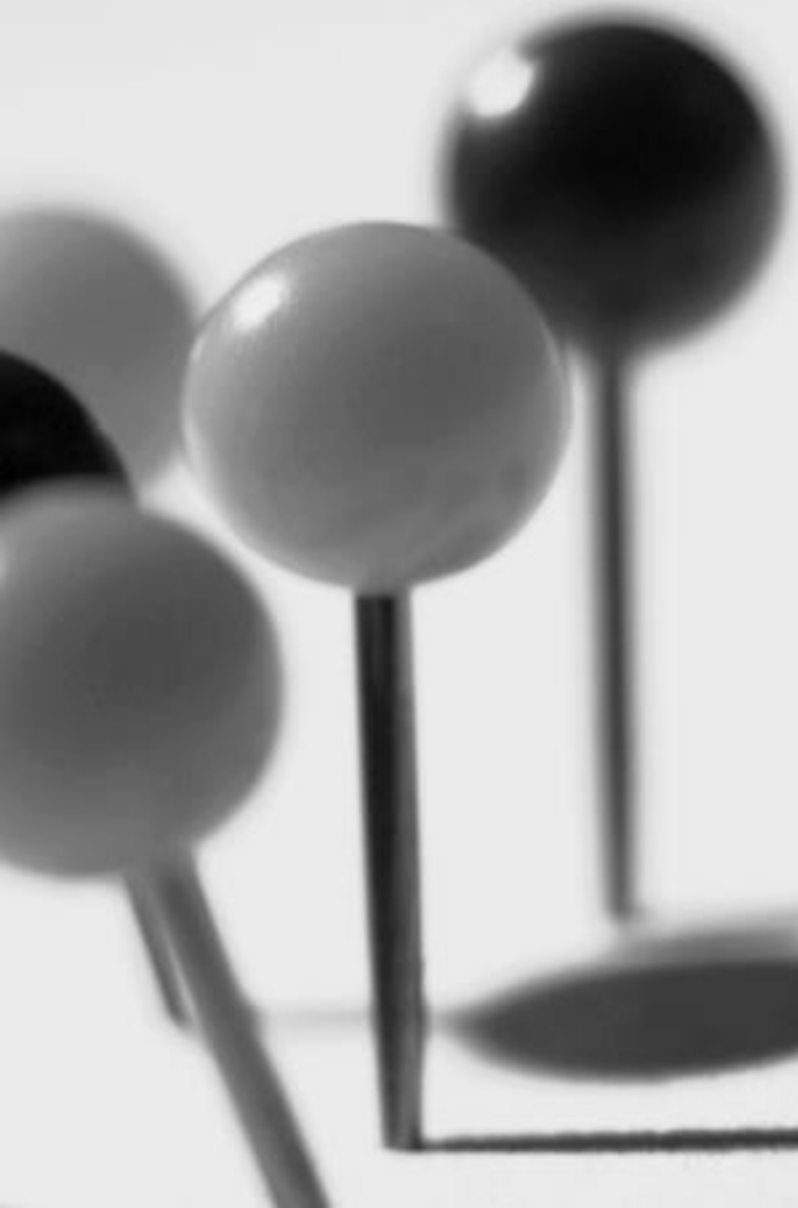

Common Blind Spots in Ground Investigation, Design, Construction, Performance Monitoring and Feedbacks in Geotechnical Engineering

Ir. Liew Shaw Shong

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Mission Statement

- Site Investigation
  - Planning, Execution & Interpretation
- Forensic Investigation
  - Stability of Piled Supported Retaining Wall
  - Embankment Distress (Strain Incompatibility)
  - Abutment Distress due to Piled Embankment Failure
  - Unreliable Facing Capacity of Soil Nailed Slope
  - Illusive End Bearing Pile Capacity
  - Non-linearity Elasto-Plastic & Hysteresis Phenomena of Pile-Soil Interaction Performance

Site Investigation

- List CEO and key management by name.
- Include previous accomplishments to show that these are people with a record of success.
- Summarize number of years of experience in this field.

Lessons Learnt on Stability of a Piled Retaining Wall in Weak Soils

Ir. Liew Shaw-Shong

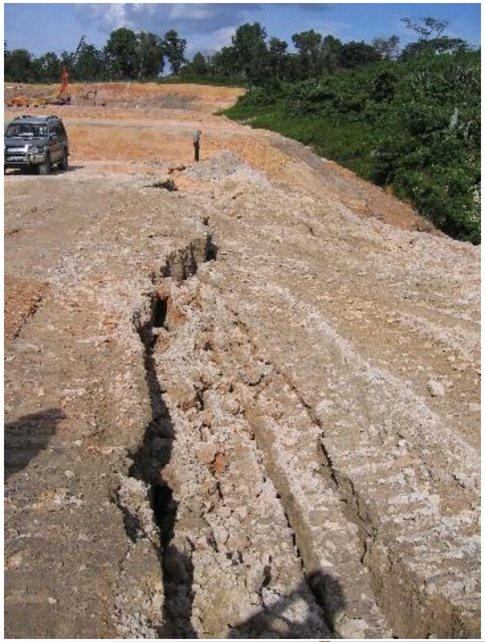
Content

- Chronological events
- Distress conditions of wall
- Desk study & subsurface conditions
- Forensic investigation (Geotechnical & Structural assessments)
- Probable Causations
- Remedial Solution
- Conclusion

Chronological events

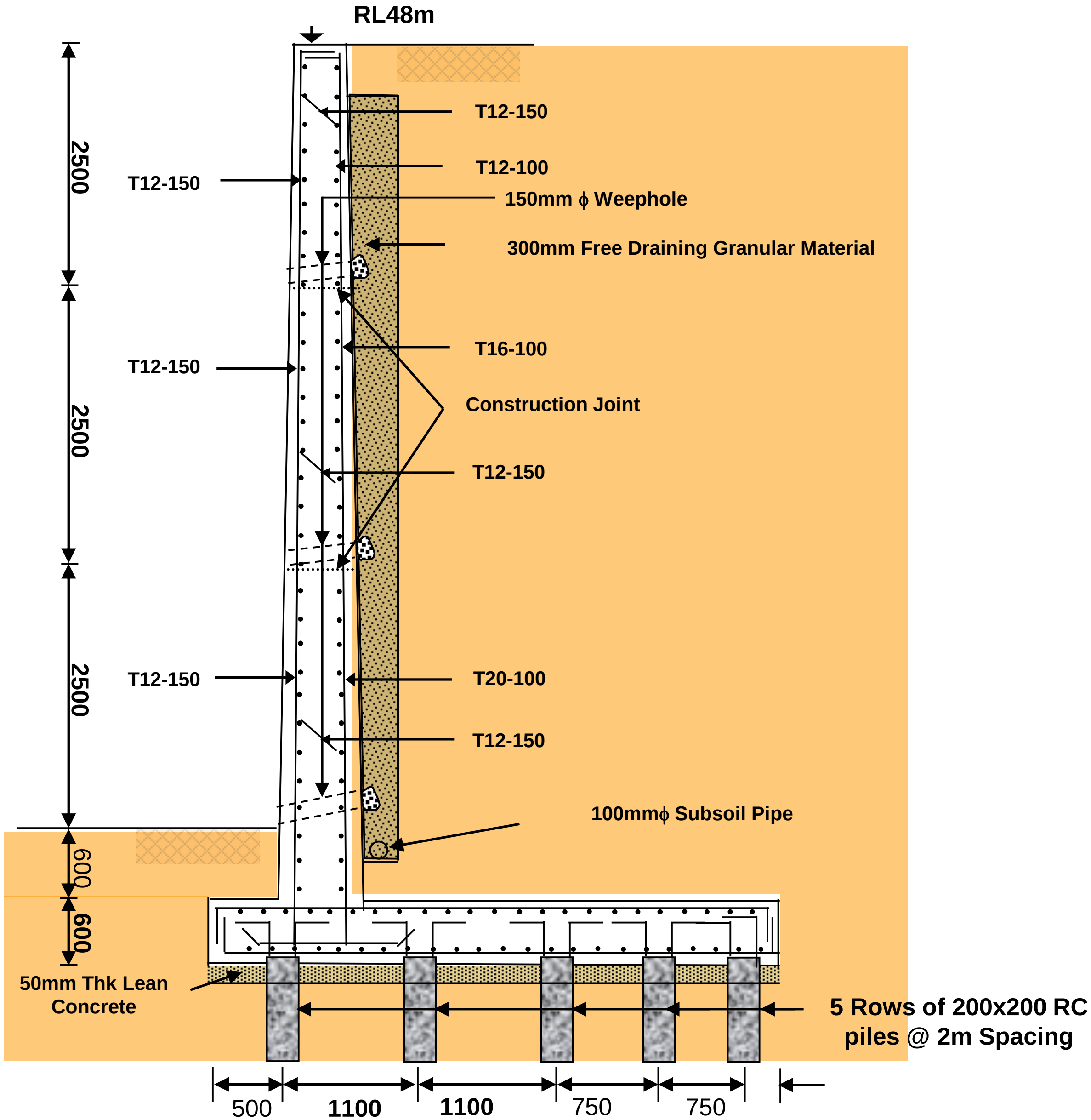
- First SI : Jan 2005 (Within project site)
- Second SI : May 2005 (at wall area)
- Wall Distress : Feb 2006 (After prolonged rain)
- Forensic Investigation : Feb to Mar 2006

Tension Crack & Wall Distresses



Overall View of Site

Cross Section of Wall

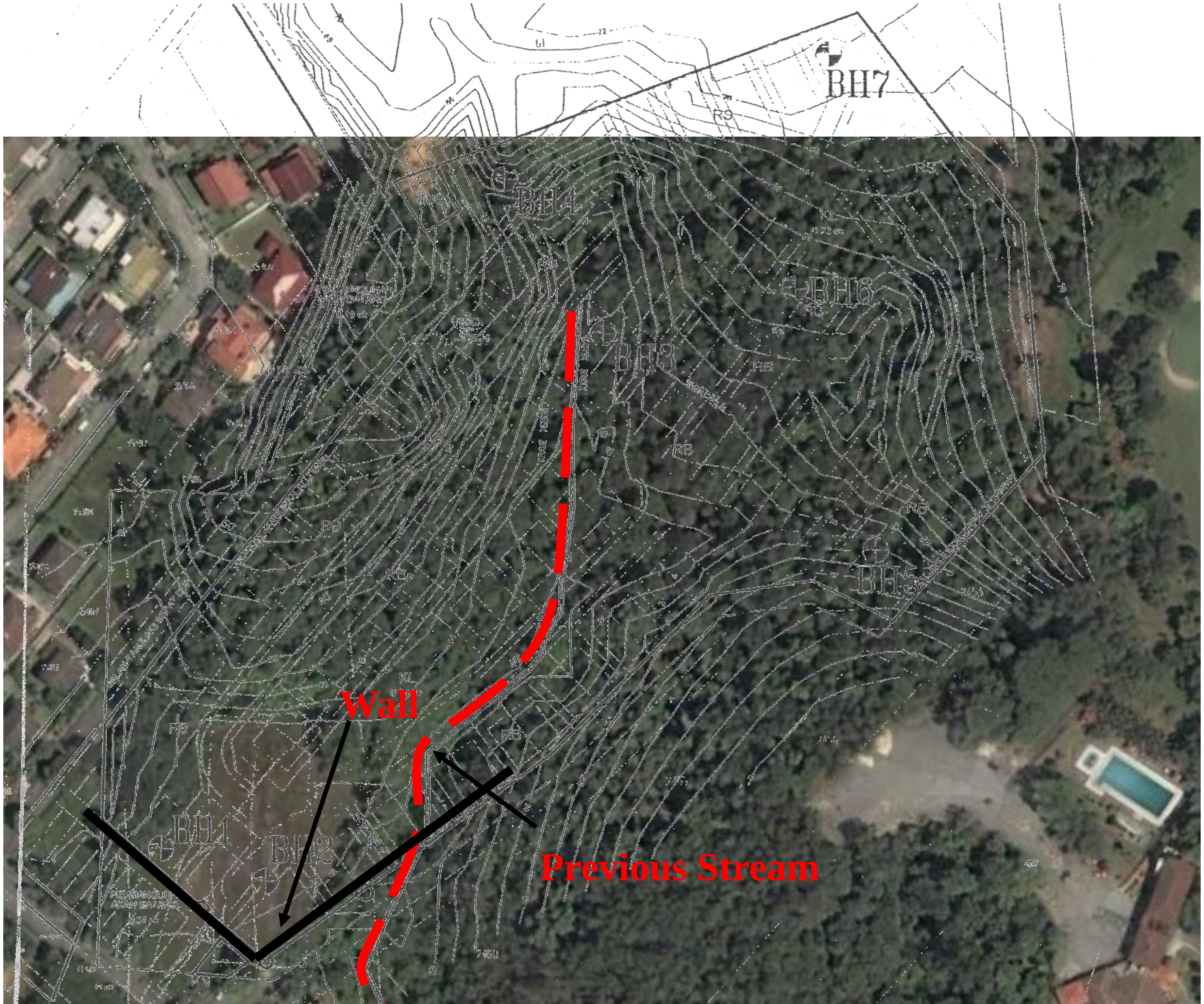


Weephole Drains

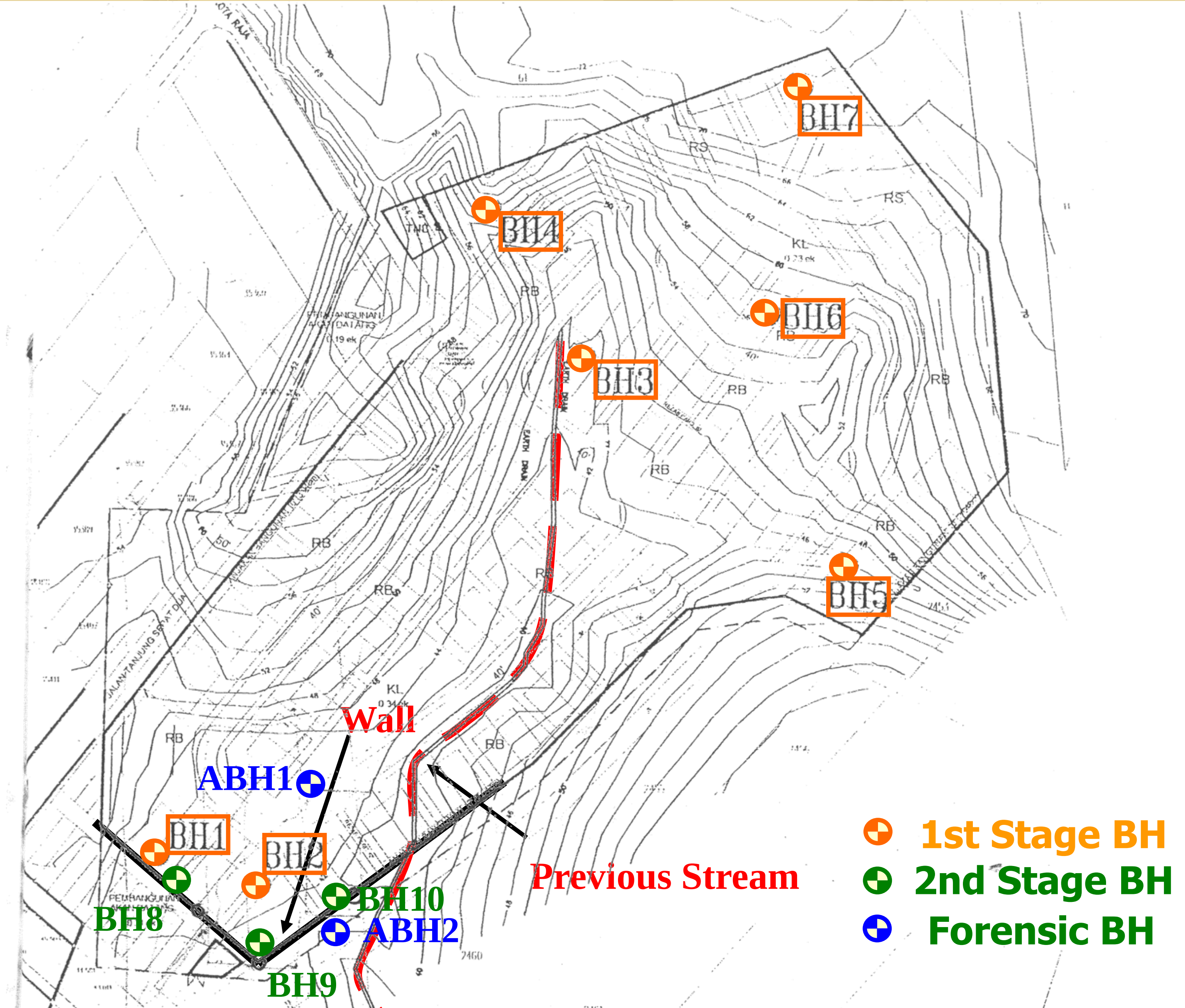
Erosion by Weephole Discharge

Erosion of Wall Base

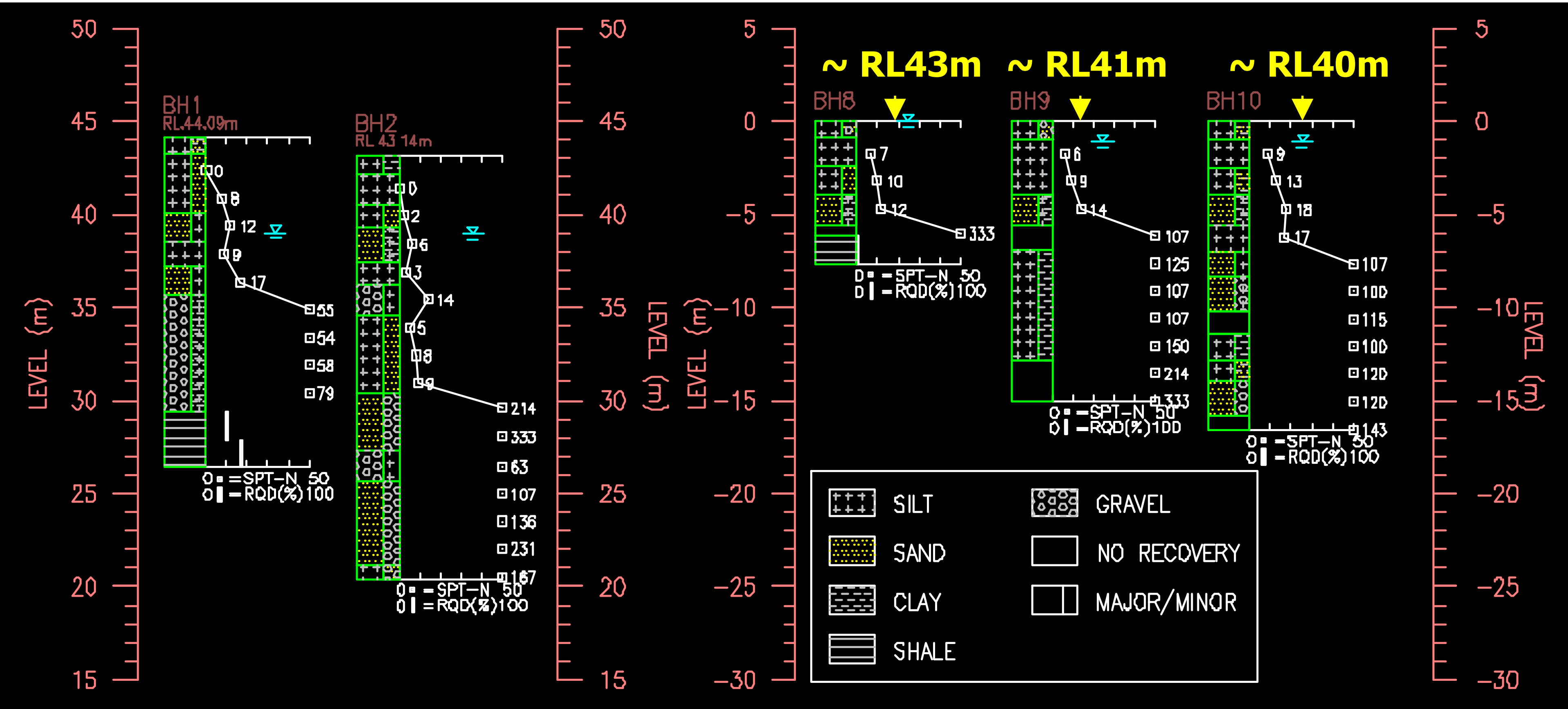
Aerial View (Pre-development)



