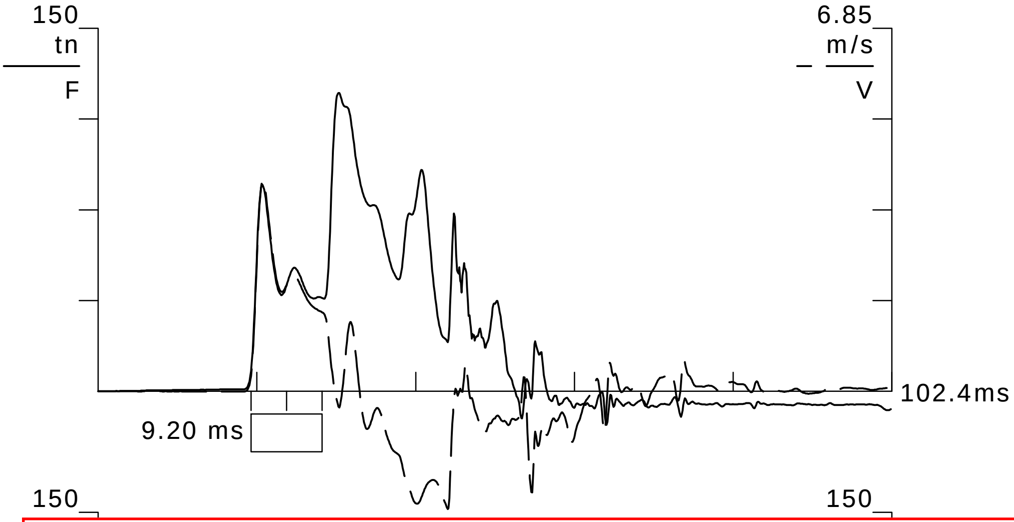
VUL06 10.75x0.25"CEP

This is a subsequent blow (116) for the same pile shown on the previous page (blow 64). It also shows the complete data record of 102.4ms.



BN 116
08-Oct-96 2:28:29 PM
RMX 137 tn
FMX 123 tn
EMX 1.34 tn-m
RX0 144 tn
QUT 111 tn
TSX 41.1 MPa
CSB 249.3 MPa
DMX 23.1 mm
DFN 0.8 mm

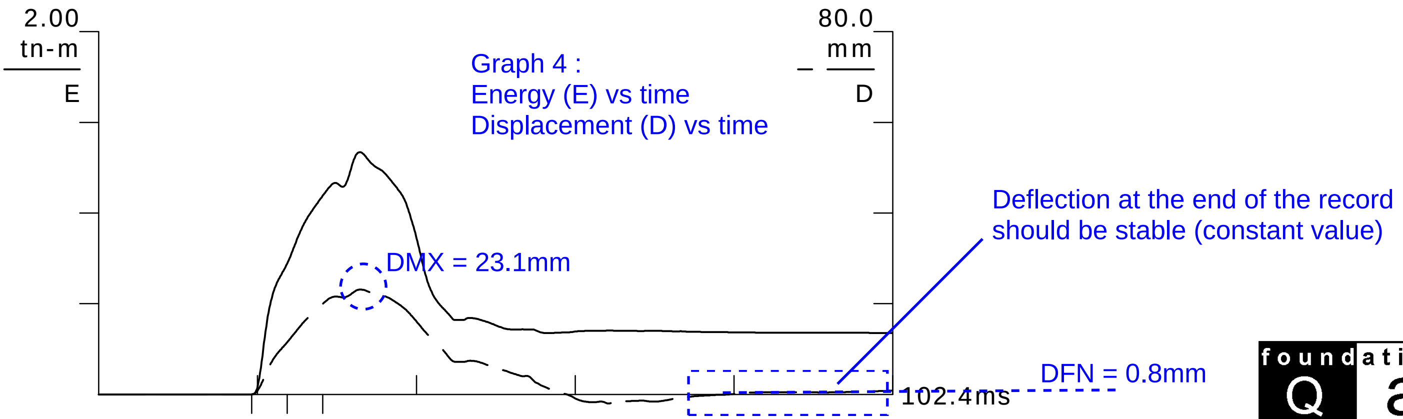
LE 23.6 m
AR 53.20 cm^2
EM 2109 t/cm2
SP 7.88 t/m3
WS 5123.7 m/s
EA/C 21.9 tn-s/m

INTERPRETATION

1. The pile-top acceleration is measured.
2. Pile-top velocity is computed by integration of the acceleration signal with time.
3. Pile-top displacement (movement) is computed by integration of the velocity record with time.
4. Graph 4 shows the variation of Displacement (D) on Right Axis as a function of time.
6. The maximum movement can be printed in the output quantity list as the value DMX.
7. The final movement can be printed in the output quantity list as the value DFN.

REVIEW

1. The final movement, DFN, should be equal to the pile set which is physically measured on the pile. As the final displacement is computed by double-integration of the acceleration signal over the full record, it is very sensitive to small errors in the acceleration signal. The PDA automatically adjusts the data to ensure zero velocity at the end of the record, however, it is necessary to check that the final displacement is a stable value (indicating pile at rest). The PDA operator should carefully review and adjust the data to establish the best estimate of DFN.
2. Differences between DFN and set may result from incorrect adjustment of the data, or accelerometer instability.
3. Differences between DFN and set may result from poor measurements on site, or because site measurements are generally an average over 10 blows, whereas the PDA gives the set for an individual blow.
4. If the full record is not plotted, it will not be possible to evaluate the stability of the displacement record at the end.
5. The difference between DMX and DFN (DMX - DFN) should be equal to the temporary compression.
6. DMX is generally very reliable, so any differences between (DMX - DFN) and temporary compression may be due to errors in DFN or field measurement errors.



foundation Q a

ESTABLISHING RELATIONSHIP BETWEEN PDA AND DRIVING FORMULAE

PDA

PILE DRIVING ANALYZER ®
Version 2000.084
EX-6
K45;24"OCT/15VOID A1+F1

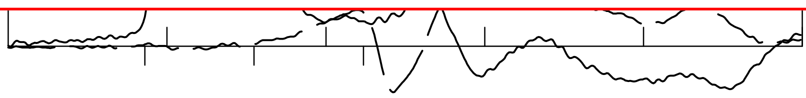
BN	15
20-Nov-90 3:14:00 PM	
FMX	524 tn
RMX	300 tn
SFT	200 tn
RX0	456 tn
QUT	513 tn
QUS	513 tn
SET	3.0 mm
DMX	17.6 mm
DFN	3.0 mm
LE	28.7 m
AR	1938.44 cm^2
EM	402 t/cm2
SP	2.40 t/m3
WS	4053.8 m/s
EA/C	192.4 tn-s/m
F12	A12

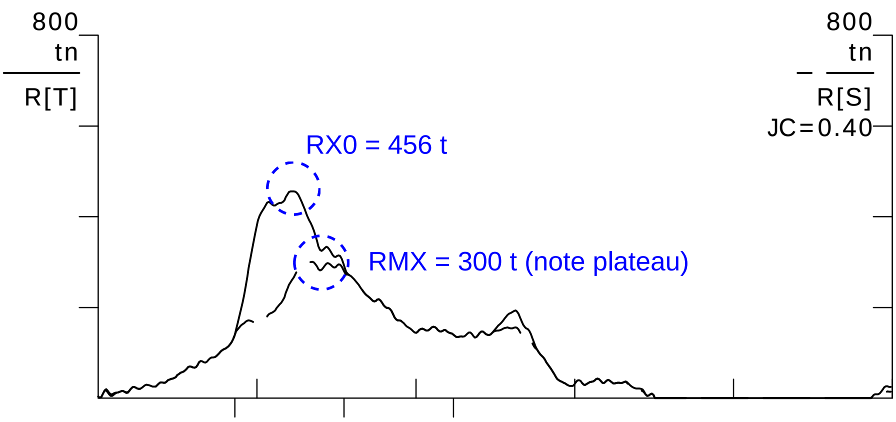
DISCUSSION

1. It is not common to PDA test every pile on a project, although in critical cases this may be recommended. In most projects 5% to 25% of piles are tested. This varies with project and country.
2. It is necessary to develop acceptance criteria for the remainder of untested piles.
3. In some cases it may be appropriate to base acceptance on a depth criterion.
4. In many cases it is more appropriate to base acceptance on set criteria using an Energy Formula or Driving Formula.
5. When little pile set-up is expected, it may be most convenient to base the acceptance criteria on DRIVING response.
6. When significant pile set-up is expected and relied on for long-term capacity, it may be more convenient to base criteria on RESTRIKE response.

