The Midland Geotechnical Society

6th December 2010

Presentation by:

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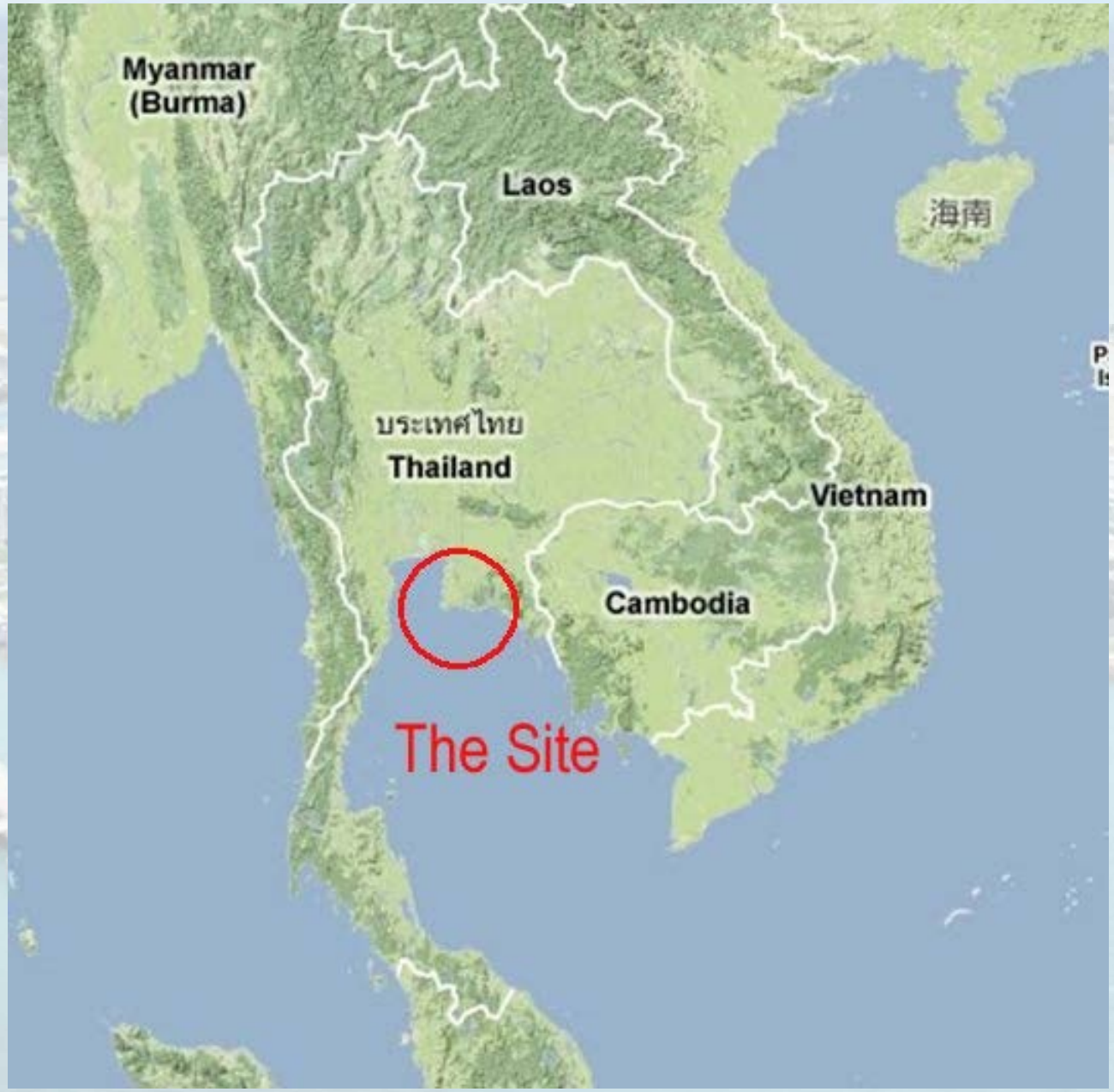
- Raison Foster Associates

Investigations of Structural Damage to Driven Precast Concrete Hollow Cylinder Piles

Does the Specialist Contractor Really Know What He is Doing?

- Chris Raison BEng MSc CEng MICE MASCE
- Raison Foster Associates

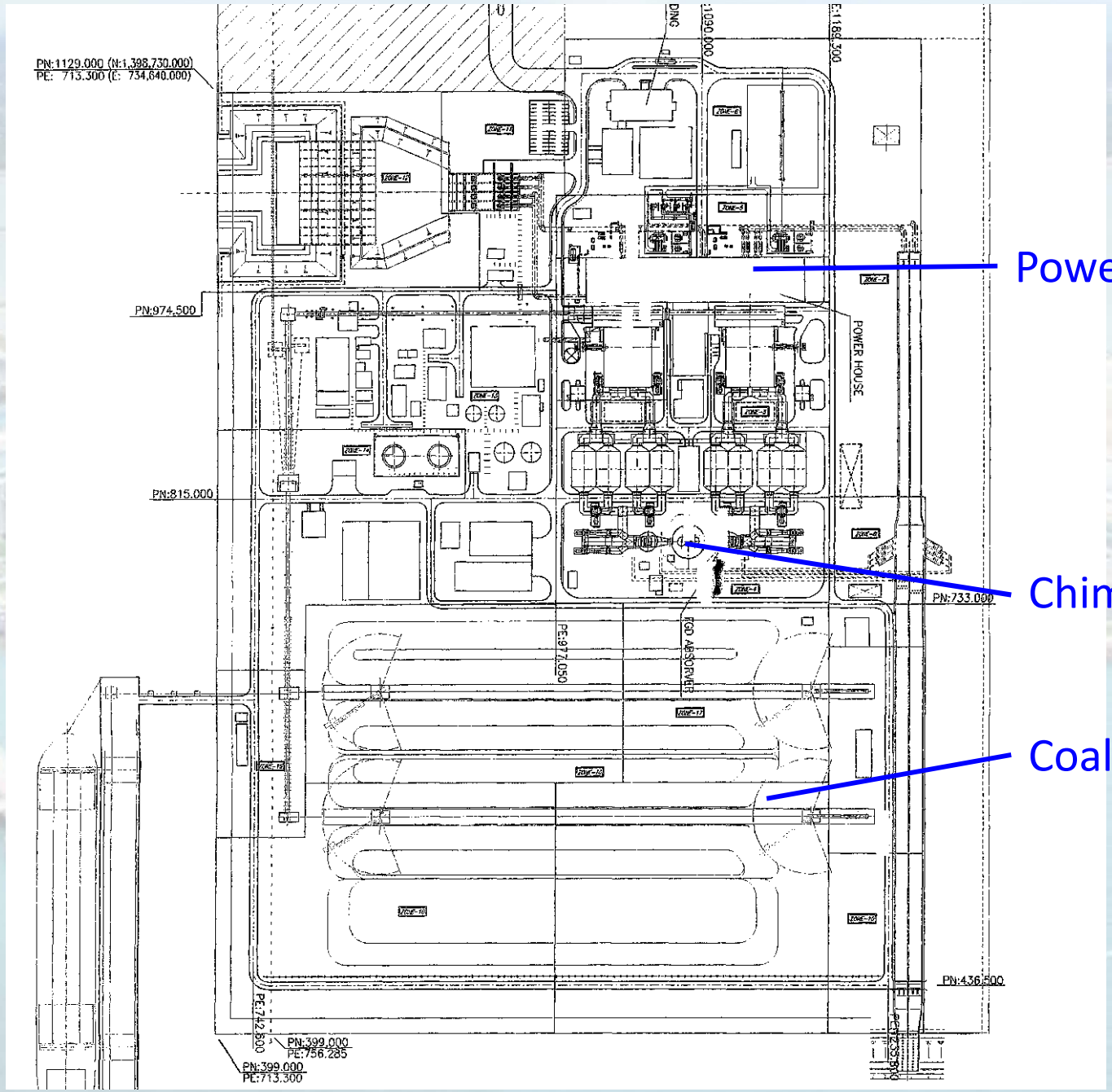
Map Ta Phut, Thailand - Site Location



Map Ta Phut, Thailand

- New coal fired power station
- Construction started in 2004
- Construction complete in 2007
- Built on new reclamation just off coast
- All structures founded on driven piles
- Problems initially with Power House foundation piles
- Major problems with Chimney foundation piles

Plant Layout



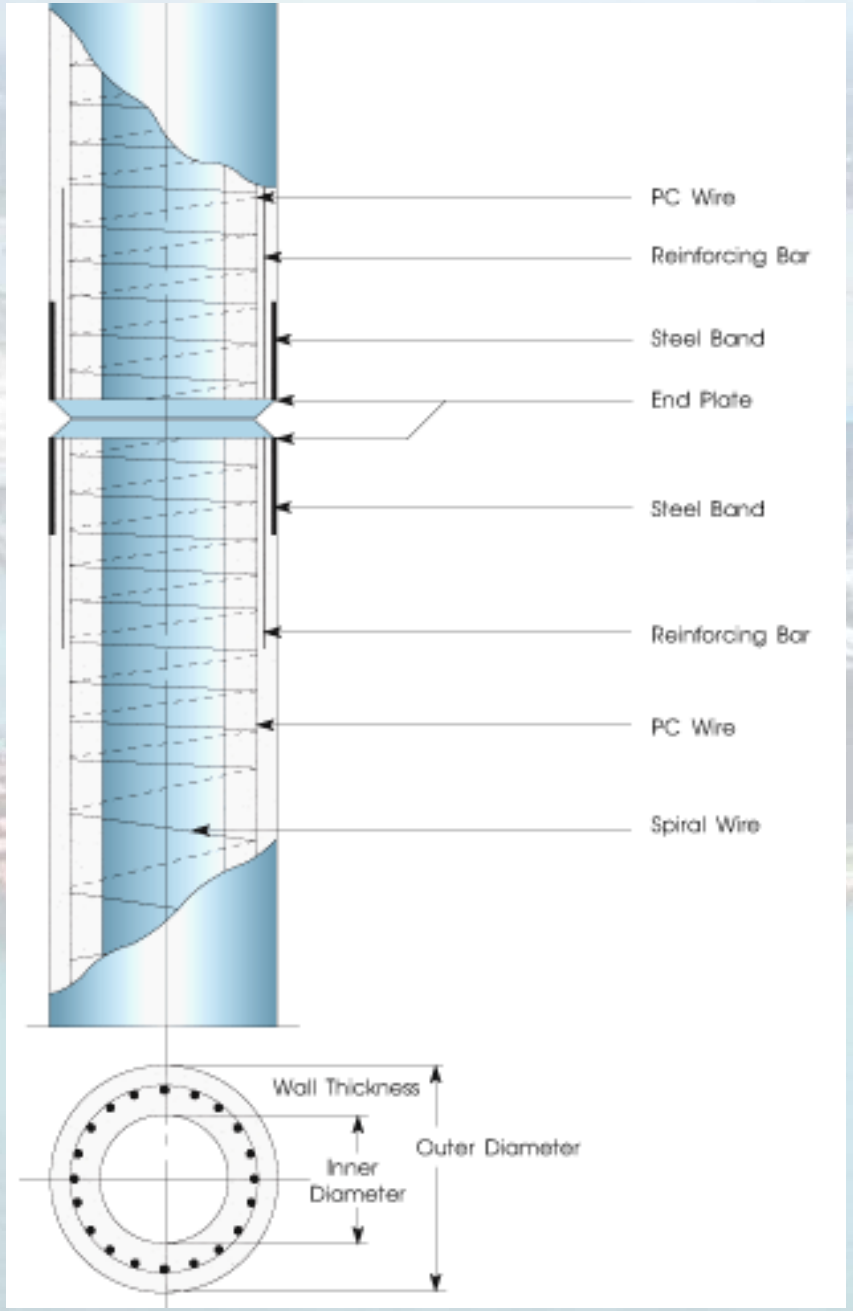
Finished Power Station

Finished Power Station

Prestressed Precast Spun Piles (PSC)

- Circular hollow section (8m, 10m and 12m lengths)
- Most piles 2 sections with welded joint
- Driven open ended but soil plug forms
- 400mm, 500mm and 600mm outside diameter
- 75mm, 90mm and 100mm wall thickness
- 600mm used for Power House and Chimney foundations
- Lightly reinforced:
  - 18 number 7mm wire (fy 1700N/mm^2)
  - Concrete fcu 50N/mm^2

