

Detection of toe damage in steel piles driven to bedrock

1995 PDA User's Days, Cleveland

Hicham Salem, Fred Agharazi, and Bengt H. Fellenius

Damaging compressive stresses can develop at the pile toe when piles are driven to bedrock or in bouldery conditions. High-strain testing methods using the Pile Driving Analyzer (PDA) have been used successfully to detect pile damage along the pile. Toe damage, however, especially at an early stage of damage, is hard to identify from the PDA measurements, but a close study of the wave traces can provide some leads, as presented in the following recent case history.

Six steel pipe piles were driven to severely fractured bedrock and extracted. The test piles consisted of about 33 m long, 610 mm diameter steel pipe piles with 12.5 mm wall. Three different rock shoe arrangements were used, as shown in the photos below: open-toe unprotected, open-toe equipped with a ring shoe, and closed-toe with a cone point shoe. The test piles were named according to their shoe arrangement and the order of driving. Four of the six piles experienced toe damage.



Open, unprotected
OPEN 1, OPEN 2



Open, ring shoe
RING 1, RING 2, RING 3



Closed, cone shoe
CONE 1

The pile driving was monitored by the Pile Driving Analyzer (the gages were attached to the piles about 2 m below the pile head). Pile driving diagrams of the test piles (attached) were produced from the dynamic monitoring ASCII data. The beginning of the fractured rock layer is obvious in the driving diagrams. In particular, from the toe compression stress (CSB) showing a sharp increase in toe stresses when the pile toe encountered the bedrock.

When extracting the piles after the driving and restriking, four piles were shown to have toe damage: Piles Open 1, Open 2, Ring 2, and Ring 3. But for Pile Open 1, temporary reductions in the toe stress (CSB) were observed when advancing the pile in the fractured bedrock. Such zones pertaining have been circled in the driving diagrams.

The illustrations below show photos of damaged pile toe combined with traces of force and velocity, and wave-up and wave-down from the end of driving of each pile. A close examination of the force and velocity traces shows an early velocity rise at Time T2, $2L/c$ after Time T1, the start of the hammer impact. Similarly, the wave-up and wave-down traces show an early tensile reflection. For comparison, records are also included from the driving of the damaged piles prior to the damage occurrence and from piles that were not damaged.

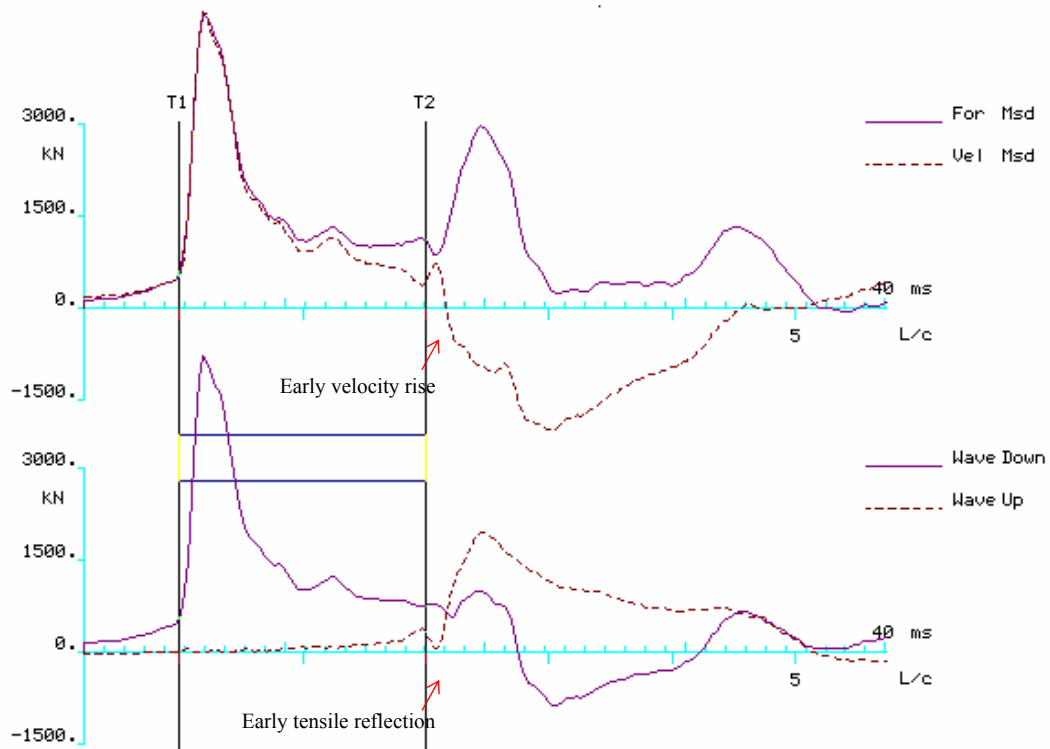
The following presents wave traces before and after the observed damage. Traces from undamaged piles are included for reference.

