Challenges in Design and Construction of Deep Excavation

for SEAGC 2018

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CONTENTS

INTRODUCTION

- Deep basement construction
  - Urban areas for parking space
  - Infrastructures, e.g. MRT

- **High Risk** associated with deep basement construction!

Excavated depth

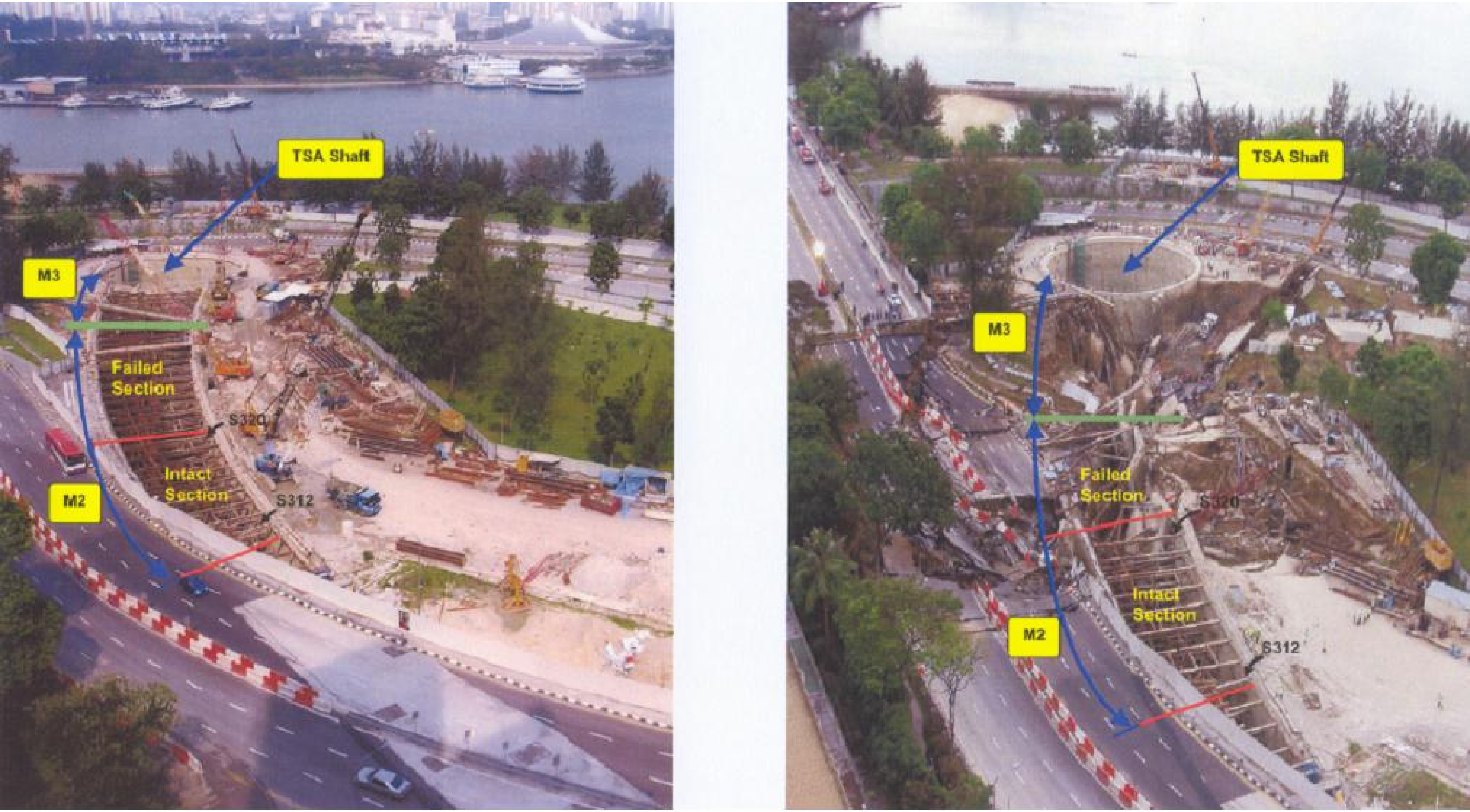
24.5m - 28.5m (6-level basement)

Retaining wall

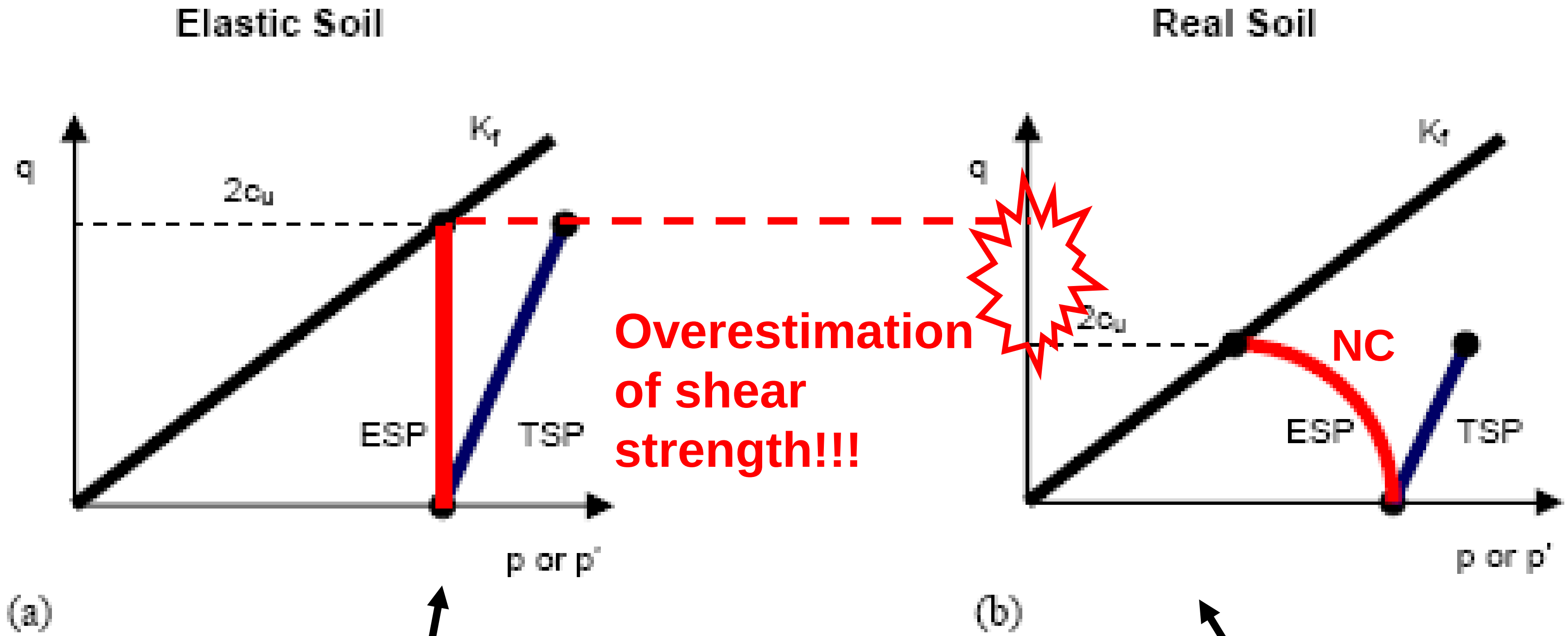
1.2m thick diaphragm walls

FAILURES of DEEP EXCAVATION

FAILURES of DEEP EXCAVATION



INTRODUCTION



Stress path using Mohr-Coulomb model

Stress path of real soil


AFP

INTRODUCTION

INTRODUCTION

INTRODUCTION

Common questions in Deep Excavation:

What are the parameters involved ?

What are the pitfalls ?

How to avoid failures ?

Which temporary earth retaining system to use ?

DESIGN CONSIDERATIONS

DESIGN CONSIDERATIONS

Design Flowchart for Excavation Works

1. Project information study
- ✓ Determine depth/area/ sequence of excavation.
- ✓ Understand project requirements/ specifications.

2. Site location study
- ✓ Study the topography, hydrography, historical usage of site location.
- ✓ Study site condition surrounding excavation site and identify critical buildings/structures/ utilities.
- ✓ Determine the limit of work boundary.

3. Subsurface information study
- ✓ Geological study.
- ✓ Determine subsoil profiles.
- ✓ Determine groundwater level.
- ✓ Determine soil/rock design parameters.