Pile Section and Reinforcement



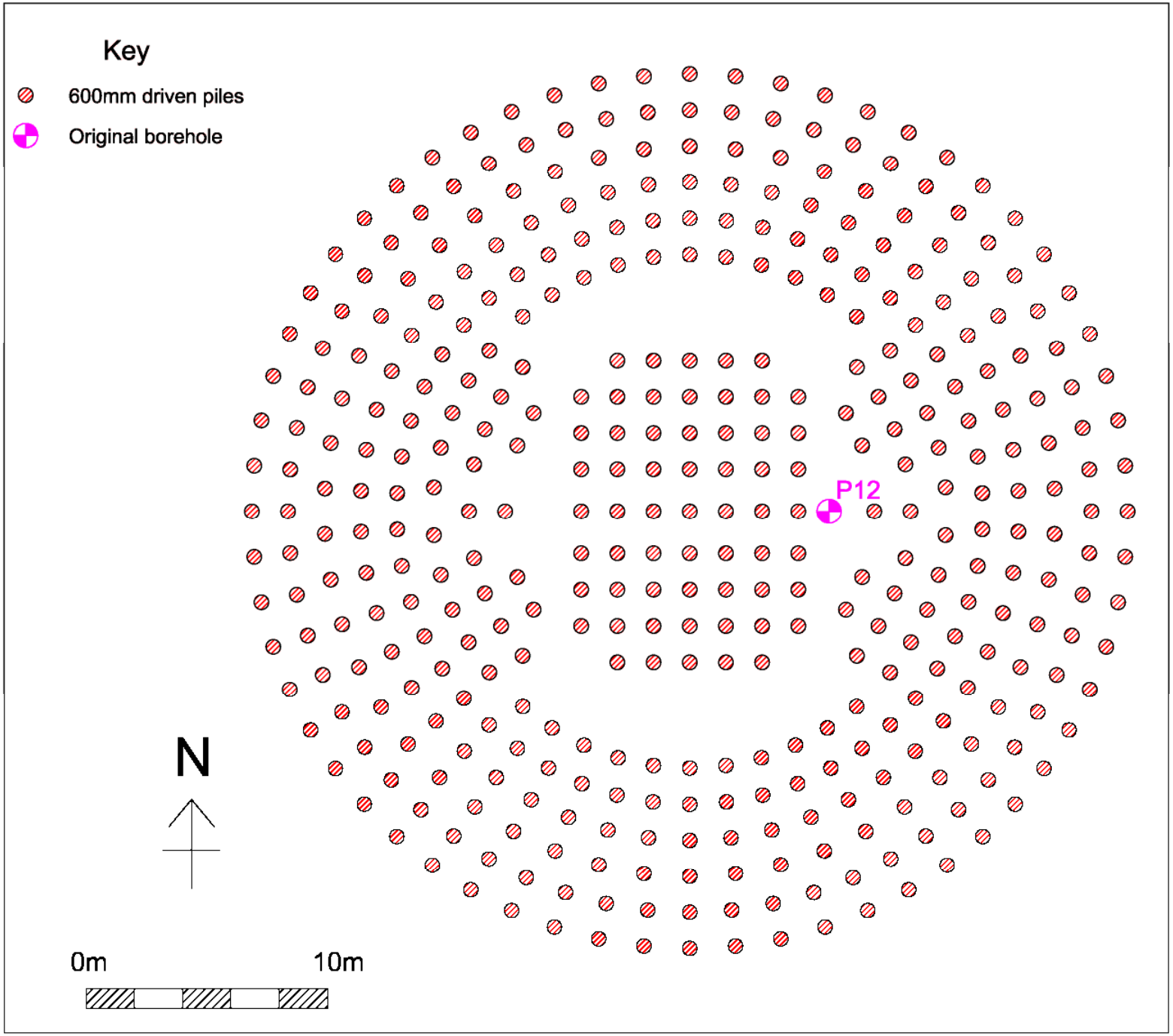
Pile End Plates and Steel Bands

Reinforcement Cage

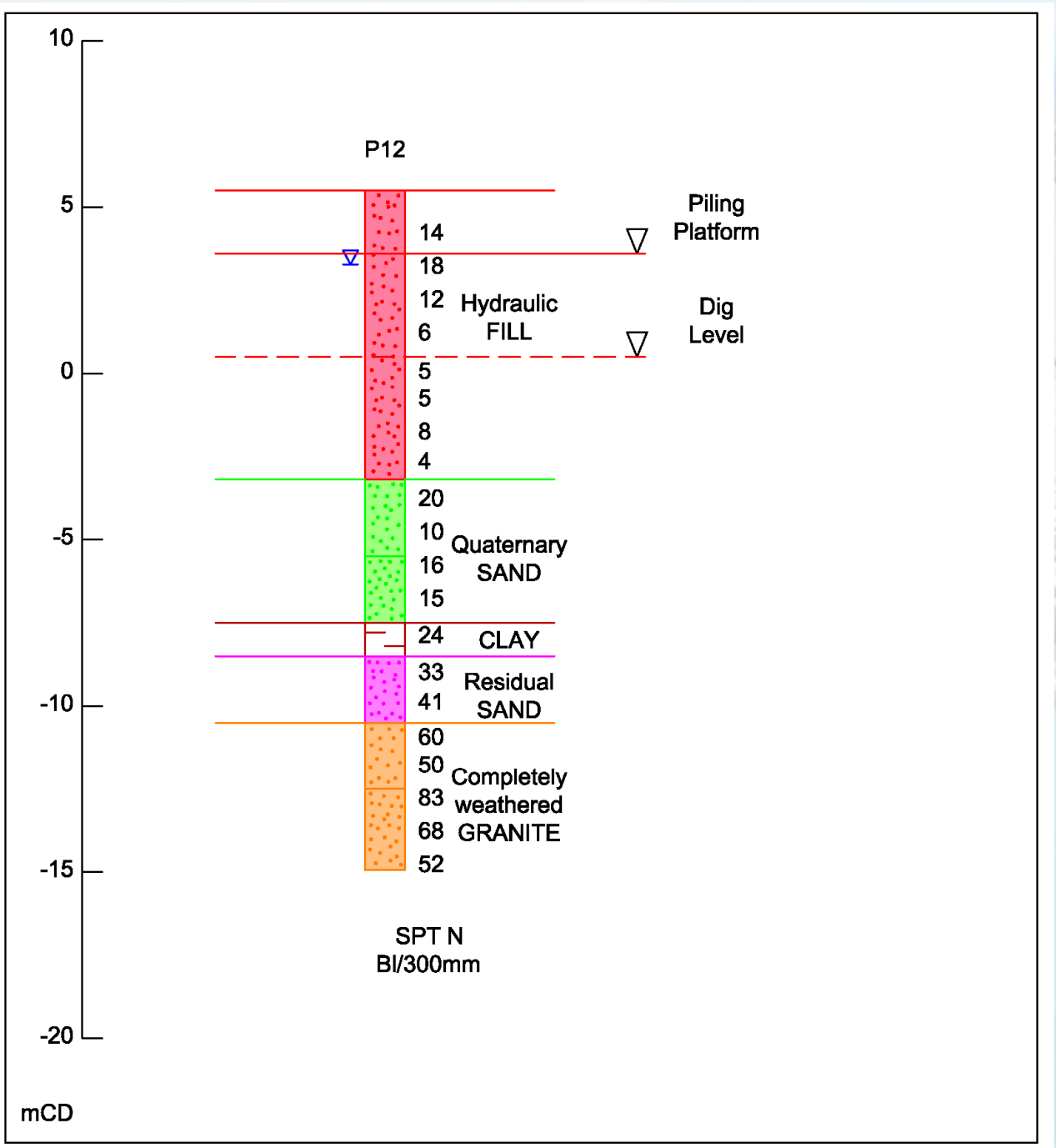
Reinforcement Placed in Mould

Concrete Cylinders for Test

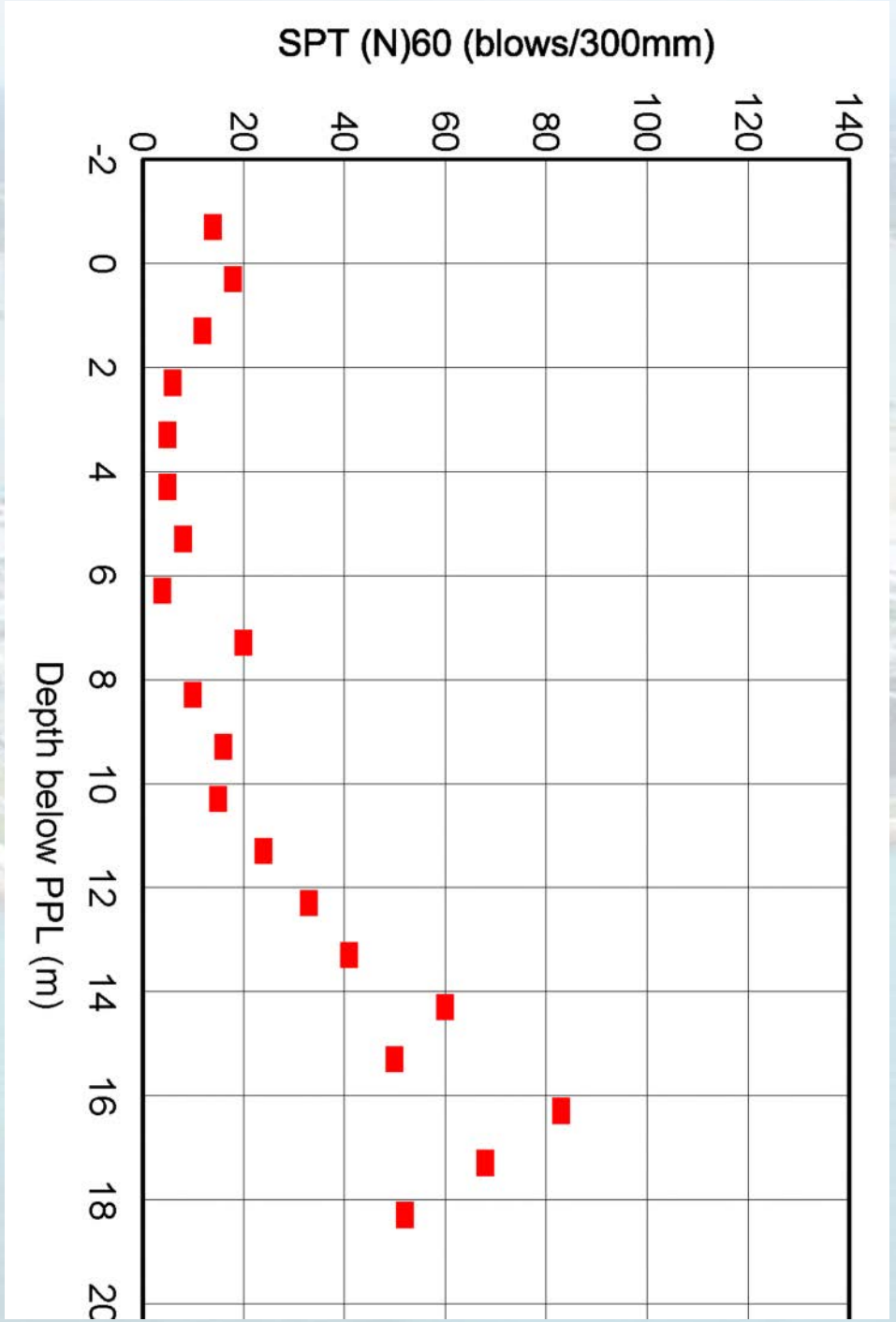
Chimney Pile Layout



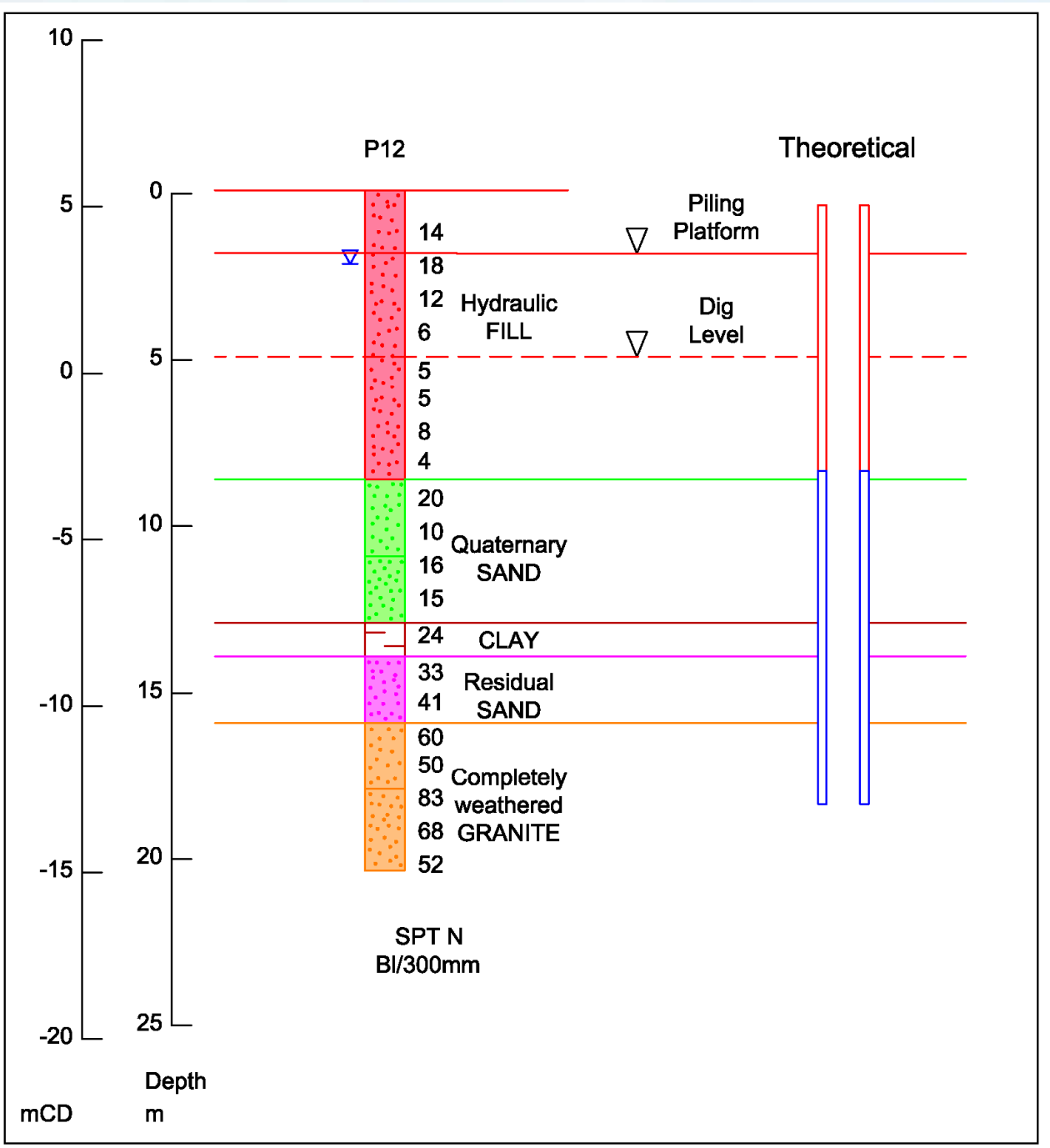
Ground Conditions



Ground Conditions – SPT Data



Proposed Piling Works



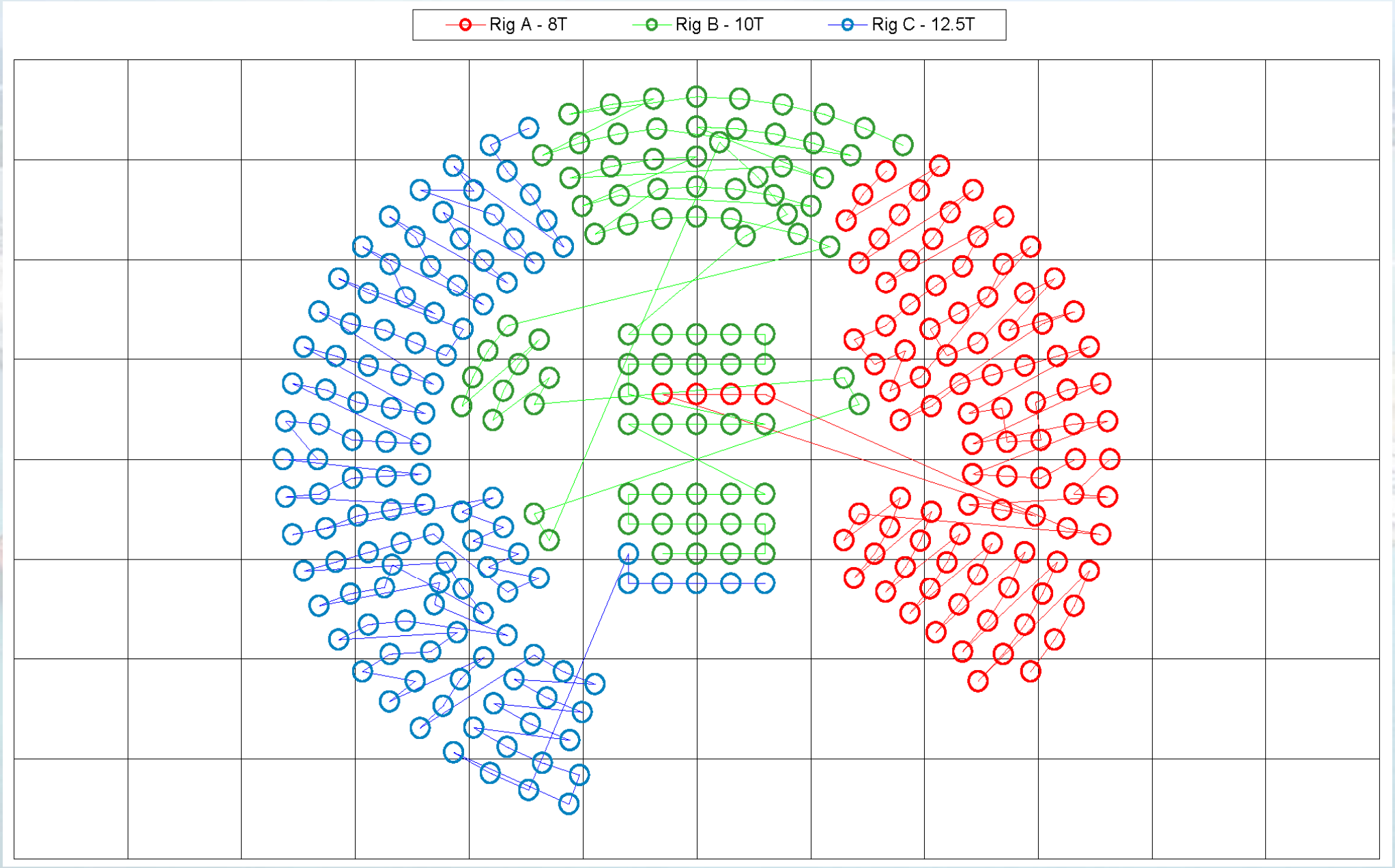
Pile Construction

Pile Construction

- Note that working platform 2m below general level
- Very congested pile layout
- Piles at 1.5m spacing (radial direction)
- 1.5m to 1.9m spacing (variable) in each ring
- Variable driven length
- Target pile length 17m (below original GL)
- (or about 15m below working platform level)

Pile Construction

Pile Construction - Sequence



Pile Problems – Power House

- Large number of piles driven across the site
- Problems first noticed in Power House
- Deep excavation with pile cut off at 5m depth
- Excavations revealed:
  - Concrete debris and reinforcement steel
  - Pile shaft appeared intact
- Contractor started investigations

Pile Problems – Power House

F14 - P1

F14 - P3

F14 - P5

TBFP FOUNDATION - P3

TBFP FOUNDATION - P4

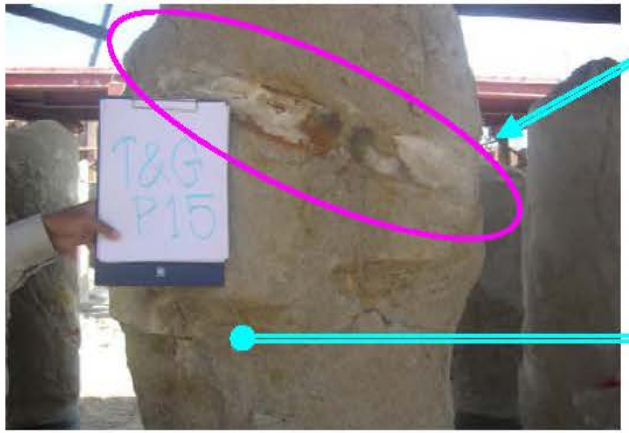
TBFP FOUNDATION - P5

Pile Problems – Power House

T & G - P2

T & G - P2

T & G - P15



T & G - P15

T & G - P15

T & G - P28

Pile Problems – Power House

- Initial conclusions:
  - Number of damaged piles limited:
    - 50 out of 493 in first area
  - Amount of debris small
  - Pile shaft appeared intact
  - No indication of problem from driving records
  - PDA testing showed bearing capacity OK

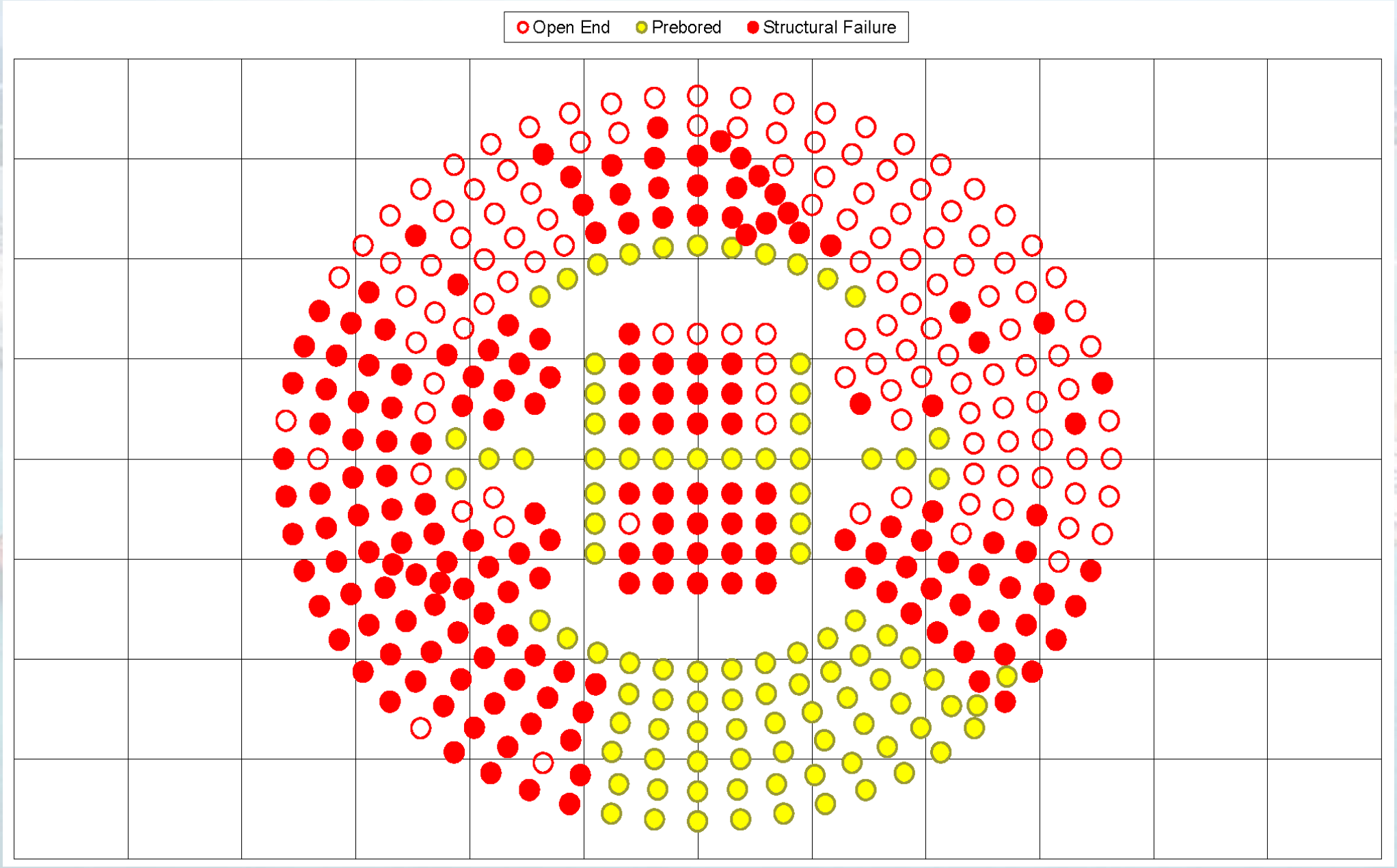
Pile Problems – Power House

- Contractor investigations continued:
- CCTV inspections carried out inside pile section
  - Number of piles showed cracks
  - 8 out of 14 piles
  - One test pile broken and kinked
- Integrity testing
  - Many piles showed anomalies in test results
  - 369 out of 412 piles
- More site investigation

Pile Problems – Chimney

- At same time, piling continued for Chimney
- Very variable pile lengths for Chimney piles
- Variable and anomalous pile drive records
- Piling works stopped because of concerns
- Investigations started:
  - 3m excavation across Chimney area
  - 179 out of 304 piles failed visual inspection
  - 239 out of 253 piles failed integrity testing
  - But 6 number PDA testing all passed