Damaged piles



Toe of Pile Open 1 after pull-out

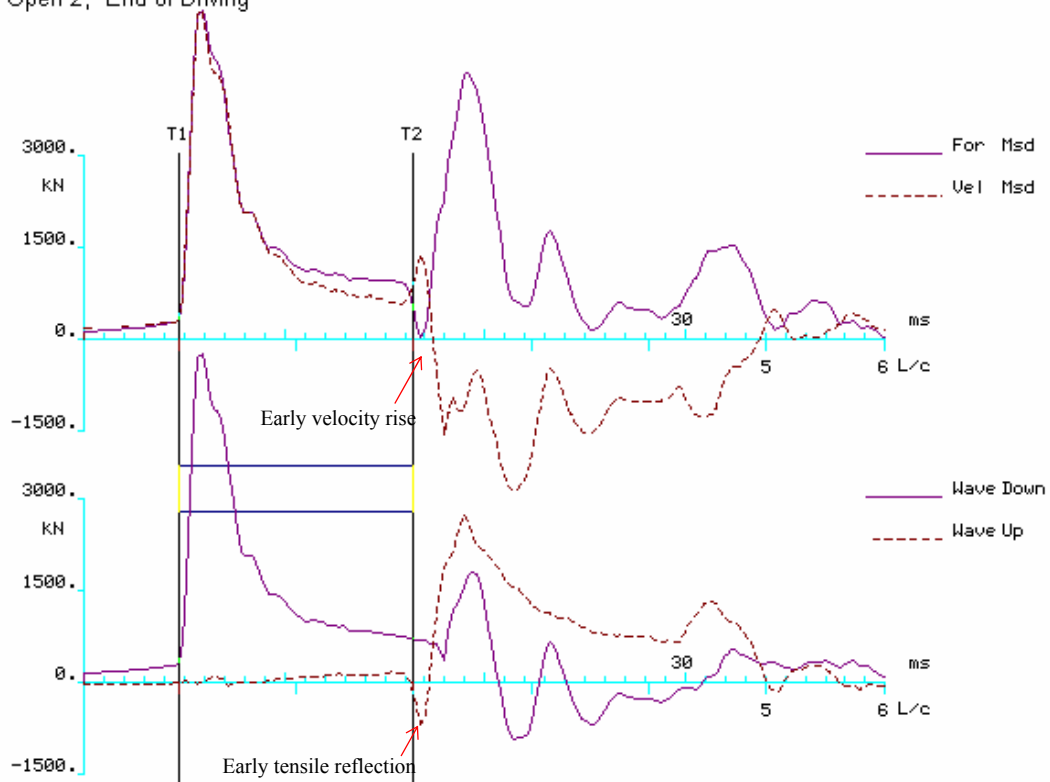
Pile Open 1, End of Driving





Toe of Pile Open 2 after pull-out

Pile Open 2, End of Driving



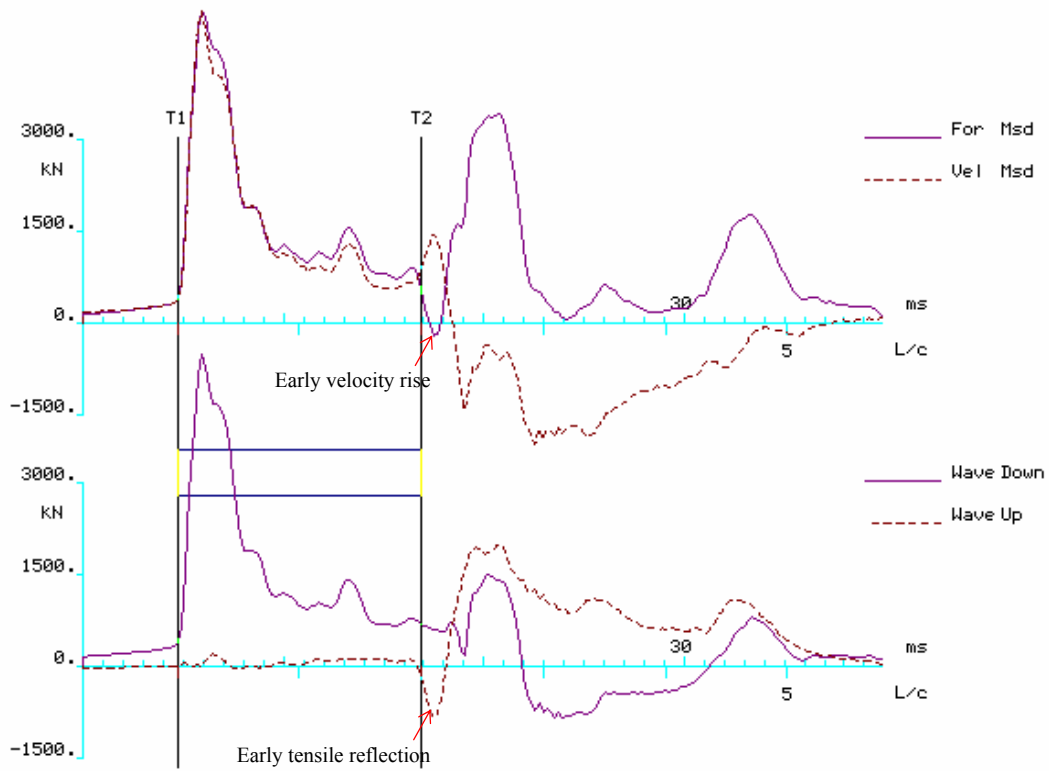


Ring 2 and Ring 3
(left to right)

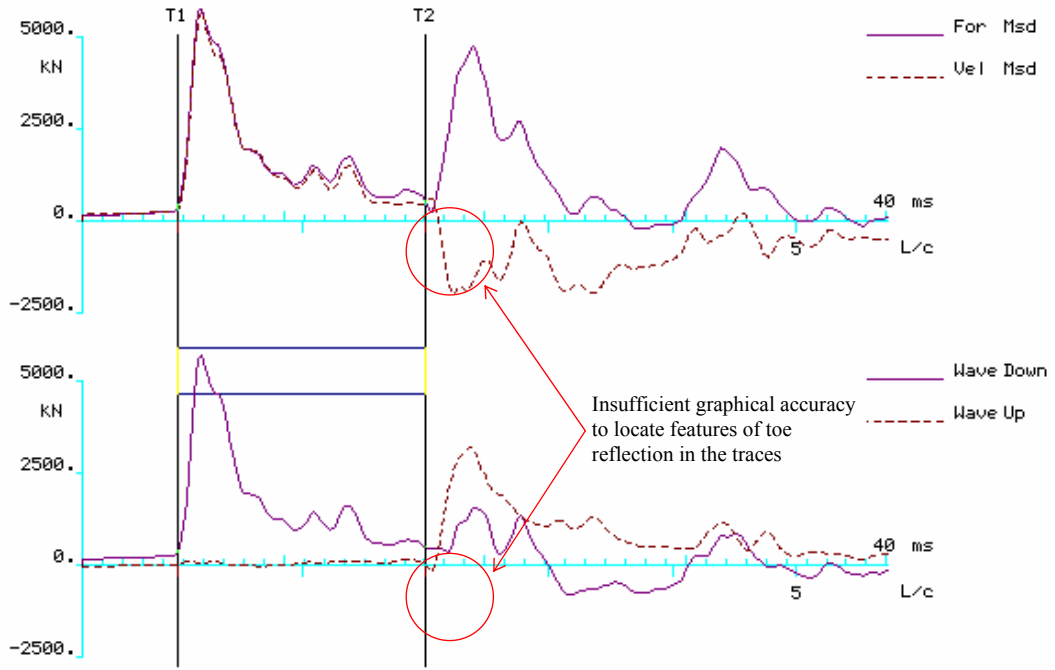


Ring 2 and Ring 3
(left to right)