Insufficient SI

Propose additional subsurface investigation (SI).

Additional SI

Sufficient SI

4. Selection of suitable earth retaining system and construction sequence
- ✓ Select wall type and support system.
- ✓ Service period (temporary or part of permanent structure).
- ✓ Economic, workability and availability.
- ✓ Determine effective construction sequence (clearly specify in drawing).
- ✓ Risk assessment for the proposed options.

5. Ultimate limit stage (ULS) analysis
- ✓ Moderately conservative soil/rock design parameters.
- ✓ Highest possible groundwater level during service period.
- ✓ Consider unplanned excavation (0.5m or 10% of the total retained height/ retained height below lowest support).

DESIGN CONSIDERATIONS

5. Ultimate limit stage (ULS) analysis

- ✓ Moderately conservative soil/rock design parameters.
- ✓ Highest possible groundwater level during service period.
- ✓ Consider unplanned excavation (0.5m or 10% of the total retained height/ retained height below lowest support).
- ✓ Surcharge load (construction/operational load or minimum 10kPa).
- ✓ Determine wall depth and support levels for following checks:
  - ➢ Wall stability check
  - ➢ Vertical stability check
  - ➢ Basal heave stability check
  - ➢ Hydraulic failures check
- ✓ Calculate wall bending moment, shear force and support load (ULS)

6. Serviceability limit stage (SLS) analysis

- ✓ Moderately conservative soil/rock design parameters.
- ✓ Highest possible groundwater level during service period.
- ✓ Surcharge load (construction/operational).
- ✓ Follow wall depth and support levels in ULS analysis.
- ✓ Evaluate deformation of retaining wall and retained ground.
- ✓ Carry out damage assessment of surrounding buildings, structures and utilities.
- ✓ Calculate wall deflection, bending moment, shear force and support load (SLS).

7. Worst case scenario (WCS) analysis

- ✓ One strut failure.
- ✓ Accidental impact load on strut.
- ✓ Flooded condition.
- ✓ Calculate wall bending moment, shear force and support load (WCS).

DESIGN CONSIDERATIONS

8. Structural design
- ✓ Determine design value (ULS x 1.0 or SLS x 1.4 or WCS x 1.05 whichever is critical) for wall and supports.
- ✓ Structural serviceability check.
- ✓ Structural durability check.

9. Design check and review
- ✓ Independent check and review as quality control procedures.

Review comments

10. Instrumentation & Monitoring
- ✓ Planning for instrument quantity and location.
- ✓ Select suitable instrument.
- ✓ Specify monitoring frequency.
- ✓ Establish monitoring triggering system with contingency plan.

11. Groundwater control
- ✓ Planning for groundwater control scheme.
  - a. Provisional recharge wells.
  - b. Provisional relief wells (for temporary uplift)

12. Drawings preparation
- ✓ Details of earth retaining structures and supports system.
- ✓ Construction sequence.
- ✓ Instrumentation & monitoring scheme.
- ✓ Ground improvement and groundwater control scheme.
- ✓ Protection works and advance work.

13. Drawings check and review

14. Drawings Issue for construction

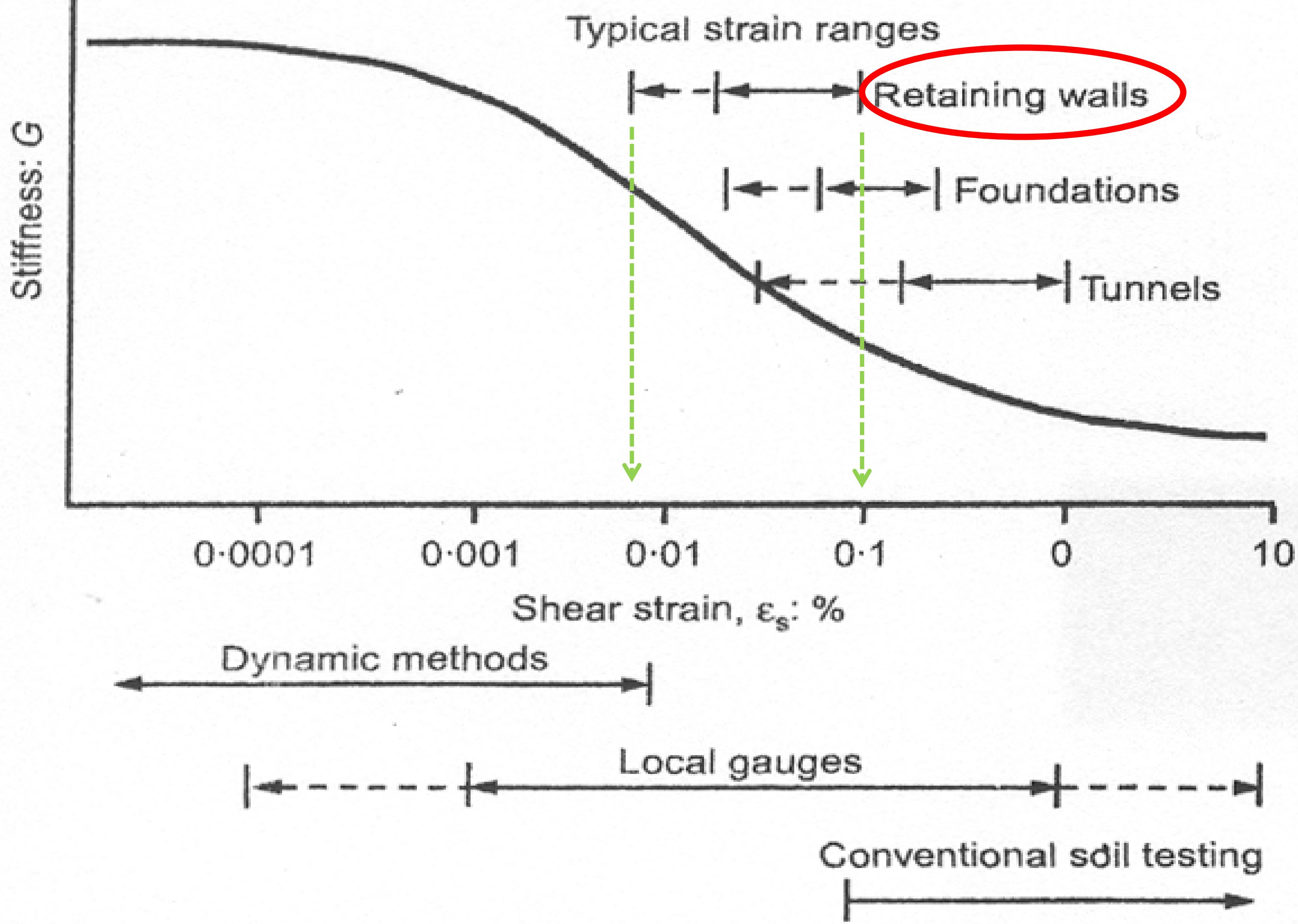
DESIGN CONSIDERATIONS

- Some important soil parameters related to retaining wall and support system design:
  - **Shear strength** parameters (s_u, ϕ' & c')
  - Soil **permeability**
  - Soil **stiffness**