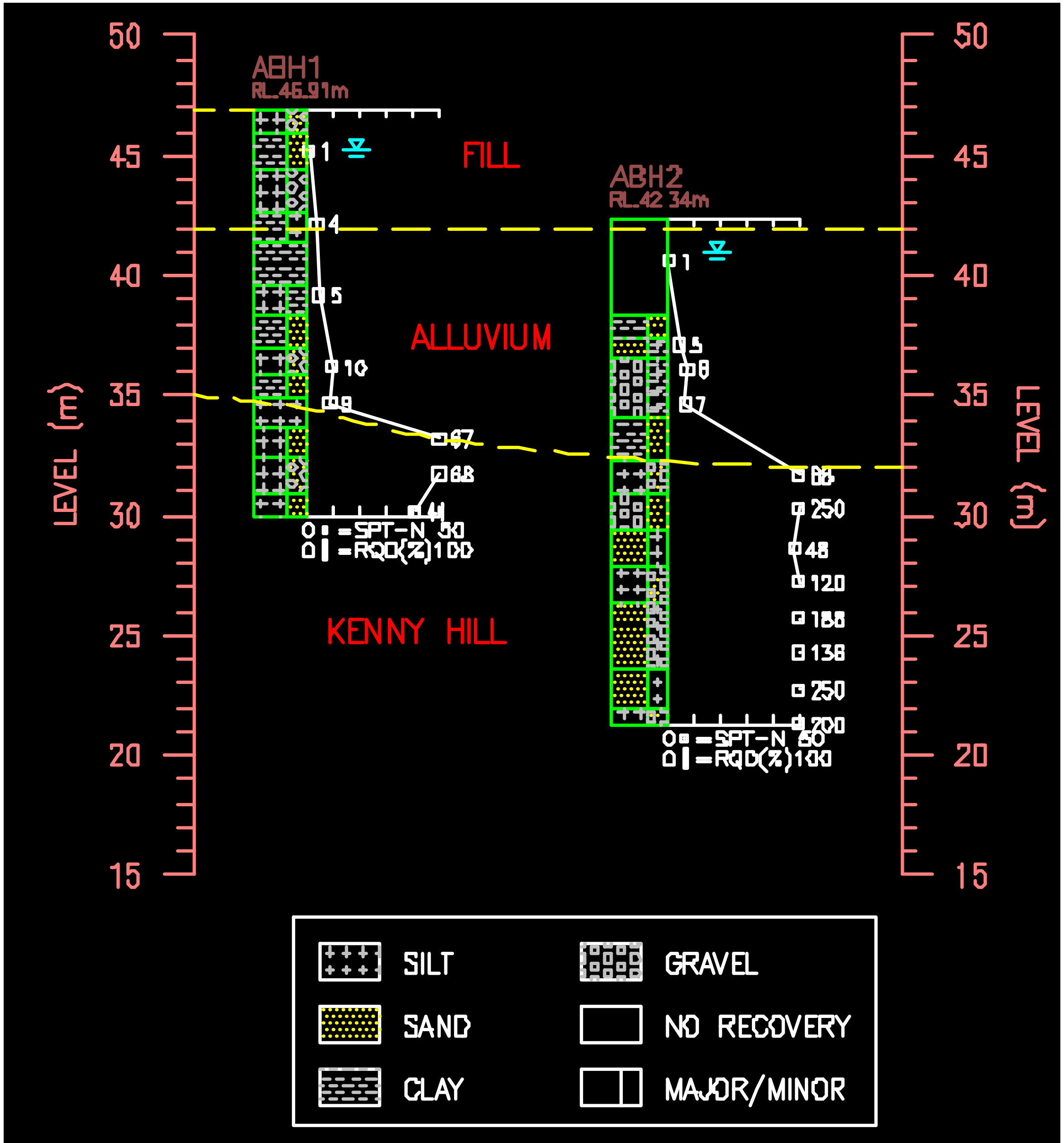
Site Topography & SI Works



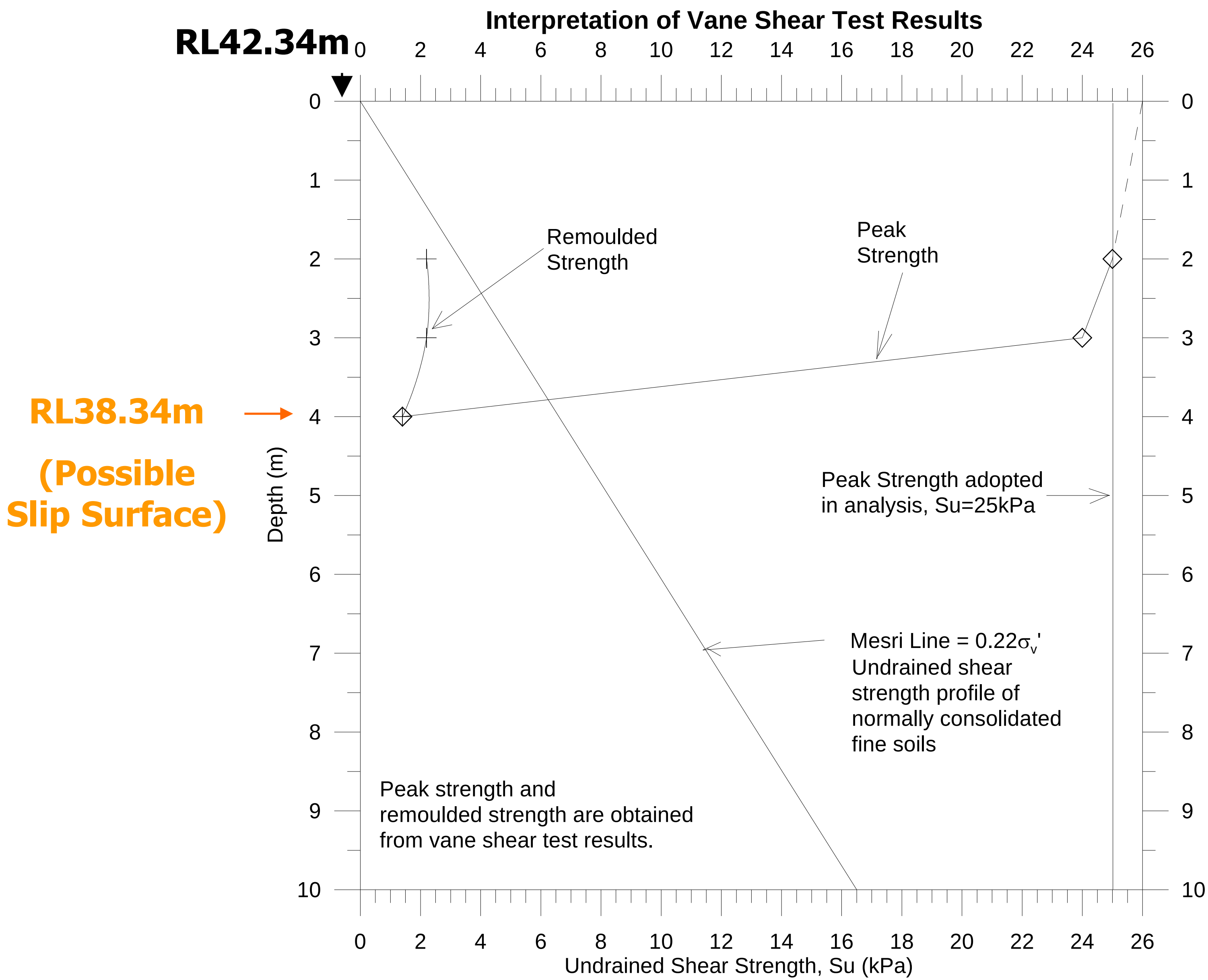
Previous 2-Stage Boreholes



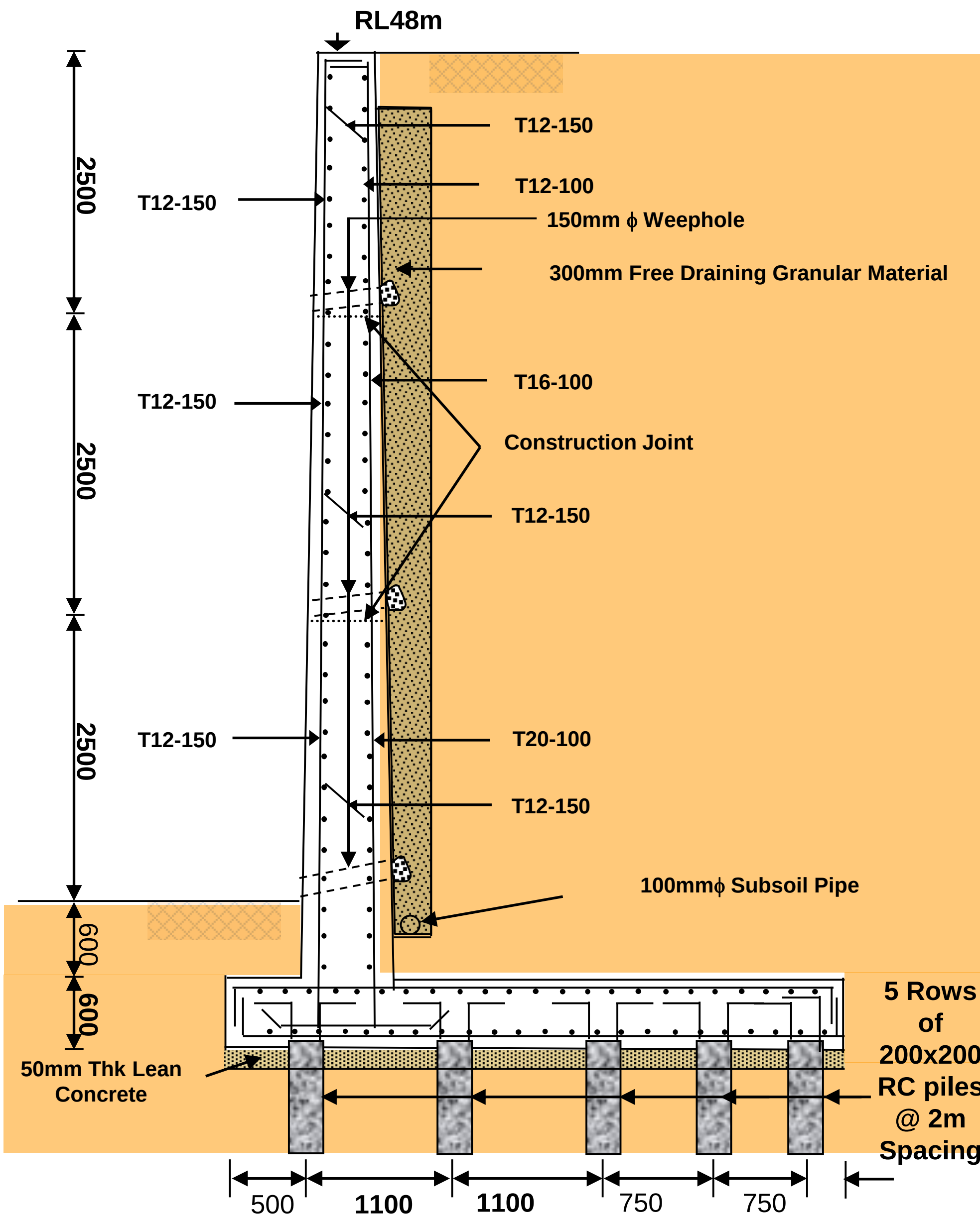
Forensic Boreholes



Vane Shear Test Strength Profile



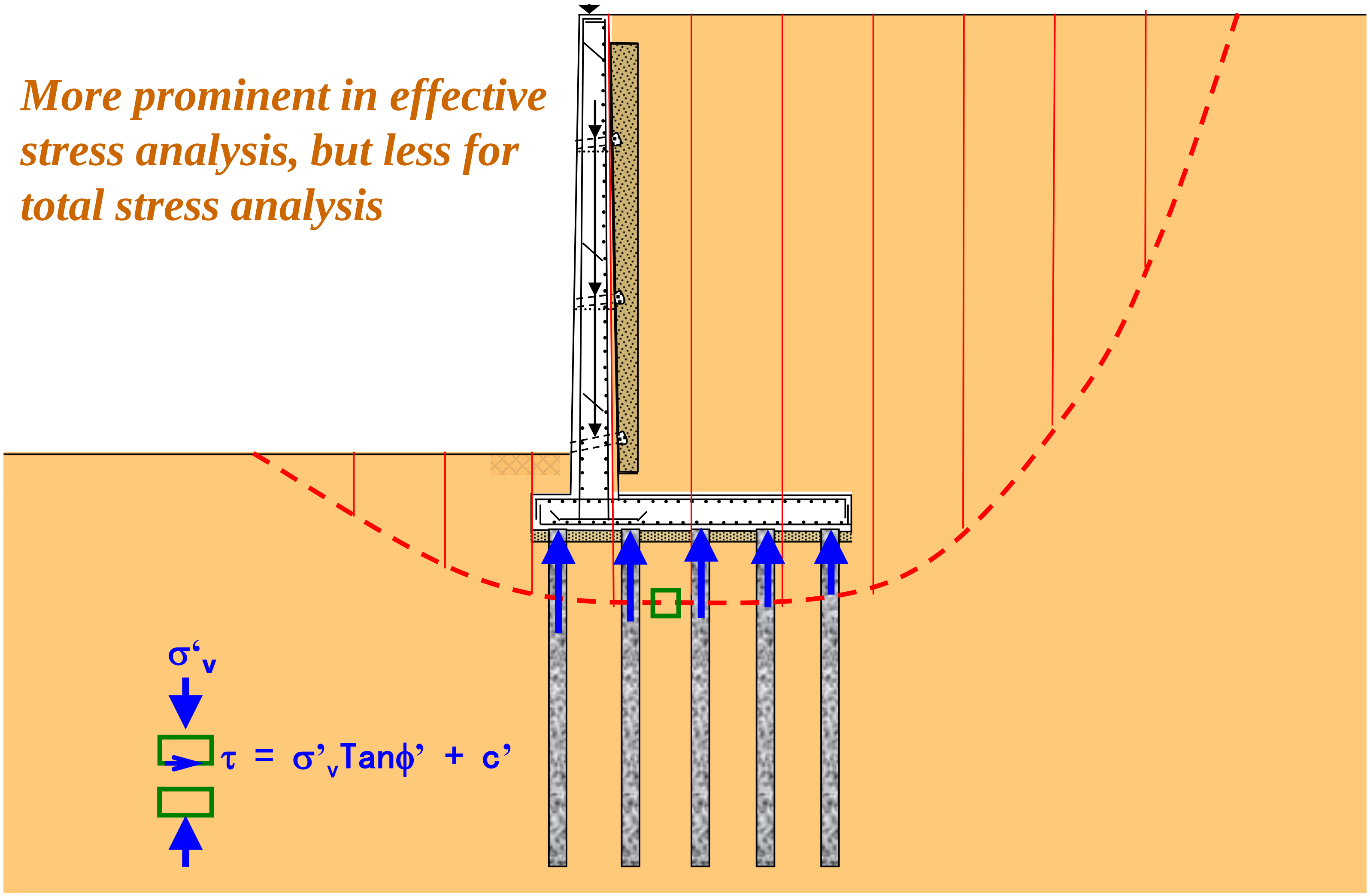
Stability Assessments



FOS Adequacy			
GWT	Over-turning	Sliding	Global Stability
RL45m	✓ **2.9>2.0**	✗ **0.97<1.0 (Failure)**	✗ **1.13/1.17**
RL42.5m	✓ **3.7>2.0**	✗ **1.34<1.5**	✓/✗ **1.19/1.25**
RL40.4m	✓ **3.8>2.0**	✗ **1.5**	✓/✗ **1.16/1.24**

Bearing Capacity is never a concern as pile foundation is designed to take the vertical loading of wall

More prominent in effective stress analysis, but less for total stress analysis



Pile Integrity Testing

Pile Structural Assessments

- Rankine Pressure
- Brom's Lateral Pile Capacity:
  - Fixed Head : 32kN/pile (Likely the case)
  - Free Head : 20kN/pile
- Ultimate lateral pile capacity reached when RL42.5m<GWT<RL45m

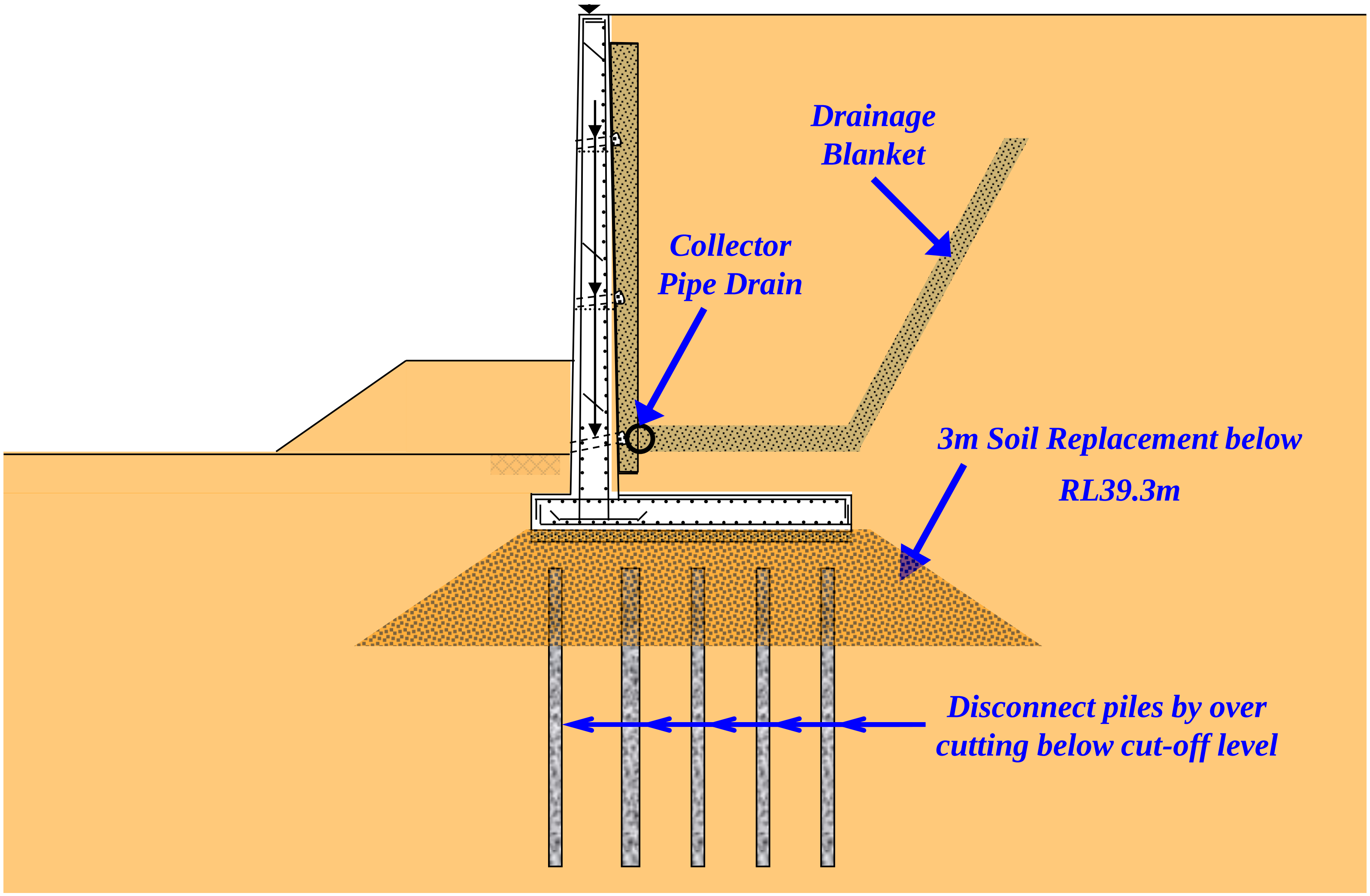
Probable Causes of Wall Distress

- Potential perched water regime in natural valley terrain after raining
- Rise of groundwater increases the lateral force on wall
- Inadequate lateral pile resistance
- Reduction of effective soil strength due to reduction of vertical stress as wall loading carried by piles

Remedial Solution

- Soil Replacement for upper weak soil
- Overcut existing piles below new wall base
- Construct stabilising berm in front of new wall
- Provide subsoil drainage behind wall to control rise of groundwater seepage

Remedial Solution



Conclusion

- Potential perched water regime in natural valley terrain after raining
- Rise of groundwater (inefficient sub-terrain drainage) increases the lateral force on wall
- Inadequate lateral pile resistance
- Reduction of effective soil strength due to reduction of vertical stress as wall loading carried by piles
- Slender vertical piles not suitable for supporting wall on weak & compressible soils (Poor lateral resistance)
- Remedial works : Soil Replacement + Subsoil drainage + Stabilising berm
- Solution : Raked piles in combination of vertical piles (Serviceability limit state)

Role of Extendible Basal Reinforcement for Embankment Construction Over Soft Soils

- Introduction
- Problem Statements & Distress
- Back Analysis
- Discussions
- Conclusions
- Recommendations

Introduction

- Embankment ➔ Raised fill platform with side slopes to support structure and infrastructure developments.
- Stage construction + additional reinforcement ➔ Ensure acceptable side slope stability
- Basal reinforcement ➔ To minimise spreading failure of compacted embankment fill over weak supporting subsoils

Basal Reinforcement

- Shall be designed in accordance with BS8006.
- Consideration ➔ Strain compatibility between embankment fill and basal reinforcement system.
- Tensile strain in basal reinforcement shall be controlled to avoid cracking in embankment fill.

Basal Reinforcement

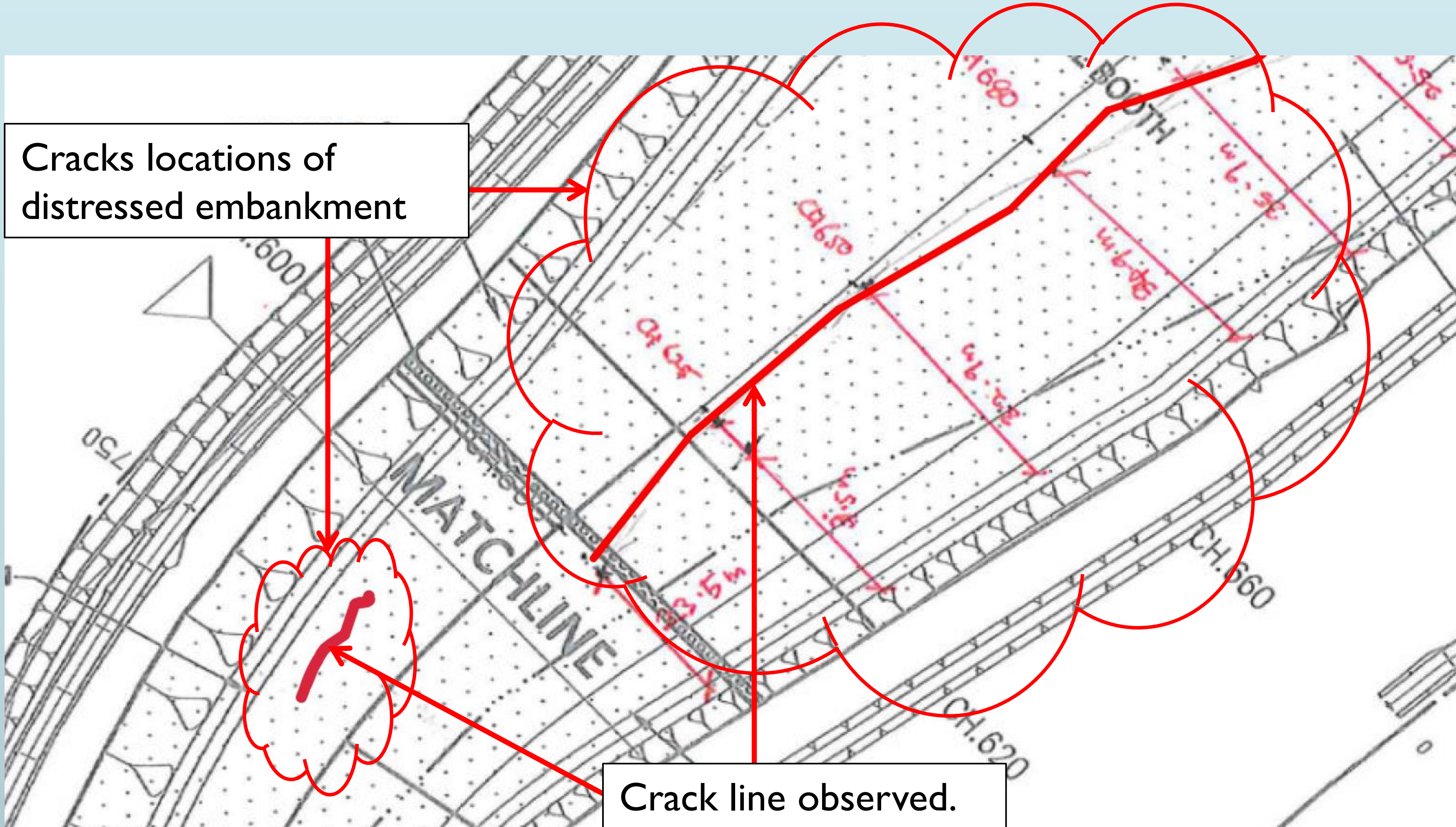
- If the embankment is strained to excessive tensile crack, the embankment fill material strength is doubtful.
- Thus, case study of an instrumented embankment construction with extendible basal reinforcement have been used.
- This may call for a review of the permissible strain of extendible basal reinforcement with brittle compacted fill.