Pile Ring 2, End of Driving

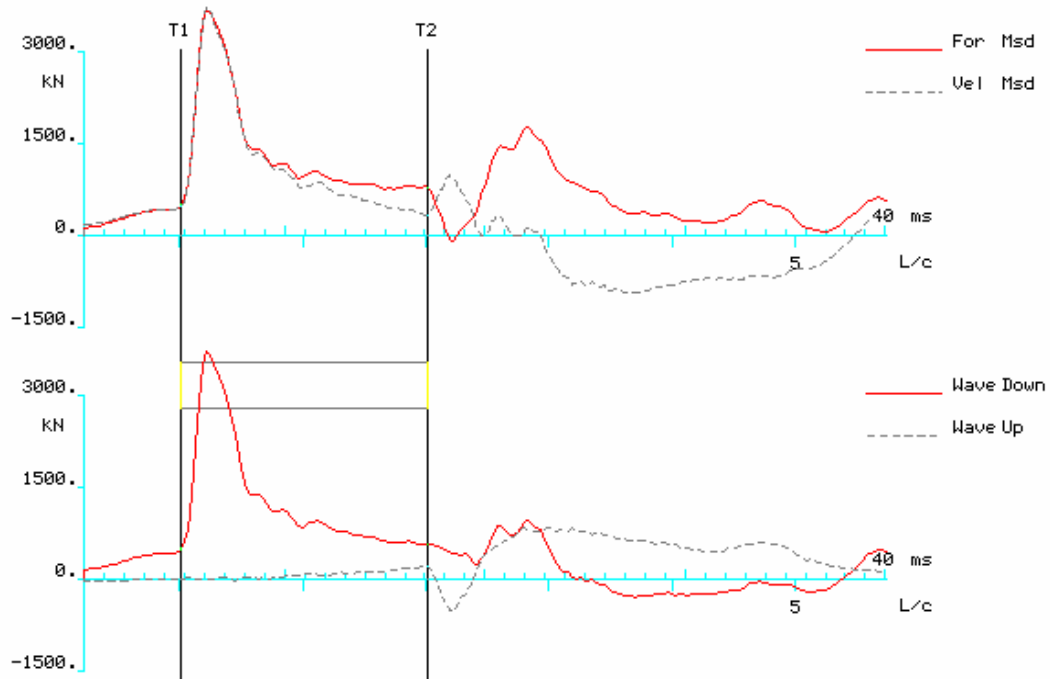


Pile Ring 3, End of Driving

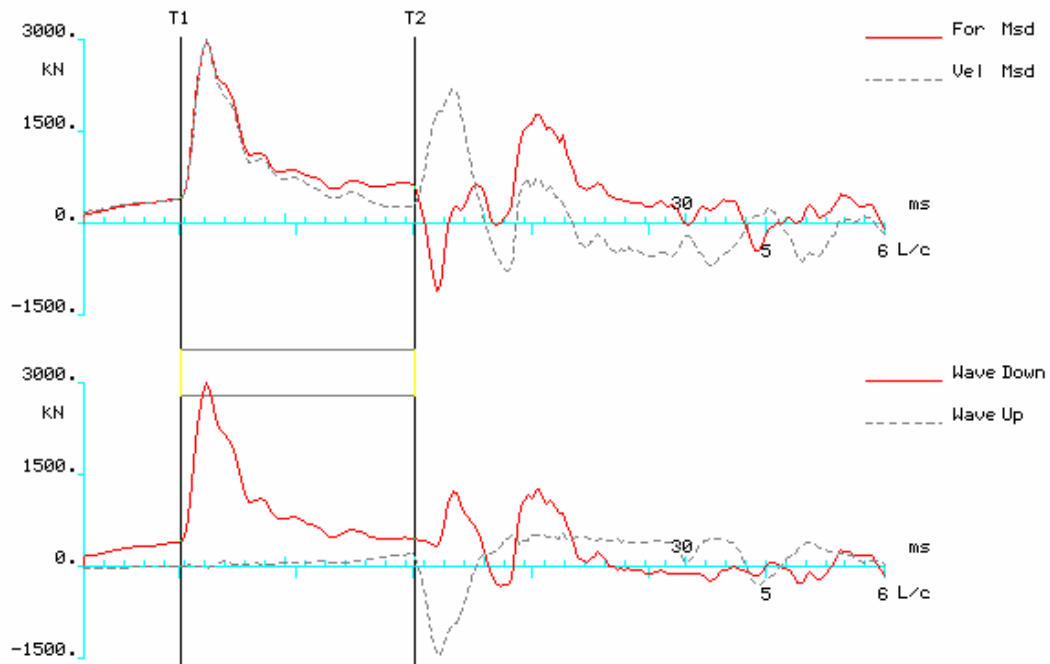


Pre-damage traces

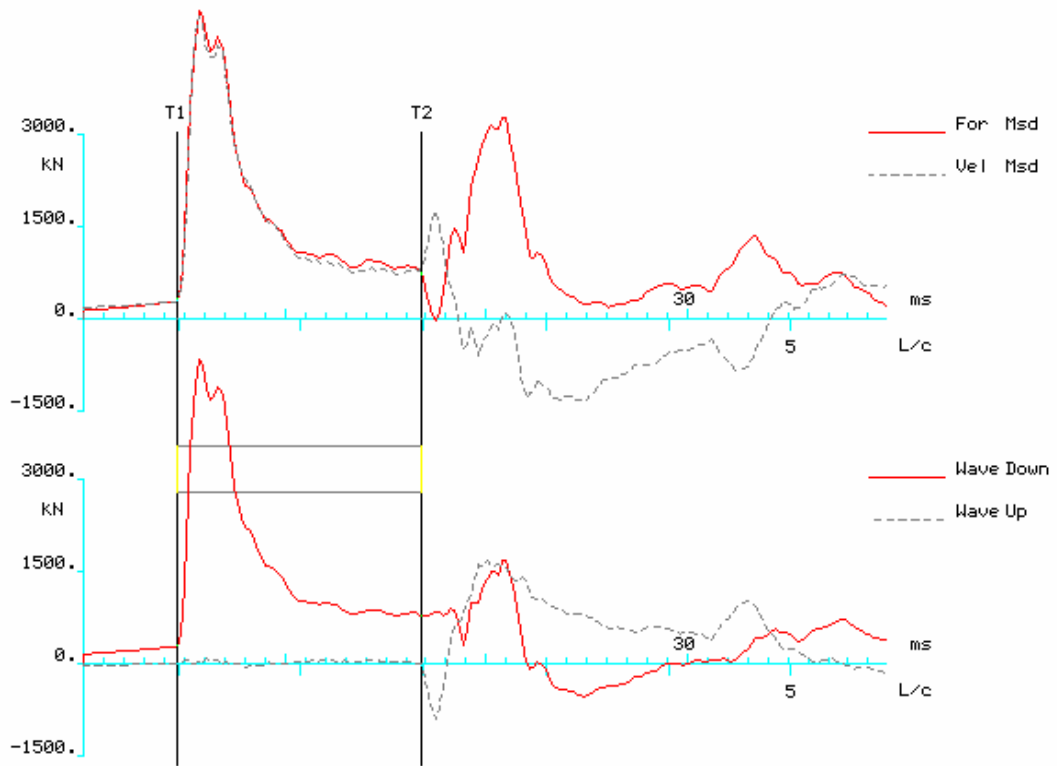
Pile Open 1, Moderate Driving