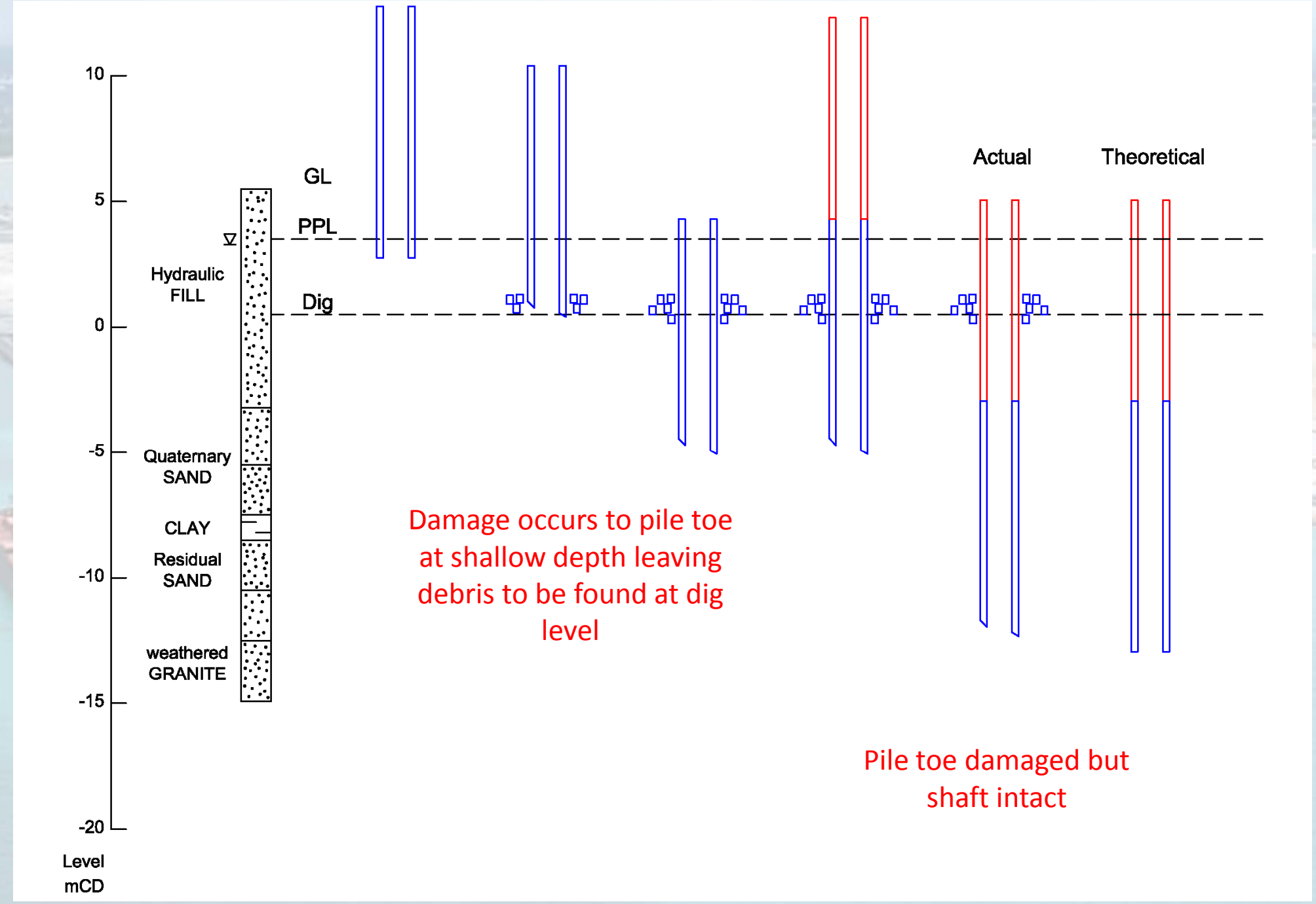
Pile Problems – Contractor Review



Pile Problems – Contractor Review

- Contractor claimed damage was just at toe of pile
  - Debris included steel toe bands
  - Intact pile driven through debris

Pile Problems – Contractor Review



Pile Problems – Contractor Review

Contractor's Argument:

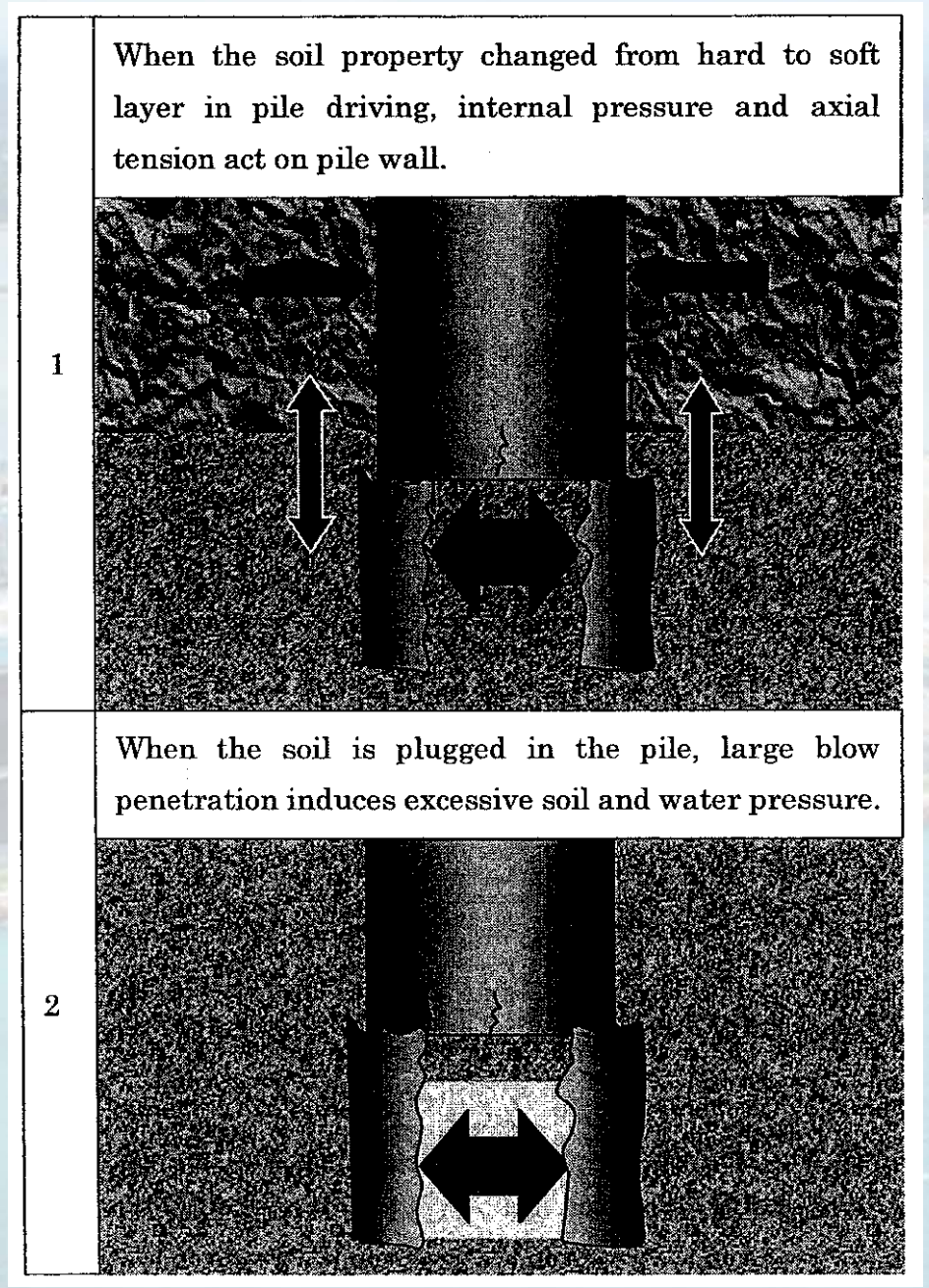
Damage occurs to pile toe at shallow depth:

1. Dense layer over less dense layer
2. High soil plug soil and water pressures

RFA View:

Unsubstantiated theory

Pressures cannot develop to high enough level to 'explode' pile toe by internal radial pressure



Typical Pile Damage

Typical Pile Damage

Typical Pile Damage

Pile Problems – Contractor Review

- Remedial works – Existing but damaged piles
  - Bore out plugged spoil
  - Place reinforcement and concrete
- Remedial works – Remainder of piling
  - Use pre-bore and fit steel plate at toe
  - Reduce hammer energy (weight and drop height)

Pile Problems – Contractor Review

- Remedial works carried out for many structures
- But remedial works abandoned for Chimney:
  - Percentage of damaged piles too high
  - All piles replaced by pre-bored piles
- Problem resulted in:
  - Large costs for replacement piles
  - Large costs for remedial works
  - Significant delays to follow on works

Pile Problems – Insurance Claim

- Contractor prepared insurance claim
- Client's general 'all risks' policy (12 Insurers)
  - Cover-all policy for accidents, unforeseen issues
  - Covers additional costs
  - Available to Client, Main Contractor & Specialists
- Initial claim about US$10 million

- Policy has 'claw backs' or exclusions
- Dispute arose over how to apply exclusions

Pile Problems – Investigations

- Insurance Companies start investigations:
  - Local Engineer
  - International US Company
- No one could determine what had gone wrong
- Disagreement between Investigators and Contractor
- RFA approached for third opinion
  - Review based on documentation only
  - Full piling records
  - Photographic evidence

RFA Pile Assessment

- Detailed review of pile installation records:
  - Pile drive blows
  - Pile geometry – top level, toe level, pile segments
- Detailed review of pile test data
  - Static load test
  - PDA test data
  - Integrity test data
- Detailed assessment of photographic evidence
- Other data – GI, pile design, Contractor reports, CCTV logs

RFA Pile Assessment – Pile Records

BLCP, 2x700 MW Coal Fired Power Plant, Map Ta Phut, Thailand

QUALITY CONTROL INSPECTION REPORT : PILING - P.C.PILES

Ref. No.: TNC-PC- 2707

Subcontractor Thai Nishimatsu Construction Co.,Ltd

Building / Location: BLCP CHIMNEY Spun Pile Shape/size: ☑ 600 ☐ 500 ☐ 400

Reference shop drawing no.: 38CC-2051

Pile Location 251

Driven Date 8/05/04

Note: In case of Nonconformance occur, NCR report shall be submited Refering TNC011-NCR.....

Pile Driving Time

Section	Start	Finish
Lower	13.10	14.10
Welding	14.13	14.25
Upper	15.06	15.57

Pile Production Data

Upper Pile.: 21/4/04 Length 8 Pile Production 110012

Lower Pile.: 17/11/03 Length 12 Pile Production 301585

Pile Driving Data

Ground Elevation -2.00 m. Pile Top Elevation -2.819 m.

Hammer HNC-R193 Pile Tip Elevation -22.97 m.

Ram Weight 12.5 Penet. 10 blows 1) 1.3 cm.

Drop Height 0-60 2) — cm.

Applied Steel Follower ○ Y / ○ N 3) — cm.

Part 1 **Request for Inspection : Piling - P.C Piles**

Item	Description	1st inspection Date / Time pass	1st inspection fail	2nd inspection Date / Time pass	2nd inspection fail	3rd inspection Date / Time pass	3rd inspection fail	Remedial works / Comment
1	**Pile Acceptance**							
	(a) Type,diameter,length of pile	✓						
	(b) Transportation of Pile	✓						
	(c) Pile Number	✓						
	(d) Date of Casting	✓						
	(e) Factory Inspection marking	✓						
	(f) Cracks on piles	✓						
	(g) Defects on piles	✓						
2	**SET UP OF PILE DRIVING MACHINE**							
	(a) Soil/Ground surface condition			✓				
	(b) Underground facilities service							Reminder
	(c) Driving machine condition			✓				
	(d) Hammer capacity / condition			✓				
	(e) Steel Follower			✓				
	PILE PREPARATION							
	(a) Survey/ Coordinates/ Pegs			✓				
	(b) Reference Bench Mark			✓				Bench Mark No. ☐ BM01 ☑ BM02
	(c) Pile handling			✓				
	(e) Acceptance Marked on pile			✓				
	(f) Wooden Cushion			✓				Approved by TNC
4	**DRIVING / HAMMERING**							
	(a) Pile position (both vertical and horizontal)			✓				
	(b) Pile driving record (see below)			✓				
	(c) Joints Welding (see below)			✓				
	(d) Final Drop (see attached sheet)			✓				

RFA Pile Assessment – Pile Records

Part 2 **Pile Driving Record and Welding Joint**

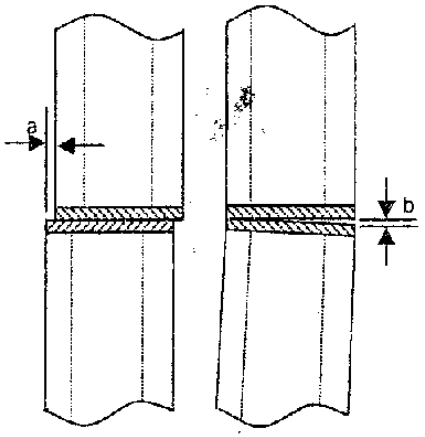
Piling Depth	Drop Height	Blow Count
1.00	0.70	19
1.00	"	27
3.00	0.20	33
4.00	"	52
5.00	0.30	67
6.00	"	60
7.00	0.40	68
8.00	"	50
9.00	0.50	19
10.00	"	32
11.00	0.60	98
12.00	"	77
13.00	"	103
14.00	"	155
50	"	58
15.00	"	59
50	"	56
16.00	"	50
25	"	75
50	"	91
75	"	21
17.00	"	26
25	"	29
50	"	31
75	"	31
18.00	"	38
25	"	39
50	"	44
75	"	47
19.00	"	51
25	"	54

Piling Depth	Drop Height	Blow Count
50	0.60	58
75	"	62
20.00	"	64
25	"	66
50	"	70
75	"	73
21.60	"	101 CM / 20

Remark: .....

Driven Length 20.82 m. Steel follow

Part 3 **Inspection of Welding Joint**



Actual for a and b

Size	a (mm)	b (mm)
ϕ 400	—	—
ϕ 500	—	—
ϕ 600	1	2

Maximum Tolerance for a and b

Size	a (mm)	b (mm)
ϕ 400	2.0	4.0
ϕ 500	2.0	4.0
ϕ 600	2.0	4.0

Result of Liquid Penetrant Inspection Test :

1st Check ☐ Pass ☐ Fail

1st Rectification ☐ Pass ☐ Fail

2nd Rectification ☐ Pass ☐ Fail

Checked by.....(TNC)

(.....Mr. Prin P.....)

Site Engineer

Comment .....

..... Satisfied ☐

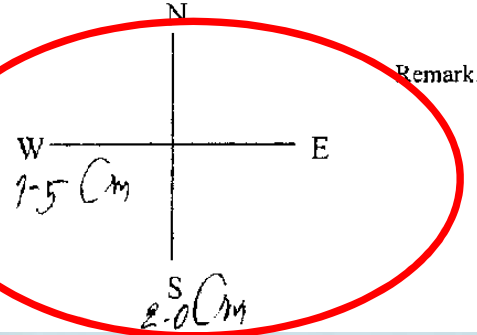
..... Unsatisfied ☐

..... Inspected by .....(IQI)

(Liquid Penetrant Inspection Report shall be submited) (Mr.Ngamsak J. or Mr. Somchart K..)

Welding Inspector

Part 4 **Pile Deviation Check** (3)



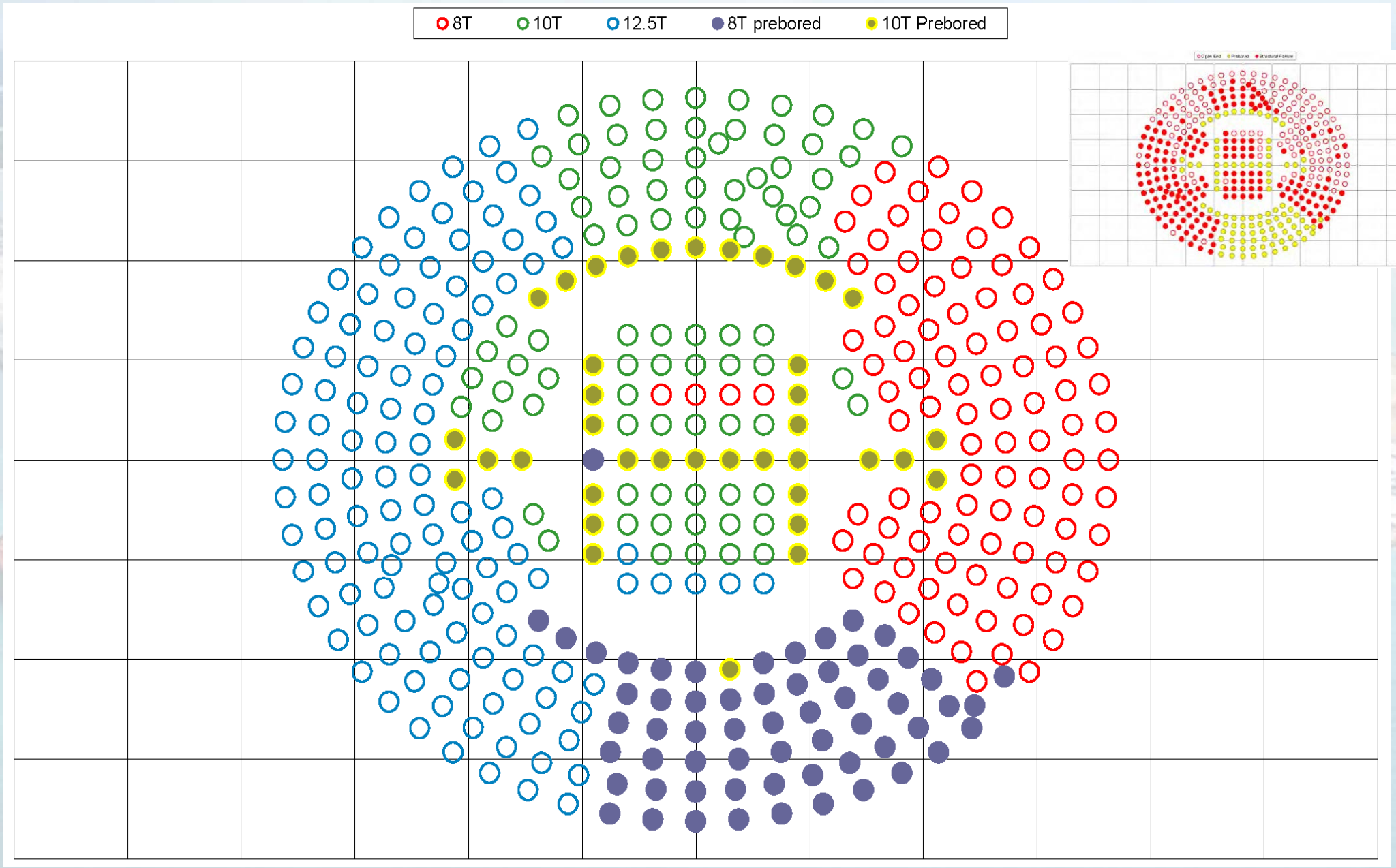
Remark: .....