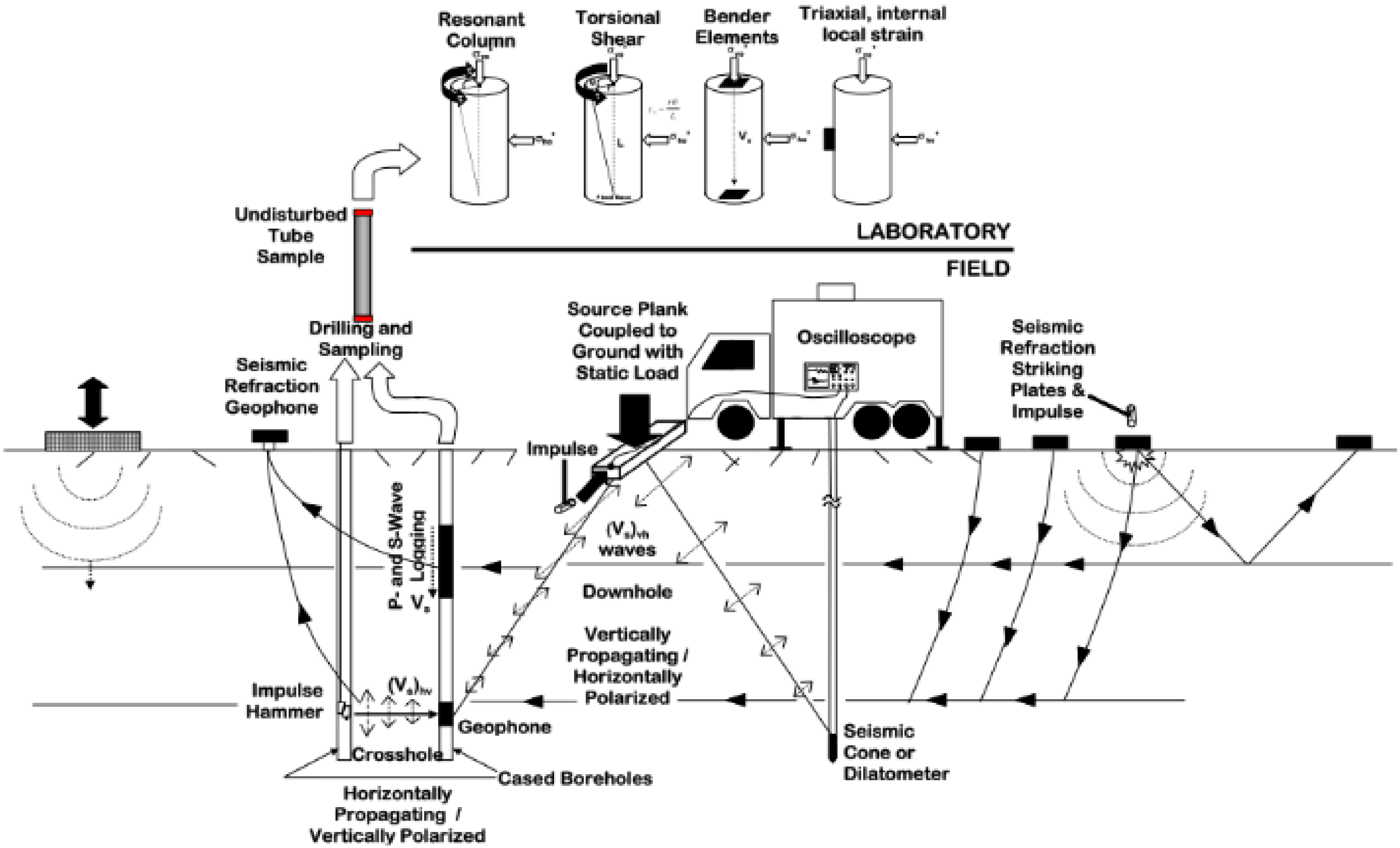
DESIGN CONSIDERATIONS

- Soil stiffness
  - Important parameters for retaining wall design BUT **difficult to obtain reliably**
  - In Malaysia, pressuremeter, shear wave velocity and compare with **empirical correlations**
  - **Laboratory tests unreliable** and values obtained significantly smaller than appropriate values for retaining wall design
  - Designer should be aware of **small-strain** nature of retaining wall design

DESIGN CONSIDERATIONS



DESIGN CONSIDERATIONS



Field and laboratory methods to evaluate shear wave velocity

DESIGN CONSIDERATIONS

Typical values of maximum small-strain shear modulus

Soil Type	Maximum small-strain shear modulus, G_0 (kPa)
Soft clays	2,750 to 13,750
Firm clays	6,900 to 34,500
Silty sands	27,600 to 138,000
Dense sands and gravels	69,000 to 345,000