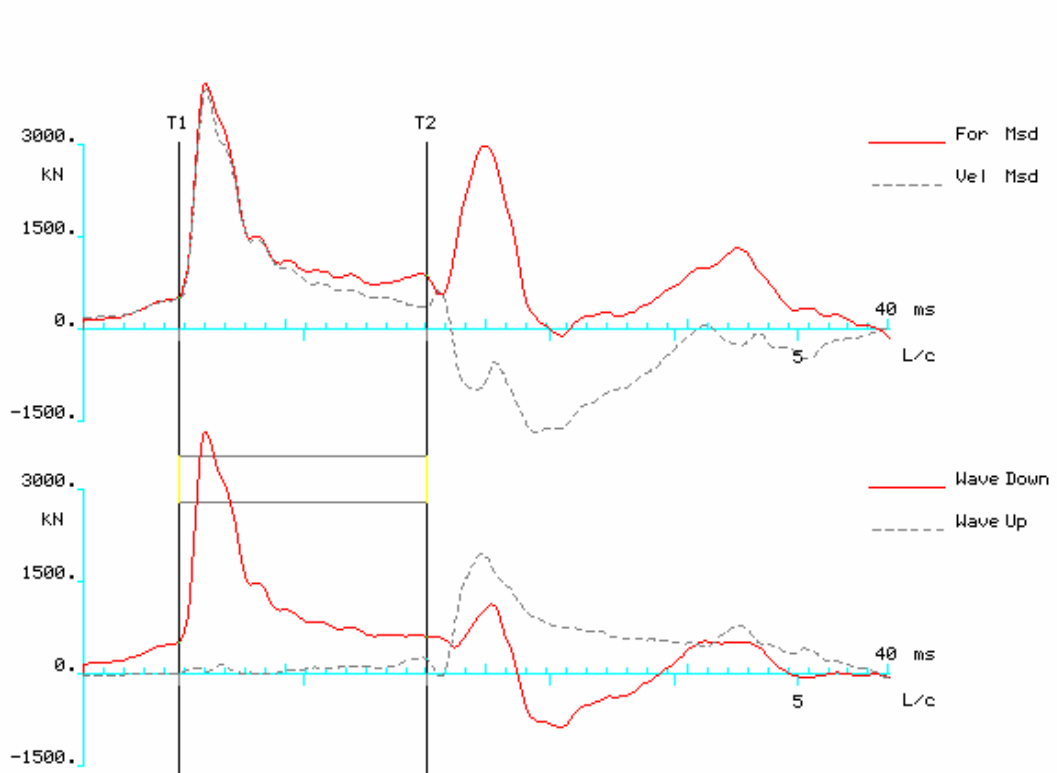
Pile Open 2, Moderate Driving



Pile Ring 2, Moderate Driving

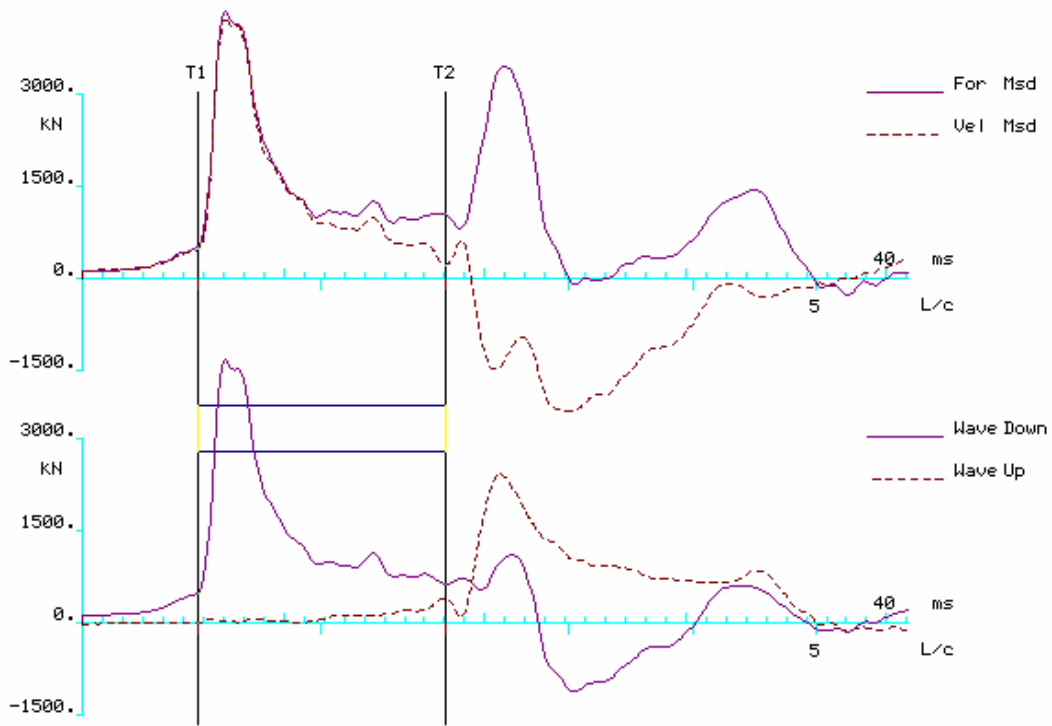


Pile Ring 3, Moderate Driving

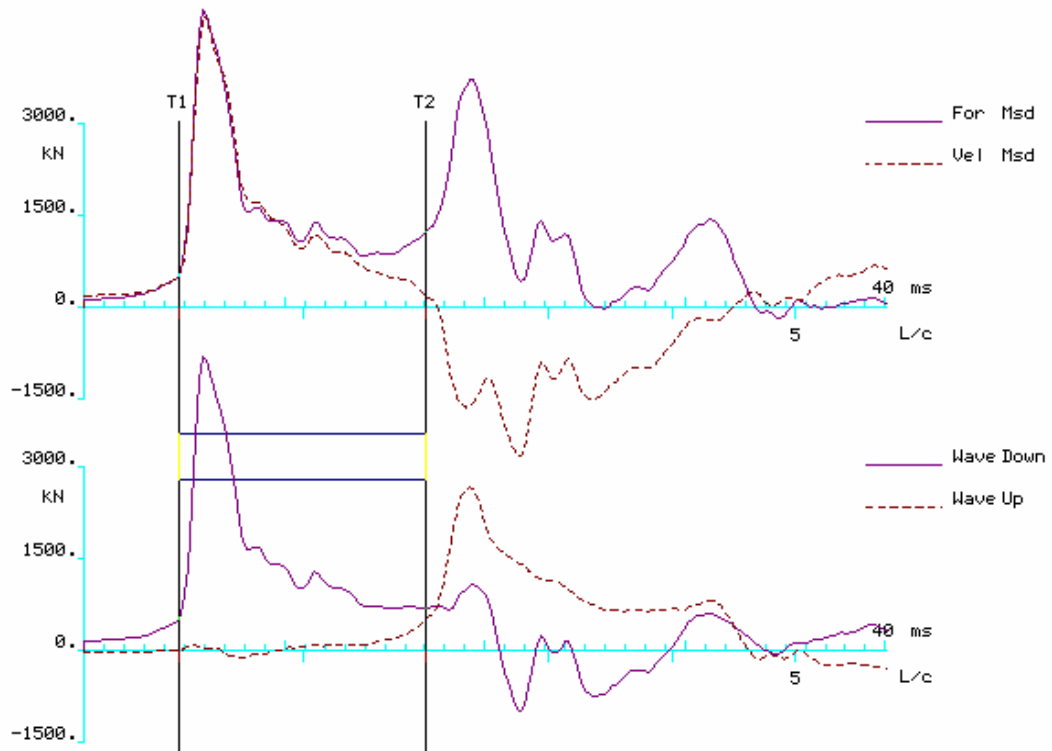


Undamaged piles