Problem Statement & Distresses

- Problem Statements
  - Embankment Fill over Soft Deposits
  - PVD with Staged Construction
  - Basal Reinforcement for Temporary Embankment Stability
  - BS8006
  - Strain Incompatibility

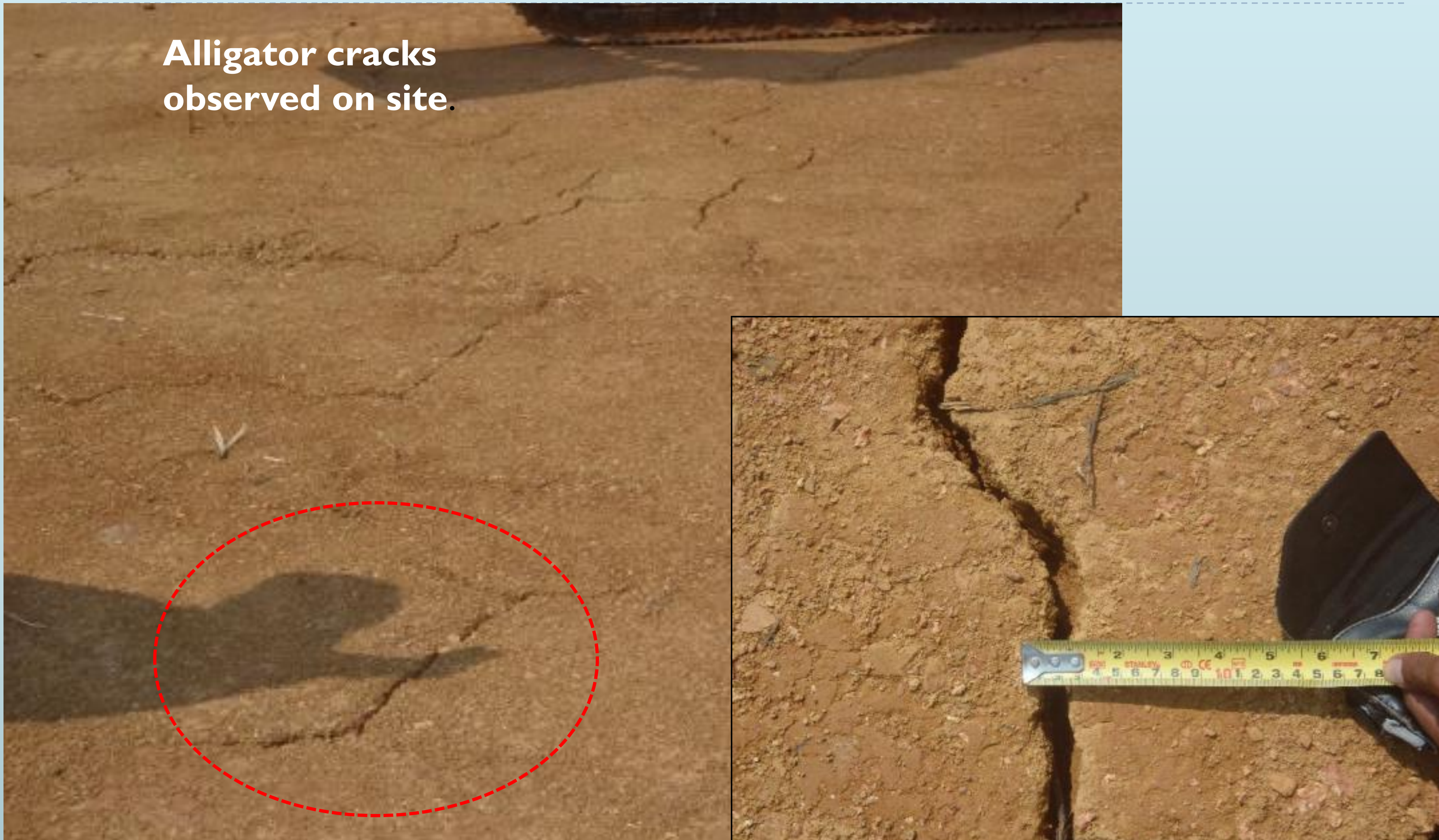
- Distresses
  - Longitudinal flexural cracks on embankment surface

Embankment Distresses



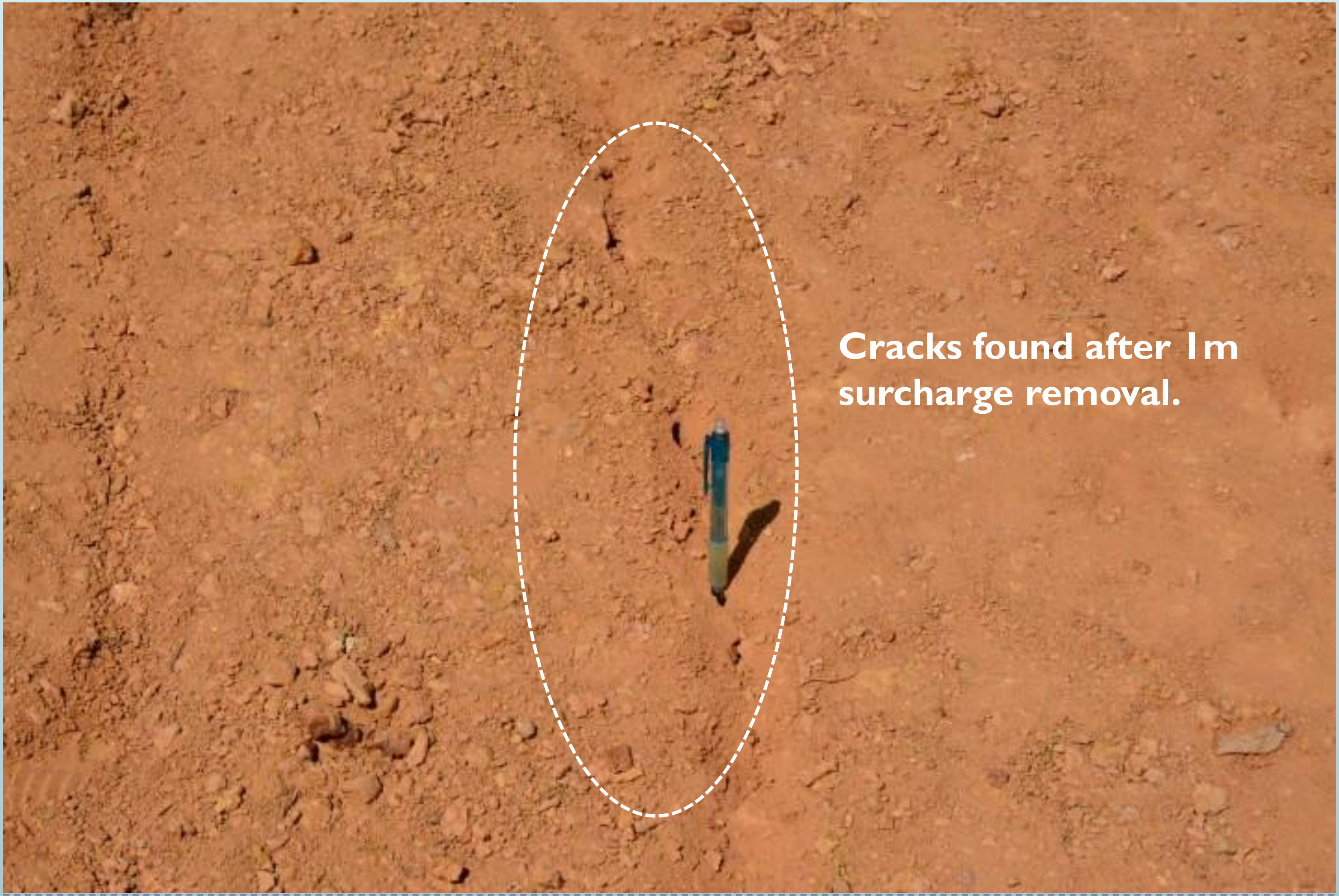
Embankment Distresses

Embankment Distresses



Embankment Distresses

Embankment Distresses

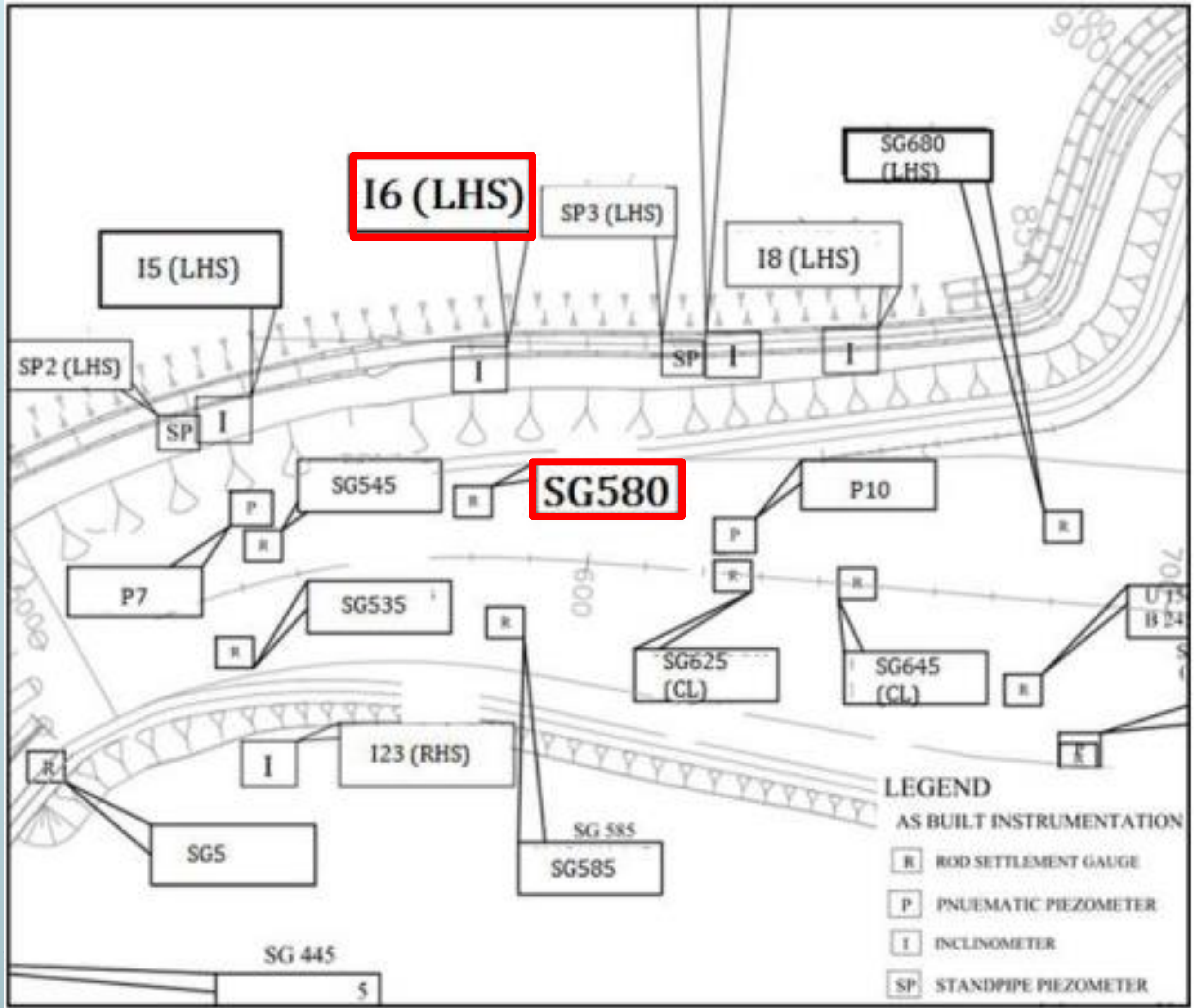


Embankment Distresses

Excavation on cracks found after 1m surcharge removal

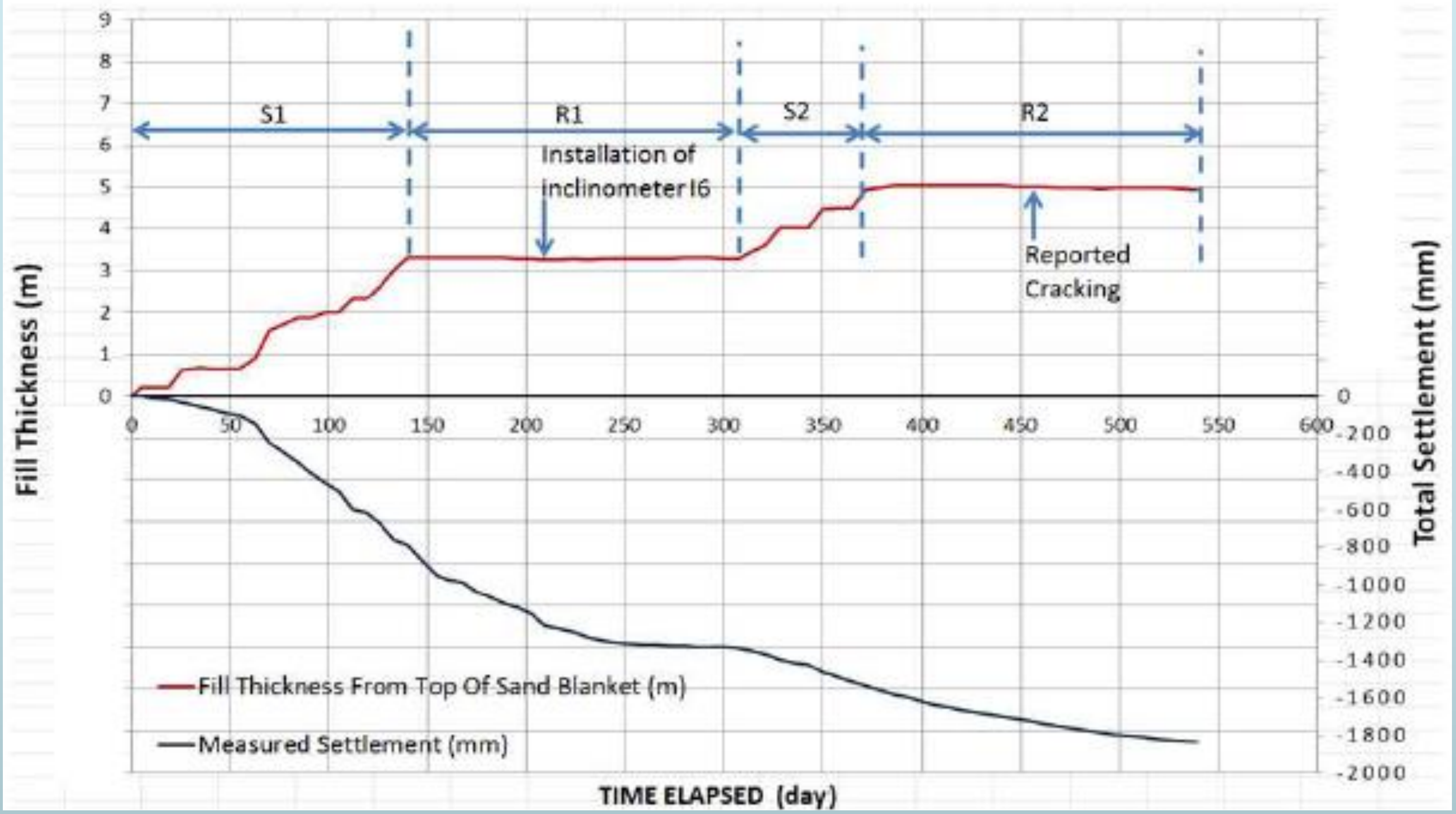
Instrumentation Layout

Instrumentation Layout Plan at Distresses area

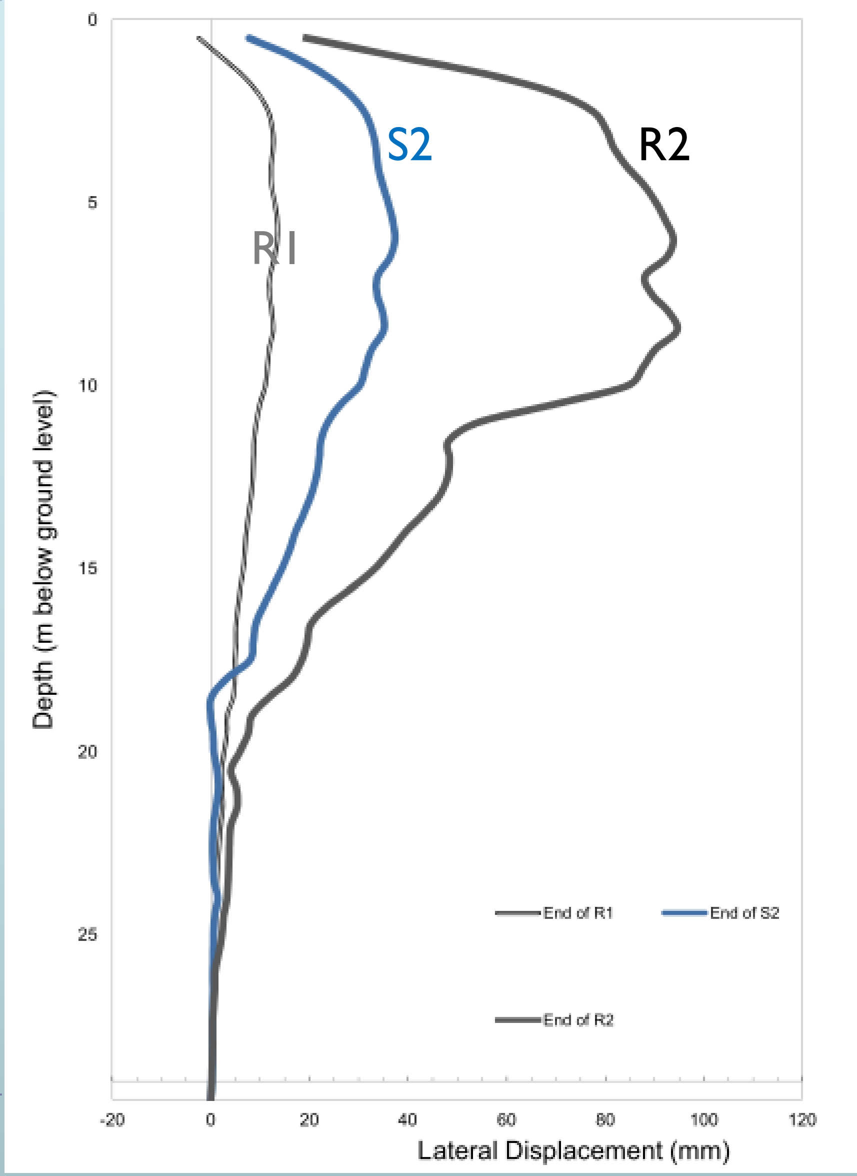


Instrumentation Results

Fill Thickness and Settlement of Embankment with time monitoring by SG580

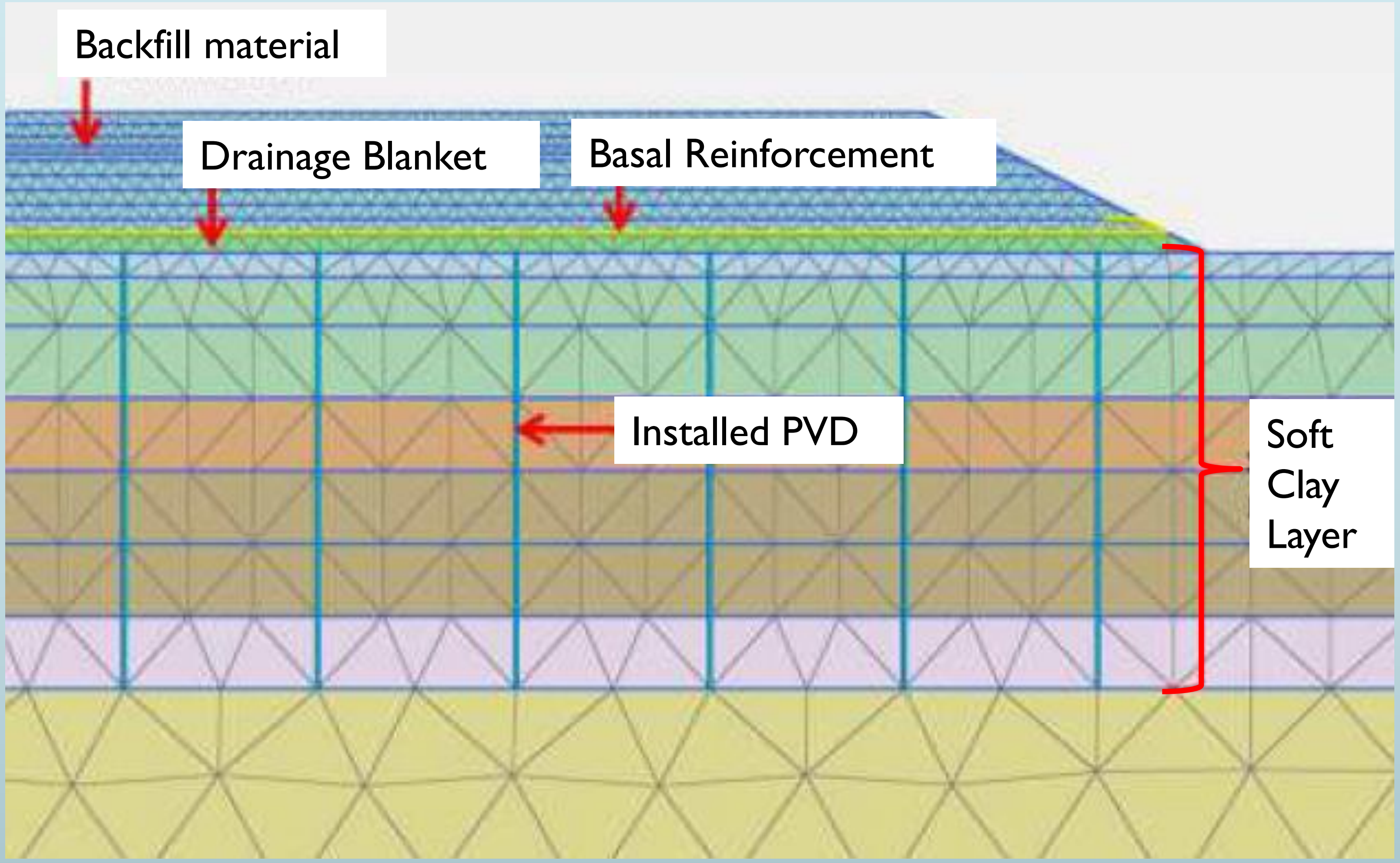


Instrumentation Results



Inclinometer I6 Monitoring Results

Finite Element Model



Finite Element Model

Back analysis to match lateral deformation and settlement profiles.