PROCEDURE

1. The set-based acceptance criteria should be based on developing a correlation between the PDA or (better) CAPWAP results and an Energy Formula Capacity based on measured driving response (set and temporary compression).
2. The ENERGY FORMULA Capacity is detailed below.
3. A correlation should be established between the PDA or CAPWAP pile capacity estimate and the EF Capacity. This is expressed as a ratio (RATIO = PDA/EF Capacity) or (RATIO = CAPWAP/EF Capacity)
4. The ratio is usually greater than 1, and in many cases lies in the range 1.25 to 1.50.
5. The capacity of untested piles can be estimated as EF Capacity / RATIO.





* QUS is the Energy Formula Capacity based on the entered SET measurement
* QUT is the Energy Formula Capacity based on the computed DFN value
* RX0 is the Case Method Capacity using JC = 0 (no damping allowance). It is equivalent to the uncorrected Energy Formula Capacity
* TC = DMX - DFN

ENERGY FORMULA (Modified Hiley Formula)

The driving formula most commonly used by PDA testers to correlate driving parameters with PDA results is :

EF Capacity = EMX / (SET + TC/2)

1. EMX (energy transferred to pile) is measured in PDA tests
2. A reliable or conservative hammer transfer efficiency can be established from these measurements.
3. Changes in hammer performance should be monitored by regular PDA testing through a contract.
4. Pile SET and Temporary Compression (TC) can be measured for each pile. These measurements are inherently dangerous and an appropriate safety procedures should be put in place on site.
5. An UNCORRECTED EF capacity estimate is obtained from the above formula.
6. The EF Capacity is usually an overestimate, because it assumes that all resistance is static. There is no allowance for dynamic reistance.

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PDA

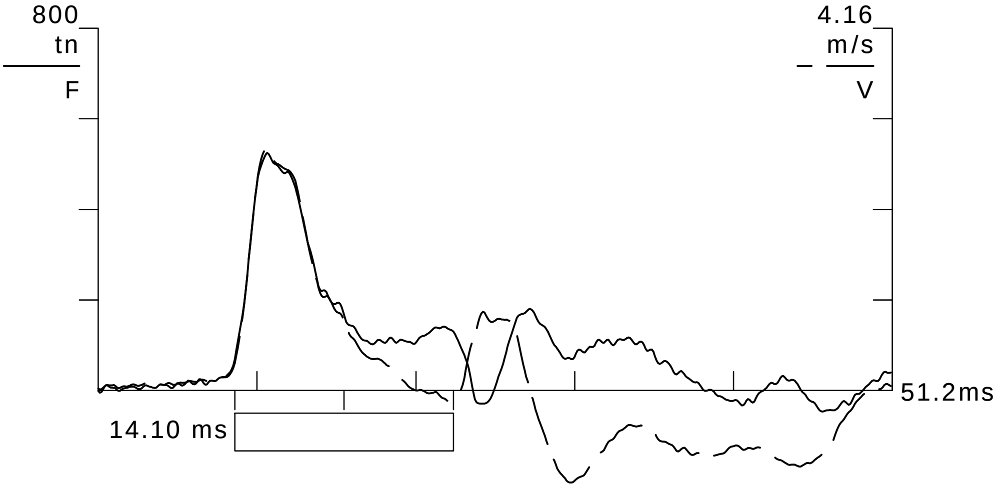
EVALUATING SHAFT FRICTION AND END-BEARING FROM PDA OUTPUT

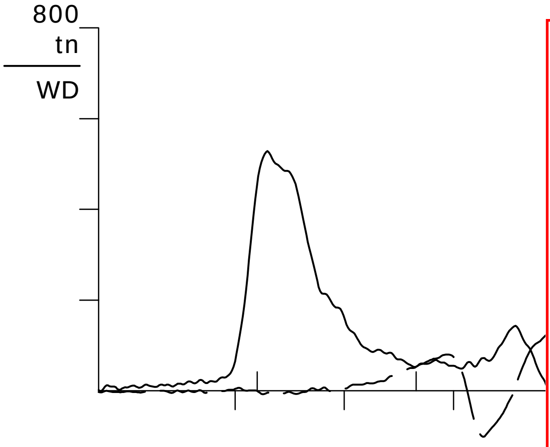
See also
Sheet "Apprximate Evaluation of Shaft Resistance Distribution"

PILE DRIVING ANALYZER ®
Version 2000.084
EX-6
K45;24"OCT/15VOID A1+F1

BN 15
20-Nov-90 3:14:00 PM

FMX	524 tn
RMX	300 tn
SFT	200 tn
RX0	456 tn
QUT	513 tn
QUS	513 tn
SET	3.0 mm
DMX	17.6 mm
DFN	3.0 mm
LE	28.7 m
AR	1938.44 cm^2
EM	402 t/cm2
SP	2.40 t/m3
WS	4053.8 m/s
EA/C	192.4 tn-s/m





800
tn
R[T]

8.0
tn-r

51.2ms

DISCUSSION

1. A unique feature of the PDA test is that it provides information on the distribution of pile resistance. This is only available from static load testing with significant instrumentation and cost.
2. The distribution of resistance is very important for correlation of the capacity with geotechnical information. It allows the designer to evaluate the effect of changes in pile length and to evaluate variability of site conditions.

REVIEW

1. The total static pile capacity (shaft and end bearing) is given by the output quantity RMX (or other Case Method estimate). This depends on correct JC.
2. The shaft resistance is given by the output quantity SFT (shaft friction).
3. The inferred end-bearing is given by the difference between total capacity and shaft friction (e.g. RMX - SFT).

NOTES

1. The SFT estimate is dependent on correct selection of the 2L/c time (see "Pile Length and Wavespeed".
2. SFT can be more reliably determined when the impact is sharp rather than highly cushioned.
3. The SFT value is automatically corrected to take into account the time during which the end-bearing and shaft resistance effects superimpose.
4. SFT is generally more reliable for long friction piles than short piles.
5. The shaft resistance in the vicinity of the pile toe can be difficult to separate from end bearing, so caution must be exercised when this component is significant.

WARNING

1. The SFT value is not corrected for the effect of damping resistance. Although no procedure is recommended, it may be appropriate to reduce SFT by 10 to 20% to account for dynamic resistance. Alternatively, it may be reduced by as much as the ratio RMX/RX0.
2. The SFT value is determined for loading in compression. It may be appropriate to further reduce the estimate of shaft resistance for estimation of shaft resistance in tension (uplift).