Pile Cone 1, End of Driving

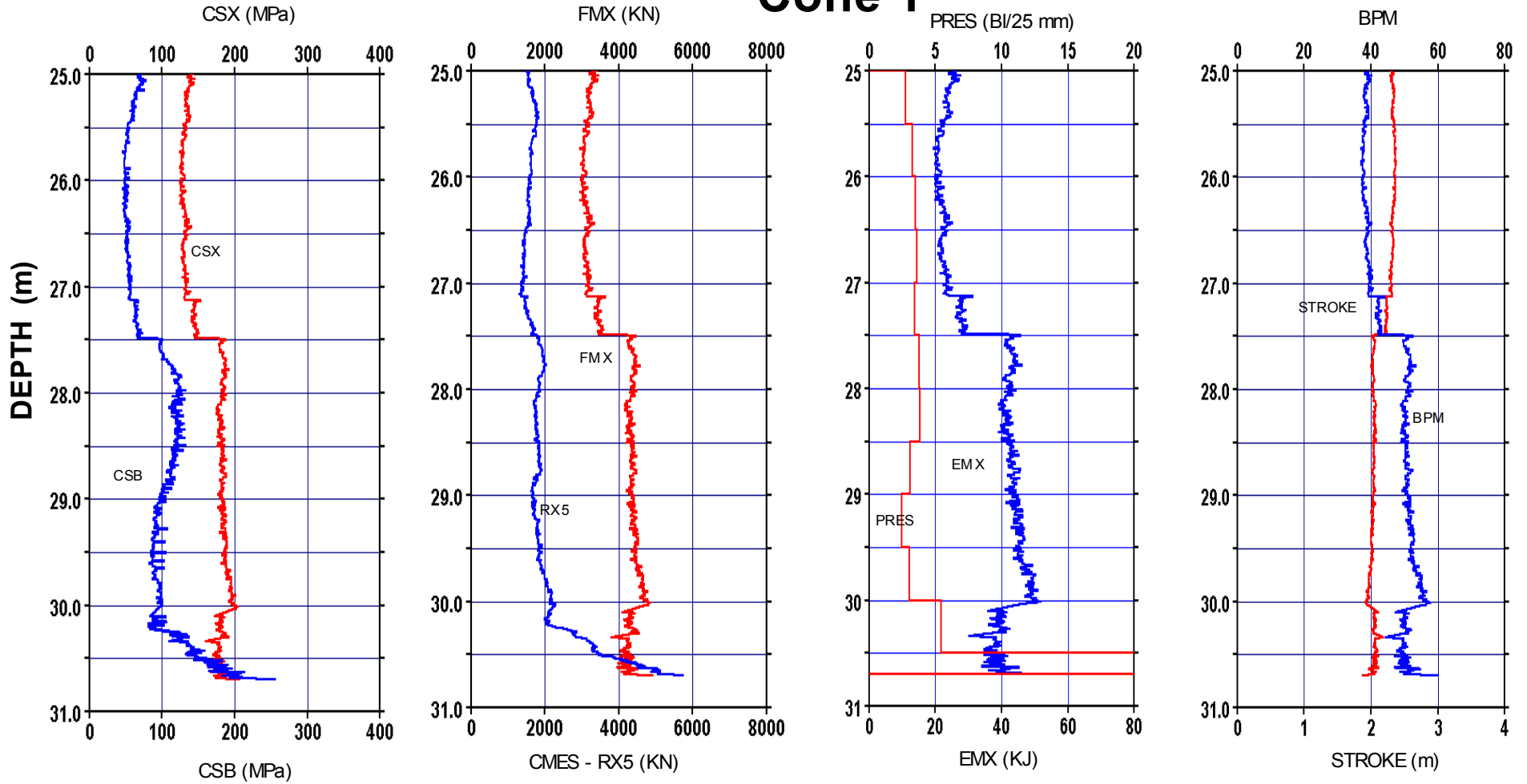


Pile Ring 1, End of Driving



PDA-Diagrams

Cone 1



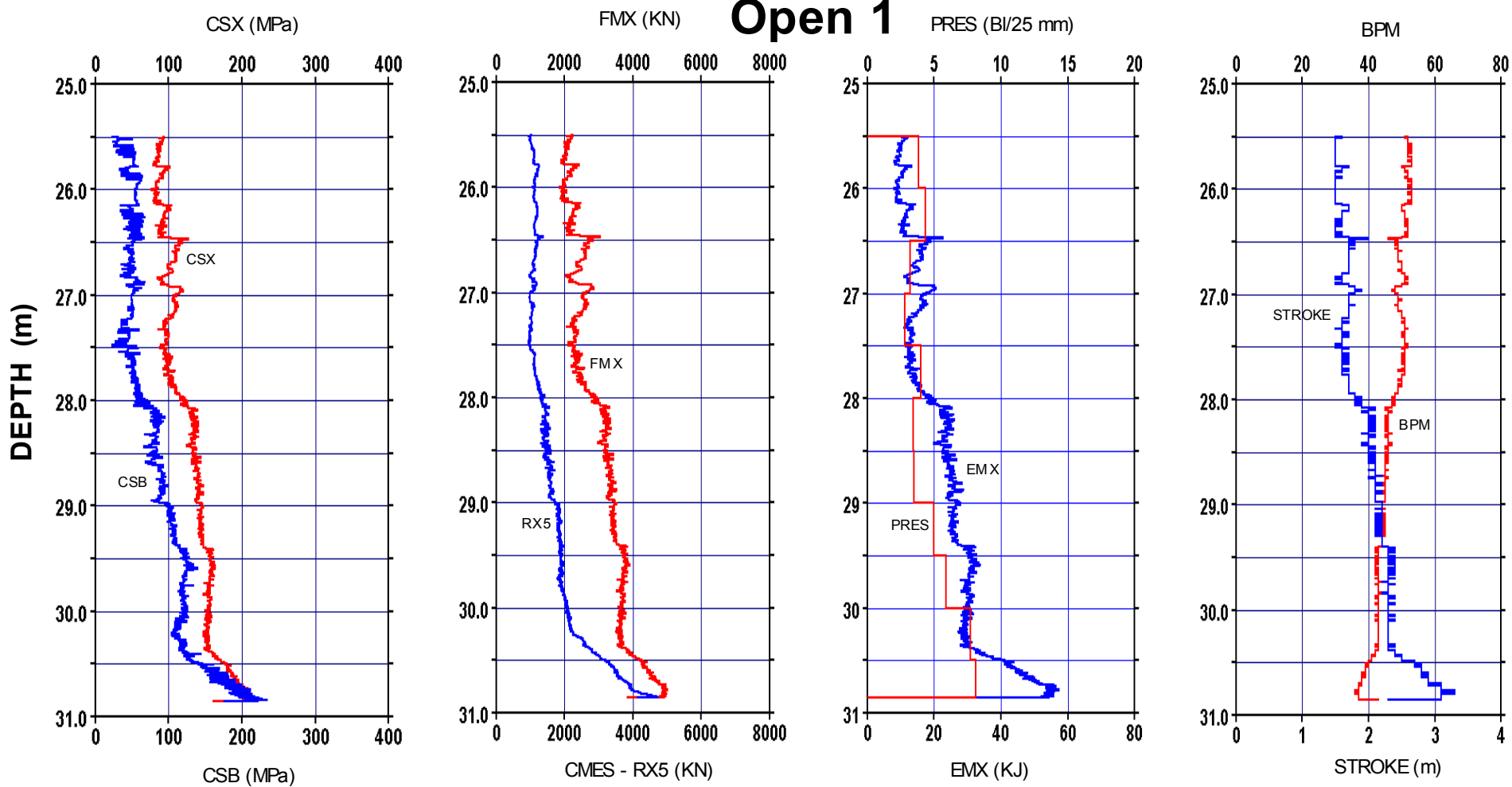
CSX : Maximum stress at head
 CSB : Maximum stress at toe