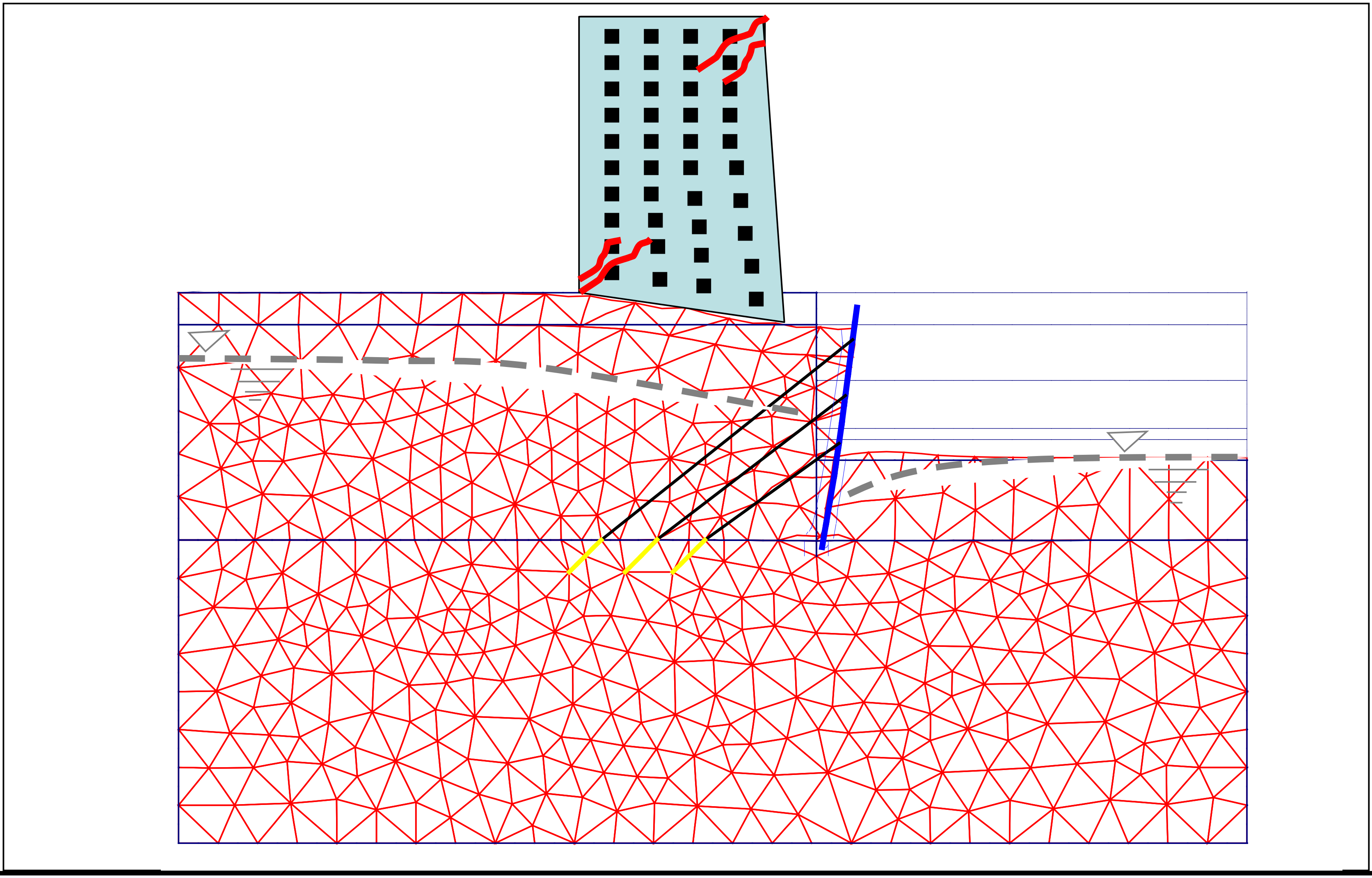
$$G_0 = 15{,}560\,(N_{60})^{0.68}$$

$$G_0 = 1{,}634(q_c)^{0.25}(\sigma'_{vo})^{0.375}$$

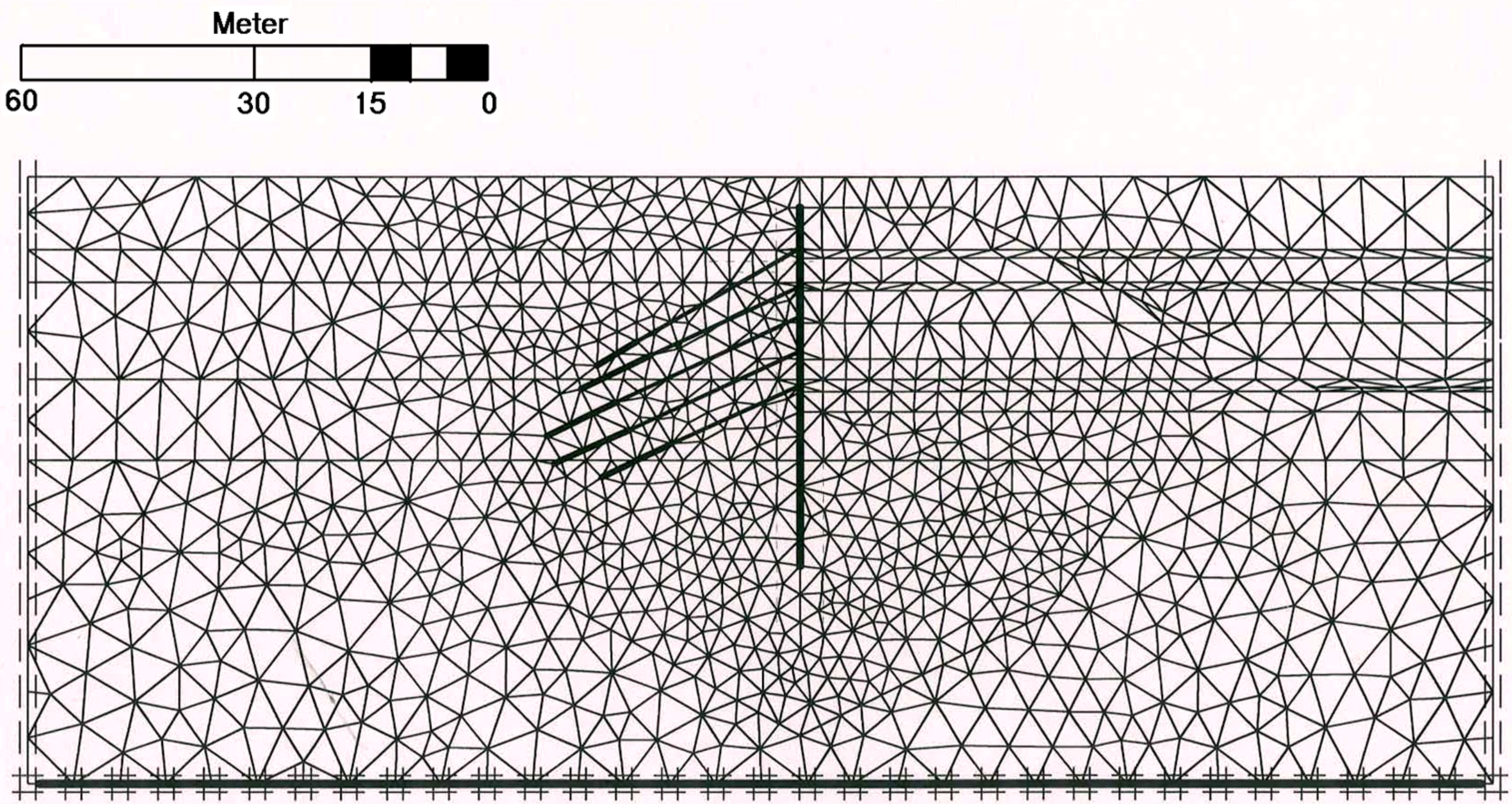
$$\gamma_{0.7} = \frac{0.385}{4G_0}\left(2c(1+\cos 2\emptyset) + \sigma'(1+Ko)\sin 2\emptyset\right)$$

DESIGN CONSIDERATIONS

GROUND MOVEMENT INDUCED BY DEEP EXCAVATION



DESIGN CONSIDERATIONS



DESIGN CONSIDERATIONS

CONSTITUTIVE SOIL MODELS

- Various constitutive soil models, e.g. Mohr-Coulomb, Cam Clay, Hardening Soil, Soft Soil, etc.
  - **Proper understanding and limitations** of each model important!
  - Incorrect use of soil models in Nicoll Highway!

CASE STUDIES

Limestone

Alluvium

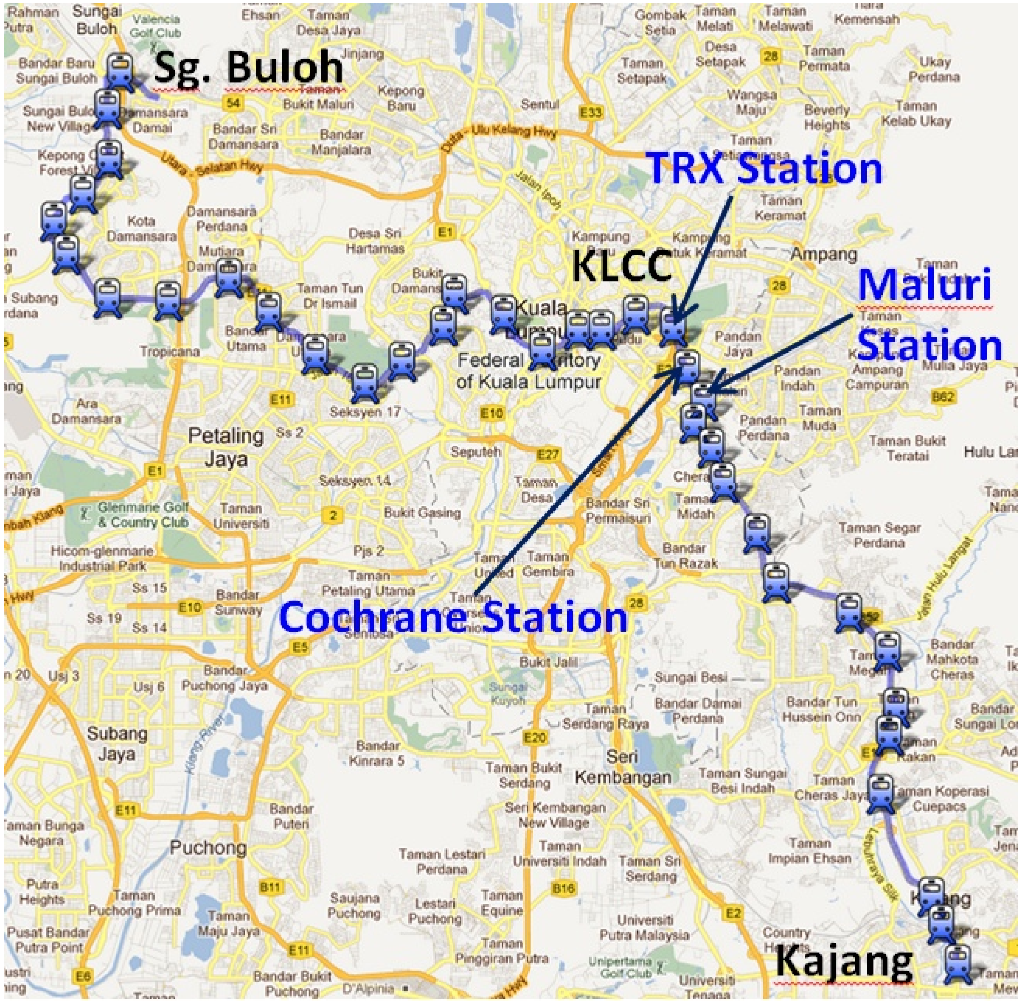
CASE STUDIES - LIMESTONE

Case History 1:
Deep Excavation for Three (3) Underground Stations for KVMRT in Limestone