EXAMPLE

RMX = 300 t
RX0 = 456 t
SFT = 200 t

1. Reduce SFT by 20%

Shaft resistance = 160 t
End bearing = 140 t
Total static capacity = 300 t

2. Reduce SFT by ratio RMX/RX0

Shaft resistance = 132 t
End bearing = 168 t
Total static capcity = 300 t

3. Undertake CAPWAP analysis of data to get more accurate estimate of resistance distribution

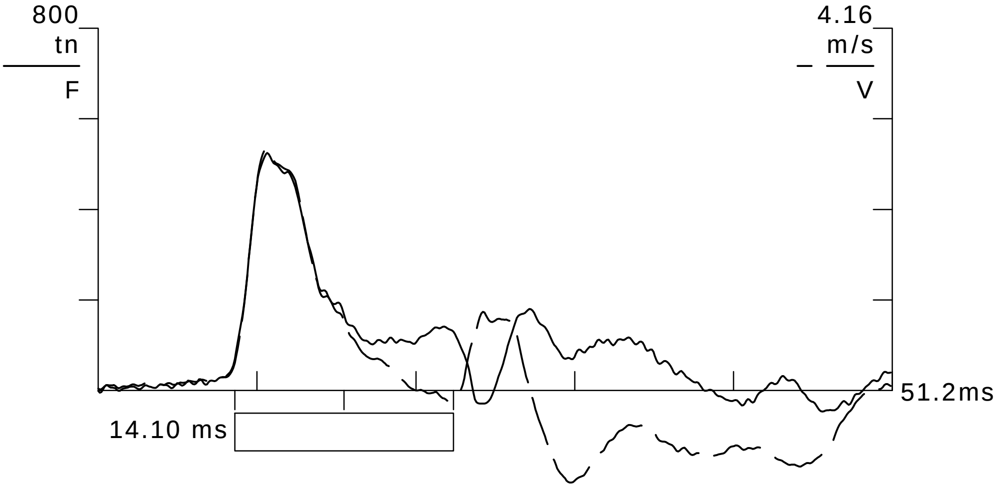
foundation QA

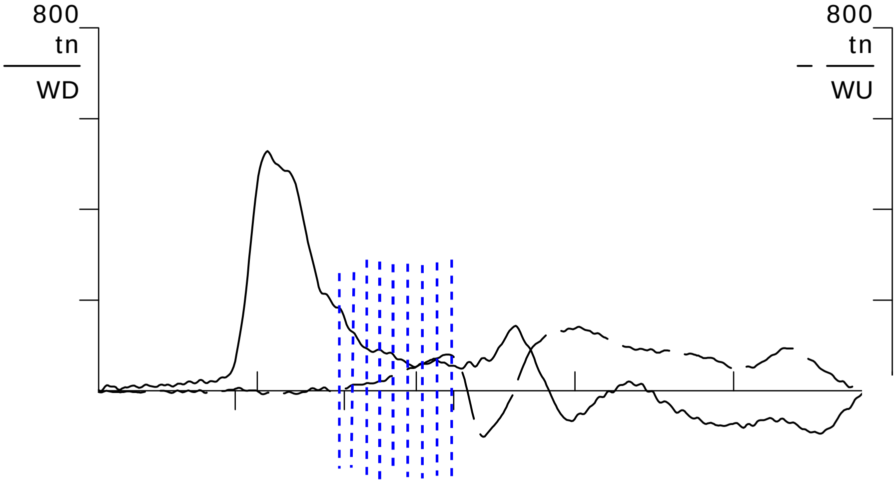
APPROXIMATE EVALUATION OF SHAFT RESISTANCE DISTRIBUTION

PILE DRIVING ANALYZER ®
Version 2000.084
EX-6
K45;24"OCT/15VOID A1+F1

BN 15
20-Nov-90 3:14:00 PM

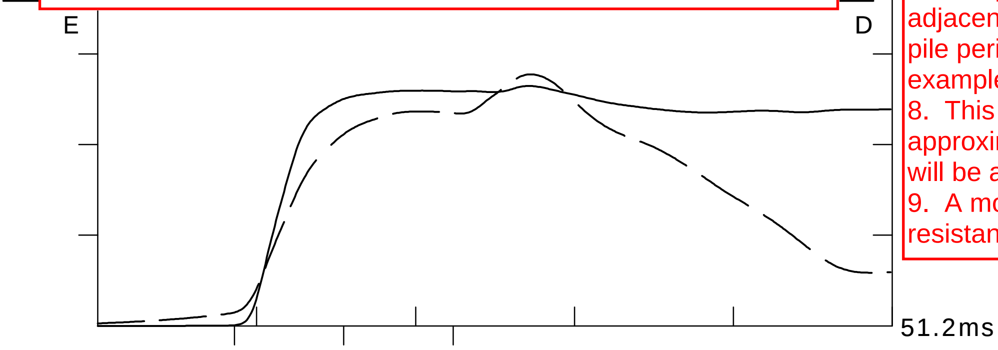
FMX	524 tn
RMX	300 tn
SFT	200 tn
RX0	456 tn
QUT	513 tn
QUS	513 tn
SET	3.0 mm
DMX	17.6 mm
DFN	3.0 mm
LE	28.7 m
AR	1938.44 cm^2
EM	402 t/cm2
SP	2.40 t/m3
WS	4053.8 m/s
EA/C	192.4 tn-s/m





EXAMPLE

Distance above toe (m)	WU (t)	Cum Friction (t)	Adhesion (kPa)
14.8	0.0	0.0	
13.0	8.9	17.7	44
11.1	17.7	35.3	44
9.3	21.2	42.4	18
7.4	37.1	74.2	80
5.6	47.7	95.4	53
3.7	58.3	116.6	53
1.8	72.4	144.8	71
0.0	84.8	169.5	62



NOTES

1. The manual checking procedure can be conducted on EITHER Graph 1 (F and V) OR Graph 2 (WD and WU).
2. It is recommended that the procedure be undertaken on WU, as it is most direct.
3. This analysis will not be valid for piles in which shaft unloading occurs before 2L/c.