FMAX : Maximum force at head
 RX5 : CMES, J = 0.5

PRES : Penetration resistance
 EMX : Transferred energy

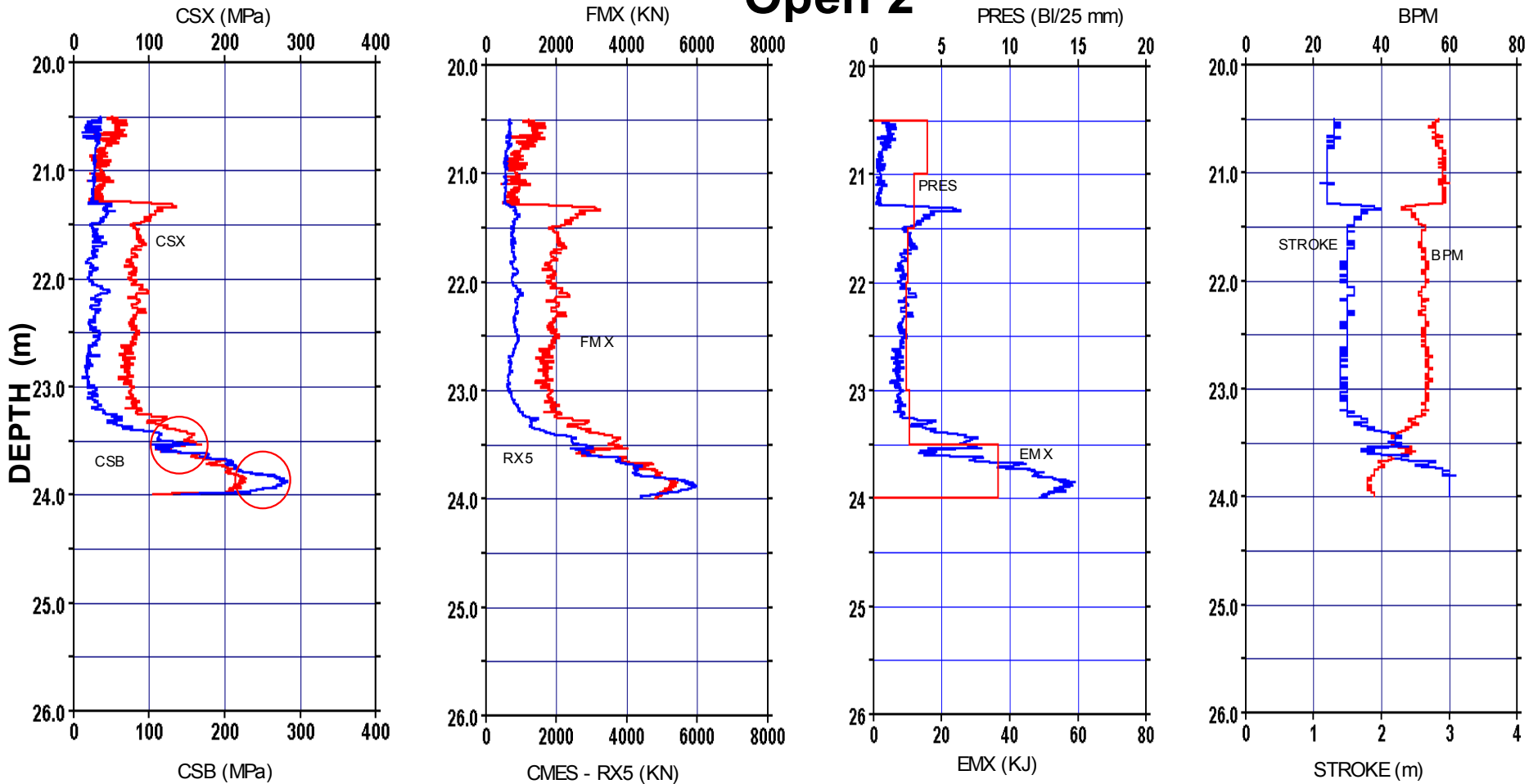
BPM : Blows per minute
 STROKE : Ram rise

Open 1



CSX : Maximum stress at head	FMAX : Maximum force at head	PRES : Penetration resistance	BPM : Blows per minute
CSB : Maximum stress at toe	RX5 : CMES, J = 0.5	EMX : Transferred energy	STROKE : Ram rise