Checked by.....(TNC)

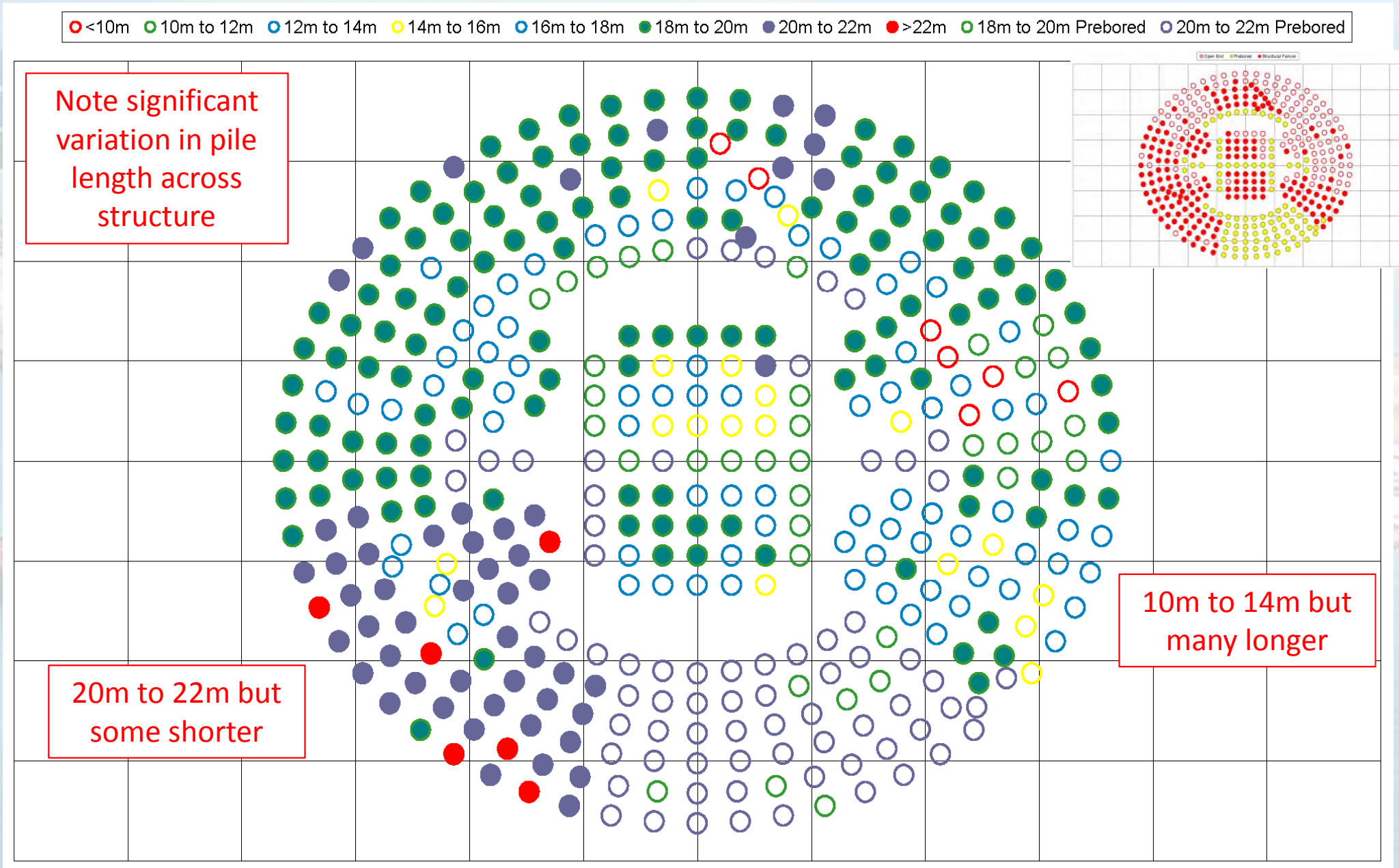
(.....Mr.Prin P.....)

Site Engineer

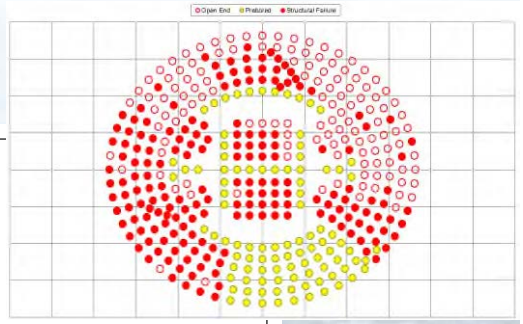
RFA Pile Assessment – Hammer Weight

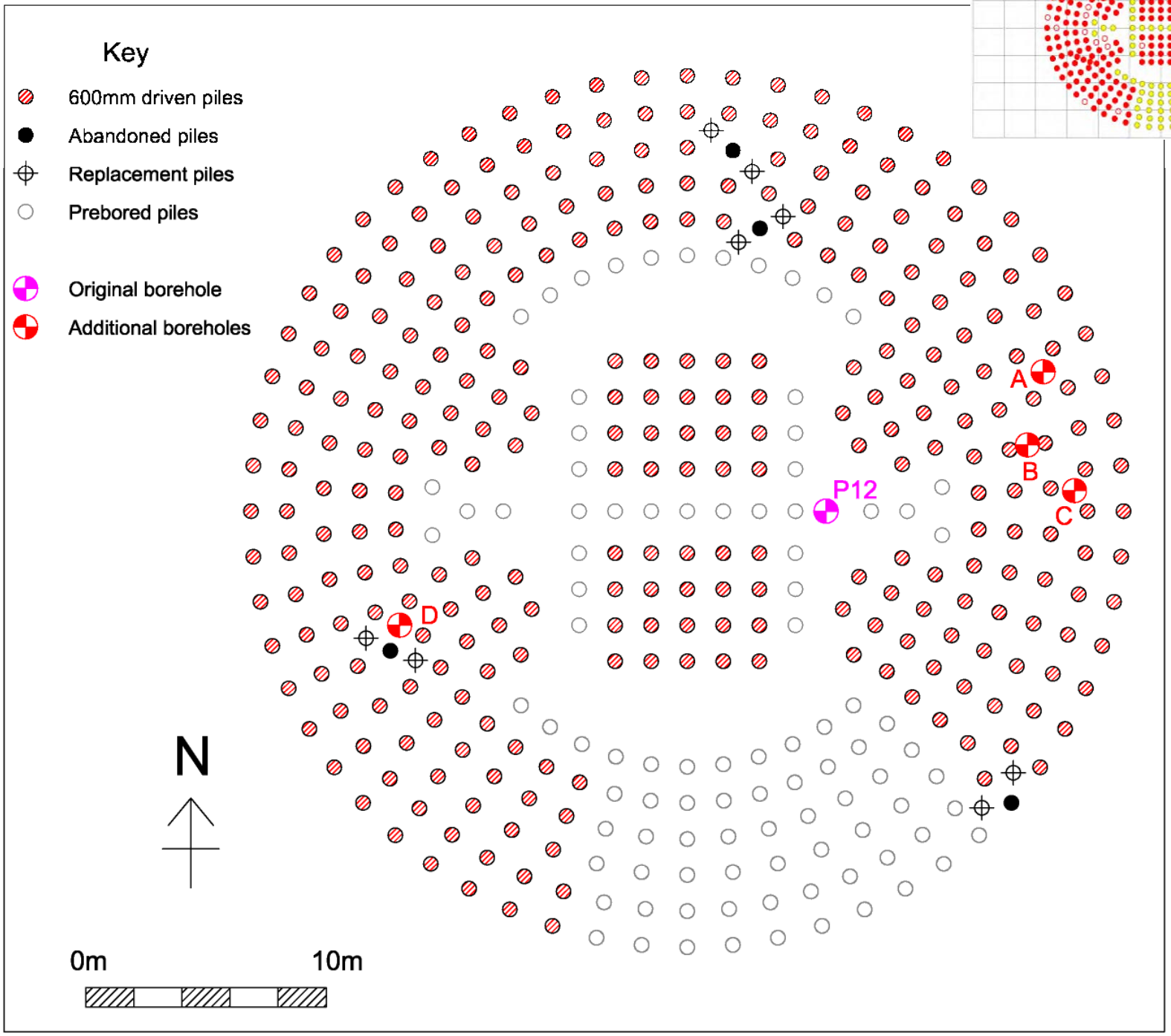


RFA Pile Assessment – Pile Length

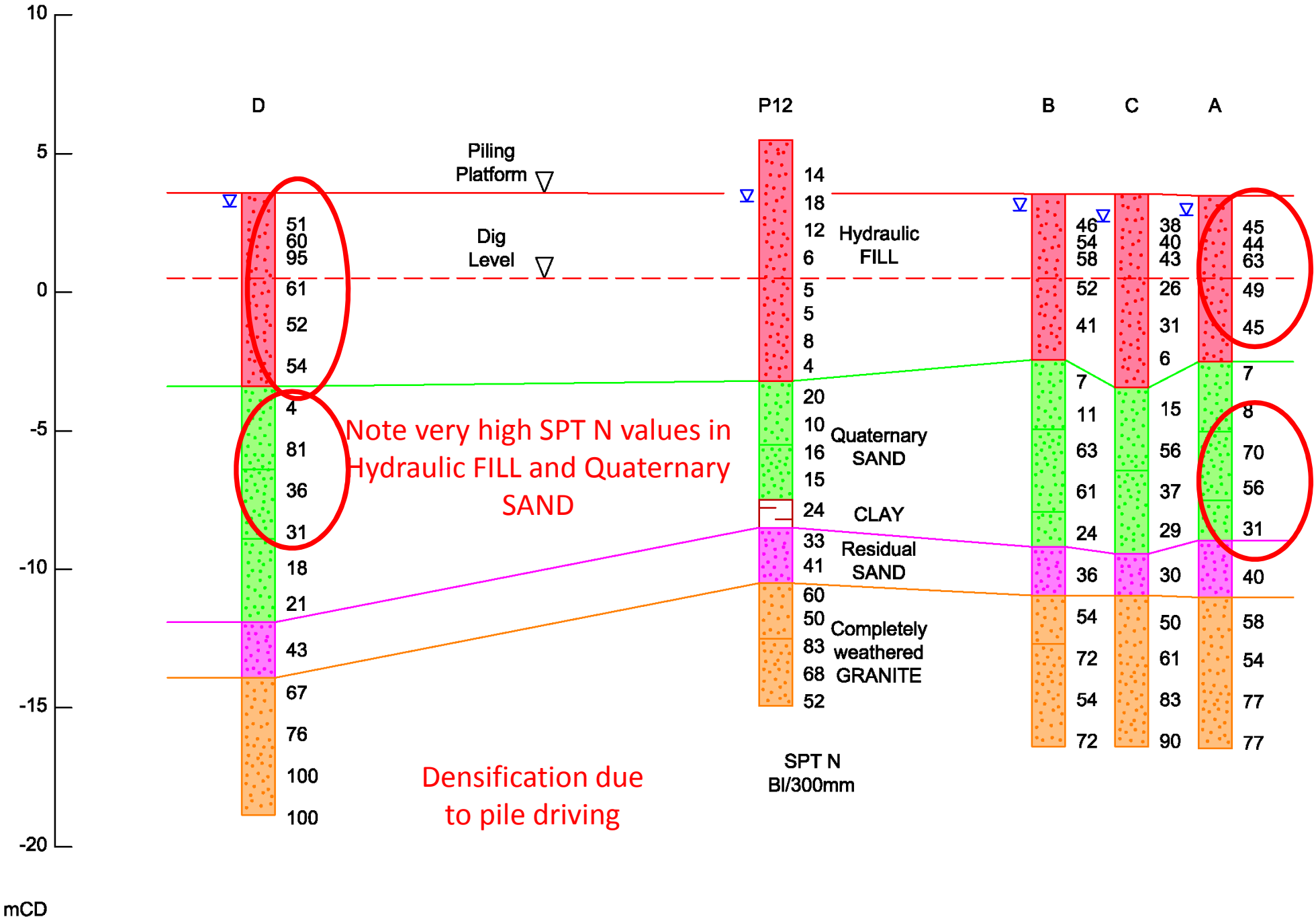


Additional Site Investigation

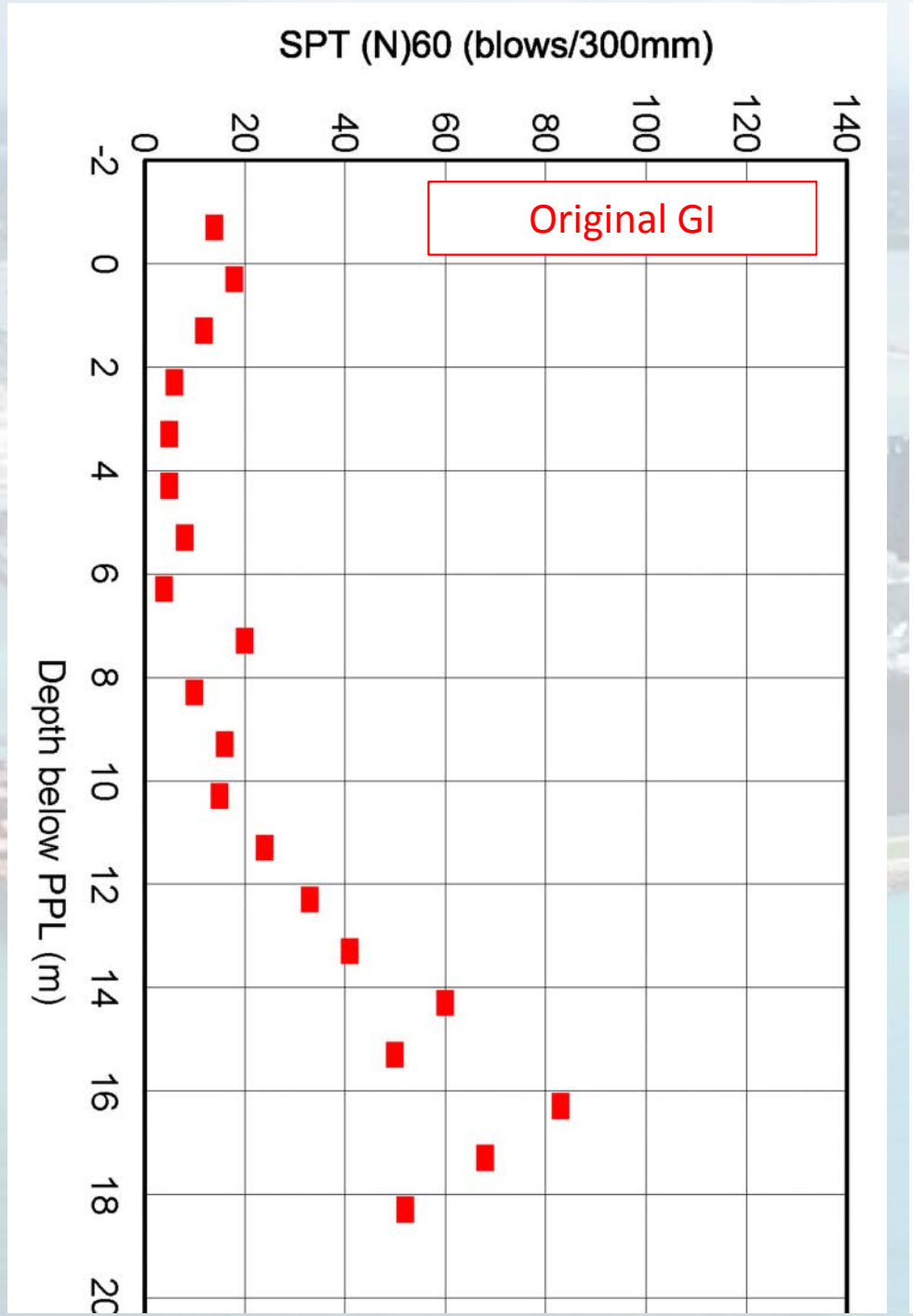


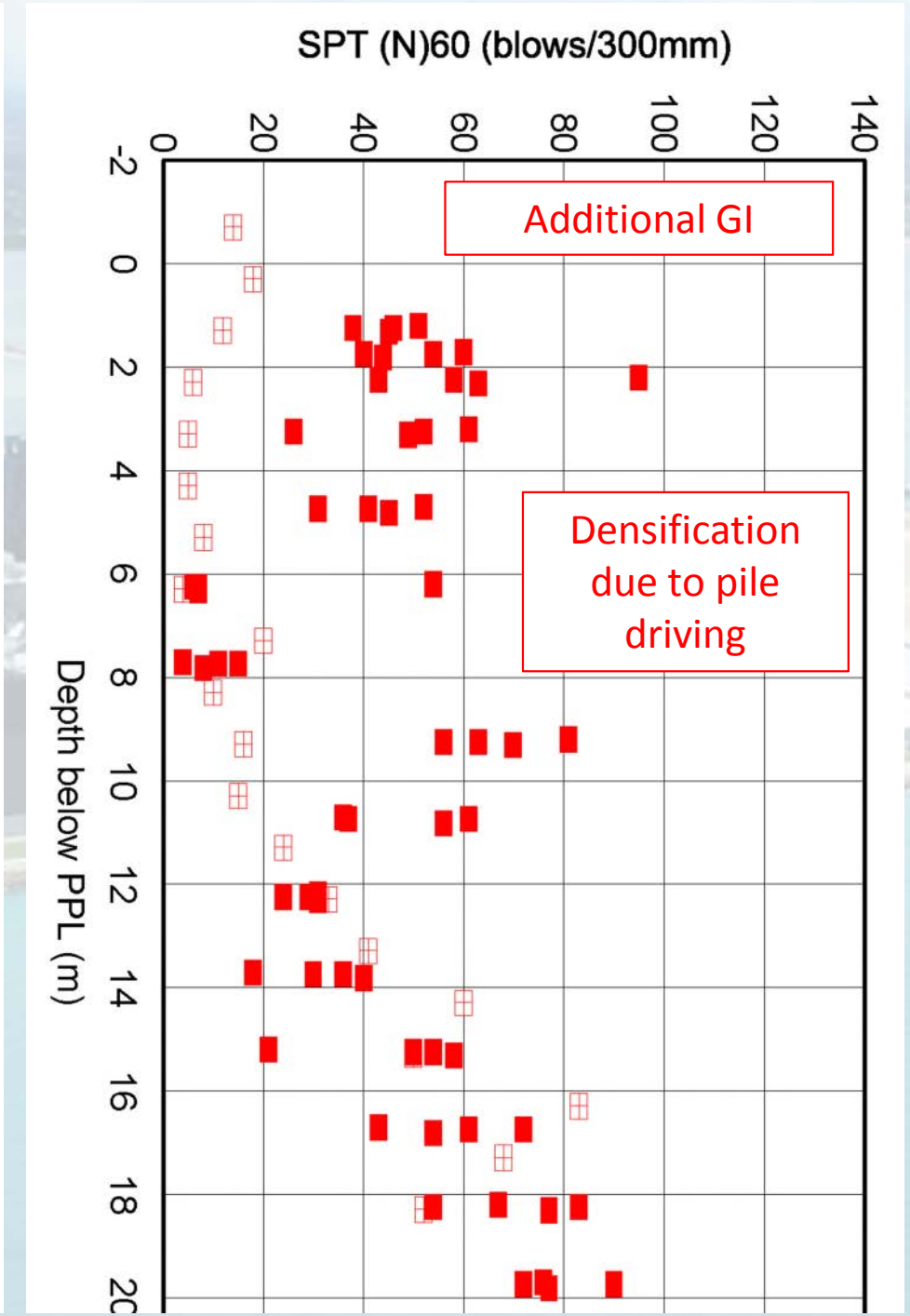


Ground Conditions



Ground Conditions – SPT Data





RFA Pile Assessment – Initial Conclusions

- No correlation between damage and:
  - Hammer weight
  - Pile length
  - Ground conditions
- But
  - Additional GI shows significant densification
  - Mainly in Hydraulic FILL
  - Also in Quaternary SAND (8m to 12m depth)
  - Many piles reached refusal at shallow depth