- KVMRT Line 1, Sungai Buloh to Kajang

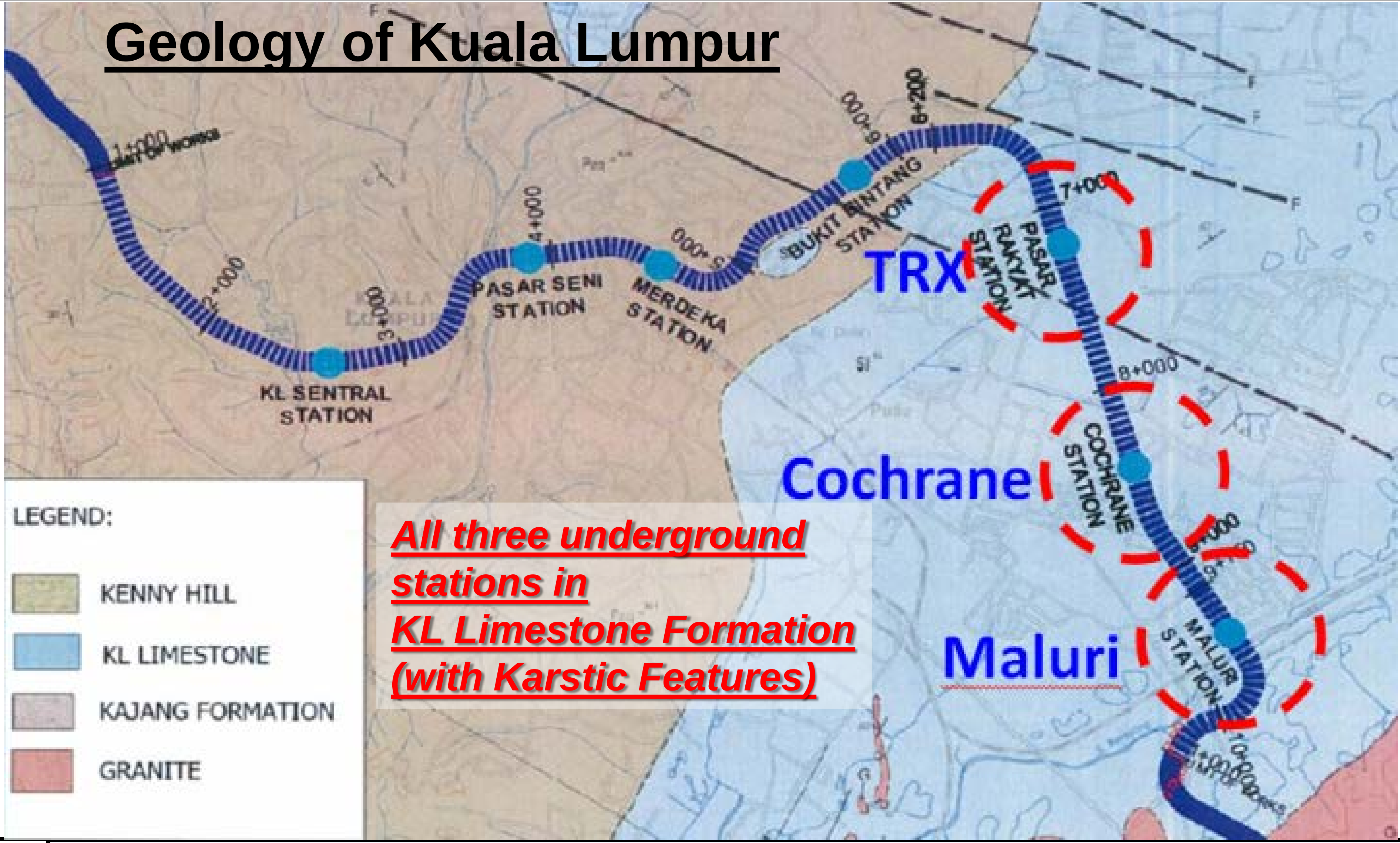
CASE STUDIES - LIMESTONE

Locations of the MRT Underground Stations



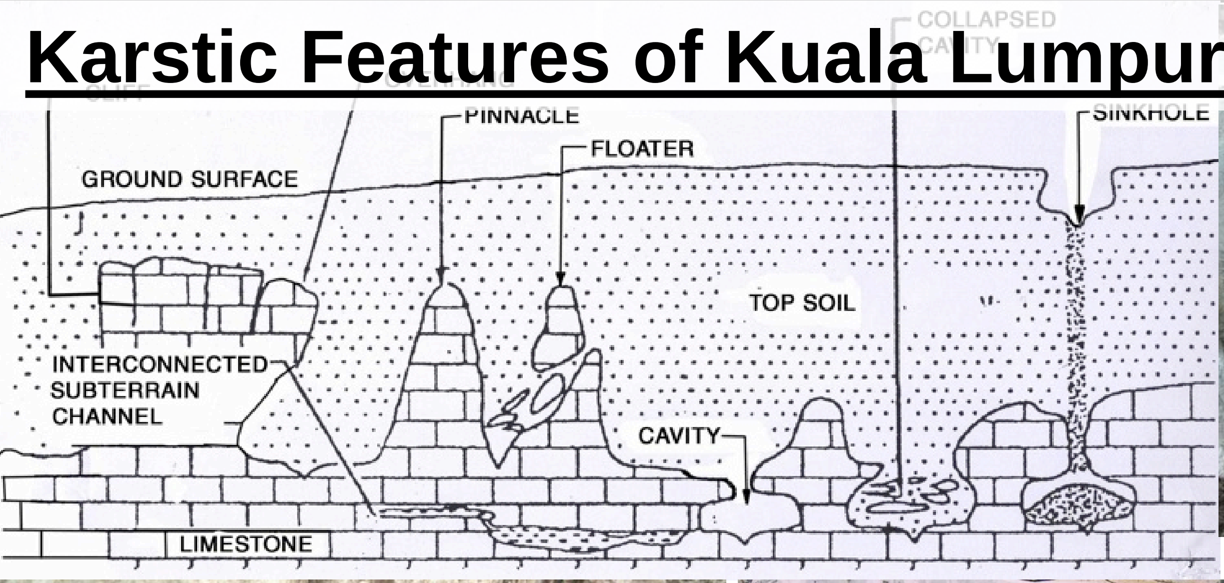
CASE STUDIES - LIMESTONE

Geology of Kuala Lumpur

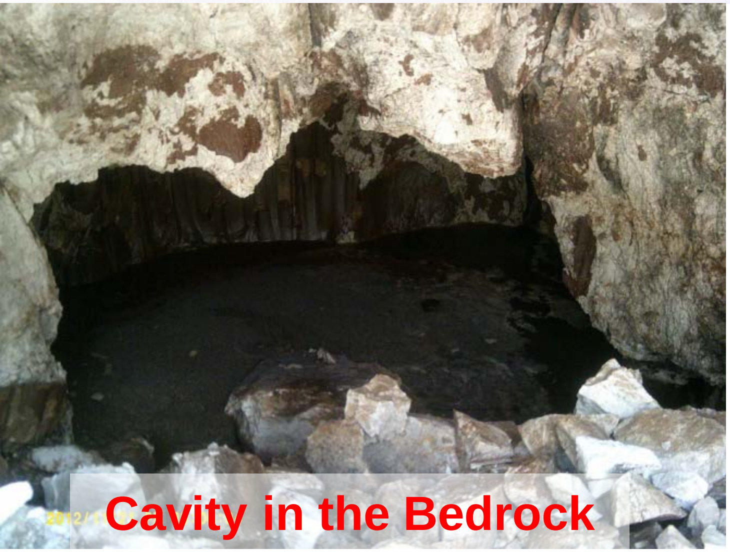


CASE STUDIES - LIMESTONE

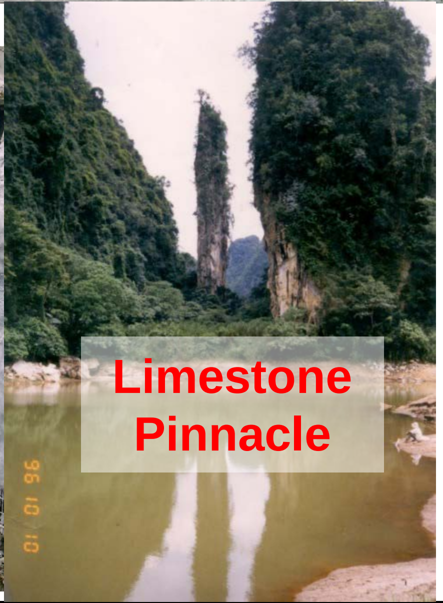
Karstic Features of Kuala Lumpur Limestone