Open 2



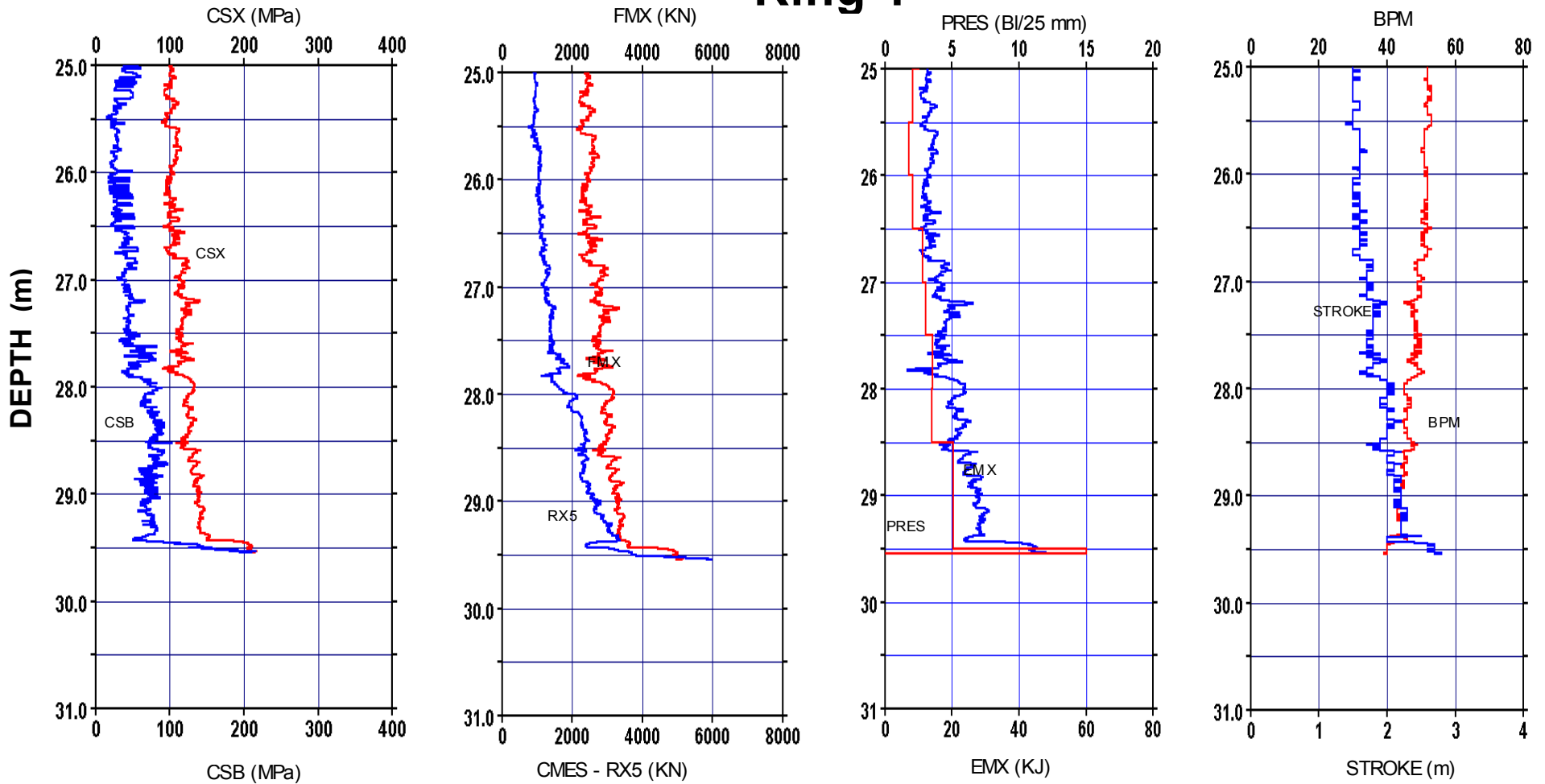
CSX : Maximum stress at head
 CSB : Maximum stress at toe

FMAX : Maximum force at head
 RX5 : CMES, J = 0.5

PRES : Penetration resistance
 EMX : Transferred energy

BPM : Blows per minute
 STROKE : Ram rise

Ring 1



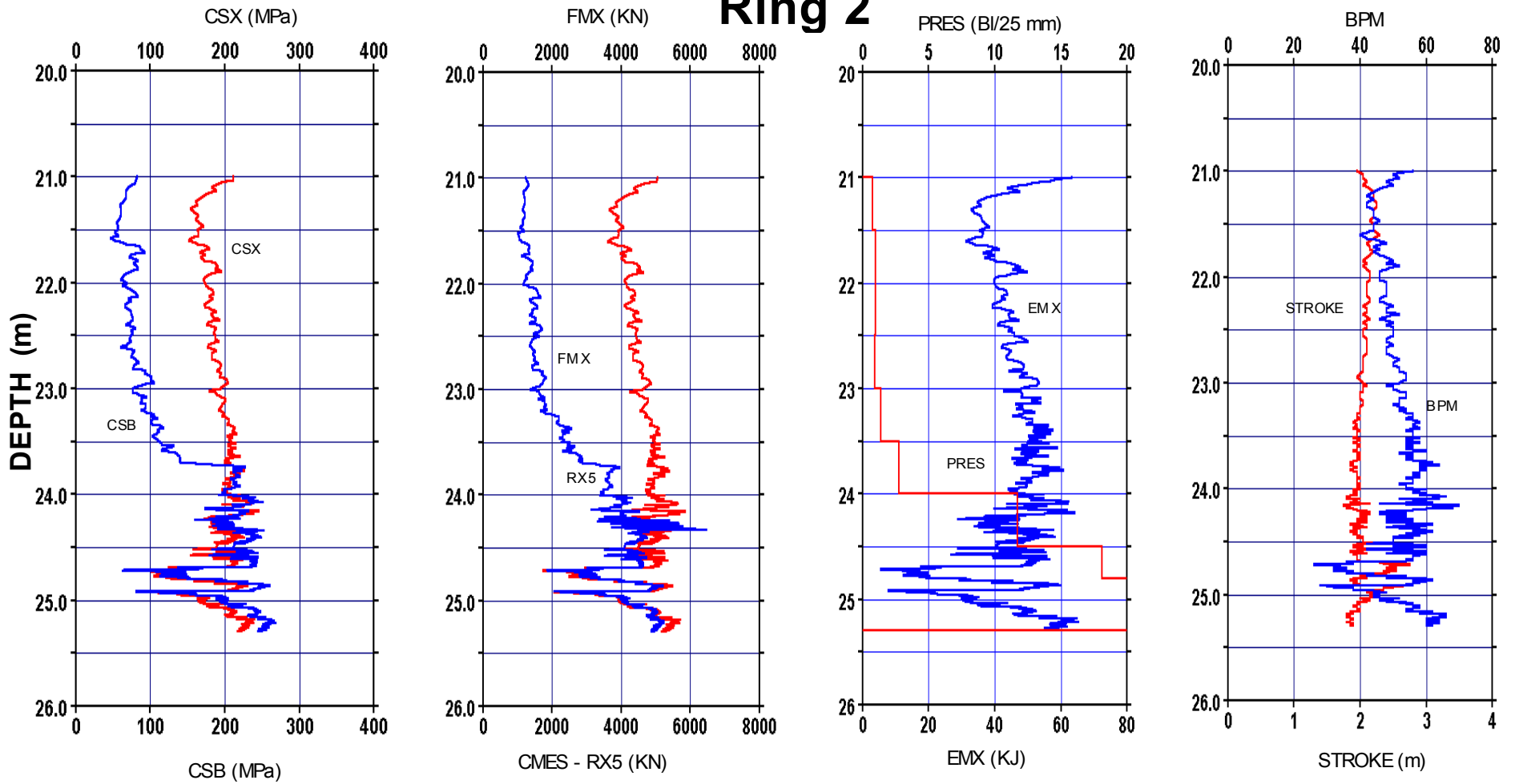
CSX : Maximum stress at head
 CSB : Maximum stress at toe