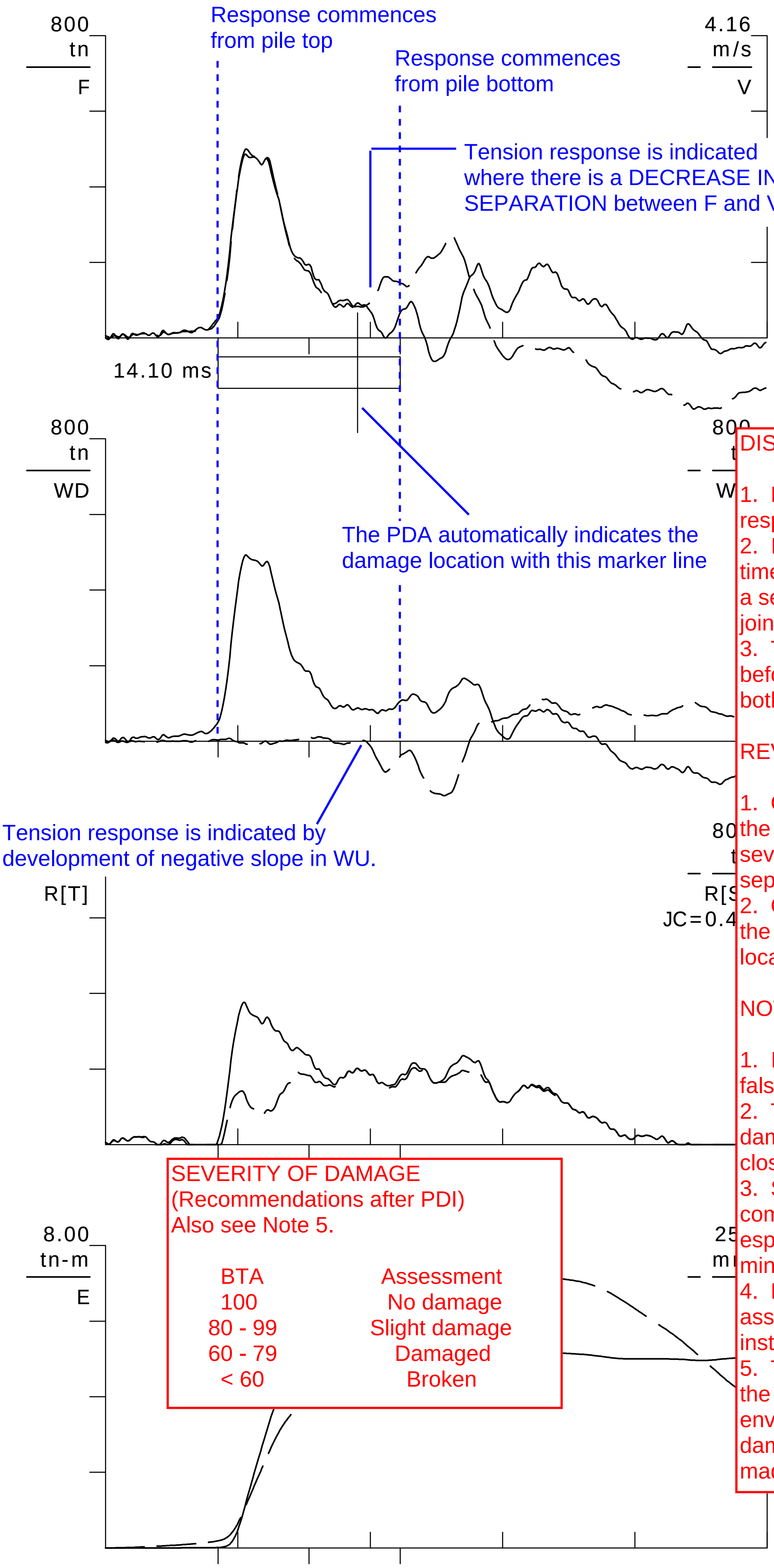
PROCEDURE

1. The pile length is represented by the pile schematic under Graph 1 (F and V).
2. Divide the WU plot into segments of equal width starting from the time of first toe response (see Graph 2).
3. The equivalent pile length for each segment can be scaled against the pile schematic (LE = 28.7m). In the example, each segment length (the distance between dashed lines) is equivalent to 1.85m.
4. Determine the WU value at the intersection of each dashed line with the WU plot.
5. The CUMULATIVE UNCORRECTED shaft resistance above each point is TWO times the WU values.
6. A correction for dynamic resistance can be applied (see sheet "Shaft Resistance and End Bearing").
7. The shaft adhesion for each segment can be computed as the difference between adjacent cumulative friction values divided by pile perimeter and segment length (see example).
8. This analysis should be assumed to be approximate. Individual segment adhesions will be affected by local impedance changes.
9. A more rigorous distribution of shaft resistance can be computed using CAPWAP.

CHECKING PILE DAMAGE

PILE DRIVING ANALYZER ®
Version 2000.084
EX-6
K45;24"OCT/15VOID A1+F1

BN	408
20-Nov-90 3:23:00 PM	
FMX	487 tn
RMX	203 tn
EMX	5.27 tn-m
TSX	3.5 MPa
LTD	21.9 m
BTA	69.0 (%)
SET	4.0 mm
DMX	23.5 mm
DFN	4.0 mm
LE	28.7 m
AR	1938.44 cm^2
EM	402 t/cm2
SP	2.40 t/m3
WS	4053.8 m/s
EA/C	192.4 tn-s/m



SEVERITY OF DAMAGE

(Recommendations after PDI)
Also see Note 5.

BTA	Assessment
100	No damage
80 - 99	Slight damage
60 - 79	Damaged
< 60	Broken

DISCUSSION

1. For a pile with uniform section, the first tension response should be reflected from the pile toe.
2. If a tension response is indicated before that time, it indicates either a reduction in pile section, a section of reduced quality material, a splice or joint, or pile damage.
3. The PDA detects tension reflections occuring before the expected toe response, and estimates both the severity and location of the damage.

REVIEW

1. Output quantity BTA (beta) is an estimate of the severity of the damage. A scale of damage severity suggested by PDI is shown in the separate table.
2. Output quantity LTD provides an estimate of the Length To Damage from the transducer location.

NOTES

1. It is important that the 2L/c time be correct, or false indications of damage could result.
2. The PDA may have difficulty in detecting damage very close to the transducer location or close to the pile bottom.
3. Soil resistance effects may reduce or completely hide the effects of pile damage, especially if soil resistance is high and 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.
5. The consequences of pile damage depend on the structure and its function, loading conditions, environmental conditions, pile manufacture and damage location - careful assessment should be made of any damage indication

Sample Specification

(electronic download available at www.foundationqa.com)

Specification for Dynamic Pile Testing

All dynamic pile testing shall comply with the provisions of AS2159-1995, or such other Standard in force.

The following matters are, where appropriate, described in the Particular Specification:

1. Particular Specification

(a) the number, type and location of piles to be tested
(b) the stages in the program of works when a phase of dynamic testing is to be carried out
(c) the minimum dynamic test load
(d) the time at which testing is required relative to the time of installation
(e) measurement of set and temporary compression details of work to be carried out on a pile head following a test.

2. Measuring instruments

Current calibration certificates shall be provided to the Engineer for all strain transducers and accelerometers and monitoring equipment before testing commences.

3. Hammer

The hammer and all other equipment used shall be capable of delivering an impact force sufficient to mobilize the equivalent specified dynamic test load without damaging the pile.

4. Preparation of the pile head

The preparation of the pile head for the application of the dynamic test load shall involve trimming the head, cleaning and building up the pile using materials which will at the time of testing safely withstand the impact stresses. The impact surface shall be flat and at right angles to the pile axis. Where pile preparation requires drilling holes or welding, this preparation shall not adversely affect the performance of the pile when in service.

Note : A driven pile would not normally need to be specially prepared for dynamic pile testing, unless the pile head has been damaged, or it is being tested after the pile head has already been trimmed.

5. Qualification of PDA Testers

Unless otherwise allowed, field testing personnel shall hold a current and valid certificate in high strain dynamic pile testing (hereafter PDA Certificate) provided by the Deep Foundations Institute / Foundation QA Pty. Ltd.

The PDA Certificate shall be deemed valid if it denotes successful completion of the examinations at one of the following listed three levels, and is current if it has been issued within the following periods after the examination has been taken:

2 years for Basic level
3 years for Advanced level
5 years for Expert level

If the field tester does not hold current and valid certification at Basic level or above, then on an individual project basis, it shall be demonstrated to the satisfaction of the Engineer or Representative that the tester will act under the supervision of either another member of the testing company who has current and valid certification, or an independent reviewer who has current and valid certificates, and that procedures for effective and timely review and supervision of results are proposed. A method statement detailing these procedures shall be lodged a minimum of 7 days prior to commencement on site. Any subsequent non-compliance with this method statement shall be submitted in a non-compliance report within 24 hours.