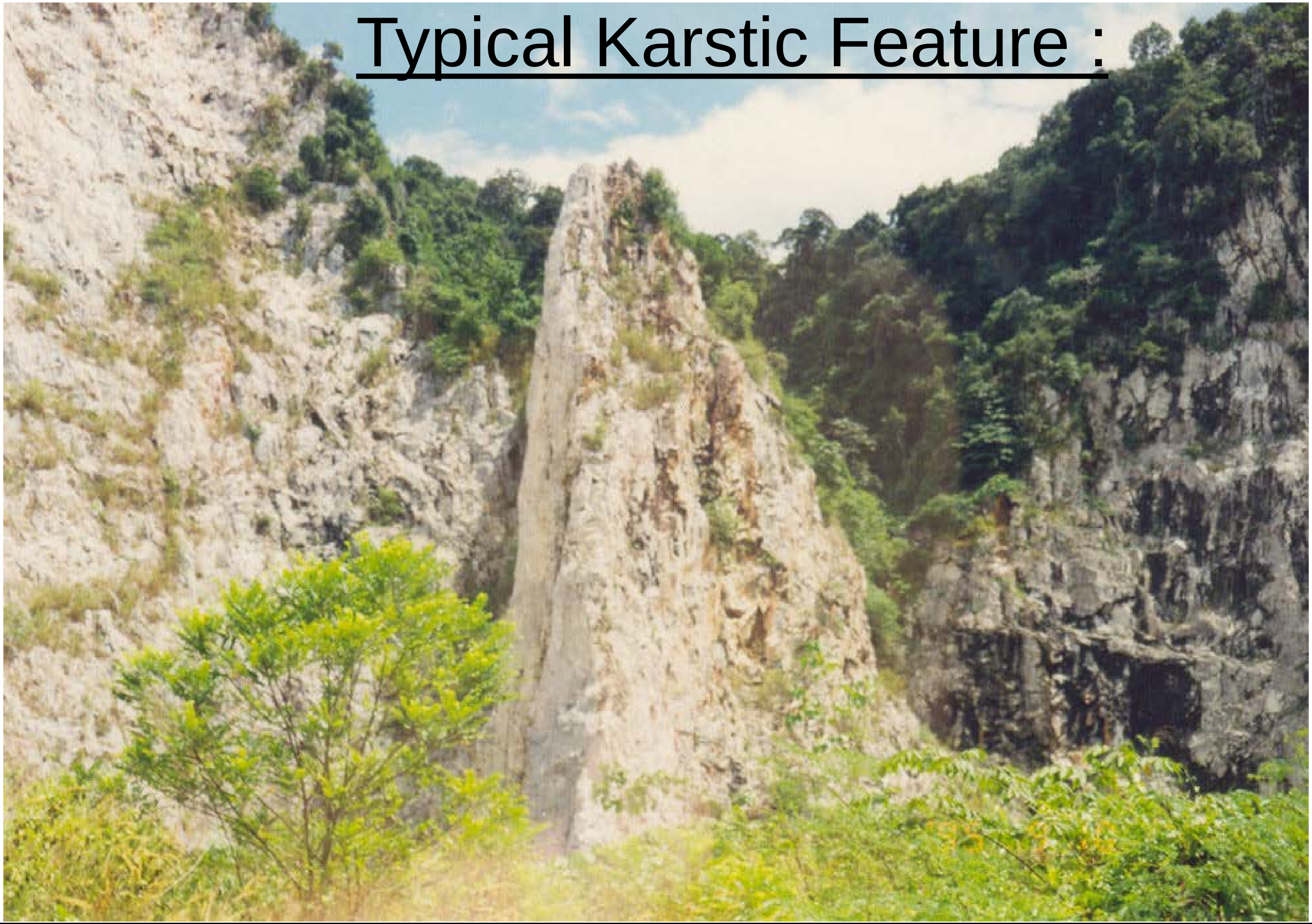
Valley in the bedrock


Cavity in the Bedrock


Highly fractured bedrock


Limestone Pinnacle

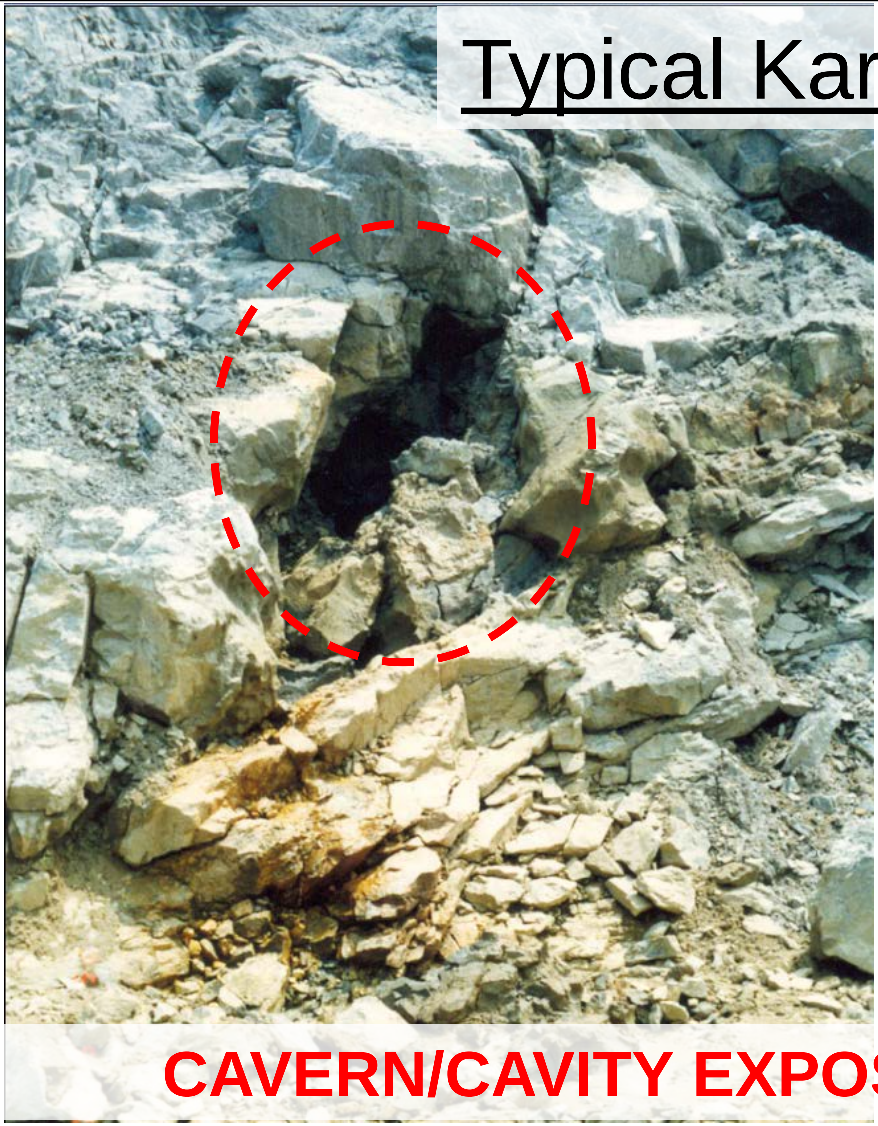
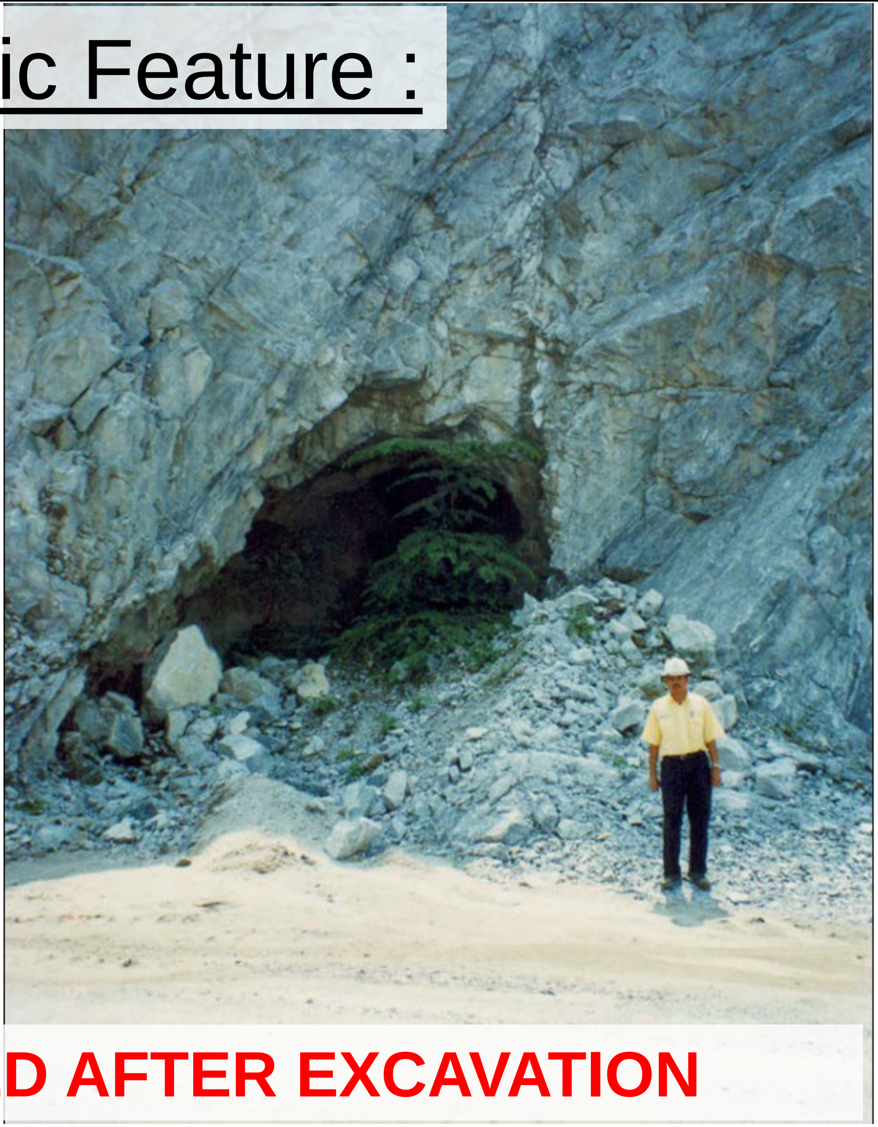
CASE STUDIES - LIMESTONE