Problem With Photographic Evidence

Problem With Photographic Evidence

Problem With Photographic Evidence

Problem With Photographic Evidence

Problem With Photographic Evidence

- There are many piles that do not fit pile toe damage theory
- The ‘smoking gun’ was the photograph of Pile 160
  - This shows lower segment cut in half by upper segment
  - It shows a badly damaged welded joint
  - It shows a leaning pile
- This shows catastrophic structural failure
- But:
  - The welded joint appears ‘intact’ (still connected)
  - Failure has occurred in the concrete shaft

The ‘Smoking Gun’ Pile 160

The ‘Smoking Gun’ Pile 160

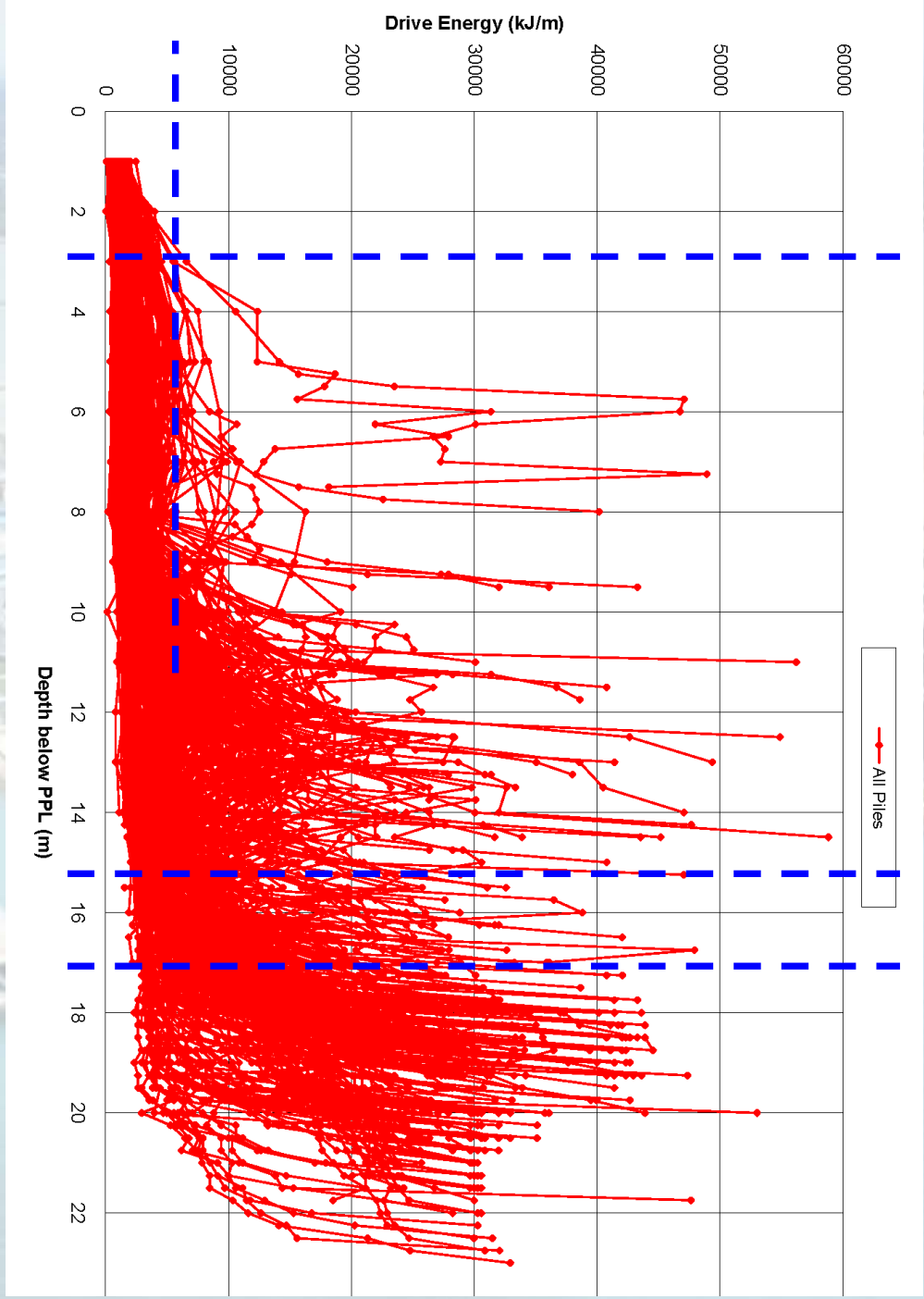
Problem With Pile Drive Blow Data

- In general, pile drive blow energy is relatively low to 8m
  - No evidence of hard driving
  - No shallow dense layers
- Drive energy = 9.8 x Weight x Height x Blows / Drive Length
  - 12.5T hammer, 0.6m drop height and 20 blow/250mm
  - Drive energy = 5,880kJ
- How did pile break at such low drive energy?

Problem With Pile Drive Blow Data

Dig level for pile cap

Level of debris



Drive Energy =

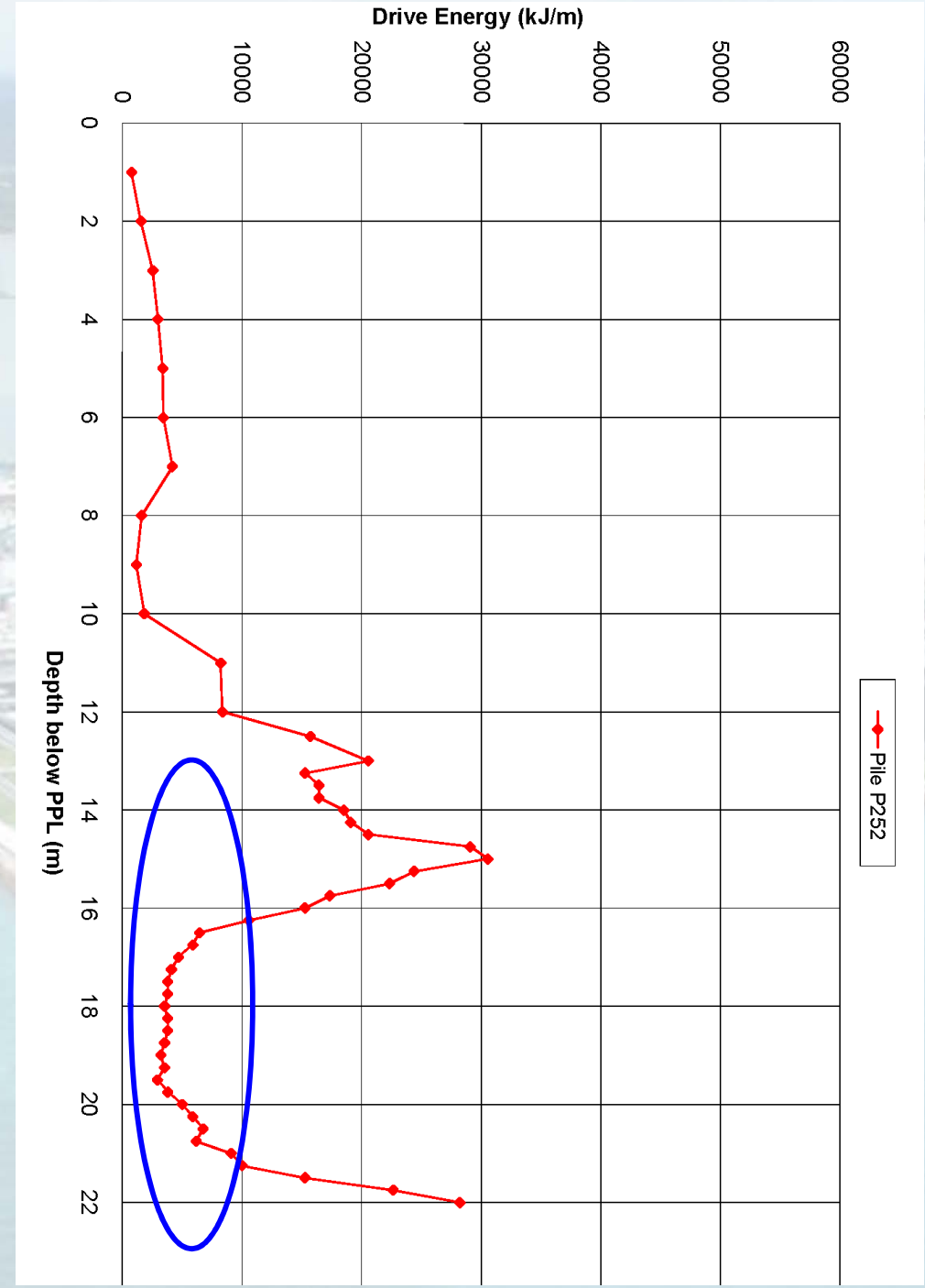
9.8 x Weight x Height x Blows / Drive Length

Range of design pile toe level

Problem With Pile Drive Blow Data

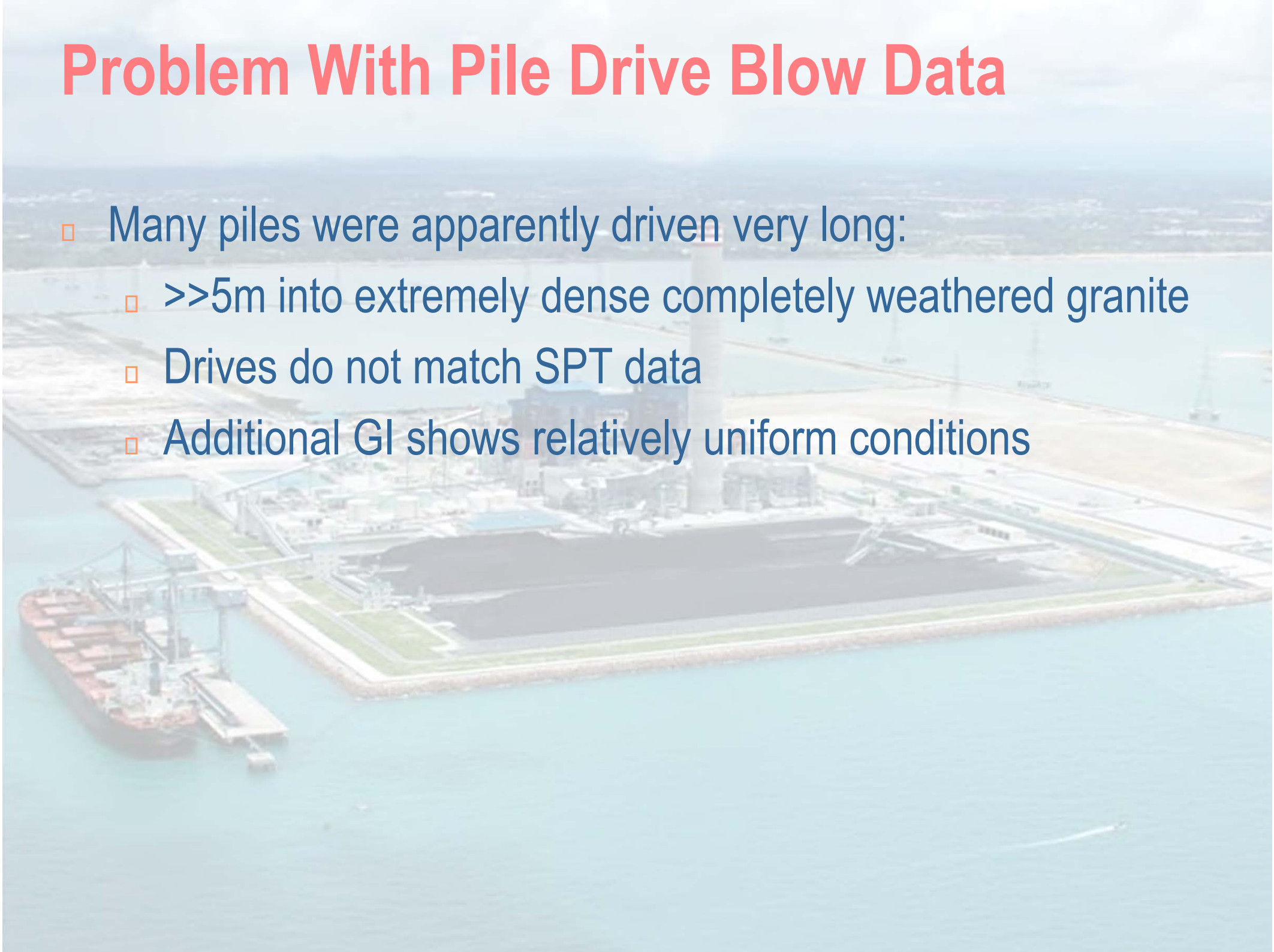
- Many piles show anomalous drive blow profiles
  - Show an increase from about 10m depth
  - Then show a sudden decrease
  - Then a final increase before reaching final set
  - Apparent length often >>15m design length
- Note that final set typically at about 30,000kJ drive energy

Problem With Pile Drive Blow Data



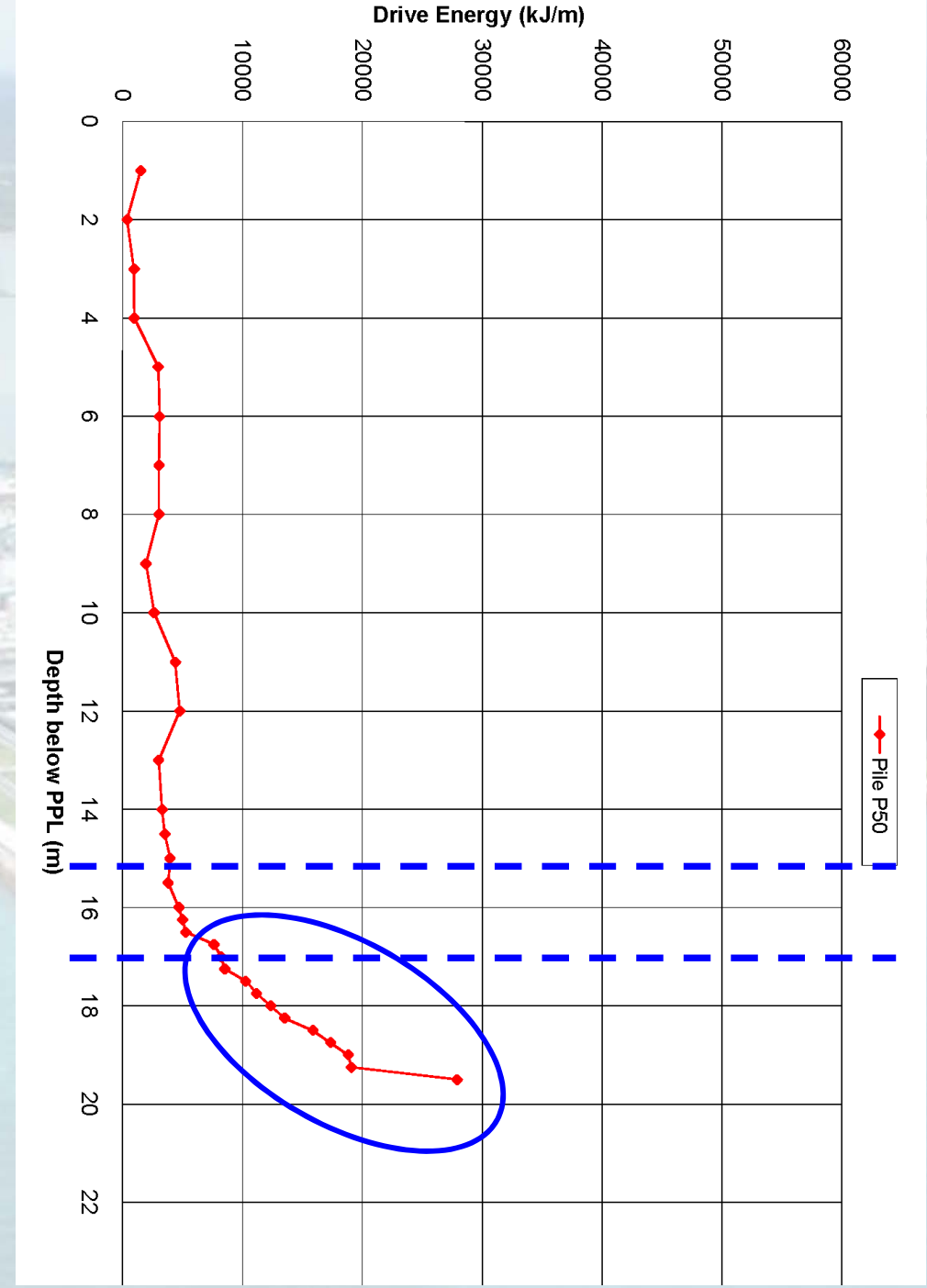
Not consistent with available borehole and SPT data

Problem With Pile Drive Blow Data



- Many piles were apparently driven very long:
  - >>5m into extremely dense completely weathered granite
  - Drives do not match SPT data
  - Additional GI shows relatively uniform conditions

Problem With Pile Drive Blow Data



Range of design pile toe level

Not consistent with ground conditions or SPT data

Other Indicators - CCTV

- CCTV survey of test pile P5-2
  - Shows break in pile shaft in lower pile segment
  - Pile shows noticeable inclination below break
- Drive blows ‘normal’