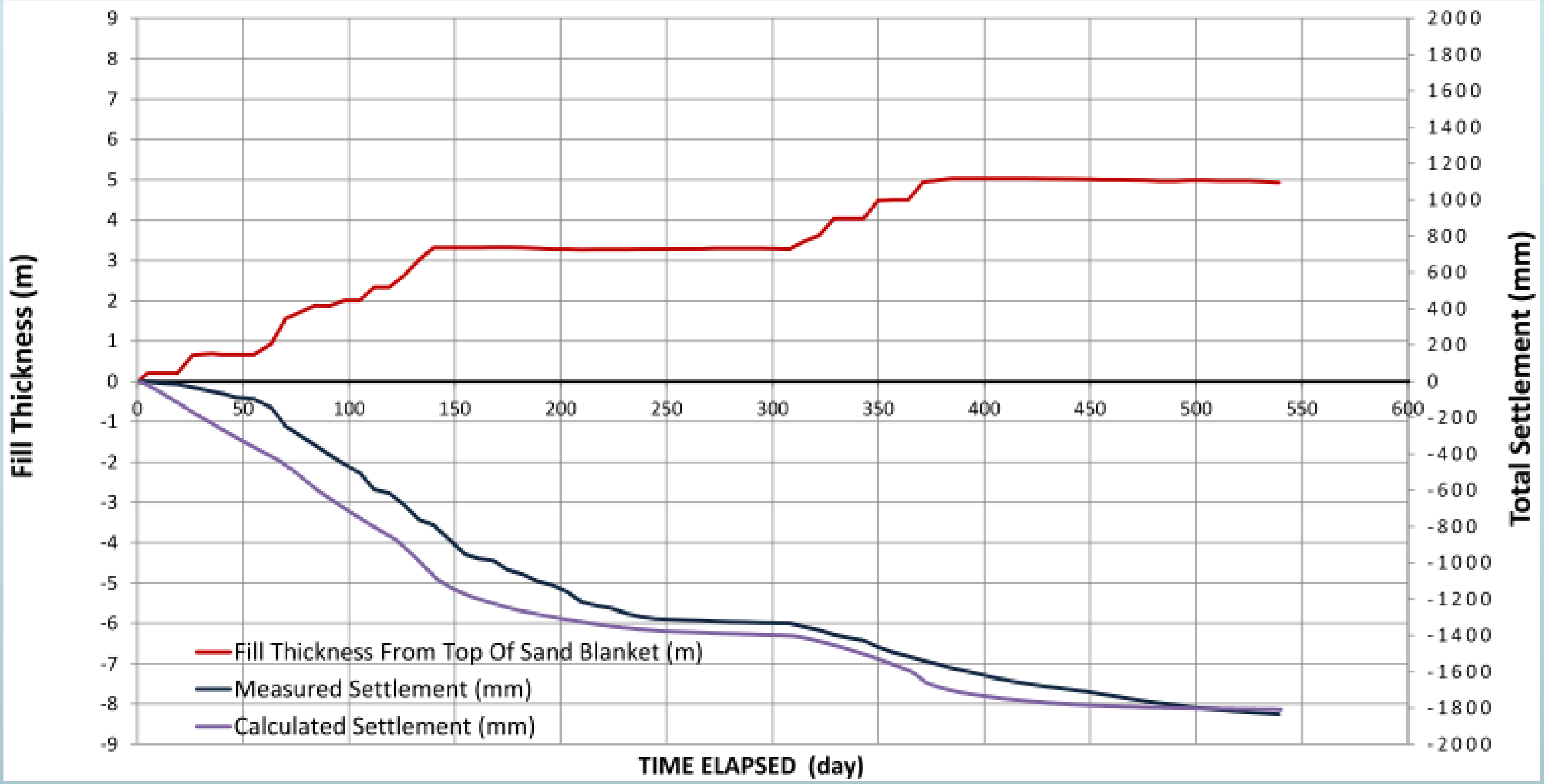
Two cases were modelled for back analysis:-

Case 1: Ultimate strength (600kN/m) mobilized at 10%

Case 2: Ultimate strength (140kN/m) mobilized at 1%

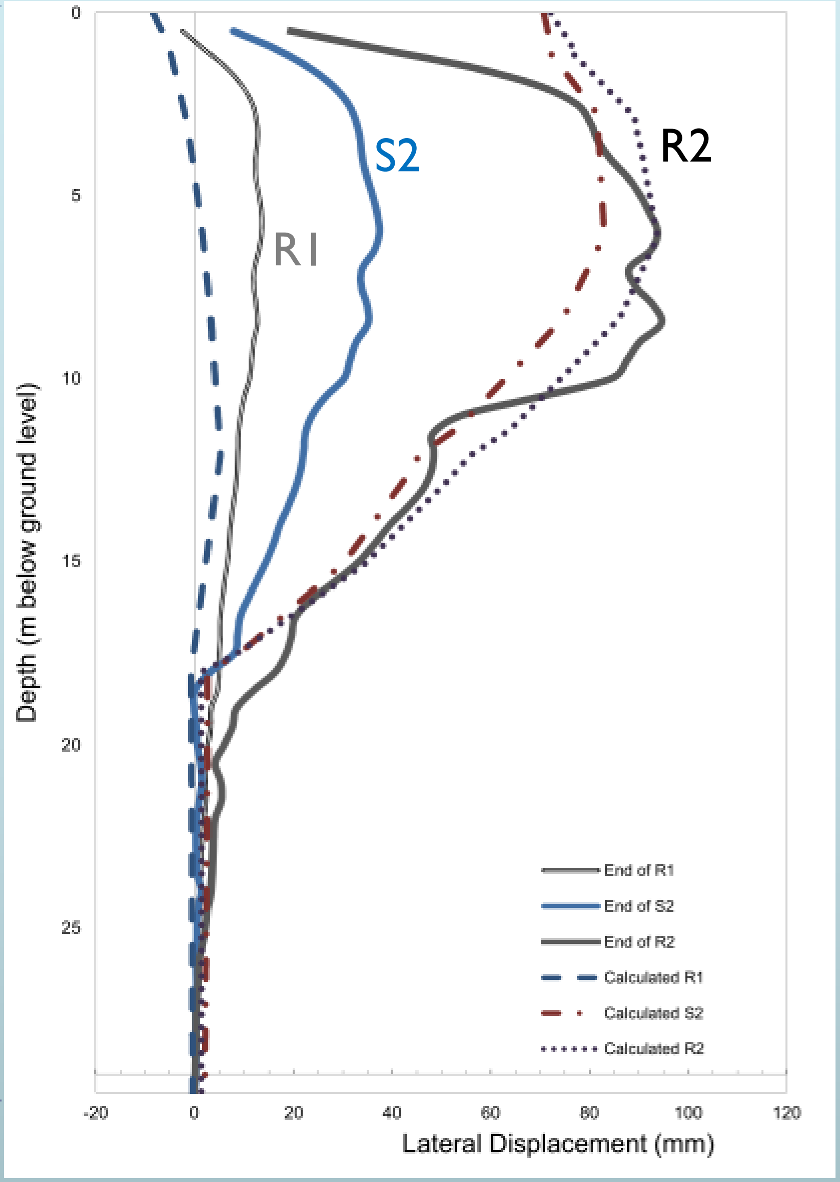
Finite Element Model

Comparison of Back Analysed Settlement Trend With Actual Measurement (Case 1)



Finite Element Model

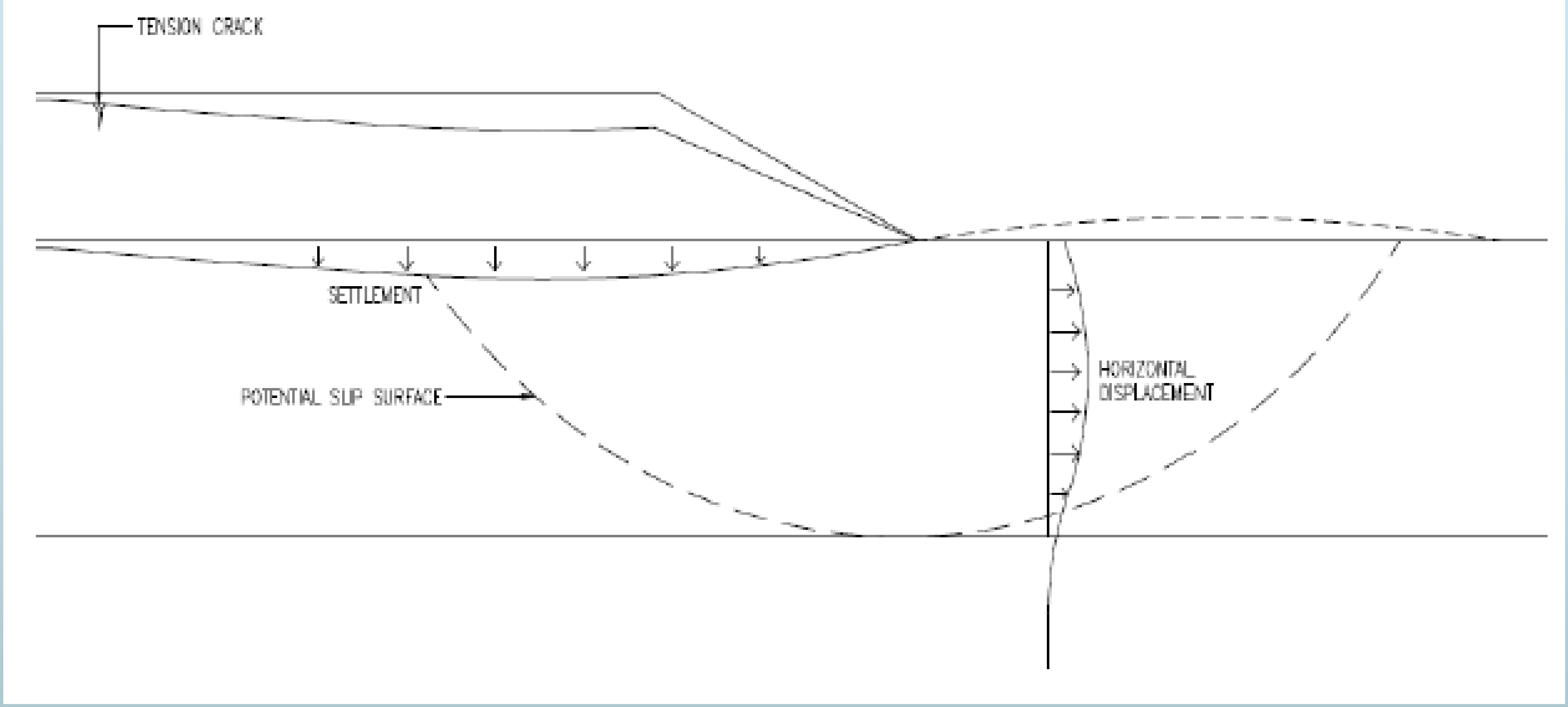
Comparison of Lateral Displacement Profile (Case 1)



Summary of Back Analyses

Stage	Tensile Stiffness	Mobilised Tensile Load / Tensile Strain	Maximum Lateral Deflection at Edge of Embankment (mm)
S1	Case 1 Case 2	40.6kN/m / 0.68% 65.9kN/m / 0.47%	267 (173)
R1	Case 1 Case 2	41.8kN/m / 0.70% 67.4kN/m / 0.48%	295 (180)
S2	Case 1 Case 2	64.6kN/m / 1.08% 106.8kN/m / 0.76%	400 (253)
R2	Case 1 Case 2	67.4kN/m / 1.12% 110.3kN/m / 0.79%	425 (265)

Probable Mechanism



Discussion

- Strain incompatibility between basal reinforcement and embankment fill could potentially cause embankment cracking.
- Average tensile strain of underlying weak subsoils is more than max. tensile strain in basal reinforcement.
- Results of back-analysis ➔ indicated mobilised tensile strength and strain < conventional assumed values for LEA stability analysis.

Conclusion

- Longitudinal cracks → Outcome of plastic straining of upper weak alluvium within the underlying subsoil below the embankment loading.
- Review on current design practice by arbitrarily adopting unrealistic high mobilised strength is needed.
- Wishful high tensile strain assumed in LEA can lead to misrepresentation on safety margin of embankment.

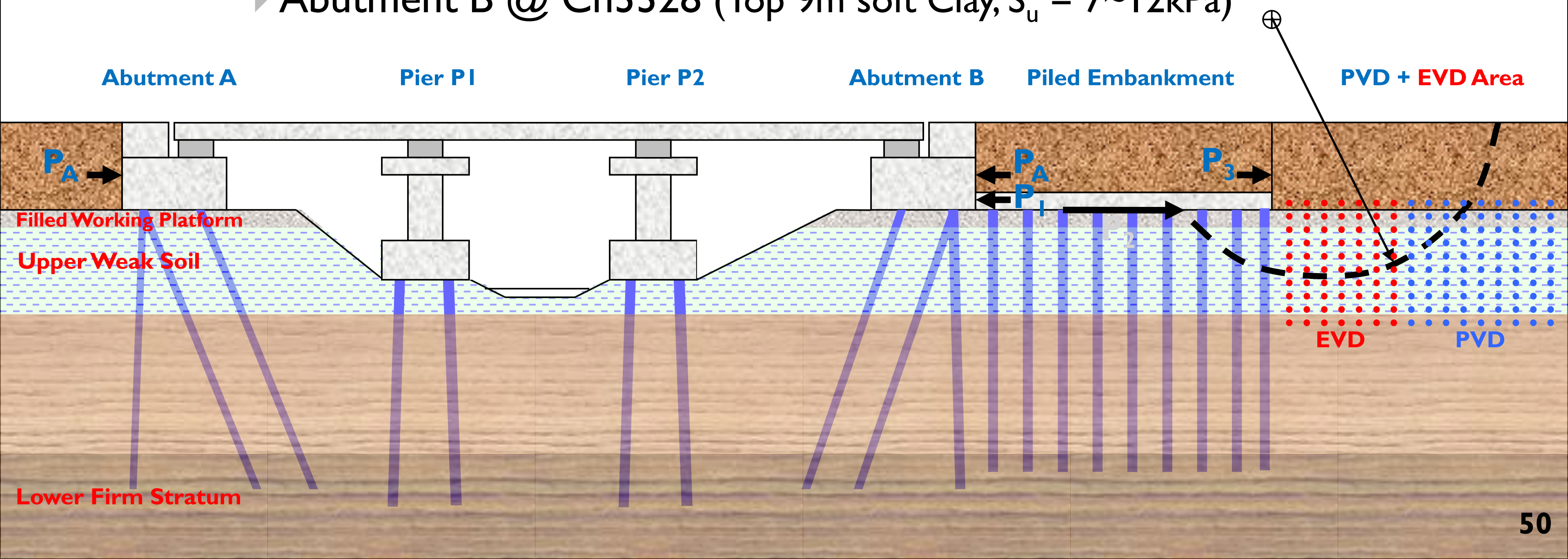
Recommendations

- Counterweight berm was proposed to solve the strain incompatibility between basal reinforcement and the subsoil.
- Instrument on basal reinforcement to reveal the distribution profile and performance of installed basal reinforcement.

Case 2: Case study on Piled Supported Embankment Failure

Site Conditions

- Embankment (maximum 5.4m high) with Piles & Ground Improvements
  - Ch3328 to Ch3375 (Top 10m soft Clay, S_u = 10~15kPa)
- Distressed Abutment
  - Abutment A @ Ch3266 (Top 15m soft Clay, S_u = 13~18kPa)
  - Abutment B @ Ch3328 (Top 9m soft Clay, S_u = 7~12kPa)



Findings from Site Inspection

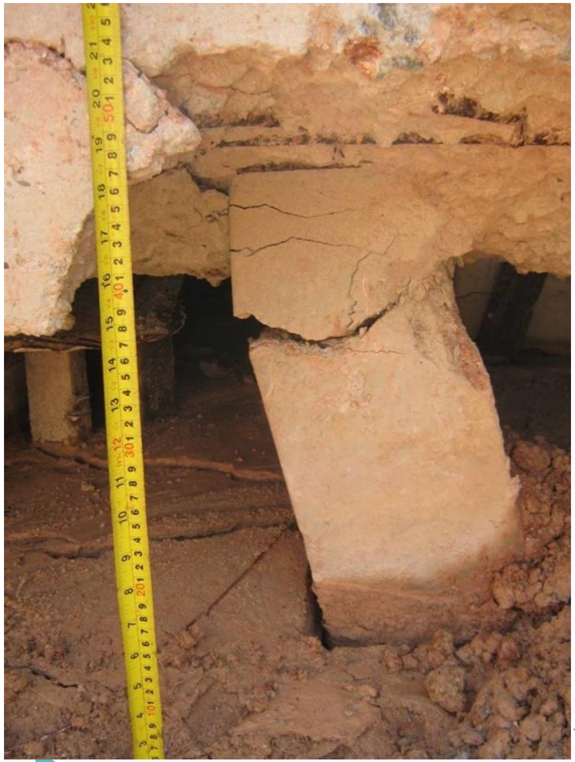
- Piles & slab of piled embankment suffered structural distress
- Settlement of 0.4 to1.0m beneath piled embankment due to consolidation of subsoils under the working filled platform.
- Bearing distortions confirmed : Bridge deck moving from Abutment B towards Abutment A

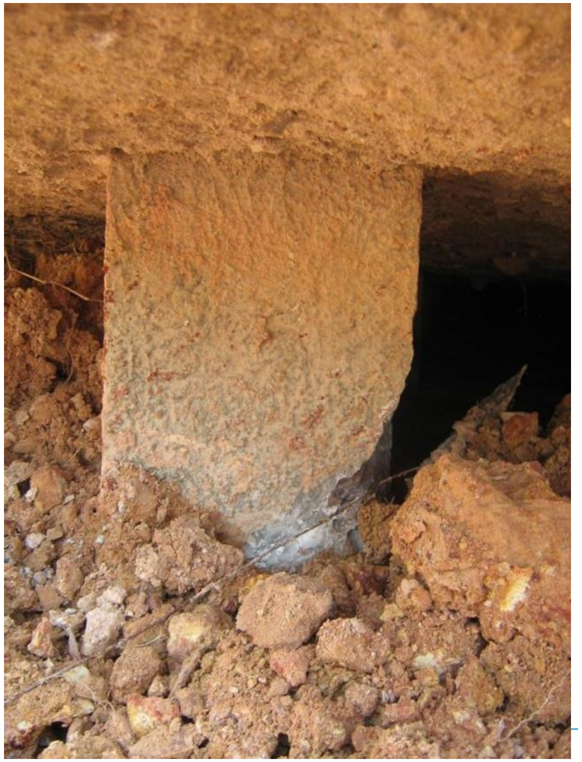
Site Inspection Findings

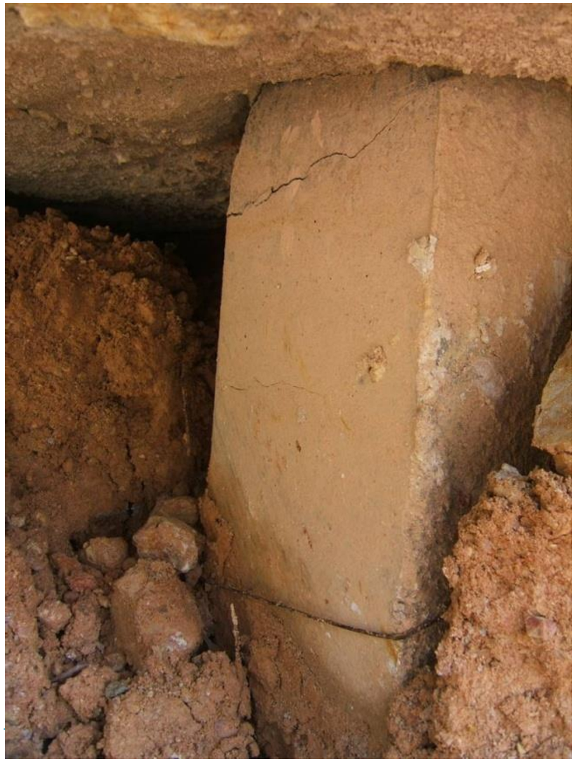
- Piled Embankment 30m from Abutment B shown structural distress

Site Inspections Findings

- Piles of Piled Embankment has shown flexural cracks







Site Inspections Findings

- Damaged piled embankment slab damaged & 100mm gap at slab joint

Site Inspections Findings

- Settlement of 0.4 to 1.0m under the Piled Embankment

Site Inspections Findings

- Bearing distortion at Pier P2

Site Inspections Findings

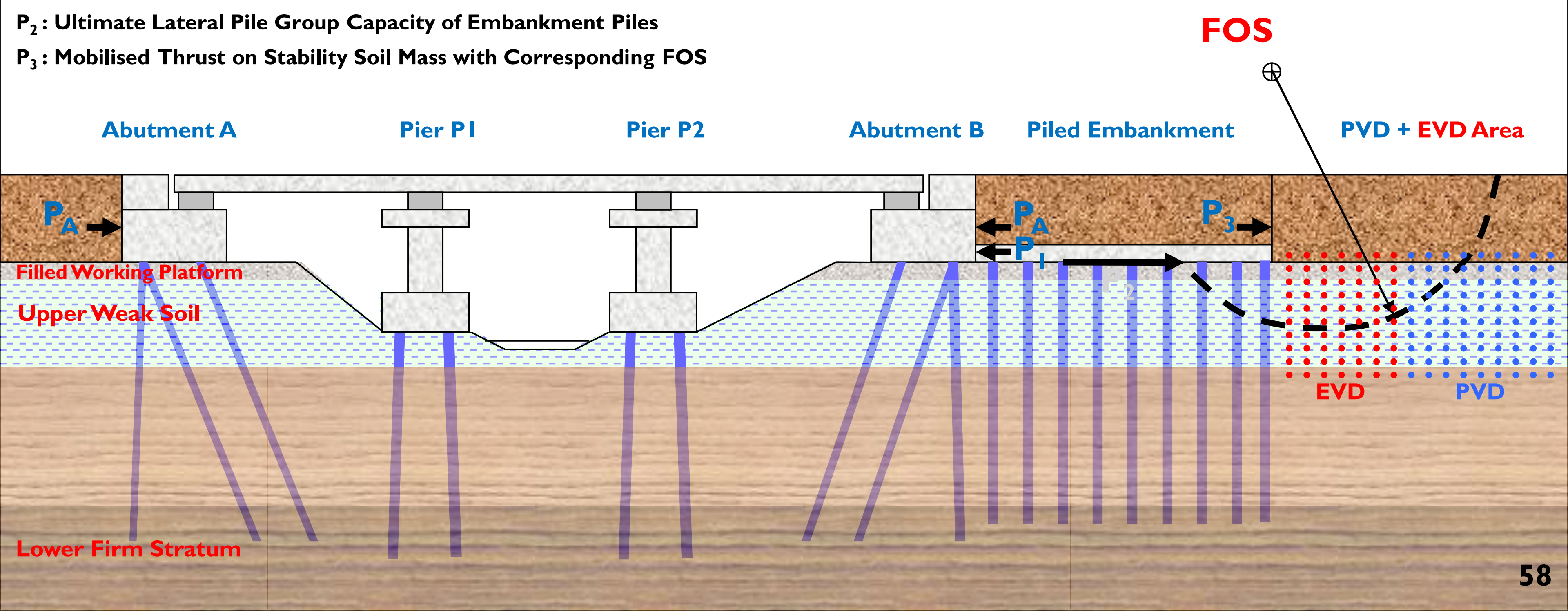
- Bearing distortion at Pier P1

P_A : Active Earth Pressure

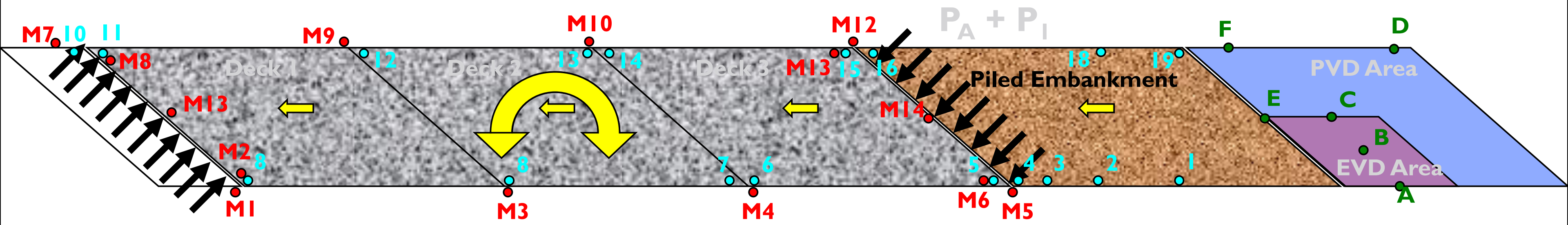
P_1 : Action/Reaction Force between Piled Embankment Slab & Abutment