6. Interpretation of tests

The interpretation and reporting of the tests shall be carried out by a tester with a current PDA Certificate at Advanced level or above, or an independent reviewer with a current PDA Certificate at Advanced level or above. The Contractor shall give all available details of the ground conditions, pile dimensions and construction method to the specialist firm carrying out the testing in order to facilitate interpretation of tests.

7. Time of testing

PDA driving tests may be carried out during the installation process in order to establish driving stresses, hammer performance, capacity assessment and integrity evaluations. Driving tests may either be conducted immediately on completion of the driving process, over a defined final length of penetration, or for the complete driving sequence. Testing of the complete installation process is recommended for the first pile installed at each project.

PDA restrike tests may be carried out after installation in order to best estimate the long-term pile capacity which may be affected by pile set-up or relaxation mechanisms, depending on the pile type and stratigraphy. The time between the completion of installation and restrike testing for a preformed pile shall normally be more than 12 hours. In the case of a cast-in-place pile shall be a sufficient time after installation to ensure that the pile is not damaged under the impact stresses.

8. Measurement of set

If specified, the permanent penetration per blow and temporary compression of the pile and soil system shall be measured independently of the instruments being used to record the dynamic test data from a fixed reference point unaffected by the piling operations. These measurements shall be made in a safe manner.

9. On-site Results

Initial results shall be provided to the Engineer or his representative immediately on completion of each test. This shall be provided in a single page hard-copy output including graphical information, pile and test identification, input parameters adopted and key output parameters, as follows:

Graphical

(a) The force/velocity-time response graph
(b) The upward- and downward wave-time response graph
(c) The static and dynamic resistance-time graph
(d) The energy-time and displacement-time graph

Pile and Test Identification

(a) Project identification
(b) Pile number
(c) Date and time of test
(d) Blow number analyzed

Input Parameters

(a) the pile length
(b) the adopted pile wavespeed at the pile head and the overall pile wavespeed
(c) the wave return time (2L/c)
(d) the pile modulus at the transducer location
(e) the pile specific weight at the transducer location
(f) the pile area at the transducer location
(g) the pile impedance
(h) the Case Method damping factor, and Case Resistance method
(i) the strain and acceleration transducers which were operational
(j) any adjustment factors applied to the measured data

Key output results

(a) the maximum force applied to the pile head
(b) the maximum pile head velocity
(c) the maximum energy imparted to the pile
(d) the maximum displacement of the pile head
(e) the pile capacity estimate
(f) the pile integrity factor (β)
(g) the maximum compressive stress in the pile
(h) the maximum tensile stress in the pile
(i) the estimated final pile set

10. Final Report

A full report shall be given to the Engineer, within 10 days of the completion of testing.

The hard-copy results provided on site shall be included and summarized. Any revision of results provided at the site, either due to adjustment of the data, use of different input parameters, or selection of a different blow, shall be noted, and the revised results included. Further wave equation analysis using the CAPWAP or TNOWAVE programs, shall be included.

The key results of field and office analyses shall be summarized, preferably in tabular form. The following additional information shall be provided for each pile tested:

(a) date of pile installation
(b) location of each pile
(c) length of pile below commencing surface
(d) total pile length
(e) hammer type, drop and other relevant details
(f) blow selected for subsequent analysis
(g) magnitude and location of possible pile damage.
(h) permanent residual movement of pile head after each blow
(i) temporary compression
(j) capacity estimate using a driving formula based on measured energy, set and temporary compression

For piles selected by the Engineer, an analysis of measurements from selected blows shall be carried out using a numerical model of the pile and soil (e.g. CAPWAP or TNOWAVE) to provide the following information:

(a) complete summary, including all model inputs
(b) maximum mobilized geotechnical strength, R_{ug}

(c) pile head movement at serviceability load
(d) pile head movement at maximum mobilized geotechnical strength
(e) distribution of mobilized static soil resistance
(f) distribution of soil stiffness and damping
(g) deduced static load deflection behaviour of the pile at the head and toe
(h) assumptions made in the analysis
(i) discussion of analysis, as necessary

Acknowledgment.

This specification draws heavily from the Specification for Piling and Retaining Walls, published by the Institution of Civil Engineers.

References.

AS2159-1995. Australian Standard. Piling – design and installation. Standards Australia, 1995, 52 pages.
Institution of Civil Engineers. Specification for Piling and Retaining Walls. Thomas Telford, 1996. 207 pages.

Electronic Format.

This specification is available for download in electronic format at www.foundationqa.com

Technical papers on quality assurance

The need for Quality Assurance in the Dynamic Pile Testing Industry

J.P. Seidel
Monash University, Melbourne, Australia

ABSTRACT: The theme of this StressWave 2000 Conference "Quality Assurance on Land and Offshore Piling" is one that is timely and worthy of exploration. This discussion paper has taken a broad view of many aspects of quality assurance as they apply to engineering projects. The role of dynamic pile testing in the quality assurance process is highlighted. It is concluded that as dynamic pile testing is a key aspect of quality assurance in many foundation contracts, it is essential that dynamic testing also be subject to the same rigor of quality assurance. It is asserted that the current *ad hoc* training process is unsatisfactory. The paper argues for an industry standard for training and evaluation of competency. Several models are suggested. This should be associated with a system of formal review for testers deemed to have only basic skill levels. A scheme for prequalification for testing contracts, which applies conditions to testers with basic skill levels, is also suggested.

1 INTRODUCTION

Quality assurance has become a catch-cry in many countries around the world. Like motherhood, the pursuit of quality cannot be criticized. However, unlike motherhood, the meaning of the term "quality assurance" is open to interpretation. Clients can also try to effect quality assurance on their projects in several ways.

In this section, a number of different methods and applications of quality assurance will be discussed in principle and with reference to both civil engineering projects and dynamic pile testing.

1.1 *Quality Assurance Systems*

In some countries, the term Quality Assurance (QA) denotes a system of checking, reporting and documentation which that has become an integral part of the contractual process. The purpose of the QA system is to set in place a process which will ensure the final built quality of the product. Implementation of the QA system is usually the responsibility of the entity (contractor, specialist sub-contractor etc.) performing the work. There is no direct supervision of the contract by the client or his representative. Any aspect of the work which does not conform with the specification is the subject of a Non-Conformance Report, NCR (a particular terminology used – equivalent terminologies are possible). Submission of an NCR flags a problem which requires explicit consideration and rectification before consequent work can proceed. All work or rectification must ultimately meet the contractual and specification requirements.

Although ensuring the final construction quality by this process is a laudable goal, the reality is that quality assurance techniques do no more than address consistency of processes and adherence to target outcomes. Quality Assurance as a system is well suited to processes such as manufacturing, which are repetitive, devoid of subjective decision and where the product can be tested or measured to ensure compliance with specification. Mass production of consumers products is an ideal application.

By inference, QA techniques are not well suited to processes which are one-off, involve subjective decisions and experience, and where the end-product is not always available for direct measurement. Most civil engineering projects would fall into the latter description.

Foundation engineering, in particular, is a field in which the knowledge and experience of each member of the team – designer, construction engineer, foreman and crew are critical to successful construction. Each project, and even each pile within a project brings new challenges because of the uniqueness of the ground and groundwater conditions. For instance, the pile driver must be responsive to changes in pile blow count, and must be aware of conditions that will potentially damage the pile during installation. The driller must prevent collapse of the shaft, and must be sensitive to the drilling equipment to ensure that a suitable founding layer has been attained. These are all aspects of the process which are based on knowledge, experience, subjectivity, good practice, and even intuition, which cannot be defined in a contract specification, or measured for compliance, and are therefore outside the ambit of a QA System.