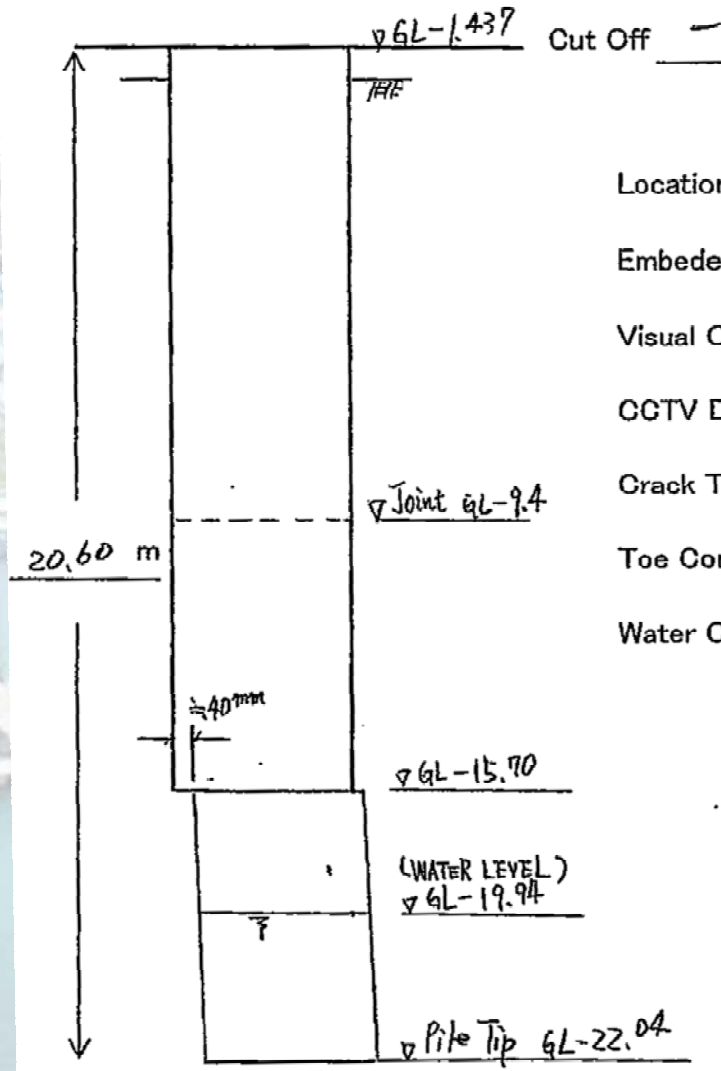
- Static load test shows excellent bearing capacity
- PDA test shows good bearing capacity

- Records suggests pile is 2m short compared to drive

Other Indicators - CCTV

Pile Investigation by CCTV

Pile No. P5-2 Test Pile



Location	Beside Chimney
Embeded Length Pile (m)	15.20
Visual Condition	—
CCTV Date	02/06/'04
Crack Type	Broken and inclination
Toe Condition	unknown
Water Condition	GL-19.9

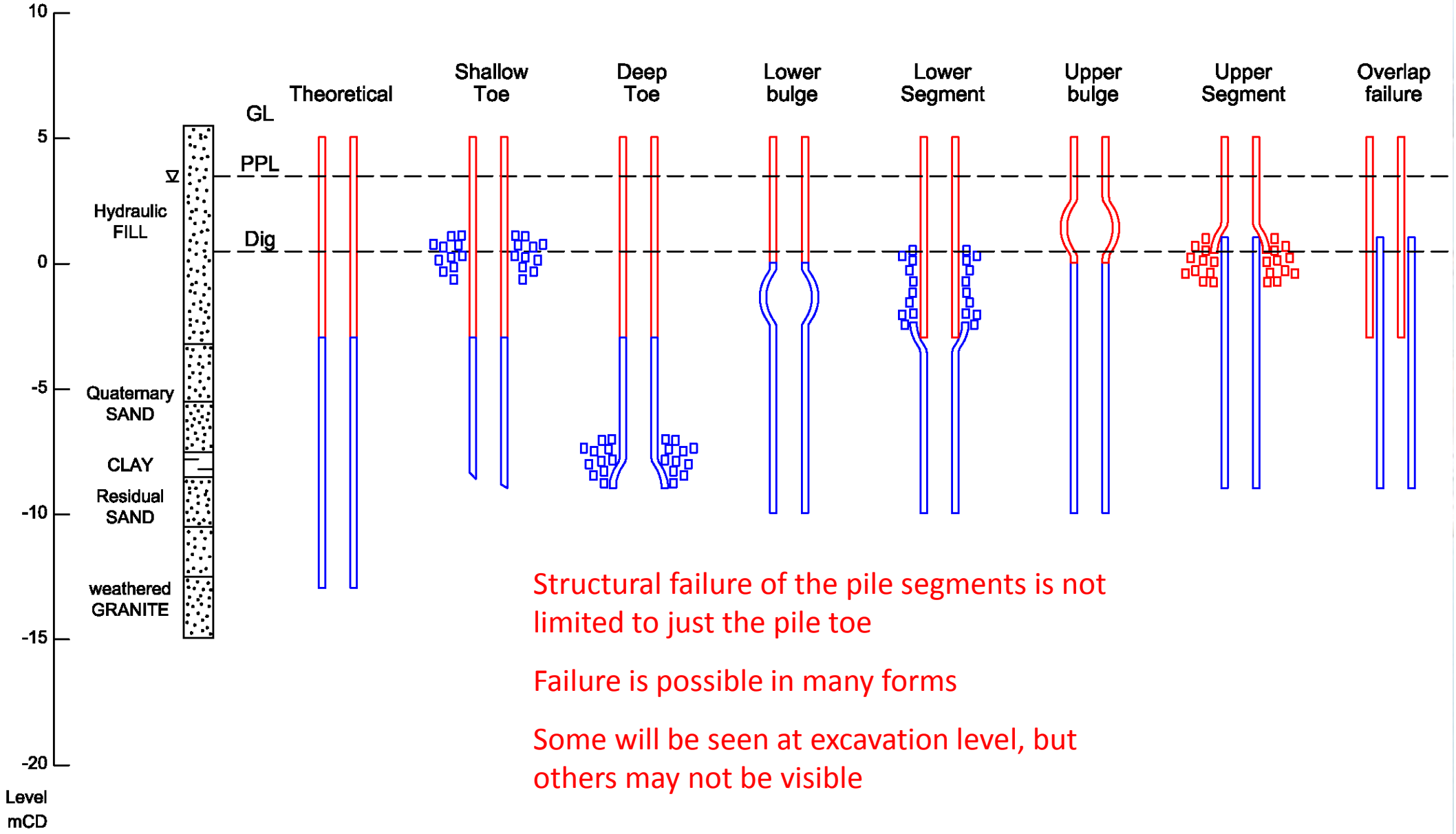
Other Indicators - CCTV

- CCTV survey of test pile P5-2
- Conclusion:
  - Structural failure CAN occur in pile shaft
  - Structural failure CAN occur at low drive energy

A Better Theory to Explain Damage

- Piles have not been damaged at a shallow depth
  - Drive energy is much too low
  - No hard layers
- Damage has occurred with pile toe at a depth of 10m to 14m
  - Drive energy is much higher
  - Significant densification of ground
- Location of structural failure is much less predictable
  - At joint, in upper segment, in lower segment – Varies
  - Much damage is unseen

A Better Theory to Explain Damage

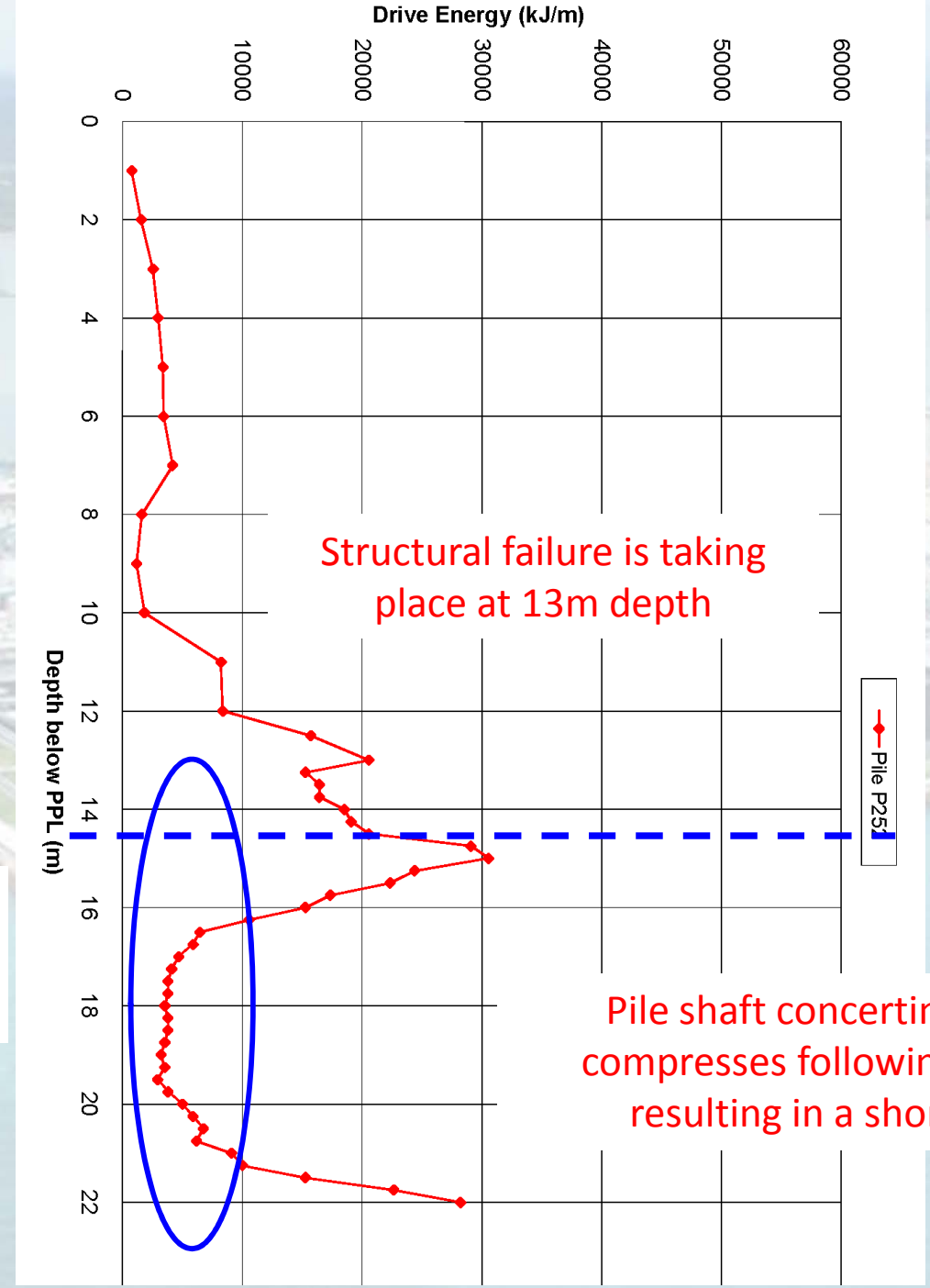


Structural failure of the pile segments is not limited to just the pile toe

Failure is possible in many forms

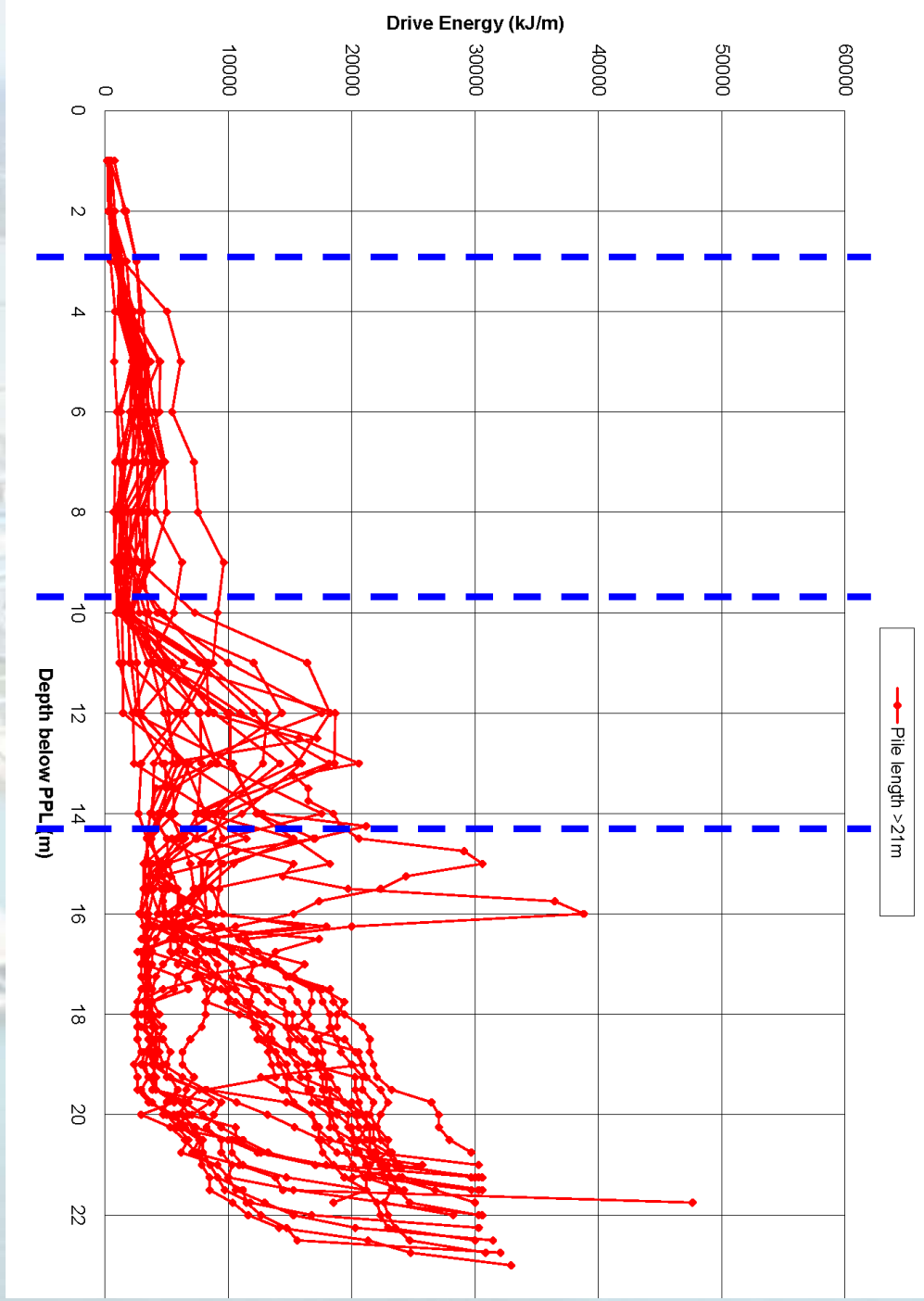
Some will be seen at excavation level, but others may not be visible

A Better Theory to Explain Damage



Pile Drive Blow Data – Piles > 21m

Dig level for pile cap



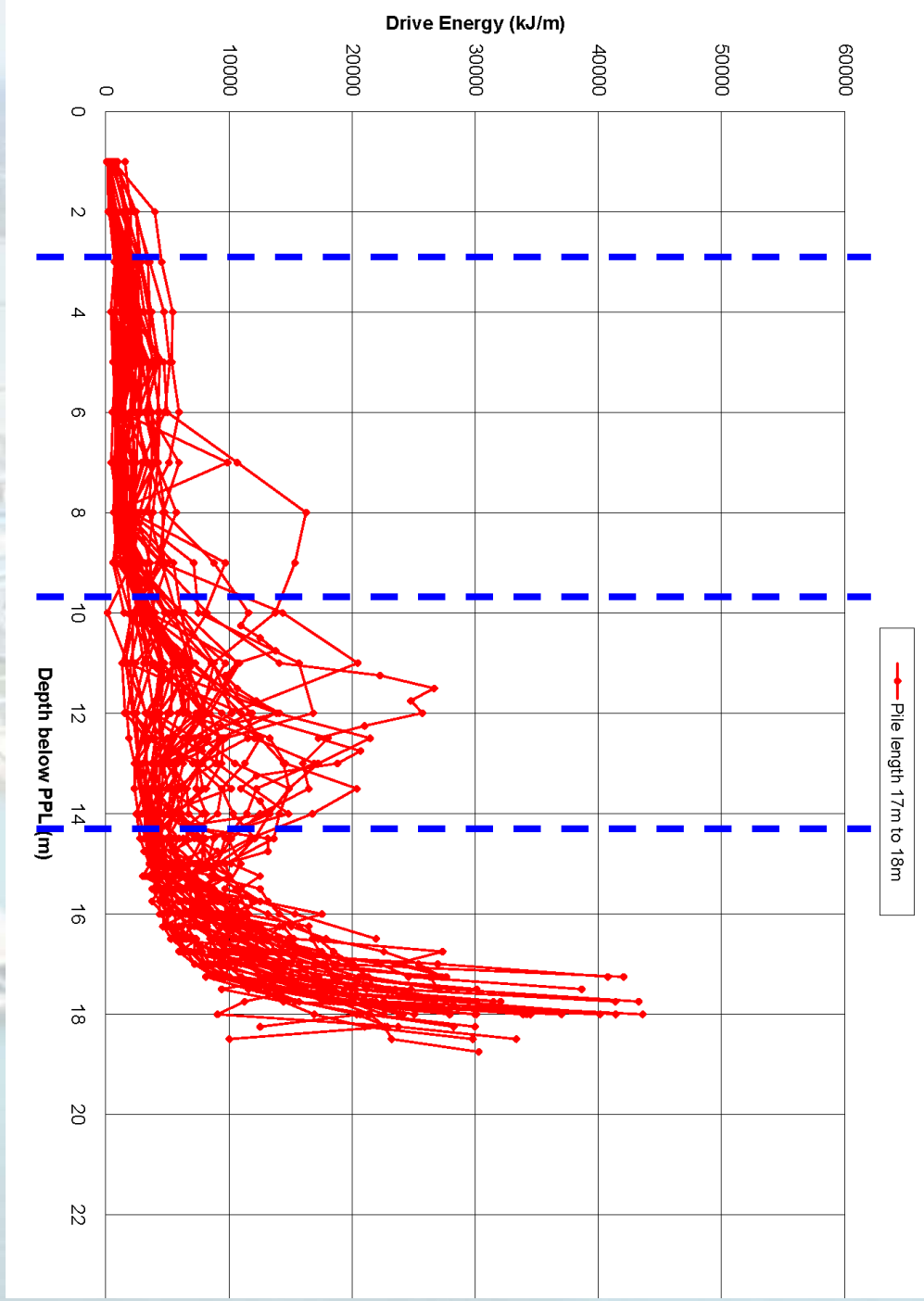
Level of debris

Depth range of probable structural failure

In this case compacted pile debris and crushed pile shaft achieves the required pile set at an ‘apparent’ deeper toe