P_2 : Ultimate Lateral Pile Group Capacity of Embankment Piles

P_3 : Mobilised Thrust on Stability Soil Mass with Corresponding FOS



- Settlement Markers (LDC) : 28 May -31 Jul 2005
- Displacement Markers (by LDC) : 02 Mar – 18 Jun 2006
- Displacement Markers (by G&P) : 25 Apr – 7 May 2007



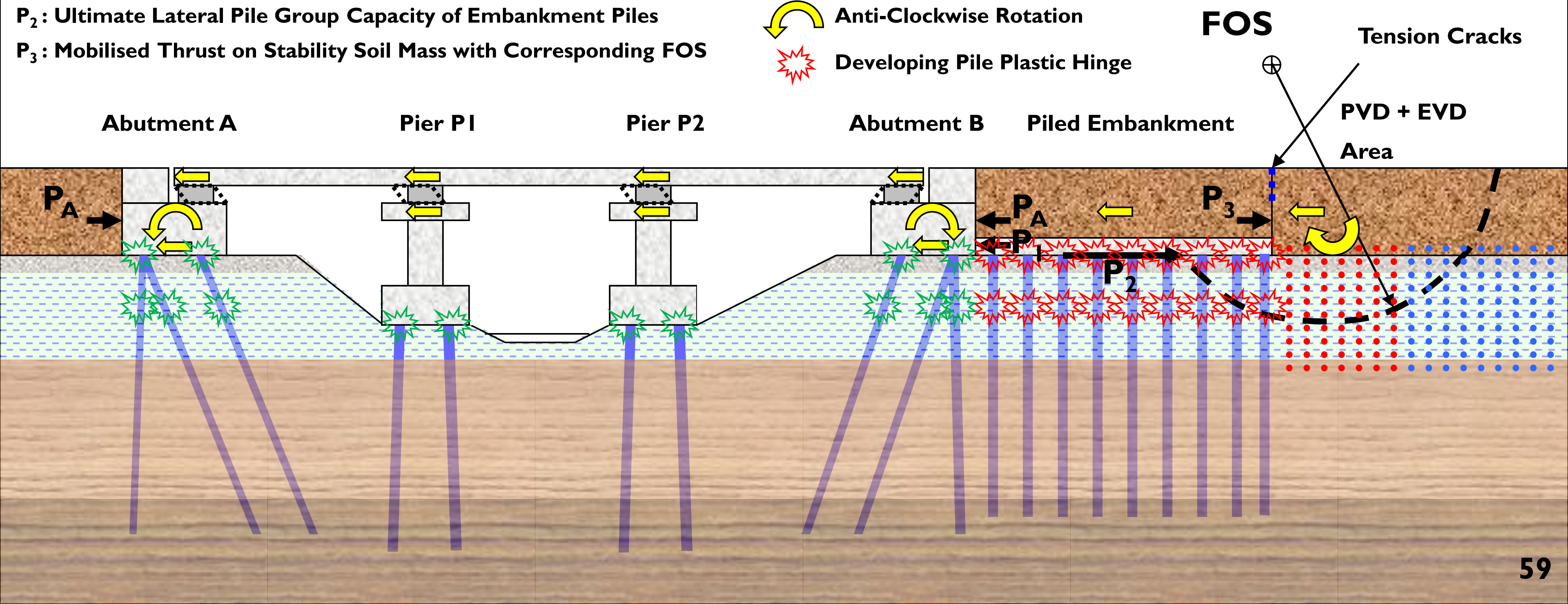
P_A : Active Earth Pressure

P_I : Action/Reaction Force between Piled Embankment Slab & Abutment

P_2 : Ultimate Lateral Pile Group Capacity of Embankment Piles

P_3 : Mobilised Thrust on Stability Soil Mass with Corresponding FOS

- Movement Direction
- Bearing Distortion
- Clockwise Rotation
- Anti-Clockwise Rotation
- Developing Pile Plastic Hinge

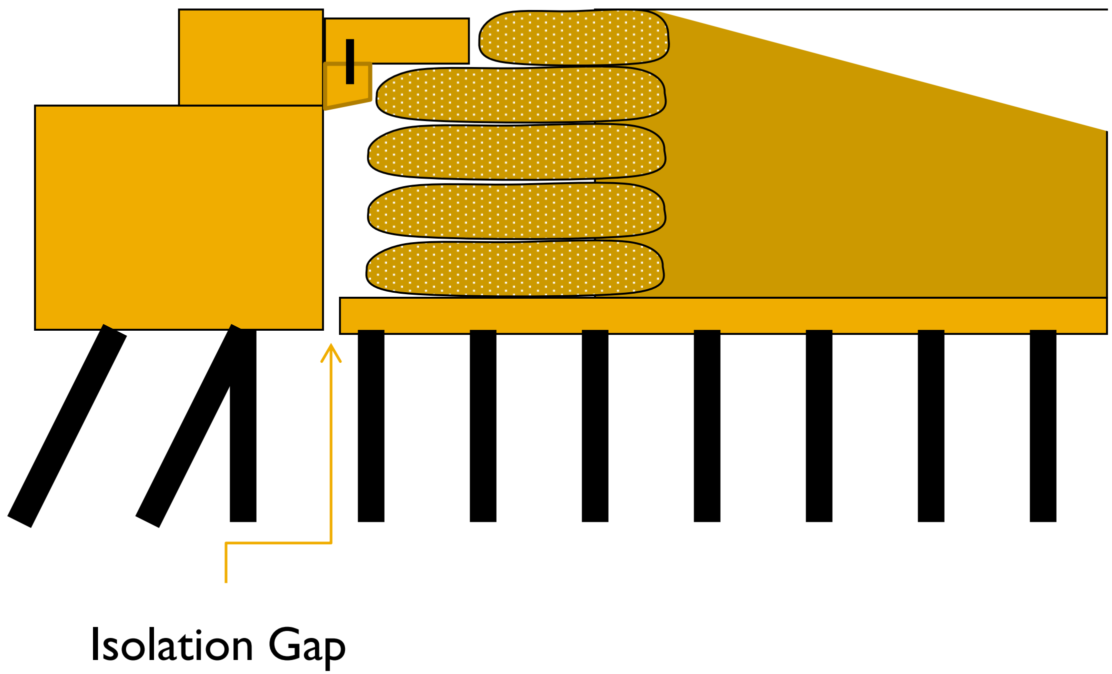


Investigation Findings

- Embankment (5.4m high)
  - Ch3375 : FOS ≅ 1.0 at Embankment on Ground Treatments
  - Causation : Inadequate FOS => Embankment instability exerting lateral stress to Piled Embankment on free standing piles due to subsoil consolidation
- Distressed Abutment
  - Abutment B : Laterally pushed by unstable embankment behind piled embankment
  - Abutment A & Two piers : Affected by lateral thrust from Abutment B (No observable distresses at the abutment pile foundation after exposure of piles)

Abutment Remedial Design

- Abutment Distress (Ch3266 to Ch3328)
  - Remedial proposal :



Conclusions

- Weak post-treatment soil strength unable to support embankment
- Creep movement of weak subsoil beneath embankment coupled with embankment instability due to low FOS
- Further consolidation of weak overburden soil, the lateral resistance of piled embankment in free standing pile conditions is weaken
- Monitored bridge displacement confirmed pattern of lateral movement of entire bridge & piled embankment
- Structural damage on embankment piles was expected as structural threshold has reached
- Use of residual strength is needed for rectifying failed embankment

Recommendations

- Construct new embankment slab at least 1m below the failed slab to prevent further consolidation settlement
- Extend piled embankment for embankment fill higher than 2m & provide isolation gap at the slab/abutment interfaces
- Use of higher strength RC pile for embankment piles
- Use of geotextile reinforcement to isolate embankment fill from both abutments to reduce direct lateral earth pressure on abutments

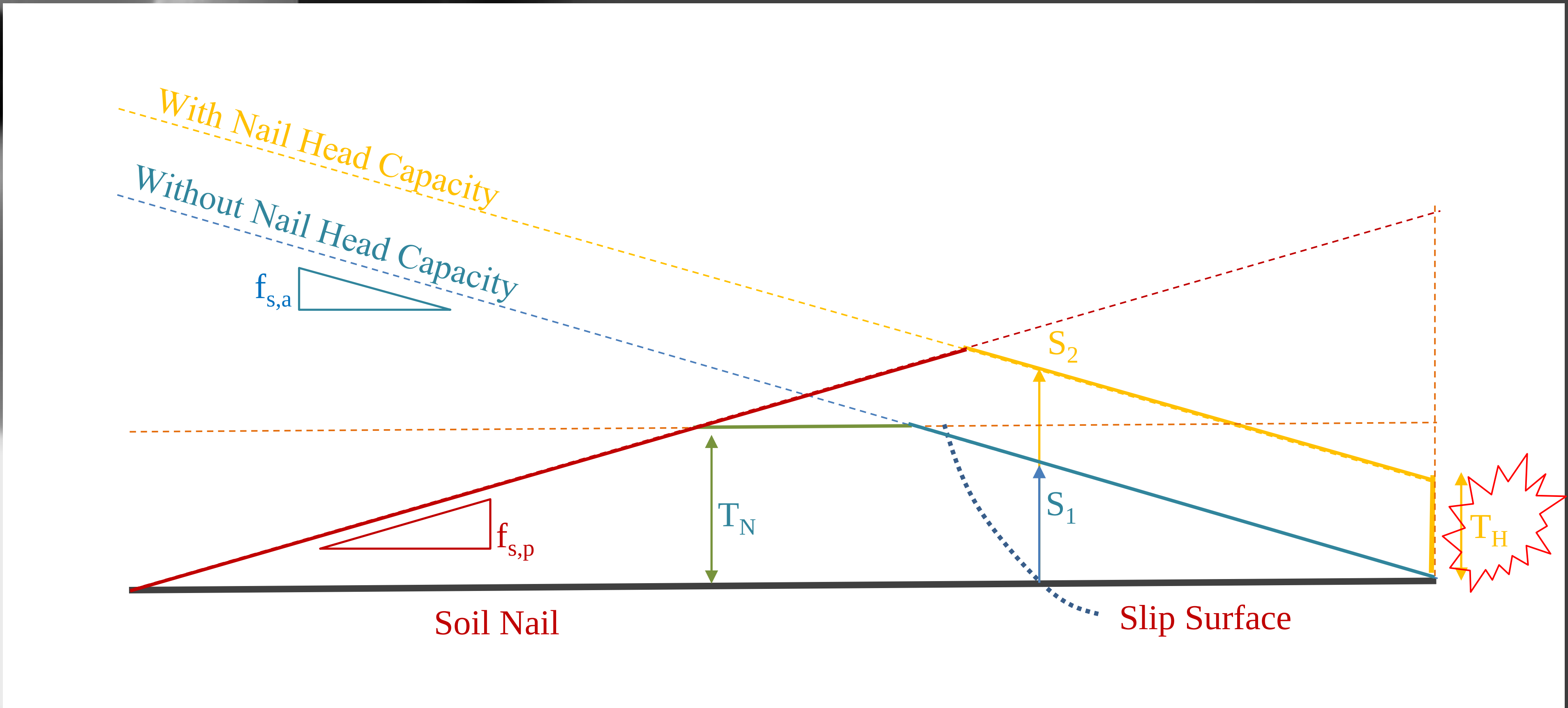
Unreliable Facing Capacity of Soil Nailed Slope

- With intention of minimized earthwork cutting forming any platform, soil nailed slope profile is normally steep
- Facing capacity has remarkable effect on Internal Stability of steep soil nailed slope
- Volumetric swelling & shrinkage of soils with moisture variation are realistic observation
- Moisture depletion after covering with shotcrete surface results in volumetric shrinkage of slope soil face leaving air gap with separation of contact with shotcrete
- Mobilisation of face capacity in uncontacted slope surface is unrealistic, thus giving incorrect safety margin of slope stability

Volumetric Shrinkage of Exposed Soil

Gap below Shotcrete Surface with Depleting Moisture

Nail Force Diagram



Case Study 1 : Reduced Empty Pre-bored Jack-in Pile Capacity in Meta-Sedimentary Formation

- Overview of pile installation & Performance
- Subsurface Information
- Contractually Scheduled MLT Results
- Additional MLT Results
- Investigation Findings
- Conclusions & Recommendations

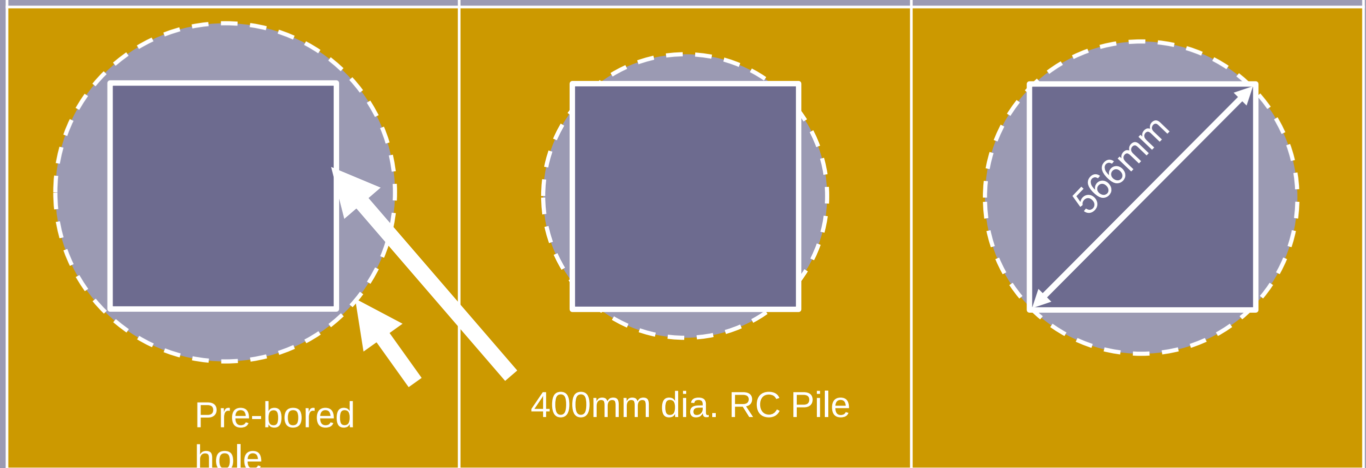
Overview Foundation System

- 400mm RC square pile

- Pre-boring was deployed to
  - Overcome intermittent hard layer
  - Avoid shallow pile penetration

- Jack-in pile installed inside pre-bored hole

Pre-bored Hole Diameter

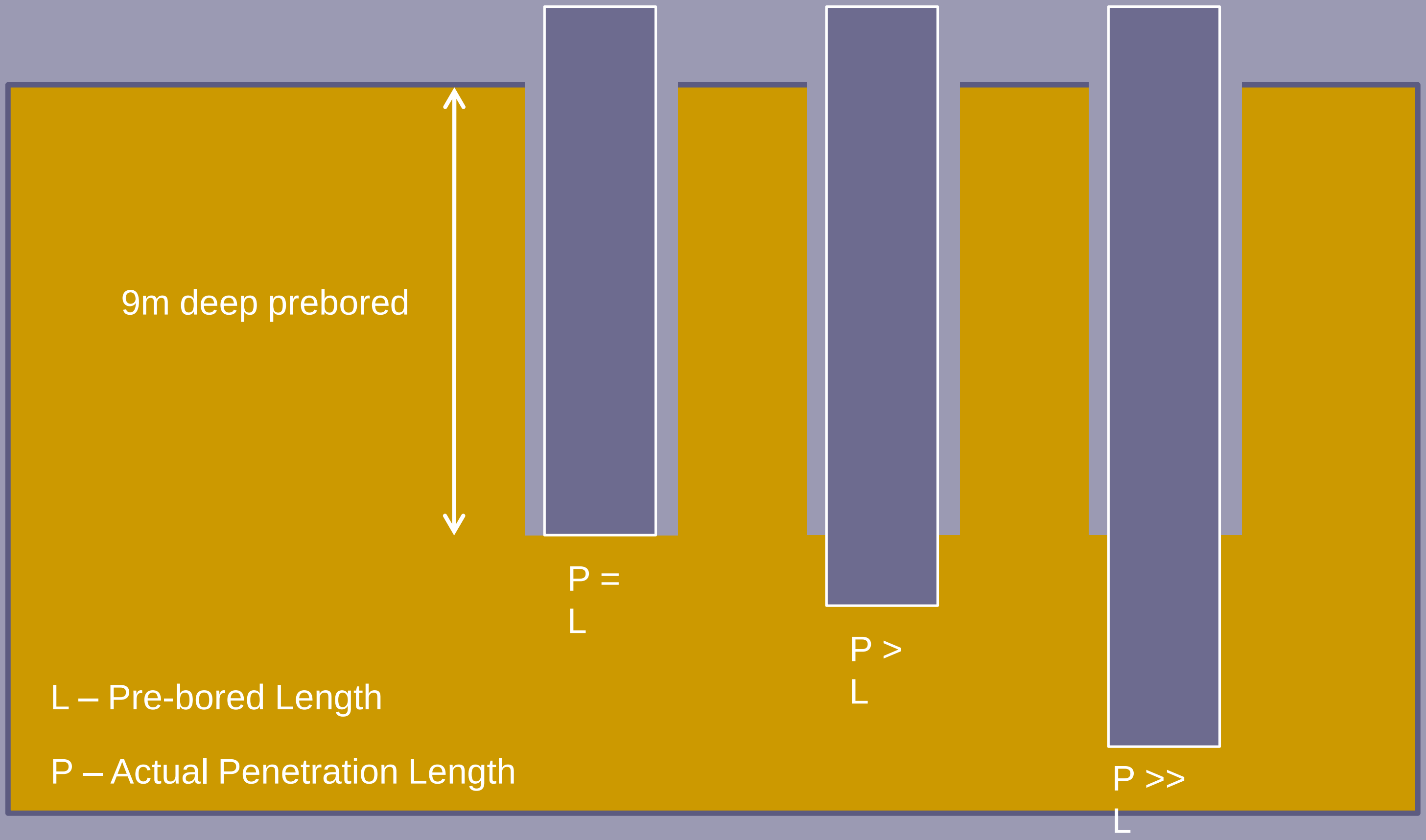


600mm diameter	500mm diameter	550mm diameter
Too large pre-bored hole	Too small pre-bored hole	Compromised pre-bored hole **(Adopted)**

Void in Pre-bored Hole Annulus

Collapsed Debris in Pre-bored Hole Annulus

Actual Scenario of Installed Piles



MLT Results

Maintained Load Test (MLT)	Pre-bored Diameter (mm)	Pile Penetration below Piling Platform (m)	Max. Jack-in Load at Termination (kN)	Achieved Maximum Test Load (kN)	Pile Top Settlement	
					At Working Load (mm)	At Max. Test Load (mm)
MLT 1	600	9.40	2160	2220 (1.71xWL)	14.0	46.00
MLT 2	500	9.30	2600	2220 (1.71xWL)	23.50	42.00
MLT 3	550	12.50	2860	2600 (2.00xWL)	5.80	21.80
MLT 4	550	9.50	2860	1406 (1.50xWL)	16.50	24.50
MLT 5	550	13.50	2860	1950 (1.50xWL)	8.50	13.00

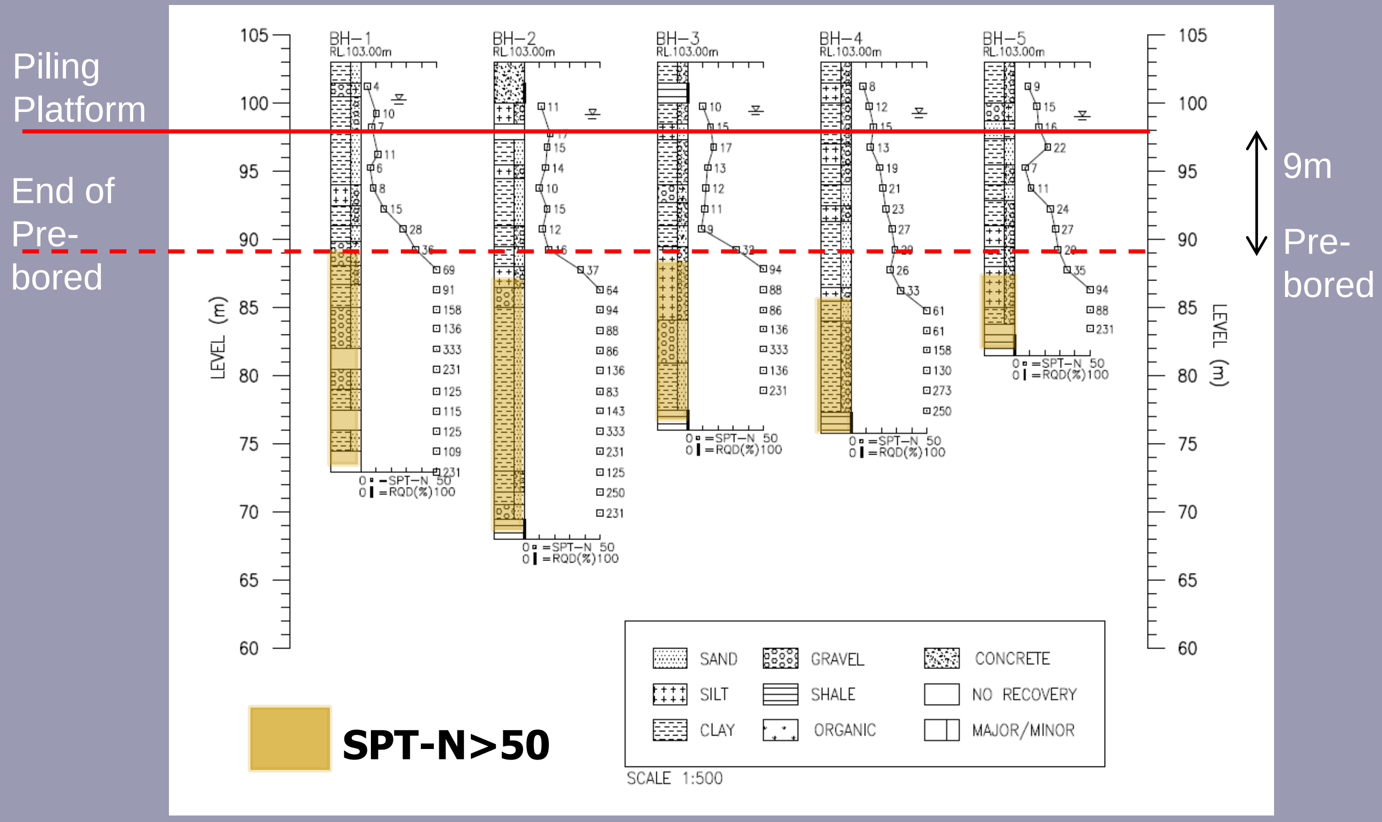
Jack-in Pile Termination Criteria

- All piles were jacked to 2.2 times pile working load
- Settlement < 5mm during 30 seconds holding period for 2 consecutive times