This is not to say that QA Systems do not have a role, or should not be an element of the engineering process. Rather, it is important that the limitations of these systems be understood and acknowledged in the formulation of a more global approach.

What must be avoided is a belief that by virtue of implementation of a QA System, that the end product is necessarily of high quality. In the author's experience, there is a real danger that the application of such techniques can actually reduce the quality of construction. The QA System requires such a plethora of documentation that time which should be spent "at the coal face" ensuring real quality is spent filling in forms to document compliance.

Dynamic pile testing can, and often is an integral part of QA systems for driven piles, usually in the aspect of confirmatory testing, which will be discussed subsequently. It is also possible and desirable, that the wider capabilities of dynamic pile testing be utilized in setting parameters or guidelines for the installation process, i.e. as an integral part of the construction control process. However, this use is generally underutilized, as it is not as easy to prescribe this type of application in the System.

It is also noted that dynamic pile testing is also applied to only a limited percentage of the piles installed on a contract (usually 15% or less). An inference must be made that the quality of the test sample is similar to the quality of the remaining piles installed.

1.2 *Quality Assurance – supervision*

A more traditional approach to ensuring a quality outcome for construction projects has been by means of independent supervision of the construction process. Typically, the client employs a person knowledgeable in construction techniques to oversee the construction in either a part-time or full-time capacity. Duties typically include taking spot measurements of critical dimensions, and ensuring compliance with the specification and with good practice. This method is still in wide use in some countries, and with particular clients.

The primary benefit of this approach is that the quality of the construction process and the completed product is assessed by a person independent of the process itself, and whose exclusive role is to check for quality. QA systems, relying as they do on self-regulation and the professional integrity of each player in the process, are open to criticism on this account.

The potential disadvantages of this approach are :

- it is an additional cost to the project;
- the liability for any problem may be partially transferred from the contractor to the supervising body;
- the effectiveness of this process is dependent on the knowledge and experience of the particular superintendent.

Particularly for foundation engineering, where many proprietary systems are used, and where the skills of foundation construction are very specialized, the ability, knowledge and experience of the person providing oversight will generally be inferior to that of the specialist foreman and crew undertaking the work. In this case, the supervision is not an effective approach for quality assurance.

In the particular case of dynamic pile testing, it is unlikely that a construction supervisor would be able to effectively oversee the testing process.

1.3 *Quality Assurance – professional review*

Quality assurance can also be applied to the engineering design and construction processes. This can be in the form of either a design check, review or independent design. The independent design would normally be performed by an external organization, but checks and reviews could be undertaken both in-house or by an independent external engineer. The use of professional reviews is common for larger or more complex projects.

It is implied in this process that the design or construction records be transparent and verifiable, and that independent reviewers with the necessary skills to interpret this information are available. Further comments on this aspect with regard to dynamic pile testing will be made later.

1.4 *Quality Assurance – Prequalification*

On larger and more complex projects, it is also common for contractors or consultants to demonstrate that they have the requisite skills and experience to successfully complete a project or provide advice. Without prequalification, the organization cannot even bid to provide services. Prequalification might typically require the organization to provide details of previous relevant projects completed; available resources; experience and qualifications of key field and office personnel and references.

Prequalification is adopted by some statutory bodies with regard to dynamic pile testing organizations. In the absence of any effective alternative, the process is typically based on whether the organization has provided testing services for a reasonable length of time, or on the advice of independent referees. To the knowledge of the author, this approach is not widespread for dynamic pile testing. It is also applied to organizations rather than individual testers.

1.5 *Quality Assurance – Direct Testing*

A key element of quality assurance in civil engineering projects is the testing of constituents, individual elements or in rare cases, large or complete systems. With specific reference to foundations, the quality of concrete is routinely tested by standard compression testing, or chemical testing. Weld quality is also evaluated by inspection and ultrasonic testing. There are either absolute or statistical standards with which the tests must comply. Such routine testing of constituents fits well within Quality Assurance Systems or more traditional contractual arrangements, as compliance or non-compliance is easily demonstrated.

The testing of individual piles is also commonly stipulated as part of a project specification. In this case, a variety of techniques can be used. For driven piles, the final pile set and (optionally) temporary compression are measured for every pile to obtain a measure of axial pile capacity using a driving formula such as Janbu, Hiley, ENR or Gates. Although these methods are applied to the entire population of piles, they are known to be simplistic estimates of capacity, and hence subject to high levels of uncertainty.

In many countries, for all but the smallest projects, more sophisticated, and hence more reliable testing is performed in some combination of static load testing, dynamic pile testing, Statnamic® pile testing, Osterberg testing and various pile integrity testing techniques. The particular testing strategy developed for each site is a function of economics, available technologies, pile type, site conditions and historical precedent.

Testing of piles as individual components of the final system also fits well within the framework of a Quality Assurance system in which quantitative outcomes can be measured against the required specification.

Engineers generally recognize that despite conducting a targeted pile testing program, some uncertainty still exists for the following reasons:

- Only a fraction of the contract piles are tested using high-level techniques. The capacity of untested piles must be extrapolated or otherwise inferred;
- Every testing method provides an estimate of the (axial) pile capacity at the time of testing, and each method has an associated uncertainty.

These uncertainties are accommodated by specification of ultimate capacities which incorporate an appropriate factor of safety or through prescribed load factors and strength reduction factors under the Limit State approach.

Nevertheless, there is an important implied assumption that the capacity estimate provided is the best, unbiased and ‘correct’ estimate available within the constraints of that technique.

2 QUALITY ASSURANCE – THE TESTING PROCESS

As noted, direct testing is a key element of quality assurance in many civil engineering projects. It is a particularly common technique in foundation engineering due to the uncertainties introduced by the natural stratigraphy which is not known perfectly in–advance of any foundation contract.

As verification is a key element of the overall construction process, it would be illogical if the testing were not itself subject to the principles of quality assurance. This section considers quality assurance of the testing process in the particular context of static and dynamic pile load testing.

2.1 *Static Load Testing*

Standards and Specifications which set minimum requirements for compliance exist as part of the framework of quality assurance for testing. For static load testing, ASTM D1143-81(1994)e1 (ASTM, 1994) is the U.S. National Code of Practice which sets standards for the equipment, calibration, procedures and records required for testing piles under axial static compressive loads. Equivalent Codes of Practice for static pile load testing are mandated in many other countries.

If tests are performed in accordance with the appropriate standard, it is generally assumed that the load-settlement response is a true representation of the pile load-settlement response. This may not, however, be entirely correct.

Fellenius (1984) describes the large errors which can be introduced by using a manometer attached to the hydraulic jack which is simultaneously a load application device and a load measurement device. It is more appropriate to use a separate load cell so that the load estimate is true and unbiased. AS2159 (Standards Australia, 1995) mandates the use of a load cell for static pile load testing.

The complexities of interaction effects between the test-pile and reaction pile, anchors or reaction weights are usually ignored, and will not be dealt with here, other than to note that both the inferred capacity and settlement characteristics can be affected. Engineering analysis is required to correct these physical effects.

It should also be noted that there are many alternative procedures for static pile load testing. Standard methods are known variously as Maintained Load Tests, Quick Maintained Load Test and Constant Rate of Penetration Test (other names are used). Within these broad categories, an infinite number of specific test regimes are possible. Due to the different loading paths, any pile subjected to the various tests will exhibit a different load-settlement response. The significance of the different responses, the separation of elastic, plastic and creep components, and the extrapolation to service behavior is a matter for engineering analysis and interpretation.