Pile Drive Blow Data – Piles 17m to 18m

Dig level for pile cap



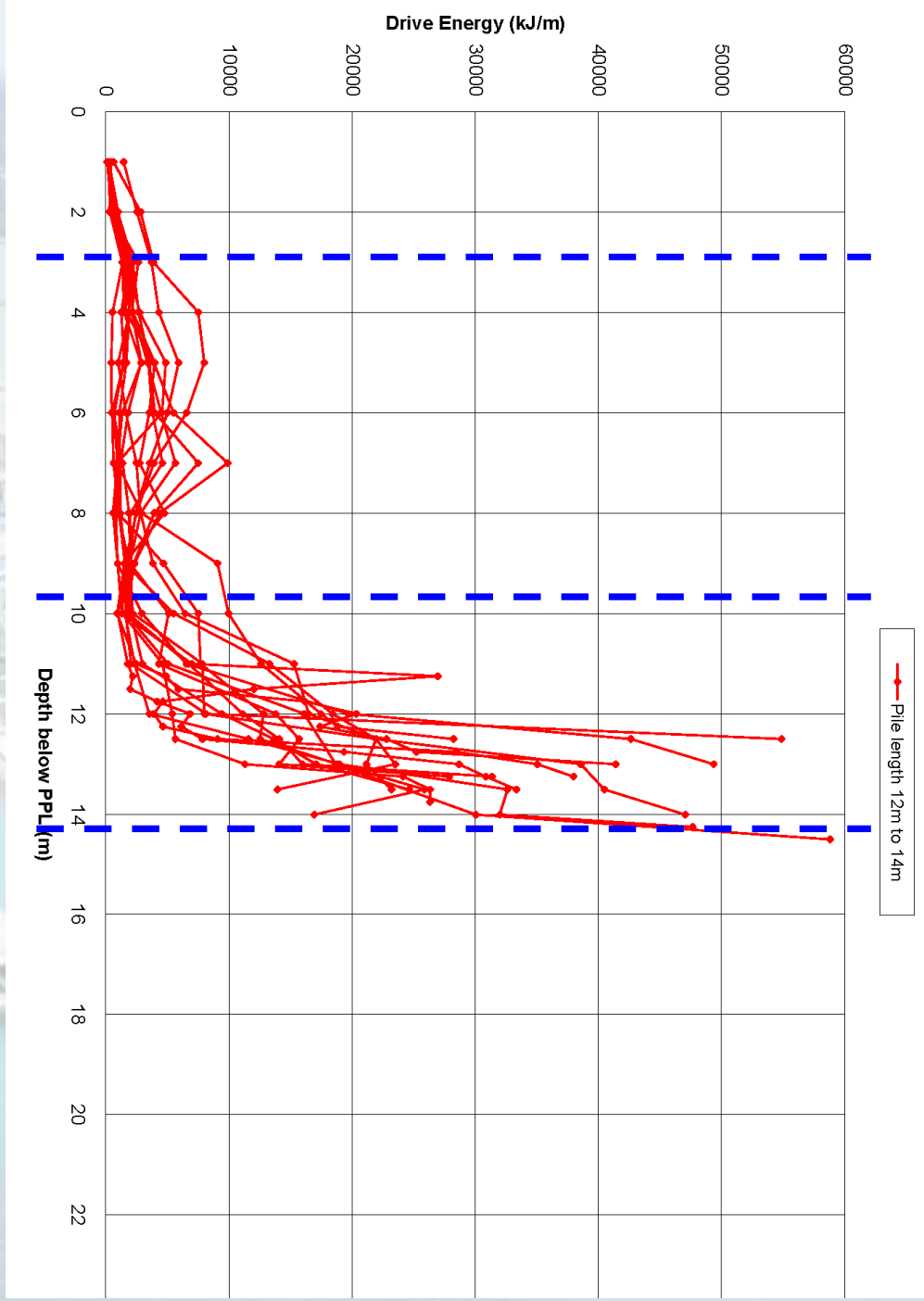
Level of debris

Depth range of probable structural failure

In this case compacted pile debris and crushed pile shaft achieves the required pile set at an ‘apparent’ deeper toe

Pile Drive Blow Data – Piles 12m to 14m

Dig level for pile cap



Level of debris

Depth range of probable structural failure

In this case compacted pile debris and crushed pile shaft achieves the required pile set

or

Pile has not failed

RFA Assessment - Damage Matrix

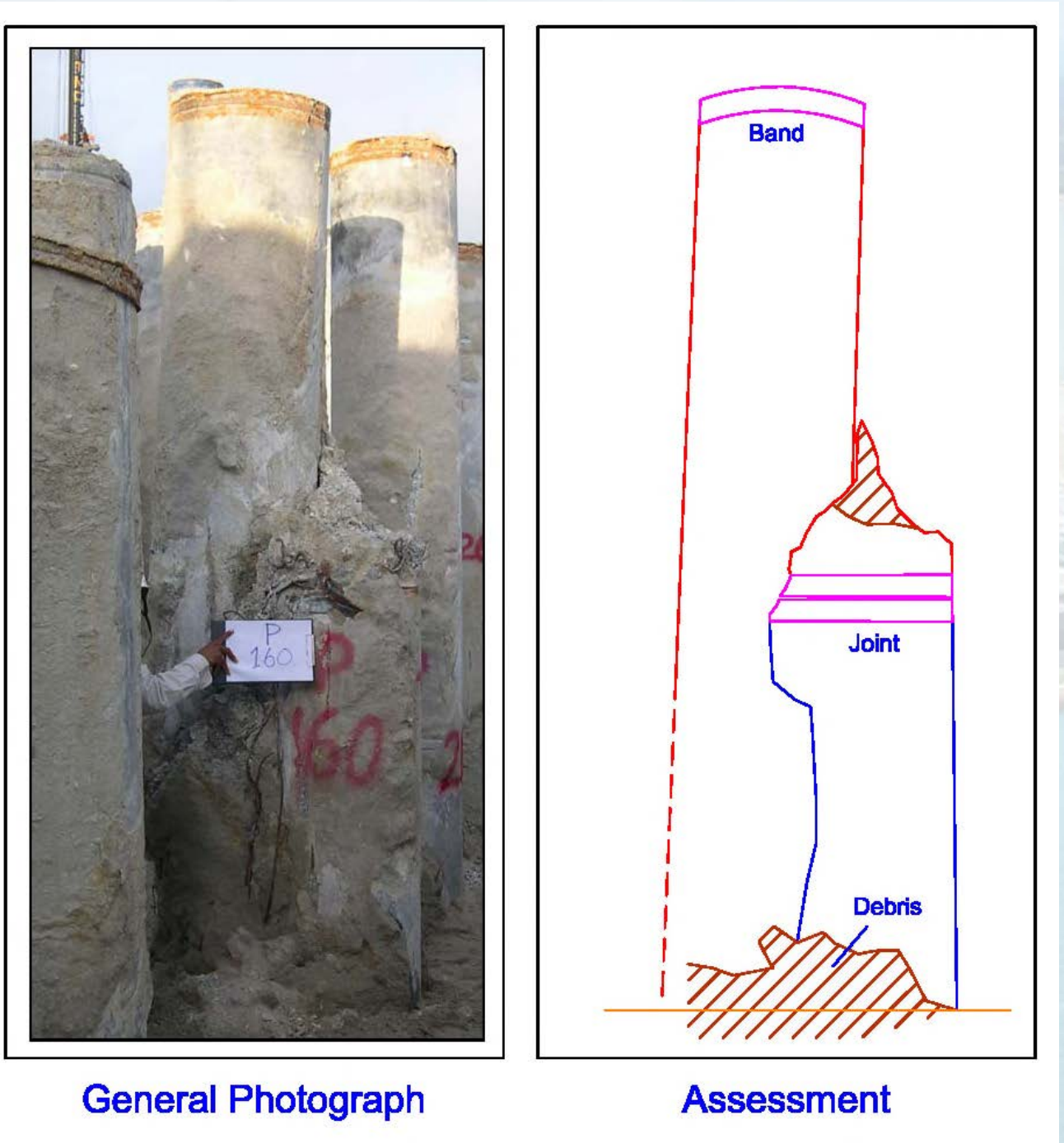
BLCP Power, Thailand

Chimney - Damage Matrix Summary

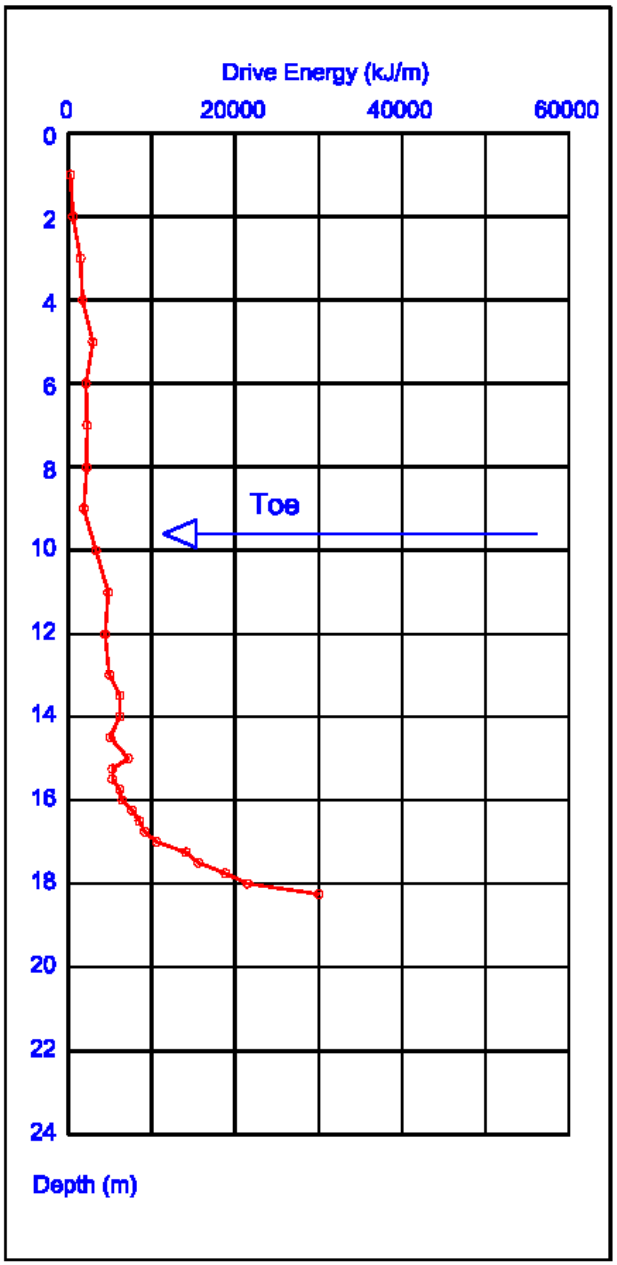
Pile Number	Prebored Closed End	Lower Pile Segment m	Upper Pile Segment m	Total Pile Length m	Theoretical Depth below PPL Pile Top m	Theoretical Depth below PPL Pile Joint m	Theoretical Depth below PPL Pile Tip m	Actual Depth below PPL Pile Joint m	Actual Depth below PPL Pile Tip m	Photographs 16th to 19th August 2004 Description of Damage and Comments CAR	TNC Failure
207		8	10	18	1.61	11.61	19.61	1.50	9.50	Possible bulge damage below pile head. Steel exposed lower down	Failed
208		8	10	18	0.55	10.55	18.55				Failed
209		8	10	18	0.96	10.96	18.96			Debris and steel	Failed
210		8	10	18	-0.13	9.88	17.88			Debris and steel	Failed
211		8	12	20	-1.64	10.36	18.36			Debris and band	Failed
212		8	12	20	-0.80	11.20	19.20				
213		8	12	20	-1.48	10.52	18.52				
214		8	12	20	-0.46	11.54	19.54			Debris and steel	Failed
215		8	12	20	-1.53	10.47	18.47				
216		8	12	20	-0.92	11.08	19.08				
217		10	10	20	-0.16	9.84	19.84				
218		10	10	20	-1.30	8.70	18.70	2.50	12.50	Upper segment burst and driven over lower. Joint about 6.2m too high. (Toe = 12.5m depth)	Failed
219		10	10	20	-0.82	9.18	19.18			Rough surface	Failed
220		8	10	18	-2.11	7.90	15.90	2.50	10.50	Burst lower section with debris. Not very clear	Failed
221		8	10	18	0.64	10.64	18.64	1.80	9.80	Lower section burst with damaged shaft. Joint about 8.8m too high. (Toe = 9.8m depth)	Failed
222		8	10	18	0.38	10.38	18.38			Debris and steel with band mark	Failed
223								2.40		Bulge and burst shaft	
223	S	A	8	12	20	0.30	12.30	20.30	1.50	9.50	Band and bulged shaft. Top of lower segment about 10.8m too high. (Toe = 12.3m upper segment - driven through lower)	Failed
223	N	B	8	10	18	-3.57	6.43	14.43	1.00	9.00	Band and bulged shaft. Top of lower segment about 5.4m too high. (Toe = 9.0m depth)	Failed
224			8	10	18	-0.25	9.75	17.75	1.80	9.80	Part of lower segment. Top about 7.9m too high. (Toe = 9.8m depth)	Failed
225			8	10	18	-0.22	9.78	17.78			Crushed concrete. Or just rough surface?	Failed
226			8	12	20	-1.91	10.09	18.09				
227			8	12	20	-2.07	9.93	17.93				
228			8	12	20	-1.40	10.60	18.60				
229			10		10	-0.55	-0.55	9.45				
230			10		10	-0.31	-0.31	9.69				
231			8	10	18	-1.78	8.22	16.22				
232			10		10	-0.54	-0.54	9.46				
233			12		12	-1.50	-1.50	10.50				
234			12	8	20	-1.67	6.33	18.33				
235			12	8	20	-0.28	7.72	19.72				
236			10	8	18	-1.52	6.48	16.48				
237			10	8	18	-2.09	5.91	15.91	2.00	12.00	Debris and part of lower segment. Joint about 3.9m too high. (Toe = 12.0m depth)	Failed
238			10	8	18	-0.69	7.31	17.31			Debris and steel	Failed
239			10	8	18	-0.33	7.67	17.67			Debris? Uncertain	Failed

- Review based on photographs and detailed pile records
- If 'joint' visible, it has been possible to estimate real toe level