CASE STUDIES - LIMESTONE

Typical Karstic Feature :

CASE STUDIES - LIMESTONE

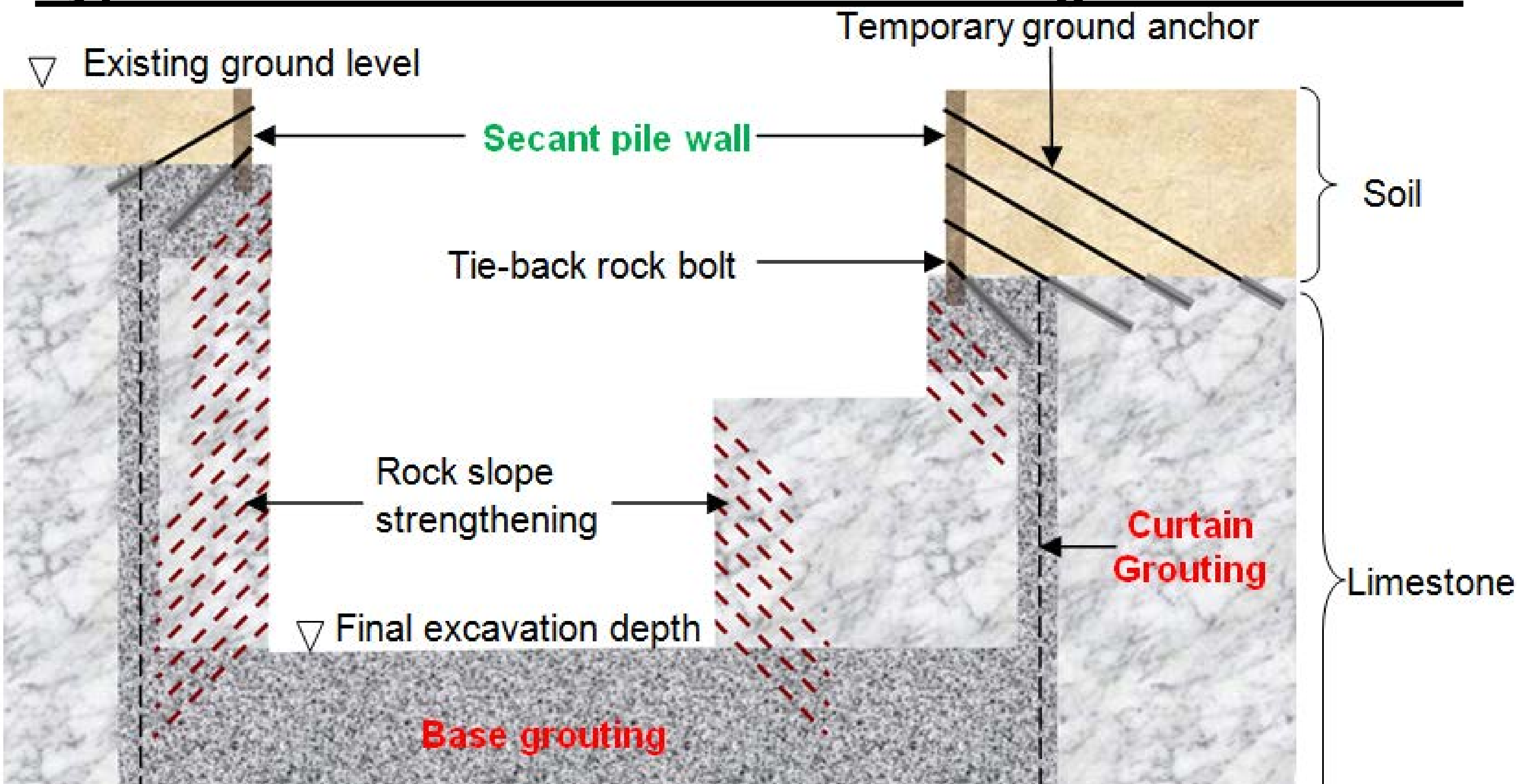



Typical Karstic Feature :

CAVERN/CAVITY EXPOSED AFTER EXCAVATION

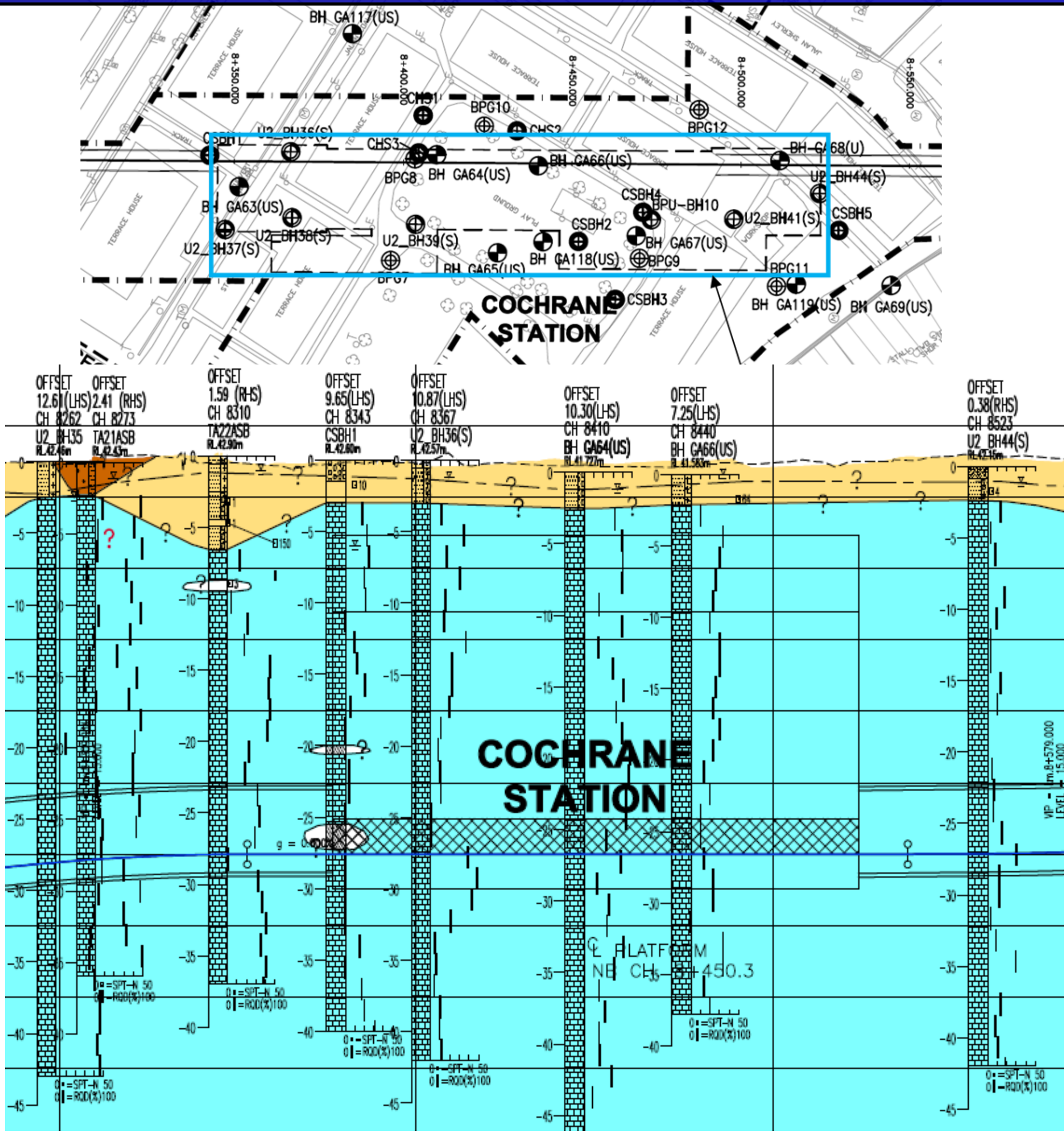
CASE STUDIES - LIMESTONE

Typical Excavation Section for Underground Station



(Note: Rock slope strengthening indicated is provisional only. Actual locations and extent of rock slope strengthening are determined after geological mapping works and kinematic analysis).