BUT

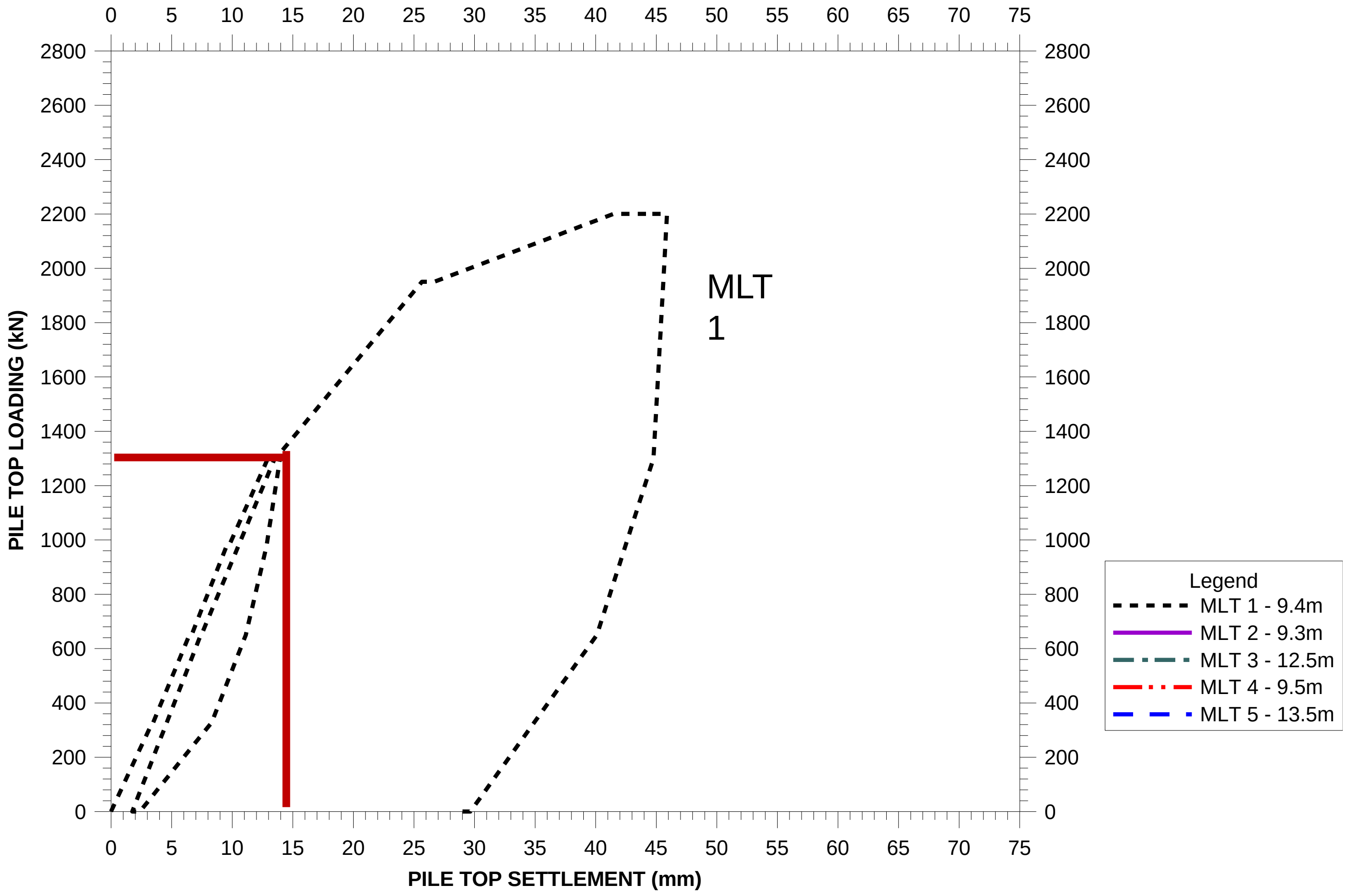
- **Max Test Load < Jack-in Load**
- **Non-conforming Piles Settlement Criteria**

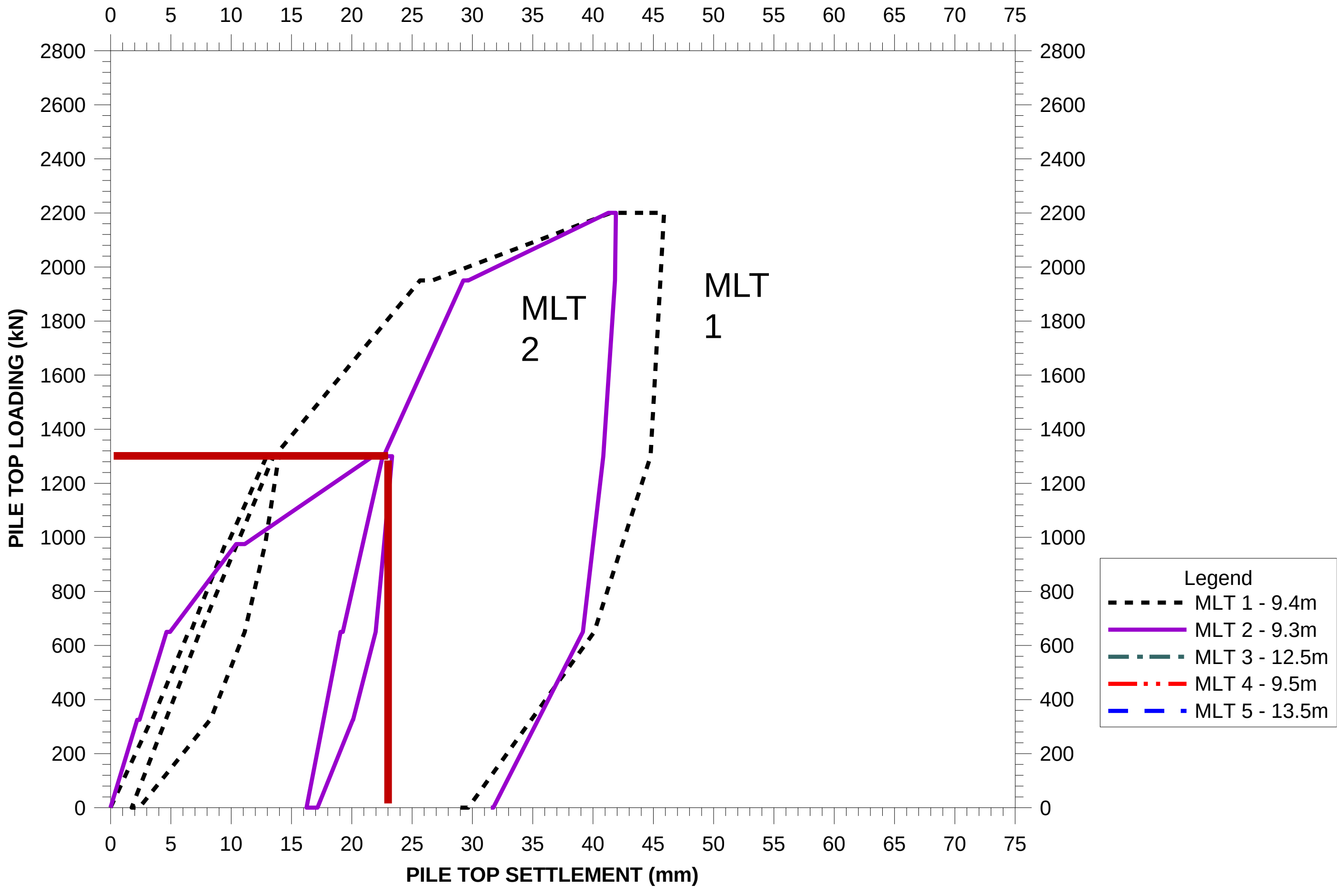
Boreholes Information



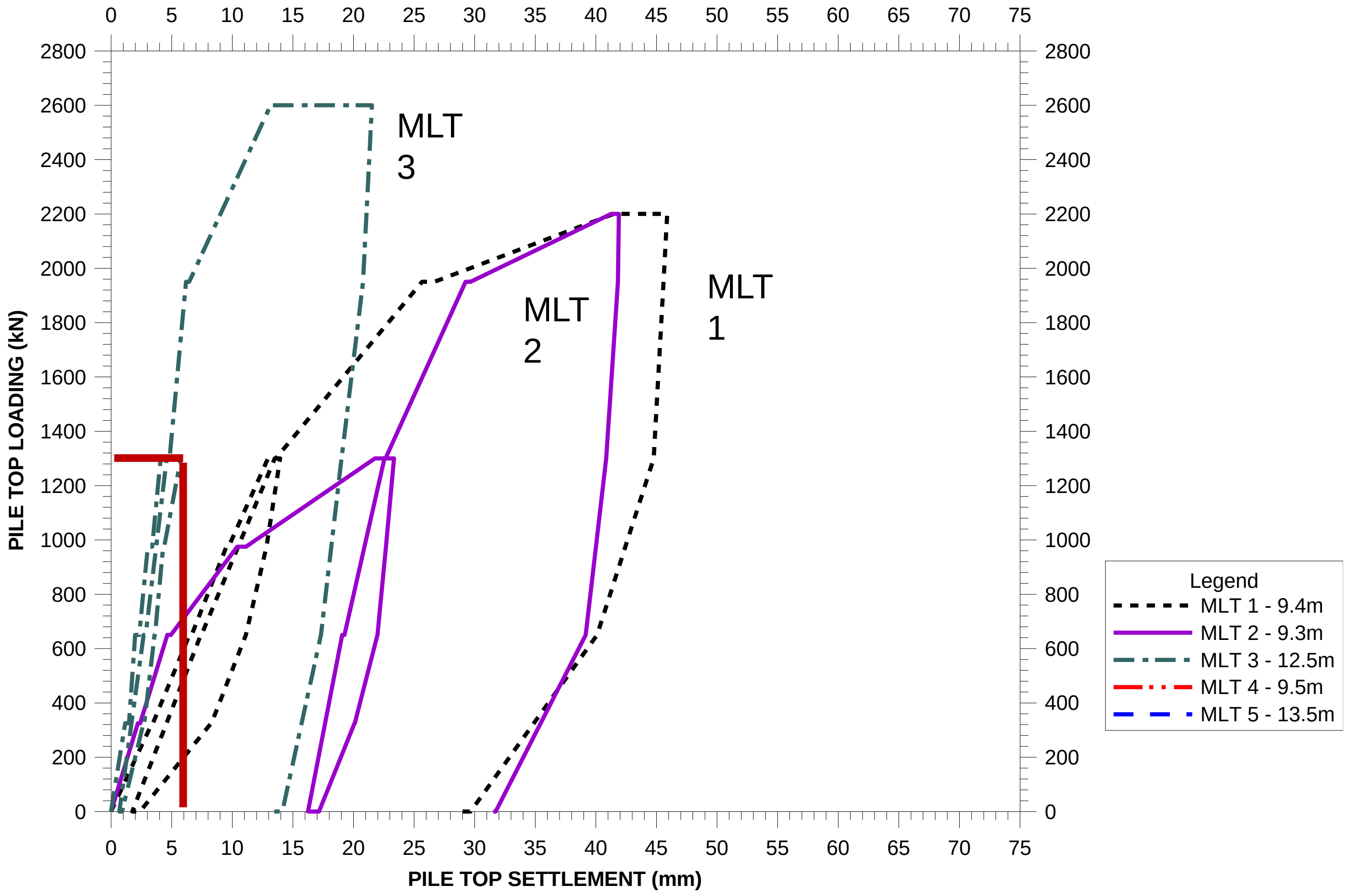
Photos of Exposed Subsoils

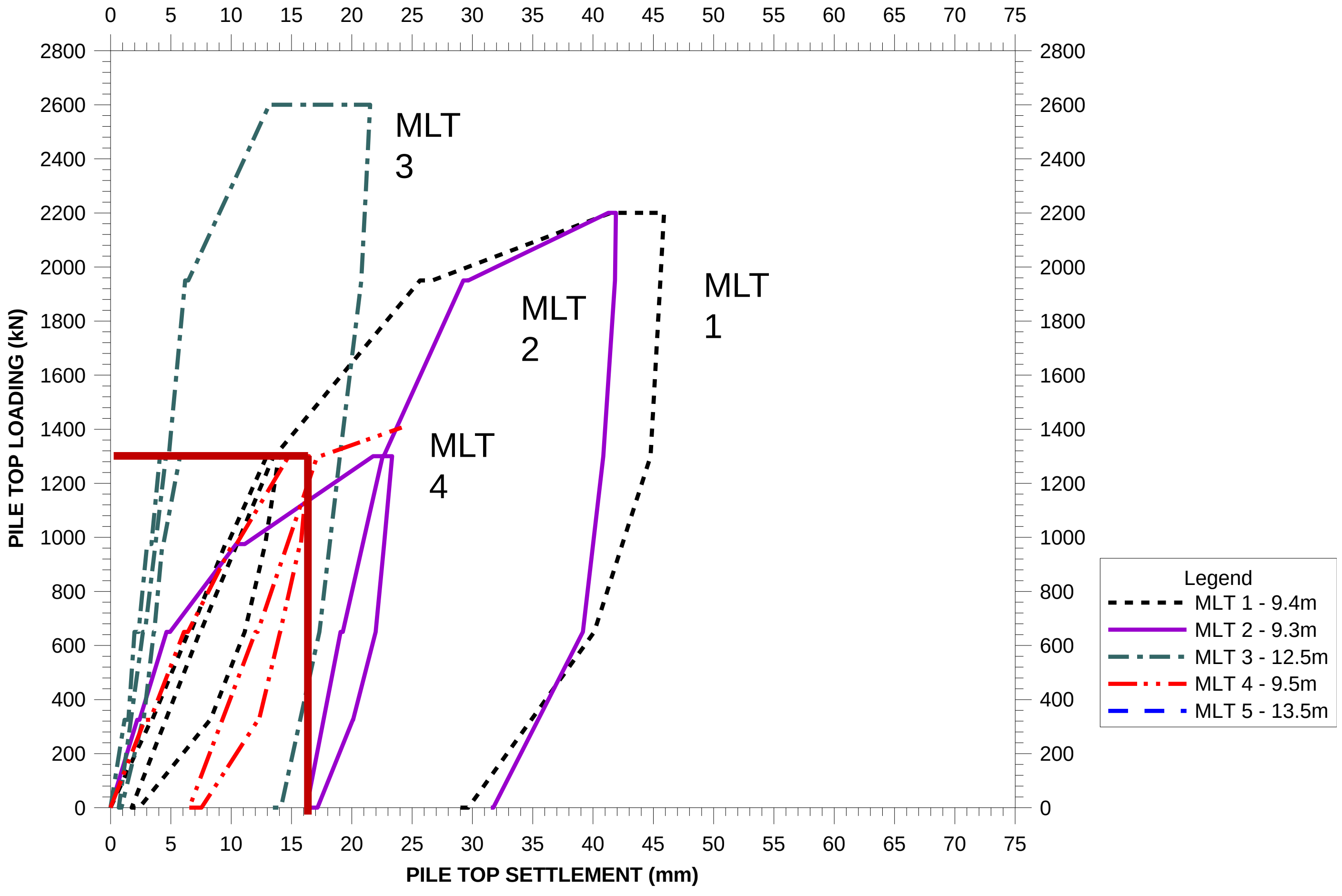
Contractually Scheduled MLT Results

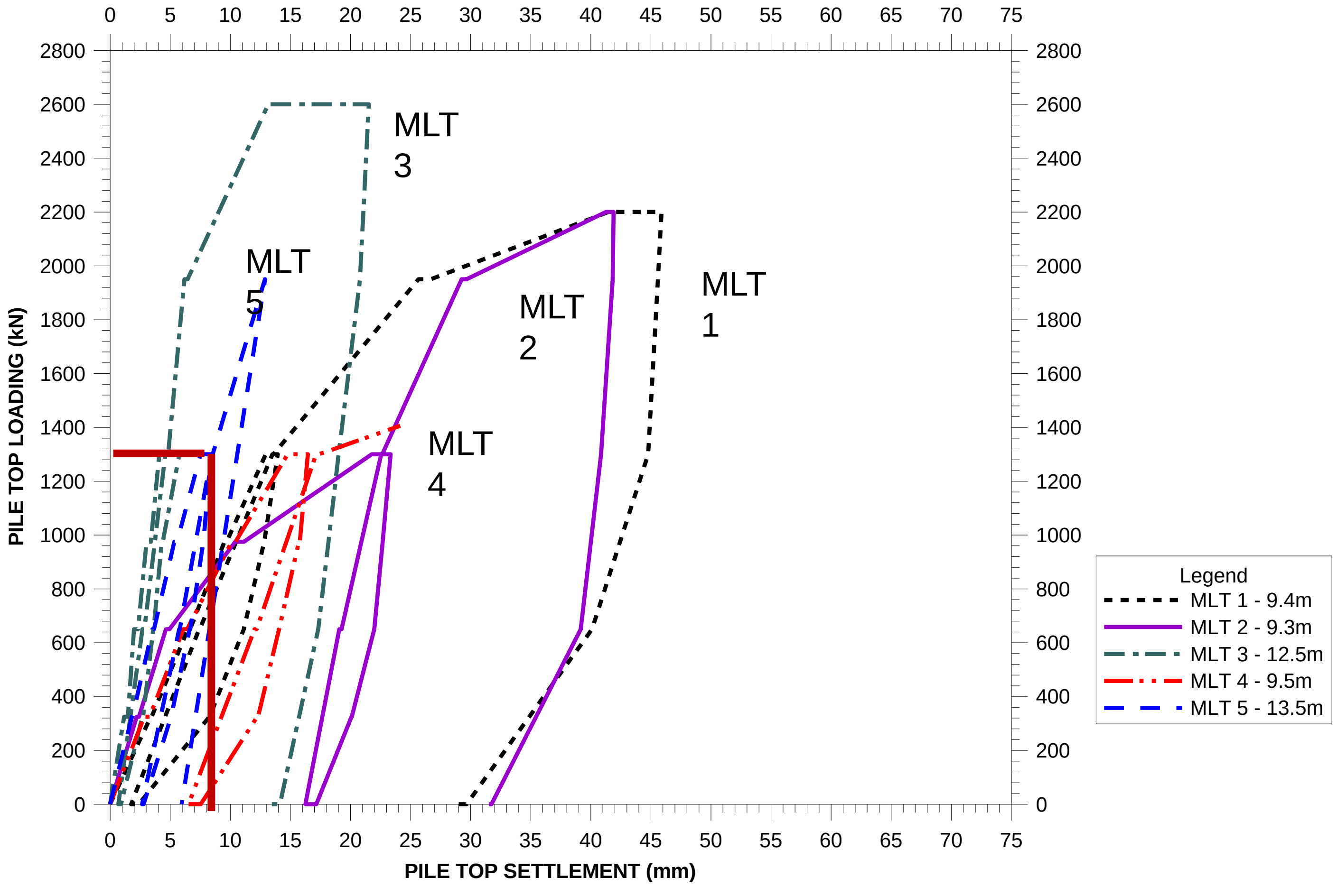

PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
MLT 1
Legend
MLT 1 - 9.4m
MLT 2 - 9.3m
MLT 3 - 12.5m
MLT 4 - 9.5m
MLT 5 - 13.5m



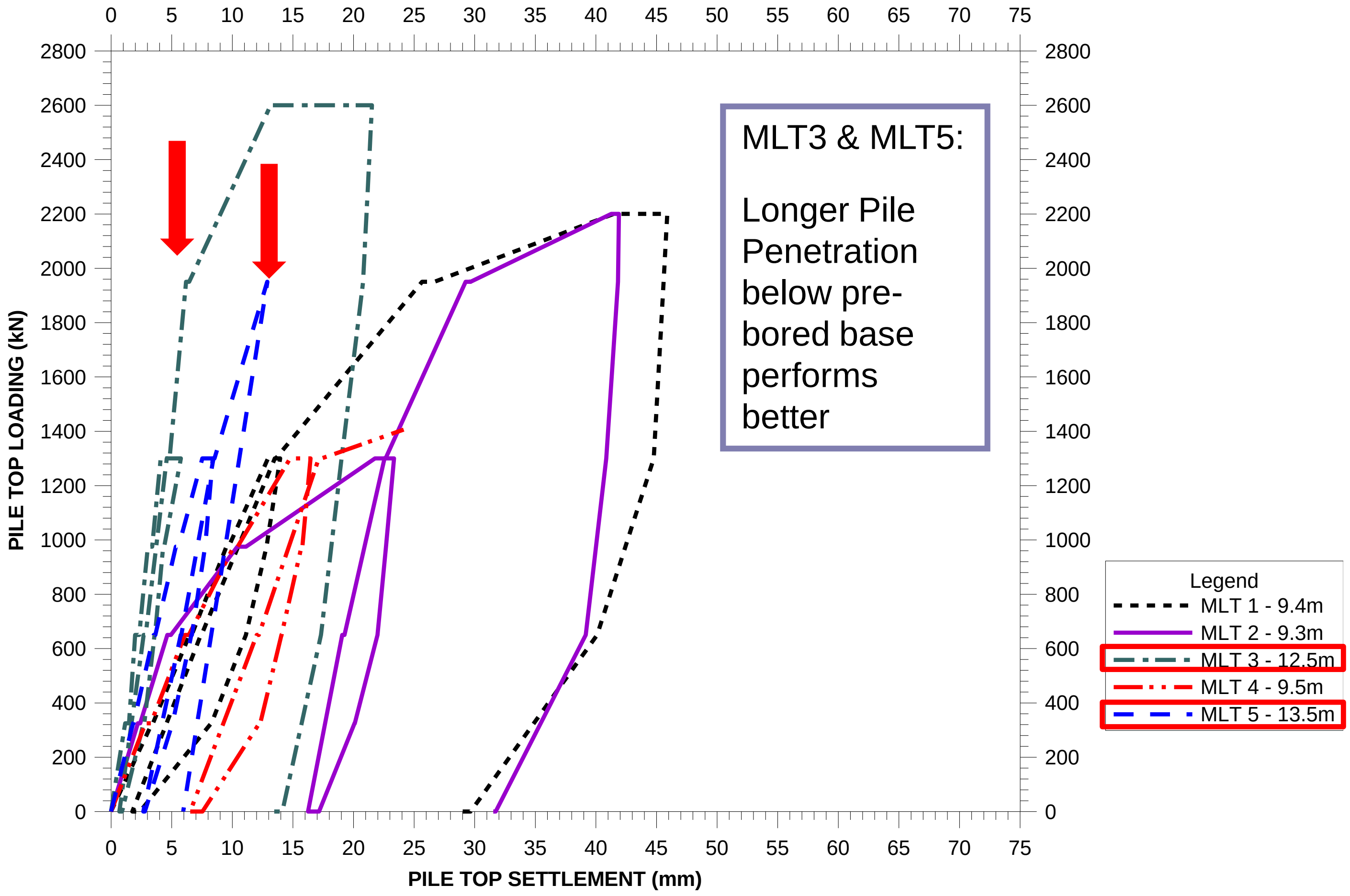
PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
MLT 2
MLT 1
Legend
MLT 1 - 9.4m
MLT 2 - 9.3m
MLT 3 - 12.5m
MLT 4 - 9.5m
MLT 5 - 13.5m


PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
MLT 3
MLT 2
MLT 1
Legend
MLT 1 - 9.4m
MLT 2 - 9.3m
MLT 3 - 12.5m
MLT 4 - 9.5m
MLT 5 - 13.5m


PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
MLT 3
MLT 1
MLT 2
MLT 4
Legend
MLT 1 - 9.4m
MLT 2 - 9.3m
MLT 3 - 12.5m
MLT 4 - 9.5m
MLT 5 - 13.5m



PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
MLT 1
MLT 2
MLT 3
MLT 4
MLT 5
Legend
MLT 1 - 9.4m
MLT 2 - 9.3m
MLT 3 - 12.5m
MLT 4 - 9.5m
MLT 5 - 13.5m



PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
MLT3 & MLT5:
Longer Pile Penetration below pre-bored base performs better
Legend
MLT 1 - 9.4m
MLT 2 - 9.3m
MLT 3 - 12.5m
MLT 4 - 9.5m
MLT 5 - 13.5m

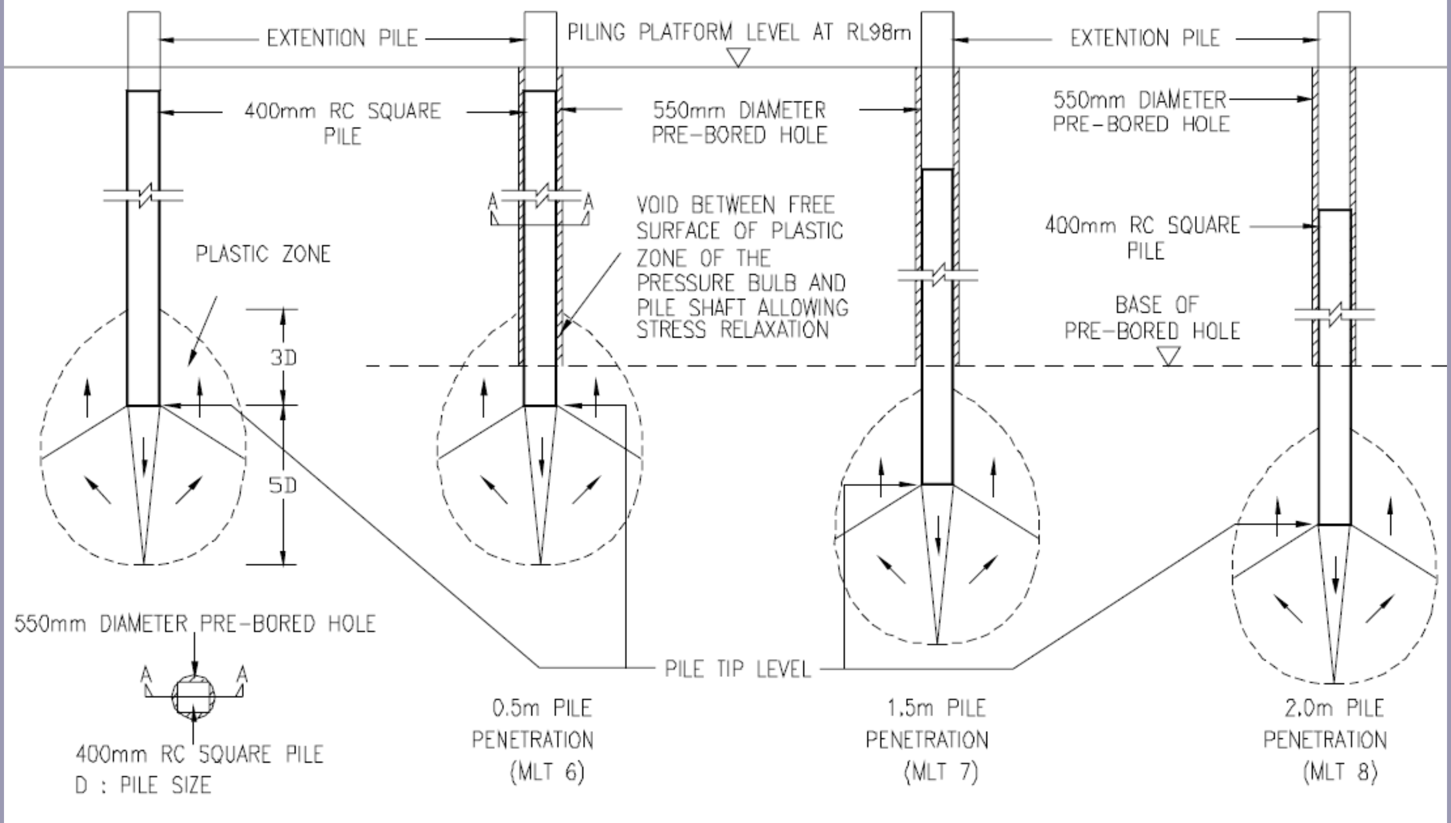
Additional MLT Results

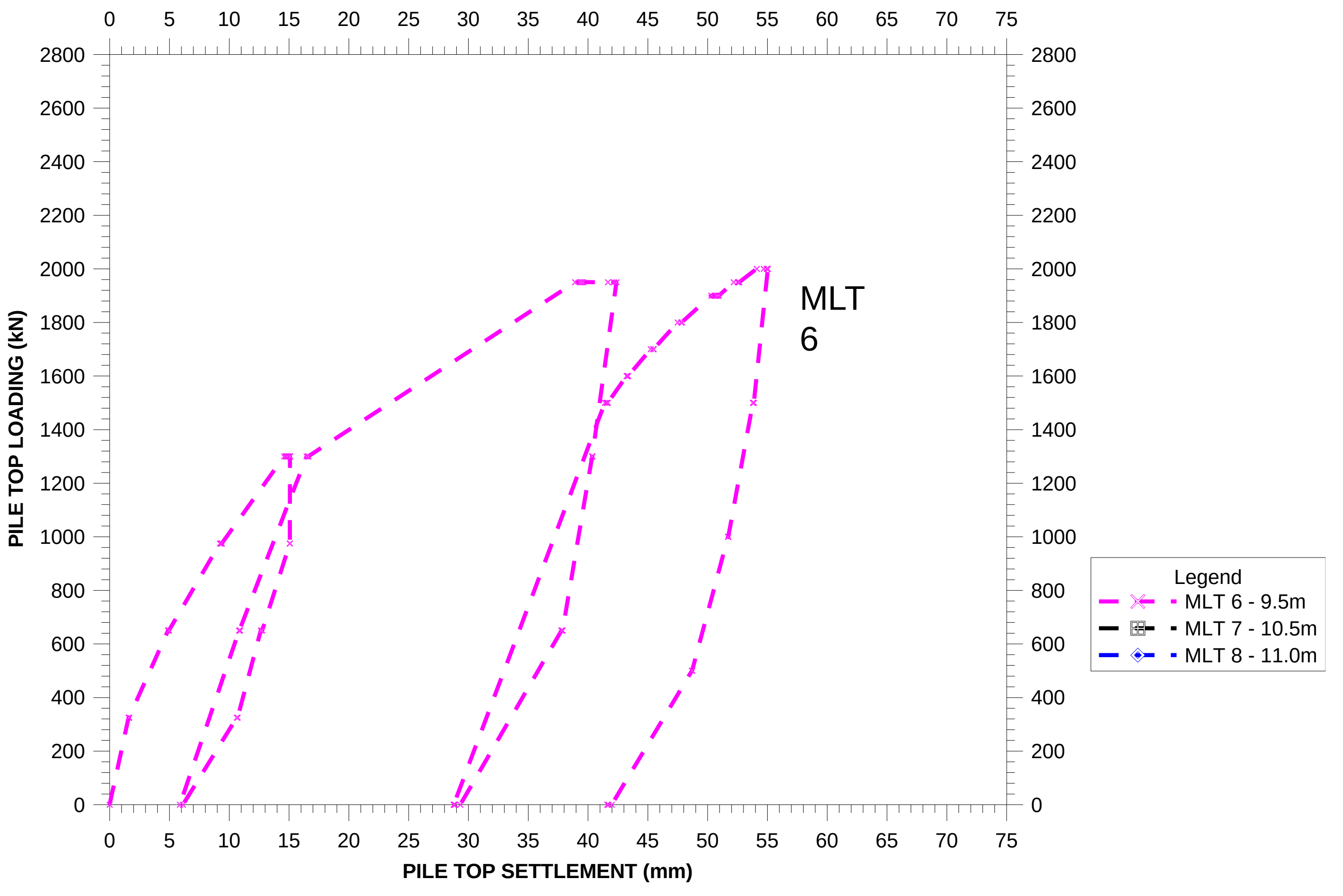
Additional MLT

- 3 nos additional MLT at various penetration below pre-bored base:

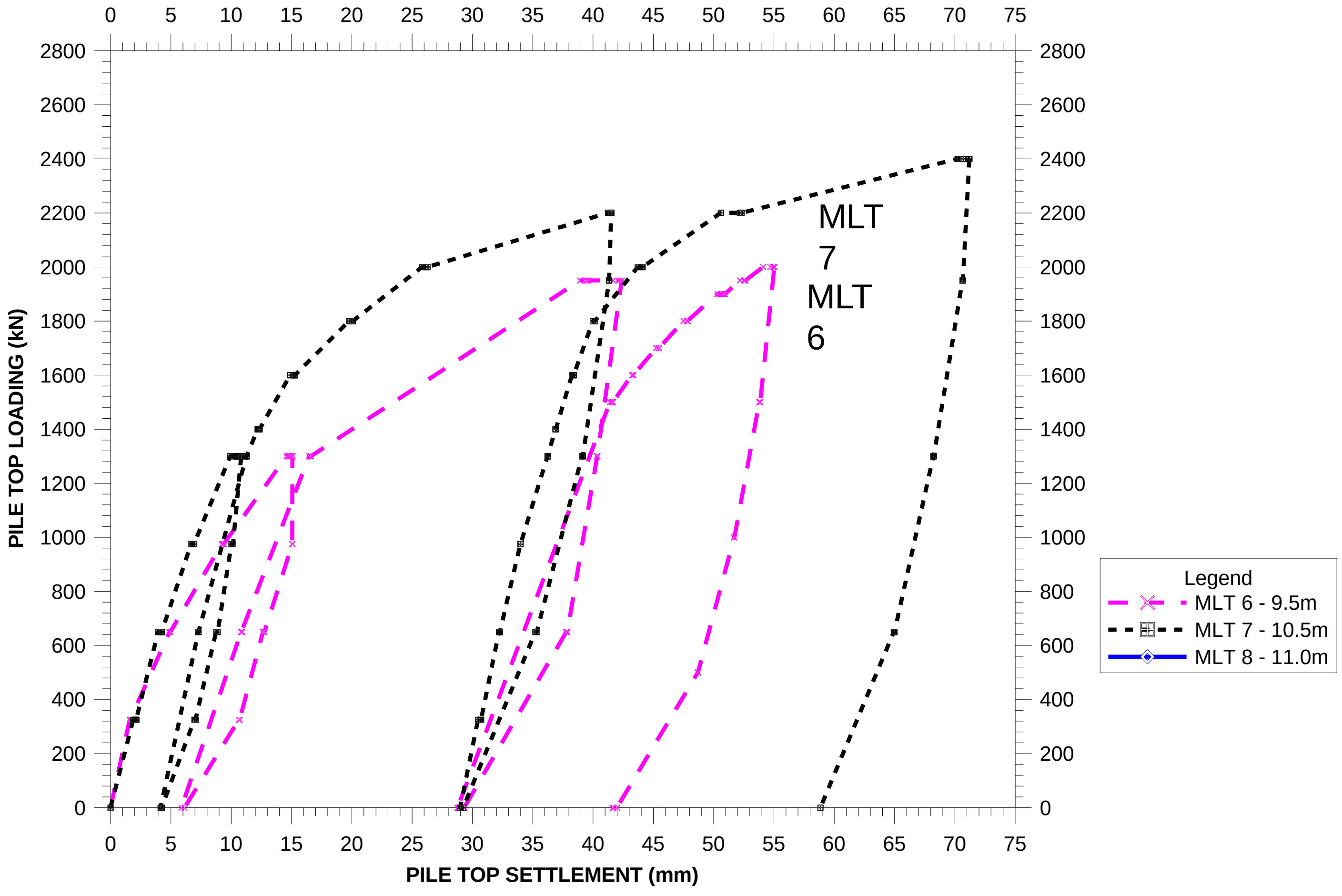
- MLT6 – 0.5m below pre-bored base
- MLT7 – 1.5m below pre-bored base
- MLT8 – 2.0m below pre-bored base

Additional MLT

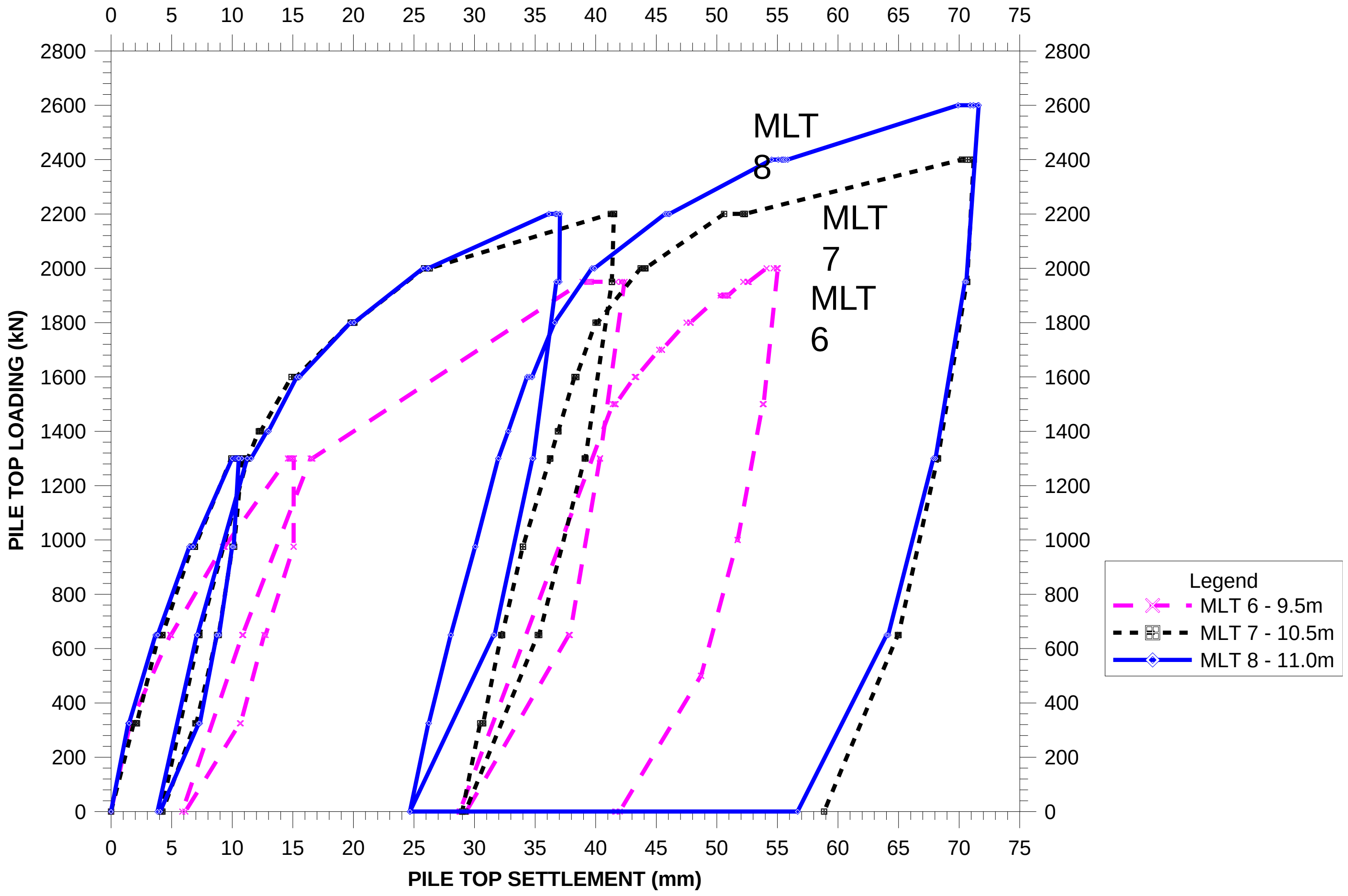




PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
MLT 6
Legend
MLT 6 - 9.5m
MLT 7 - 10.5m
MLT 8 - 11.0m



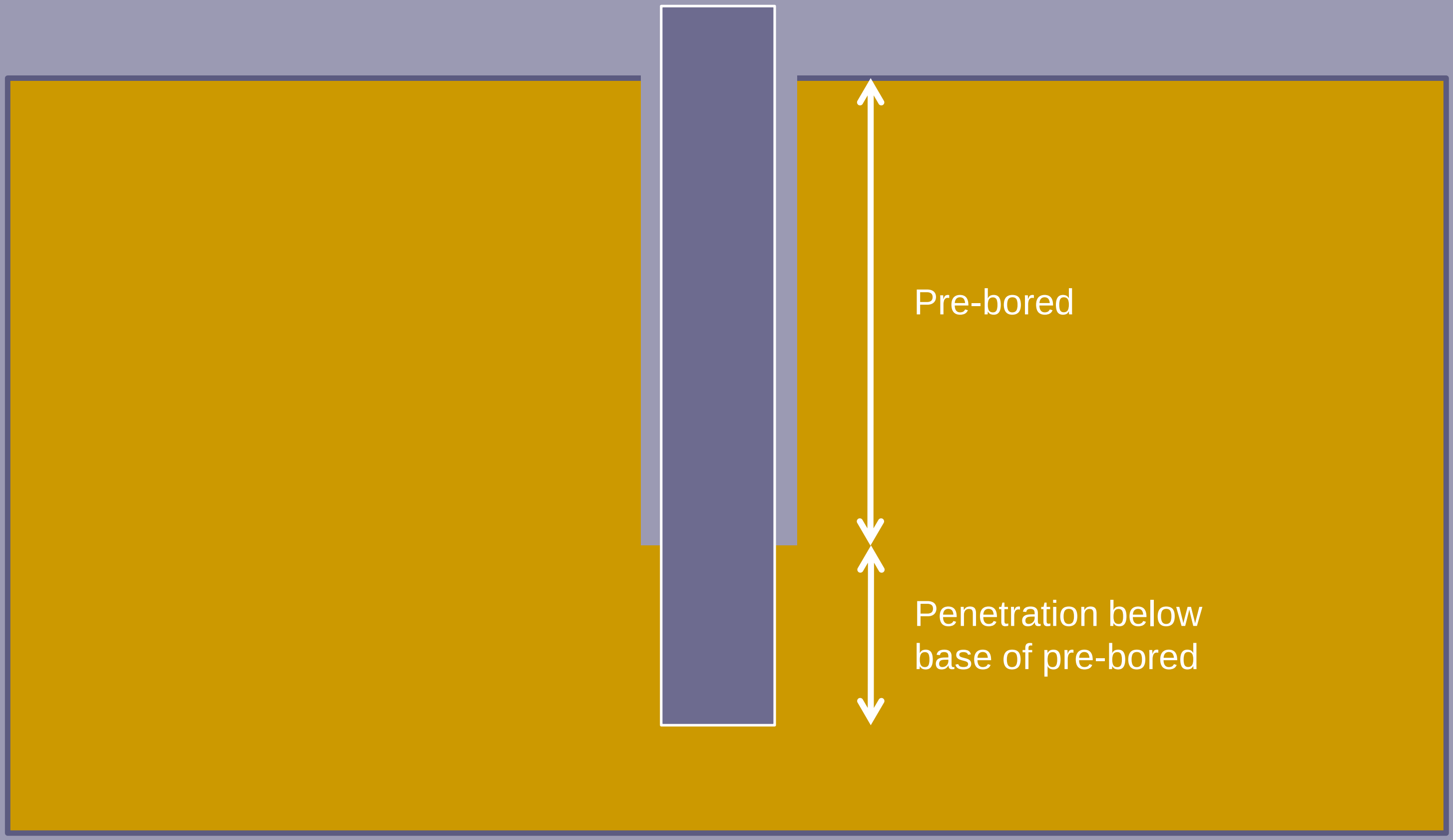
PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
MLT 7
MLT 6
Legend
MLT 6 - 9.5m
MLT 7 - 10.5m
MLT 8 - 11.0m



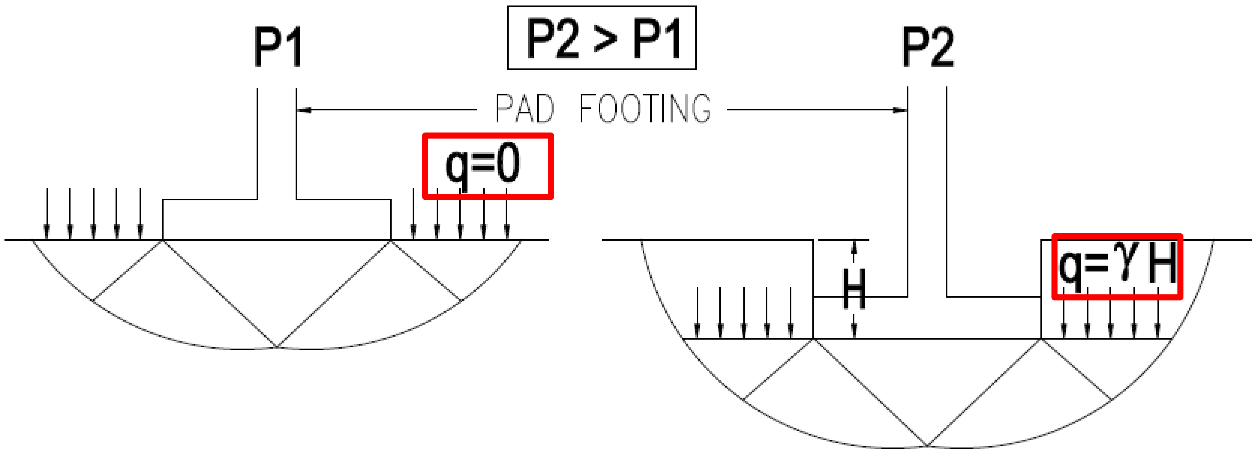
PILE TOP LOADING (kN)
PILE TOP SETTLEMENT (mm)
MLT 8
MLT 7
MLT 6
Legend
MLT 6 - 9.5m
MLT 7 - 10.5m
MLT 8 - 11.0m