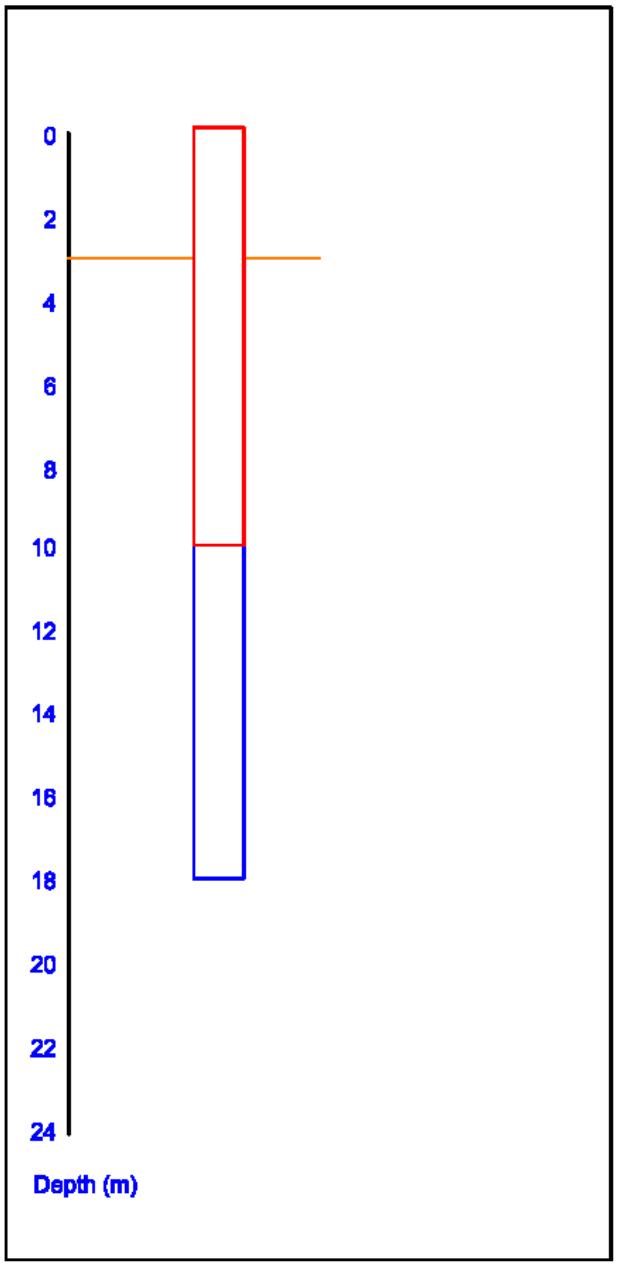
More Evidence – Pile 160



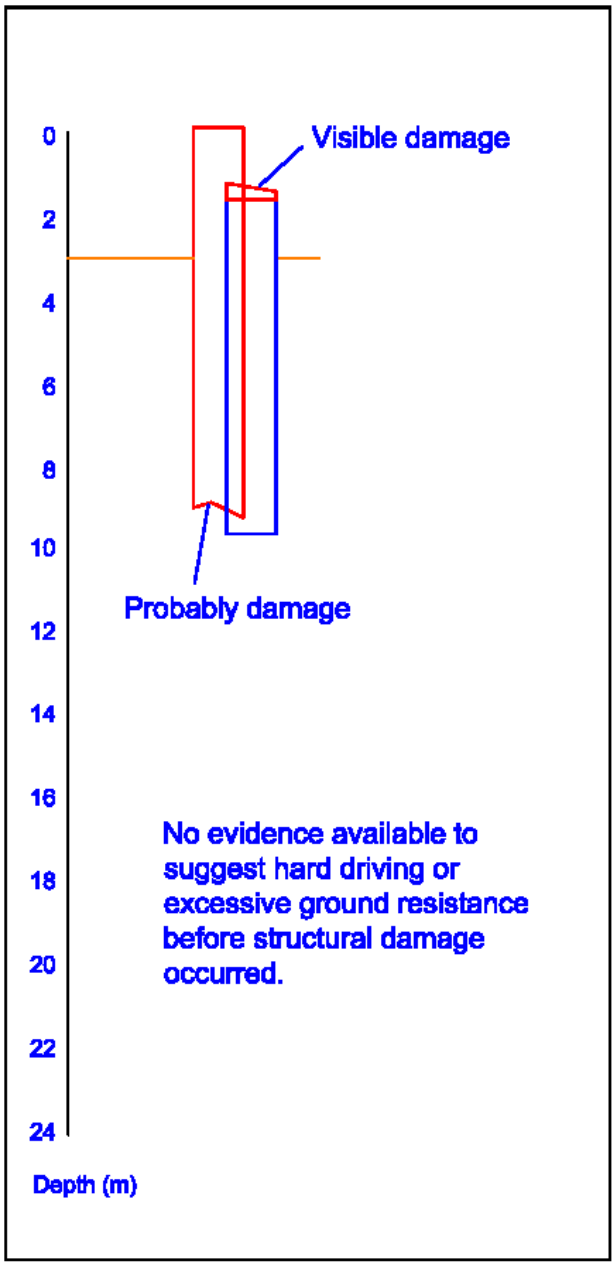
More Evidence – Pile 160



Measured Drive Blows

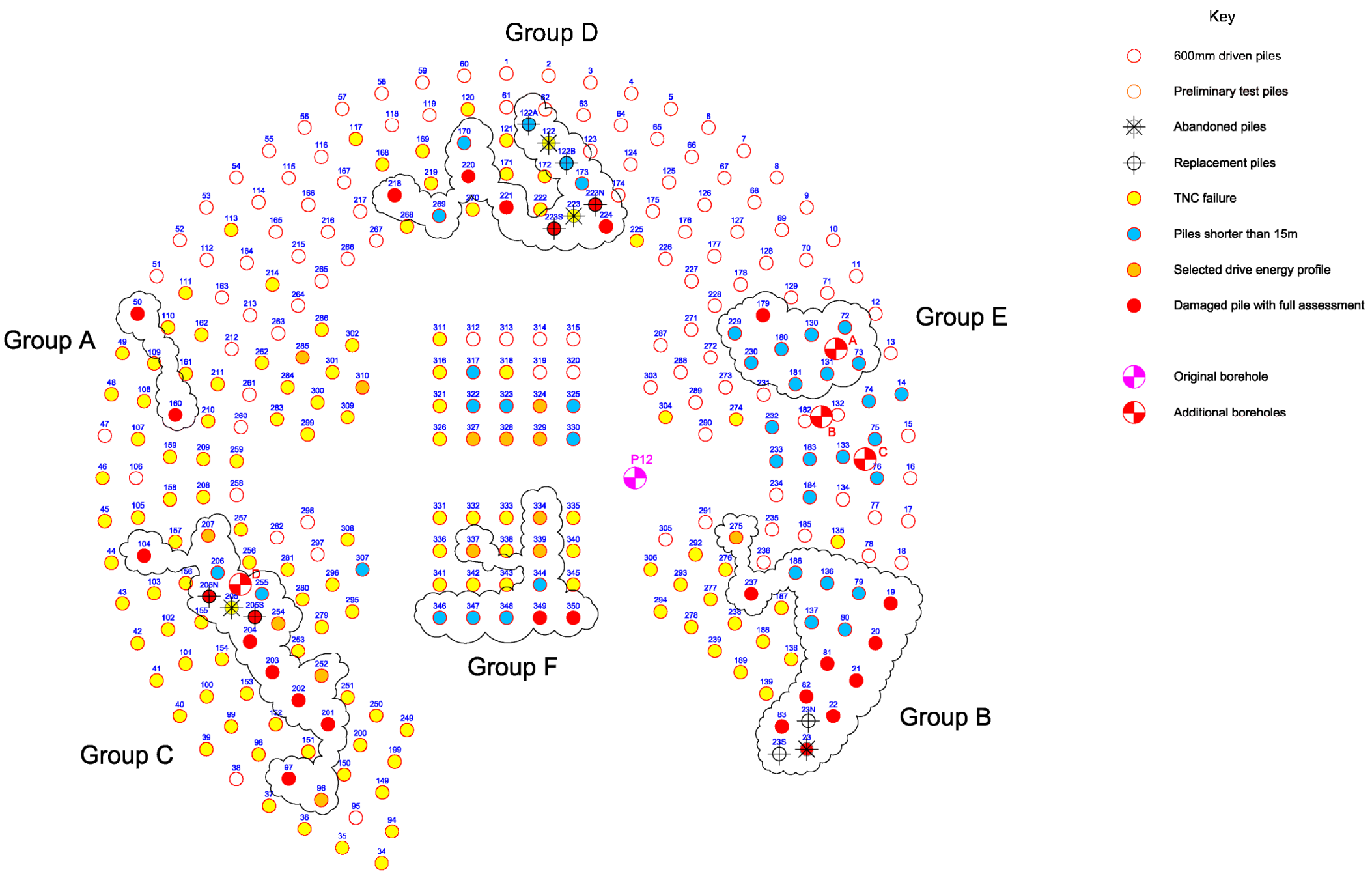


Theoretical Pile

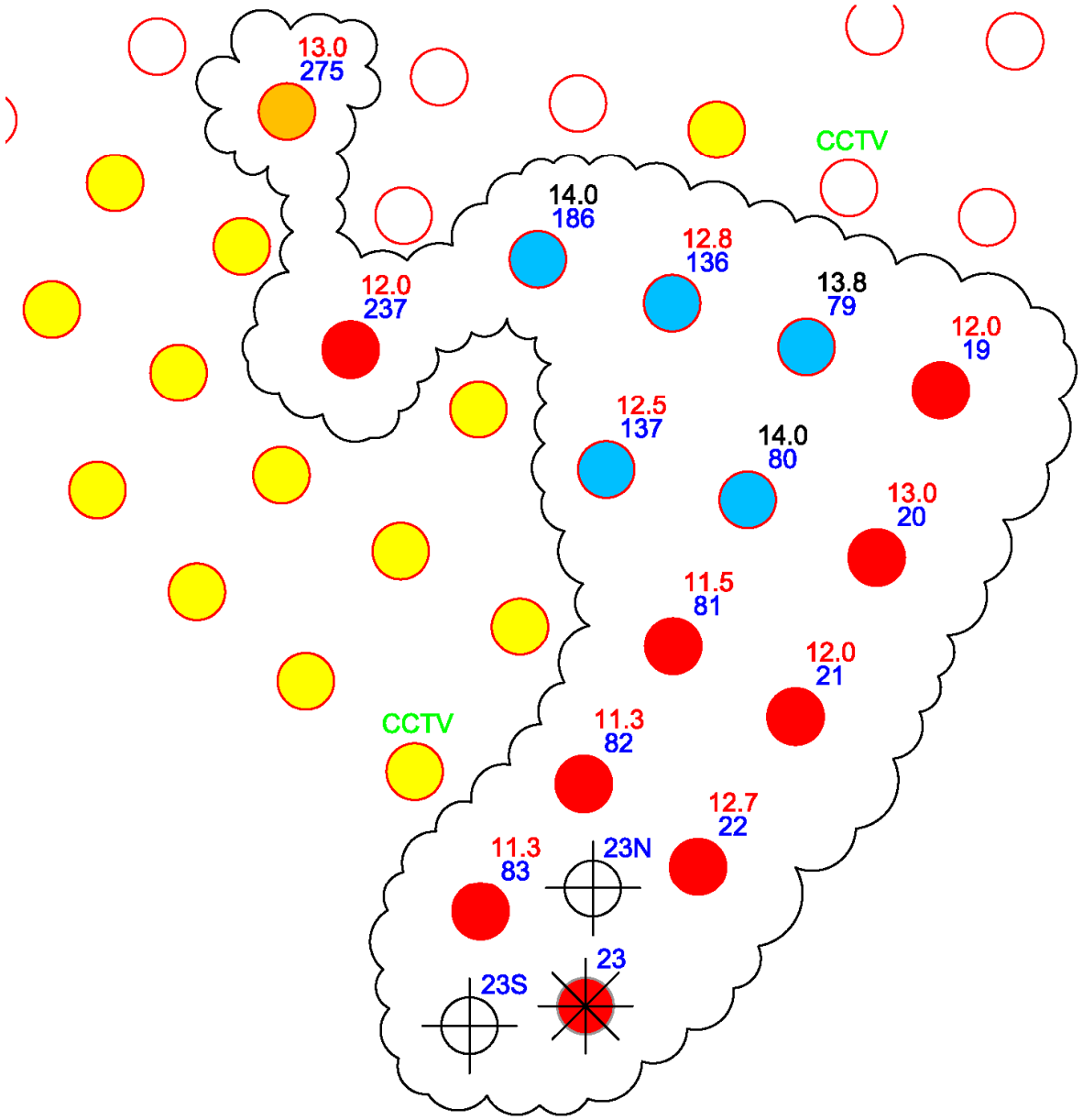


Actual Pile

More Evidence – Local Variation



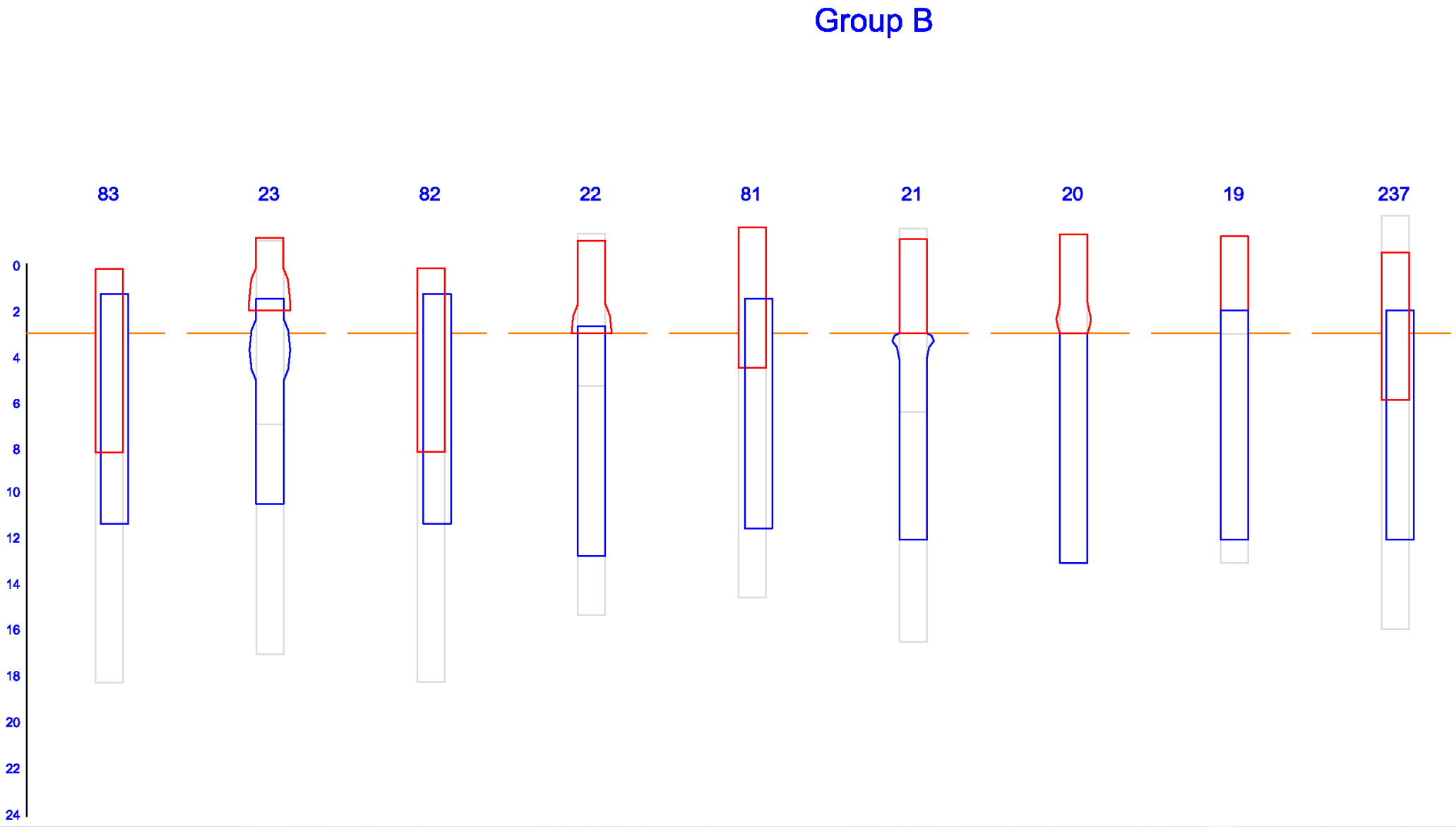
More Evidence – Local Variation



Key

- 600mm driven piles
- Abandoned piles
- Replacement piles
- TNC failure
- Piles shorter than 15m
- Selected drive energy profile
- Damaged pile with full assessment

More Evidence – Local Variation



But Why Did Piles Fail?

- Drive blow energy generally acceptable
- PDA testing confirmed stress levels during driving OK
- Concrete testing confirmed strengths OK

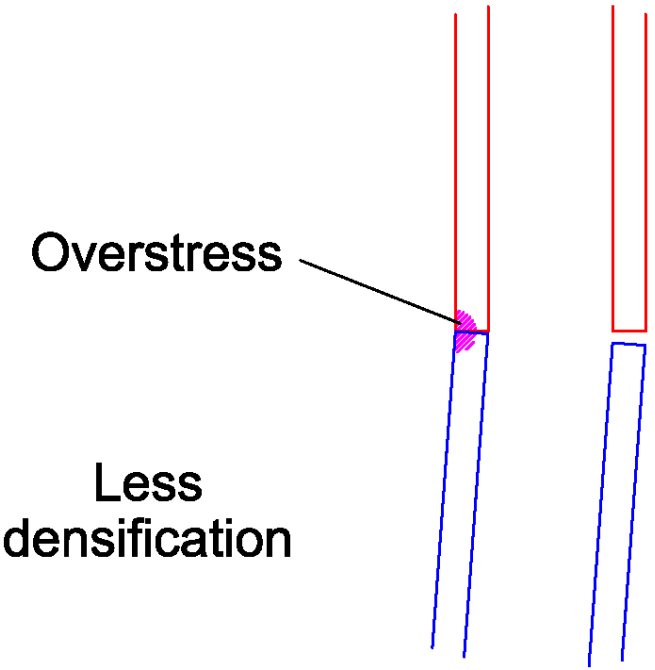
- Evidence of hard driving below 10m to 12m depth
- In some cases, much shallower (replacement piles)

- What is the missing factor or trigger for damage?

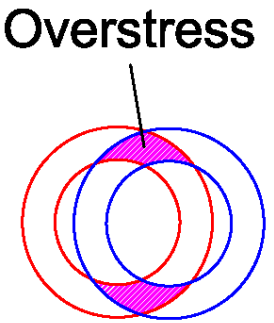
But What Was the Trigger?

- Soil densification
  - Predicted by GI Report and Designer
  - Sequence tried to mitigate
  - But very closely spaced piles (2.5 x diameter)
- Densification causes pile bending and over-stress

Overstress by Bending

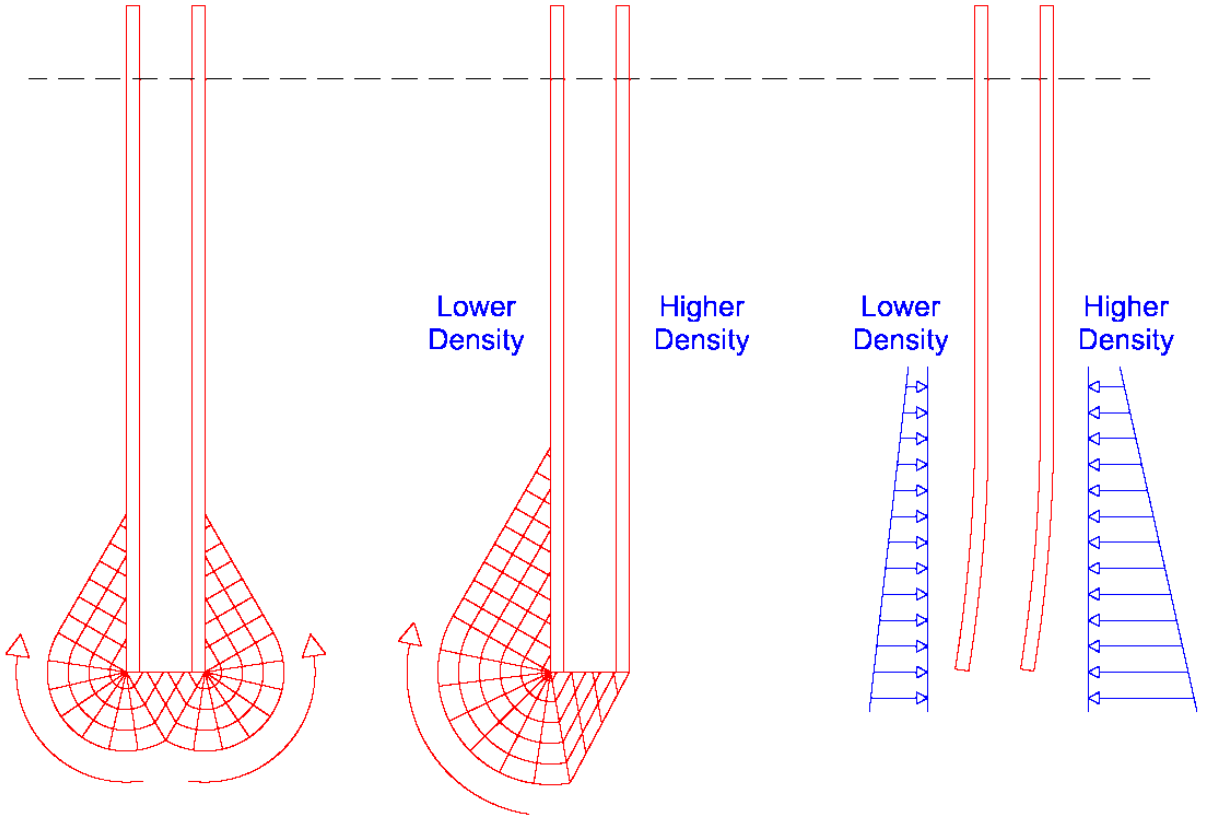


Possible bending caused by deviation of lower segment due to uneven densification of ground results in overstress on one side of pile.



Misalignment of upper and lower segments due to joint failure could result in excessive overstress.

But What Was the Trigger?



Uniform ground conditions

Normal symmetrical bearing capacity development below toe of plugged pile with soil movement in a radial direction from pile

Non-uniform ground conditions with high densification on one side

Non-symmetrical bearing capacity development below toe of plugged pile with more radial soil movement away from higher density and stiffer ground

Non-uniform ground conditions with high densification on one side

Higher horizontal stresses develop within densified ground with a tendency for the pile shaft to deviate off vertical towards the lower density lower stiffness soil

Pile bending induces compression and tension forces in pile shaft

Implications for Insurance Claim

- Policy excludes cost of correcting damage
  - Applies at the point of damage
  - If shallow failure, correction would be relatively cheap
  - Remove and replace pile
- But
  - If deep failure, may not be able to remove damaged pile
  - Remedial works may not be feasible
  - Costs to correct significantly greater

Implications for Insurance Claim

- Disagreement lead to Insurance Tribunal
  - Similar to an Adjudication
  - Legal Teams and Experts
- Started in 2008
- Evidence given in early 2009
- Unaware of any settlement to date

Conclusions

- Unusual situation that pile damage was detected so late
- Pile installation records did not pick up problem
  - No attempt to investigate long pile drives
  - Variation in pile length across site significant
  - Could have looked down pile shaft
- Densification could have been (and was) foreseen
  - Ground conditions were typical for densification
  - Pile spacing too close
  - Piling sequence planned

Conclusions

- Some damage occurred elsewhere on site
- Chimney was more severe – pile density much greater
- Contractor and Specialist did not understand the problem
  - Head (literally) in sand
  - (Possibly) expedient not to know how problem occurred

Conclusions

- Explanation for damage must be fully inclusive
  - Toe failure possible for some piles
  - Did not explain significant amount of observed damage
  - Did not explain anomalous drive blows
- Alternative theory much better able to explain all damage
- Trigger was pile bending caused by densification

- Piles either not strong enough or were defective
- Problem could have been avoided

The Midland Geotechnical Society

Thanks for you attention

Any questions?