Furthermore, Fellenius (1980) notes that the interpretation of ultimate capacity from a static load-movement curve is not unique. Application of the many constructions proposed (e.g. Davisson Offset Limit , Brinch-Hanson, Chin-Kondner) result in significantly different estimates of ultimate capacity.

It can be appreciated, therefore, that correct interpretation of the simple static load test is more complex than it would first appear. Analysis of the test data would generally be performed by a specialist geotechnical engineer using accepted methods that are in the public domain.

In general, however, the assumptions made in the analysis of the load test data are transparent (it is, after all only a correction which is applied to the measured response), and verifiable. The fraternity of local geotechnical engineers is usually large enough to enable a professional review to be made, if required.

Furthermore, as noted previously, in the majority of cases, the static load test response is taken to be a true representation of the pile load-settlement response. For contractual purposes, it is often necessary only to ensure compliance with the specification of the peak applied load and the settlement at one or more defined loads. Further analysis is not undertaken, and the test outcome is accessible and open to direct and immediate interpretation by both structural and geotechnical engineers.

2.2 *Dynamic Pile Load Testing*

Just as for static load testing, Standards exist which prescribe the requirements for dynamic pile testing methods. ASTM D4945-96 (ASTM, 1996) sets standards for the equipment, calibration, procedures and records required for testing piles using dynamic impacts. AS2159 (Standards Australia, 1995) stipulates requirements for the use and interpretation of dynamic pile testing. The Institution of Civil Engineers (ICE, 1996) have published specifications and good practice guidelines on *inter alia* dynamic pile testing. Other similar documents with national authority exist, although fewer than would exist for static load testing.

The interpretation of dynamic load tests has both similarities and differences to the interpretation of static load tests. They are similar to the extent that correct interpretation requires specialist geotechnical knowledge. However, the following important differences exist:

- The direct output of a dynamic test is not a load-settlement response, but usually pile-head strain-time and acceleration-time responses;
- The measured test response is a dynamic response, and the static behavior which is to be determined must be extracted from the test using either simplistic or more complex analytical or numerical techniques.

The fact that the direct test outcome bears no resemblance to the load-settlement response is significant. This means that most structural or geotechnical engineers are unable to interpret the test result. To this extent the results are not transparent, and the technique is therefore considered “black box” technology - sometimes with the attendant negative connotations.

Interpretation of these pile-head time records is a specialized technique, which is generally known or understood by the small number of practitioners who are providing dynamic pile testing services. This is not to say that information on how to interpret dynamic pile testing records is not well published and available in the public domain. However, the reality is that the technique is so specialized that those not directly involved simply “leave it to the experts”. Local professional review is also not generally available, as the only potential reviewers are likely to be testing or construction competitors, and commercial and professional sensitivities about releasing data have even resulted in claims of intellectual property over test records. This results in a problem with verification of results.

Dynamic pile testing suffers from the problem that if the process is not typically transparent or verifiable, the client is not in a position to independently assess the skill, understanding and knowledge of the tester. He also cannot assess whether the estimate which has been made is actually the best estimate, given the constraints of the technology.

It appears to be a universal experience, judged by the author’s personal communications with colleagues around the world, that not all practitioners providing dynamic pile testing services have adequate skills. The author is aware of cases where dynamic pile testers have given gross errors in advice due either to poor data quality which is undetected or ignored, or due to misinterpretation or incorrect analysis of the test records. For obvious reasons, these cases are not detailed here. The author's experiences are not unique.

These errors in advice (if detected by the client) can not only affect the client's confidence in the practitioner, but also their view of the reliability of the dynamic testing method in general. This has an unfortunate and undeserved flow-on effect to all practitioners.

This is to say nothing about our responsibility as professionals to provide professional advice, and our moral obligation to ensure the integrity and safety of the structure and people who could be affected by a collapse.

We must collectively address the challenge of quality assurance within the dynamic pile testing industry world-wide.

3 QUALITY ASSURANCE IN THE DYNAMIC PILE TESTING INDUSTRY

The previous section has addressed quality assurance of the testing process in the context of the foundation industry and with regard to dynamic pile load testing in particular.

The following section discusses some possible strategies to ensuring that dynamic pile testing services are provided in accordance with the principles of quality assurance. This discussion is placed in the context of current practice.

3.1 *Training*

A fundamental requirement for ensuring compliance with the principles of quality assurance is that the individual providers of advice are suitably competent.

Four stages have been identified in the general development of competence. These can be applied to the specific case of dynamic pile testing:

- Stage 1 : *Consciously incompetent.* The person is not able to perform a task in a competent manner, and is aware of their inability. This person is not a danger, because he/she will generally be prudent enough not to provide advice.
- Stage 2 : *Unconsciously incompetent.* The person is able to perform tasks at a basic level, but is unaware of what they don't know, and the implications of their advice. This person is a danger, because he/she will provide advice without the necessary skills to assess whether this is provided on a sound basis.
- Stage 3 : *Consciously competent.* This person has reached a stage where they have achieved a basic to advanced understanding. They are also aware of what they don't know and the possible implications of their lack of knowledge. In general, this person will provide advice within the limits of their knowledge, and seek assistance in areas outside their competency. They would only be dangerous when they do not seek appropriate advice outside the limit of their expertise.
- Stage 4 : *Unconsciously competent.* This person has become an expert; has an intimate knowledge of the subject area which they can apply without effort and can apply their knowledge to areas beyond their direct experience.

In developing strategies for quality assurance in the dynamic pile testing industry, all four stages of competency must be catered for and addressed. Systems should be in place both to identify the stage of competency, and to prescribe an appropriate level of autonomy or independence. It will be seen from the previous descriptions that the Unconsciously Incompetent person – unaware of their own limitations is the person that requires the greatest attention.

The key to competency is knowledge. Knowledge is typically acquired by one of three methods – by formal or informal training, education, mentoring or reading; through experience; and finally by making mistakes. All are powerful methods of learning. Obviously, in a contractual environment, the last method is undesirable, and should be avoided by one of the first two methods. Experience, unfortunately can only be acquired over time. Training is the traditional way to quickly develop competency.

There are no current standards or guidelines for training within the industry, and no standards or certification which can demonstrate competency. Because of the highly specialized nature of this field, the subject matter is not generally covered in an undergraduate engineering degree. Because of the limited interest and again because of the scarcity of people qualified to teach in this area, there are no formal post-graduate courses available in pile dynamics (to the author's knowledge). There is, therefore, no formal qualification or certification which can be obtained which indicates competency in this field.

There is no requirement to either hold a degree or equivalent undergraduate qualification in Civil Engineering, or in Engineering in general. This is not to say that such a qualification is necessary, although such a degree provides obvious background to some of the principles employed in dynamic pile testing. Guided experience, self-help and training can provide an equivalent level of competency over time.

An individual or organization new to dynamic pile testing could expect one of the following training experiences:

- An on-site training program of 1 to 3 days, generally provided in association with purchase of new equipment. Training is conducted by the equipment manufacturer, or a designated agent. This training would only be an introduction to use of the equipment and underlying theory. At the conclusion of this training, the user would be at either Stage 1 or Stage 2 competency in the above model
- An informal training program conducted on-the-job and in-house by a tester from the same organization. The trainer in this case may have been given the original training by the equipment manufacturer, or may have been given similar informal in-house training. In this way, 2nd or 3rd generation training is quite common. There are no controls on the quality of such training. It would typically concentrate more on the particular types of projects encountered, and practical aspects of testing, and would give less broad overview, principles and theory than the manufacturer's training program. Manuals will generally be made available to supplement the training. The quality of the training will only be as good as the competency of the trainer. Any misconceptions of the 2nd or 3rd generation trainer will be passed on to the new trainee.