FMAX : Maximum force at head
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 EMX : Transferred energy

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 STROKE : Ram rise

Ring 2



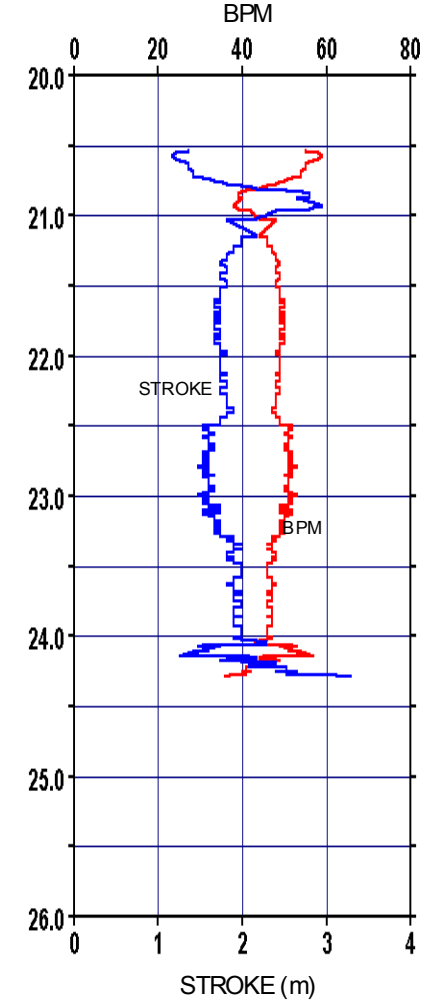
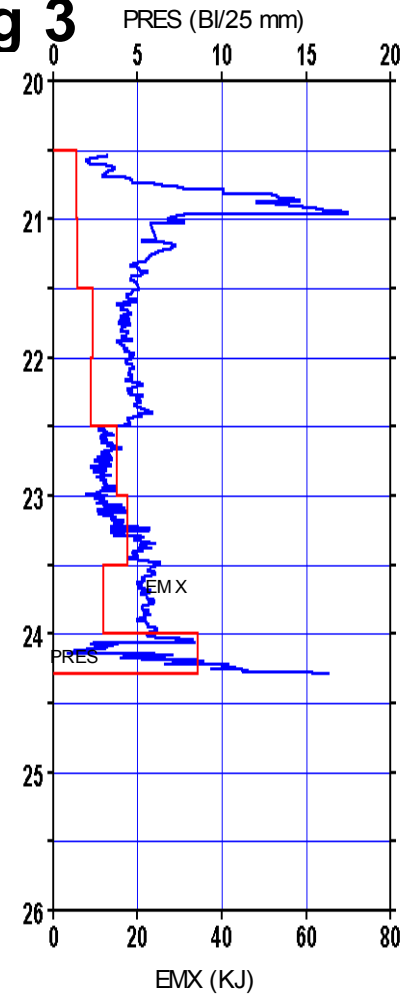
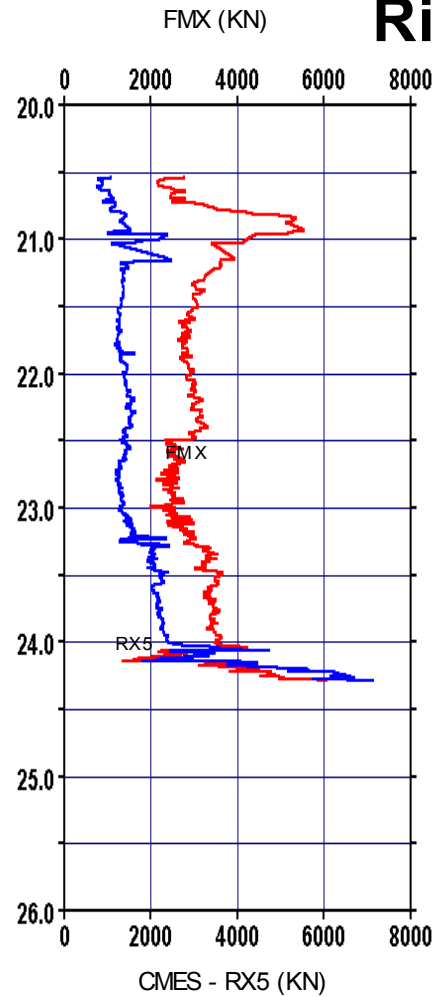
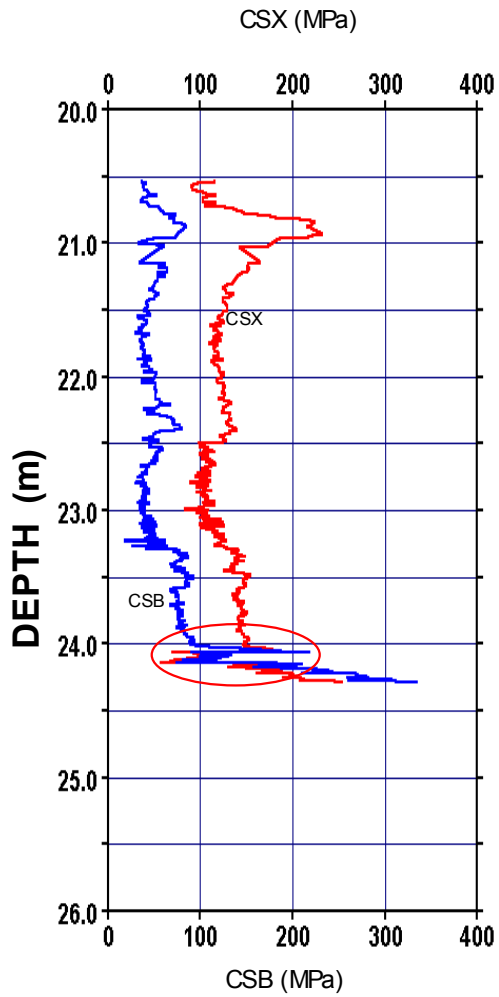
CSX : Maximum stress at head
 CSB : Maximum stress at toe

FMX : Maximum force at head
 RX5 : CMES, J = 0.5

PRES : Penetration resistance
 EMX : Transferred energy

BPM : Blows per minute
 STROKE : Ram rise

Ring 3



CSX : Maximum stress at head
 CSB : Maximum stress at toe

FMAX : Maximum force at head
 RX5 : CMES, J = 0.5

PRES : Penetration resistance
 EMX : Transferred energy

BPM : Blows per minute
 STROKE : Ram rise