MLT	Pre-bored Diameter (mm)	Pile Penetration below Piling Platform (m)	Max. Jack-in Load at Termination (kN)	Achieved Maximum Test Load (kN)	Pile Top Settlement	
					At Working Load (mm)	At Max. Test Load (mm)
MLT 1	600	9.40	2160	2220 (1.71xWL)	14.0	46.00
MLT 2	500	9.30	2600	2220 (1.71xWL)	23.50	42.00
MLT 3	550	**12.50**	2860	2600 (2.00xWL)	**5.80**	21.80
MLT 4	550	9.50	2860	1406 (1.50xWL)	16.50	24.50
MLT 5	550	**13.50**	2860	1950 (1.50xWL)	**8.50**	13.00
MLT 6	550	9.50	2860	1950 (1.50xWL)	15.08	42.38
MLT 7	550	10.50	2860	2400 (1.85xWL)	11.29	41.93
MLT 8	550	**11.00**	2860	2600 (2.00xWL)	**10.30**	50.35

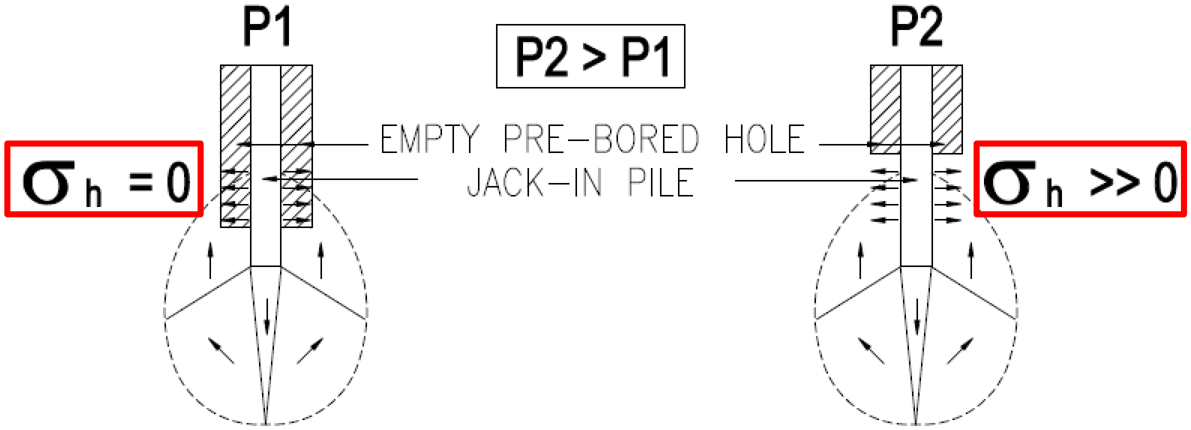
Investigation Findings



Analogy of Footing



Bearing Improvement with Toe Confinement



Conclusions & Recommendations

- Pile performance improved with longer pile penetration below pre-bored base
- Existence of pile toe softening due to relaxation of pile tip founding material
- Sufficient pile penetration below pre-bored base is important
- Recommend to seal the pre-bored hole with grout

Case Study 2: Pile Heave & Lateral Soil Displacement

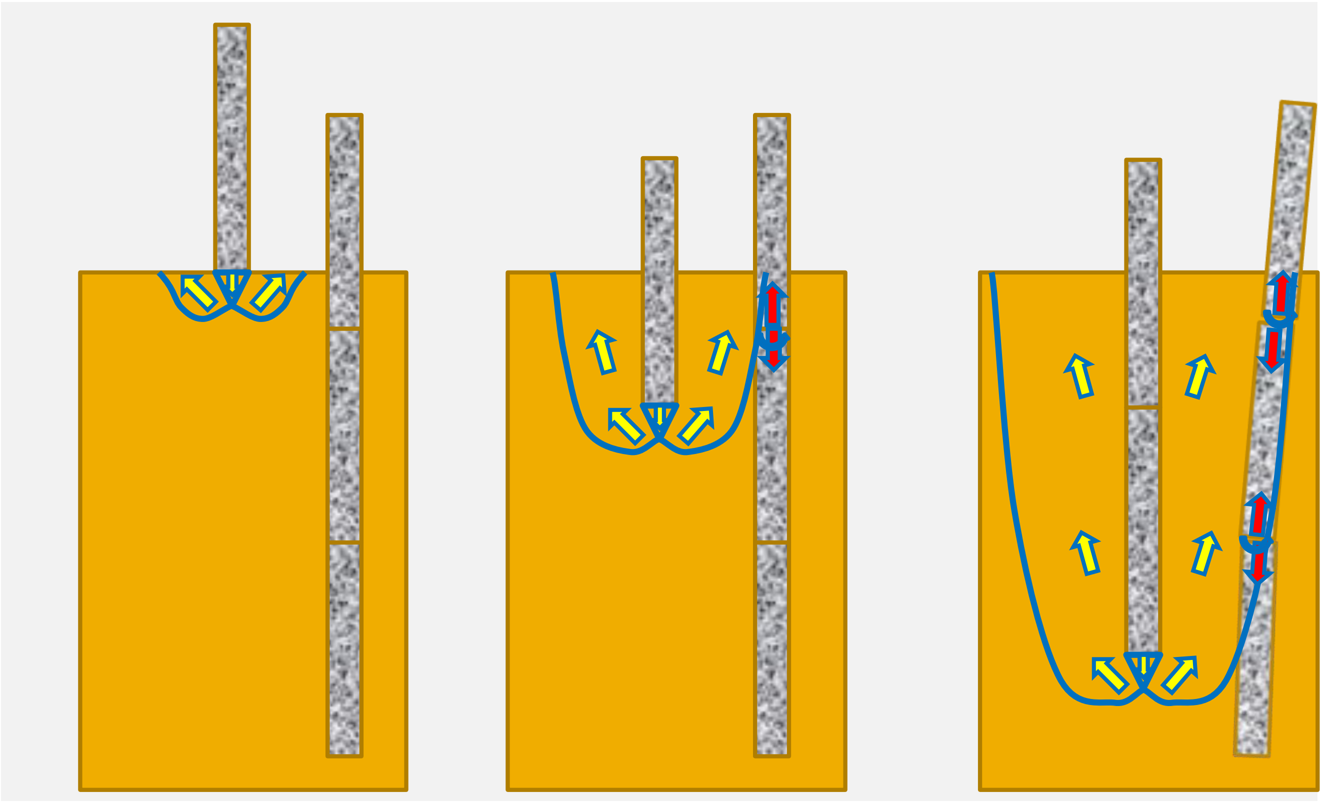
- Rapid pile installation in incompressible soft soil induces
  - Vertical heave in shallow depth (relatively less confinement from weight of overburden soils)
  - Lateral displacement in deeper depth (with soil confinement)

- Consequences :
  - Up-heaving soil movement causes tensile stress on pile & toe lift up during driving & downdrag after pore presure dissipation
  - Lateral soil displacement causes flexural stress on pile & pile deviation
  - Excessive combined tensile and flexural stresses lead to pile joint dislodgement
  - Excessive foundation settlement in post construction (pile toe uplifting & downdrag settlement)

Pile Joint Dislodgement

- Pile joints could be dislodged due to excessive flexural and tensile stresses induced by ground heave and radial soil displacement
- Detectable using High Strain Dynamic Pile Test (HSDPT)

Mechanism of Pile Heave & Soil Displacement



Case Study - HSDPT

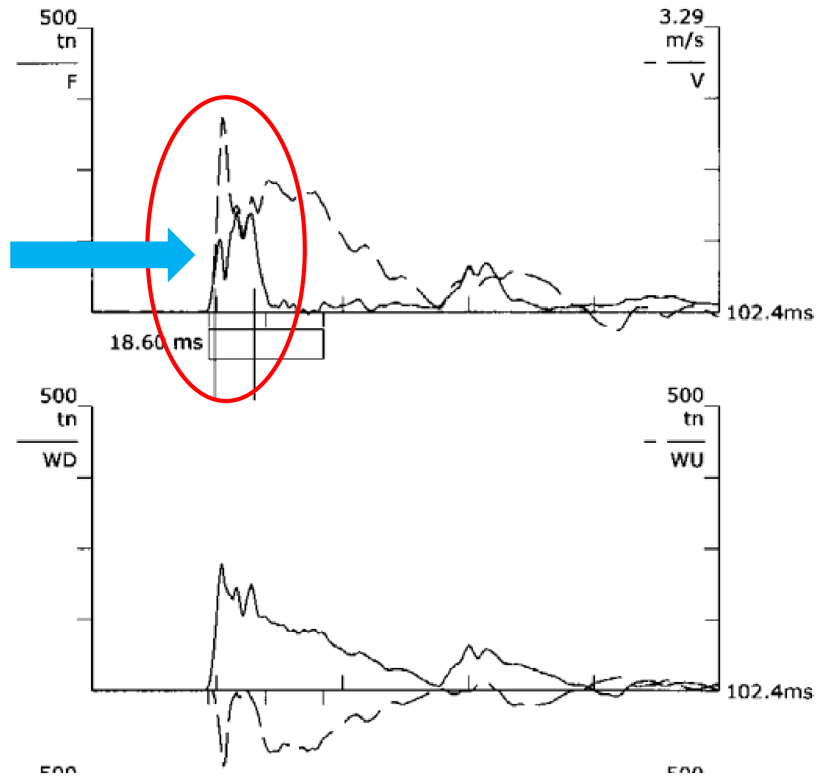
- Monitoring of pile top settlement during the HSDPT re-strike tests is summarised as below:

Cumulative Pile Top Settlement (mm)	Pile C	Pile A	Pile B	Pile D	Pile E
Upon resting 7-ton hammer on pile top	80	98	125	103	92
At the end of Restriking Test	275	399	497	186	182

Case Study - HSDPT

- Pile B
- Initial Blow

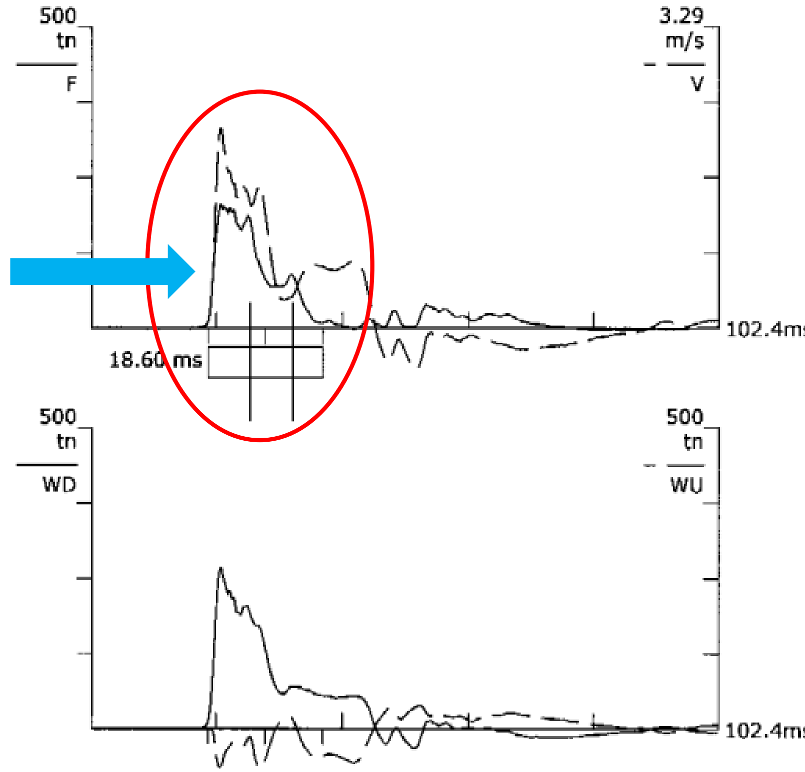
One Pile Length (12m) was DETECTED with Major Discontinuity at 'toe' (reflection)



Case Study - HSDPT

- Pile B
- Blow No. 4

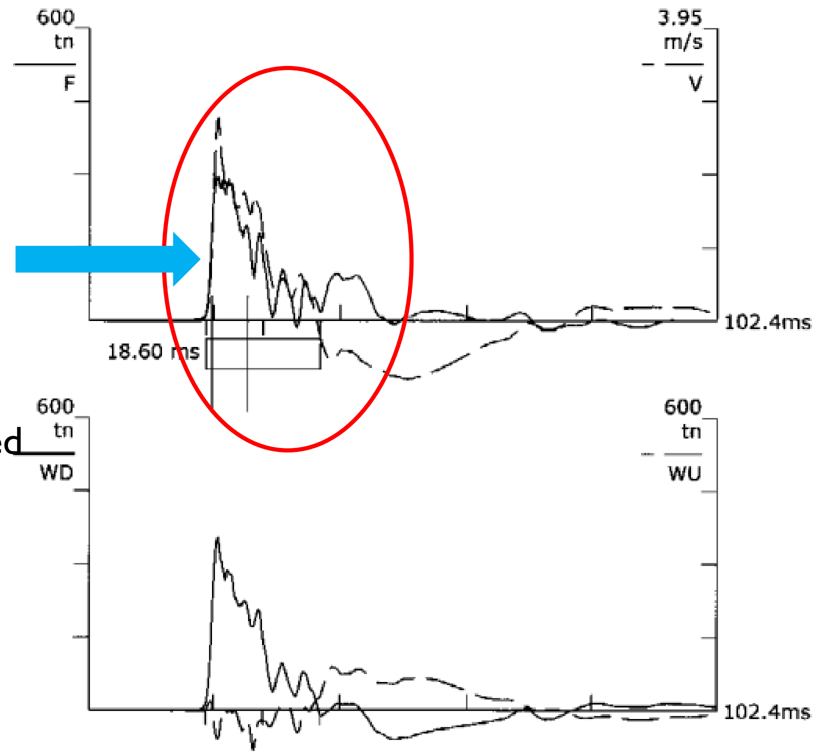
First Joint Discontinuity closed up after few blows; Two Pile Lengths was revealed with another Major Discontinuity at new 'toe' (reflection)



Case Study - HSDPT

- Pile B
- Blow No. 17

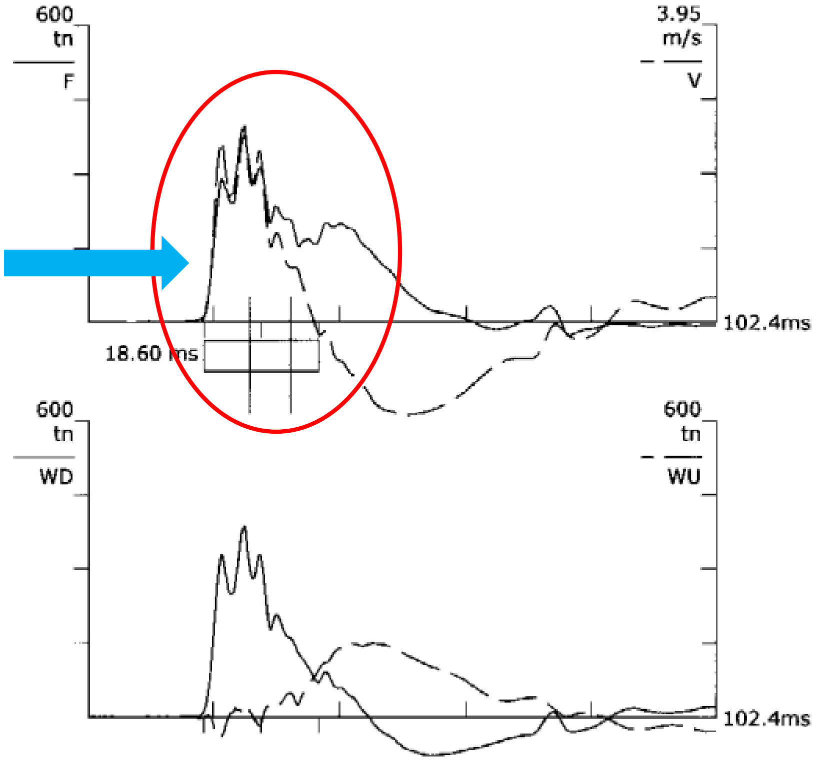
Second Major Joint Discontinuity also disappeared;
Total of Three Pile Lengths was observed



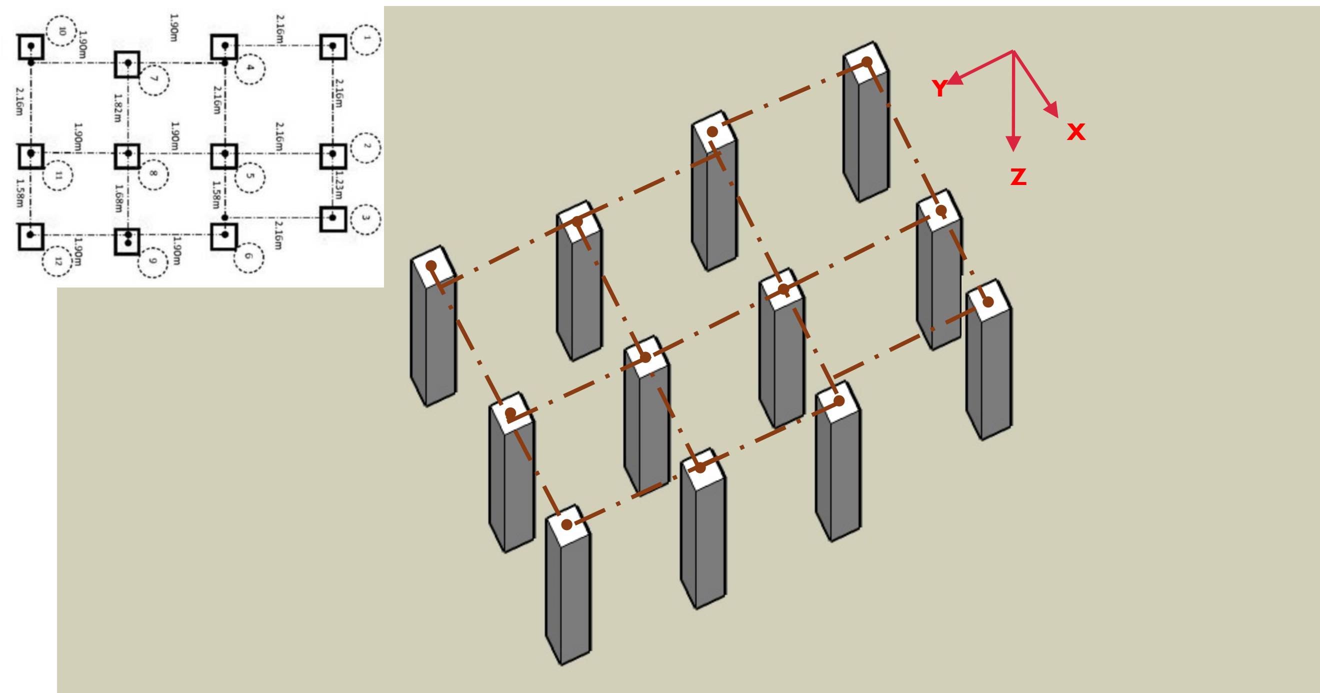
Case Study - HSDPT

- Pile B
- End of Blow

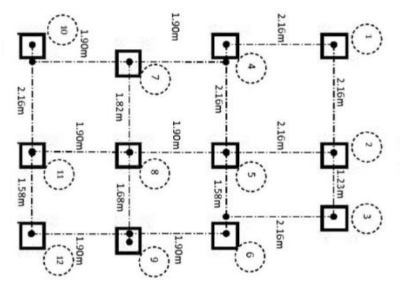
Minor velocity reflections were observable at first and second pile joints

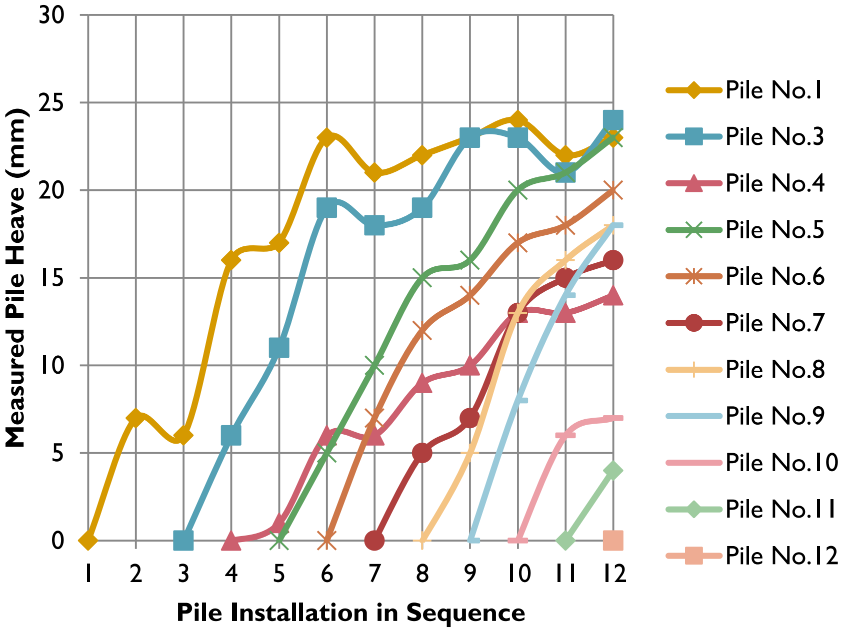


Pile Heave Monitoring Program



Pile Heave Monitoring Result





Summary

- Ground heave & radial soil displacement due to rapid installation of displacement pile in soft incompressible soft clay can pose serious integrity problem on pile foundation.
- Solutions :
  - Use larger pile spacing & reduce rate of clustered pile installation for adequate time for dissipation of excess pore pressure
  - Simultaneous pile installation at mirror pile location from centre outwards to minimise net lateral displacement, but this improves nothing on ground heave
  - Stronger pile structural strength & joint to withstand tensile & flexural stresses
  - Staggered pile installation sequence or install piles at alternate locations
  - Restrike all piles with HSDPT to detect pile integrity if ground or soil heave is observed.

Opportunities

- Identify problems and opportunities.
  - State consumer problems, and define the nature of product/service opportunities that are created by those problems.

Business Concept

- Summarize the key technology, concept, or strategy on which your business is based.

Competition

- Summarize the competition.
- Outline your company's competitive advantage.

Goals and Objectives

- List five-year goals.
- State specific, measurable objectives for achieving your five-year goals.
  - List market-share objectives.
  - List revenue/profitability objectives.

Financial Plan

- Outline a high-level financial plan that defines your financial model and pricing assumptions.
  - This plan should include expected annual sales and profits for the next three years.
  - Use several slides to cover this material appropriately.

Resource Requirements

- List requirements for the following resources:
  - Personnel
  - Technology
  - Finances
  - Distribution
  - Promotion
  - Products
  - Services

Risks and Rewards

- Summarize the risks of the proposed project and how they will be addressed.
- Estimate expected rewards, particularly if you are seeking funding.

Key Issues

- Near term
  - Identify key decisions and issues that need immediate or near-term resolution.
  - State consequences of decision postponement.
- Long term
  - Identify issues needing long-term resolution.
  - State consequences of decision postponement.
- If you are seeking funding, be specific about any issues that require financial resources for resolution.