This current *ad hoc* method of training is not an ideal, and is not consistent with a quality assurance approach.

In order to comply with quality assurance principles in training, it would be necessary to provide a consistent minimum standard of training to all new practitioners. If the training is to be industry-wide, it would be desirable to provide this through an independent industry organization or educational institution. The practicalities of providing uniform training to a dispersed world-wide market would tend to suggest the need for the material to be delivered in distance education mode. Concentrated workshops could be an alternative model.

3.2 *Testing Competency*

The purpose of training should be to establish basic competency in the providers of testing advice so that at the completion of the training period they are moving into Stage3 – Consciously Competent. Of course, this stage will not be fully reached without a period of field experience to reinforce the principles learned during training.

With further experience, discussion with peers, attendance at industry seminars and conferences, there would be an expectation that the tester would progress to advanced and eventually expert status.

Under a quality assurance philosophy. there would be a need not only to provide and undertake training, but to assess competency both of those that undertake training, and those that are already providing dynamic pile testing services

- It needs to be established that testers have achieved *and maintain* a basic level of competency, and
- Those testers moving from Stage 2 to Stage 3 (hence from a basic level to an advanced level) should receive an appropriate level of review from a tester with either advanced or expert status.

3.2.1 *Evaluation of competency*

Assessment of competency could be formulated in different ways. Some of these proposals may be difficult to develop in practice:

- By a mentoring scheme in which assessors (accredited by an independent industry group) would evaluate the competency of an applicant over a period of time. Both field and analysis skills could be assessed.;
- By an independent review panel (comprised of acknowledged industry experts) that could assess a submission from an applicant based on examples of the applicant's work; a list of projects completed; details of training undertaken and referee reports. An interview process could also be part of such a scheme;
- By standard examination. This could cover both data acquisition and data interpretation skills, but could not assess practical skills on site. A multiple-choice format would give a most objective assessment of capability

Any method used to assess competency should be able to effectively distinguish three levels of competency – basic, advanced and expert. All approaches should be capable of giving feedback to applicants on areas of weakness so that targeted training and improvement is encouraged.

As skills in dynamic pile testing need to be reinforced by regular practice, it may be necessary to instigate a system of regular review and re-appraisal, particularly for those with only basic skills, and for those who may test on an infrequent basis.

3.3 *Review*

Having established a system of assessing competency, it is a logical consequence to ensure that those practitioners assessed to have at most basic competency be required to obtain review from others with either advanced or expert status.

The ideal situation would be for such partnering to be undertaken in-house with someone with higher competency. This person would be required to "sign off" on all testing and analysis undertaken by their junior.

Where a person of higher qualification was not available within the organization, arrangements would be required for review by any eligible reviewer. The arrangements for such review, including commercial and legal aspects, would be a matter for joint agreement. It is anticipated that standing arrangements would be made with a particular reviewer to streamline the process. This would lead to an effective mentoring arrangement and encourage transfer of knowledge.

3.4 *Prequalification*

As noted earlier, prequalification is a quality assurance technique which is used for contracts requiring high levels of expertise or resources. Some statutory authorities already require prequalification for providers of dynamic pile testing services.

It is suggested that this system could be more widely adopted, and that acceptance be based on the levels of competency assessed by the evaluation process. The requirements for review, as suggested in the previous section could be formalized in the conditions for prequalification. It would be important that providers not be excluded from providing services, but rather that their provision of services should be accepted conditional on demonstration of effective and timely review arrangements.

4 BASIC SKILLS

The continuing development of dynamic pile testing equipment has enabled the operator to have a vast array of information available in real-time. Algorithms have been developed which provide critical feedback to the operator at critical stages of testing alerting the operator to potential hazards (such as development of damage, excessive stresses, excessive bending etc.) Many calculations which were previously undertaken manually are now automated, freeing the operator to concentrate on more critical observations.

Although these developments are positive, there is a danger that the operator will lose the ability to critically evaluate the results which are provided by the equipment. No algorithm is flawless, and no equipment, however smart the software, can replicate the abilities of an expert to critically evaluate the pile responses and make appropriate judgements and decisions. Without a detailed understanding of the basis for the computations, the limitations of these computations, and the implications of changes in parameters or assumptions cannot be known.

If the operator is to remain in effective control of the testing process, and not become a slave to the equipment, it is imperative that the operator develop skills to make the necessary independent critical judgements. Only by developing these skills can he progress to advanced and then expert level.

Following is a tentative list of the types of skills necessary for effective dynamic pile testing. Many of these relate to recognition of conditions from the force/velocity and upward/downward wave responses:

- Recognition of valid and invalid data in a variety of scenarios;
- Field measures required to rectify poor data;
- The principle of proportionality; pile impedance;
- The relationship between mass density, modulus and wavespeed;
- Material properties;
- Allowable stresses;
- Principles of one-dimensional wave mechanics;
- Computation of pile wavespeed in easy and hard driving conditions;
- Recognition of easy, moderate and hard driving conditions;
- Identification of high compression stress levels at the pile head and at the pile toe;
- Estimation of pile toe stress;
- Identification of high tension stresses before and after the 2L/c time;
- Identification of damage intensity and location;
- Recognition of a broken pile, pile joints and changes in section;
- Recognition of response from end-bearing piles, and piles with small and large shaft resistance;
- Estimation of end bearing, shaft resistance, and shaft resistance distribution;
- Recognizing high and low cushion stiffness;
- Recognizing bending and poor hammer-pile alignment;
- Understanding the effect of resistance, or impedance changes close to the transducers;
- Principles of valid data adjustment;
- Pile compression and tension capacity;
- Estimating Case damping factor;
- Basis of the Case method of capacity determination, and factors influencing capacity estimates;
- The implications and conditions for pile unloading;
- Pile set-up and relaxation;
- Mobilization and under-mobilization of capacity;
- Hammer performance and transfer efficiency;

5 CONCLUSIONS

This paper argues the need for dynamic pile testing to be subjected to a rigorous industry-wide quality assurance scheme, compatible with the foundation industry which the testing serves. The scheme should be one which delivers real, fundamental quality, and not one which merely produces documentation to satisfy administrative requirements for an audit trail.

Ideas for a possible comprehensive model have been suggested. The challenge to adopt such an approach should be taken up by all players in the field of dynamic testing including practitioners, industry groups and clients.

Without adopting the principles of quality assurance, the reputation of the industry as a whole will continue to suffer at the expense of alternative testing methodologies.

REFERENCES

ASTM (1994) ASTM D1143-81(1994)e1 Standard Test Method for Piles Under Static Axial Compressive Load. American Society of Testing and Materials, West Conshohocken, PA

ASTM (1996) ASTM D4945-96 Standard Test Method for High-Strain Dynamic Testing of Piles. American Society of Testing and Materials, West Conshohocken, PA

Fellenius, B.H. (1980) The analysis of results from routine pile load tests. Ground Engineering, September, 1980 : 19-31.

ICE (1996). Specification for Piling and Embedded Retaining Walls. Institution of Civil Engineers. Thomas Telford Publishing, London ISBN 0 7277 2566 1

Standards Australia (1995) AS2159-1995 Piling - Design and installation. Standards Australia, Sydney. 0-7262-9884-0