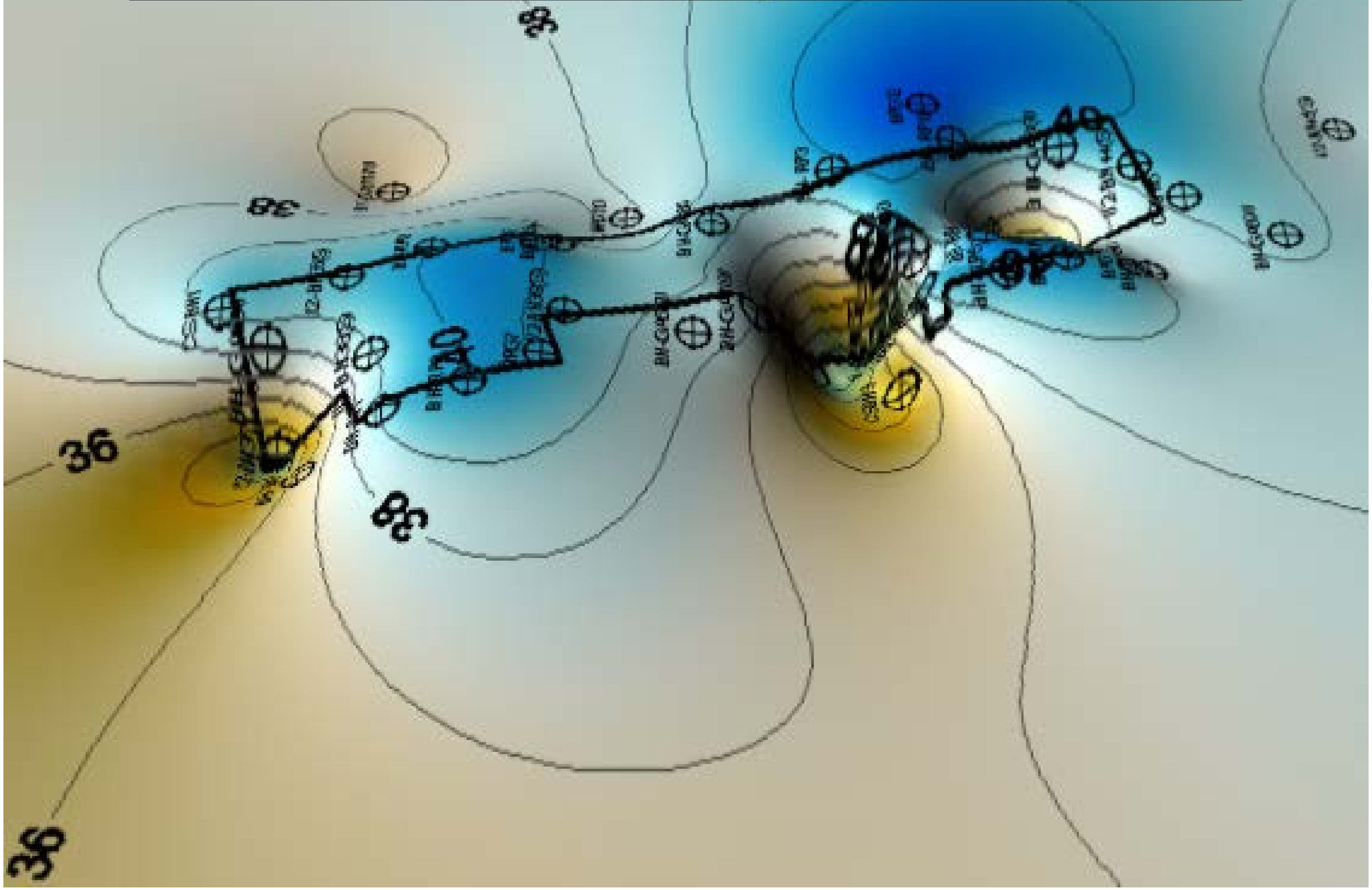
CASE STUDIES - LIMESTONE



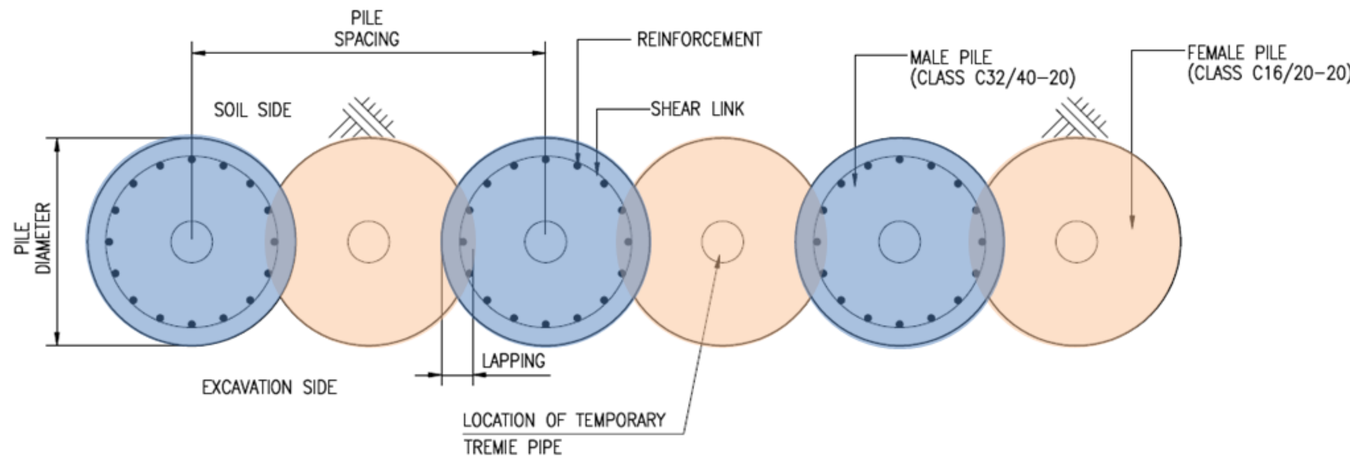
	Subsoil	Bedrock
Material type	Silty Sand	Limestone
Average depth	5m	5m below
Unit weight	18 kN/m^3	24 kN/m^3
SPT N	2 - 4	-
RQD	-	0 – 100%
Average UCS	-	50 MPa
Effective shear strength	c'= 1 kPa ϕ'= 29º	c'= 400 kPa ϕ'= 32º
Elastic Modulus, E' (kPa)	4000 - 12000	1.0E6 – 1.0E7
Hydraulic conductivity, k	1.0E-5 m/s	0 – 31 Lugeon

CASE STUDIES - LIMESTONE

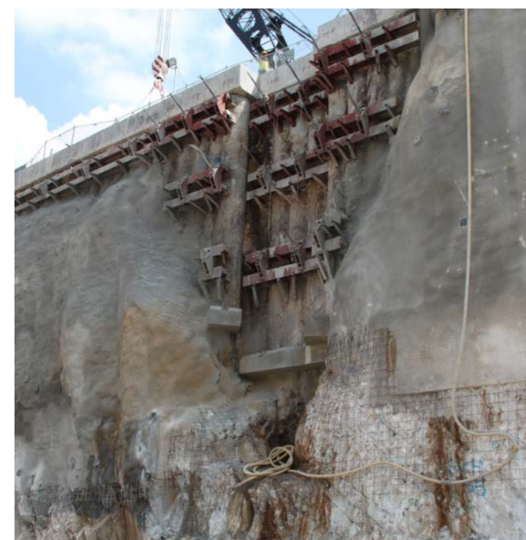
Conchrane Station Bedrock Contour



CASE STUDIES - LIMESTONE

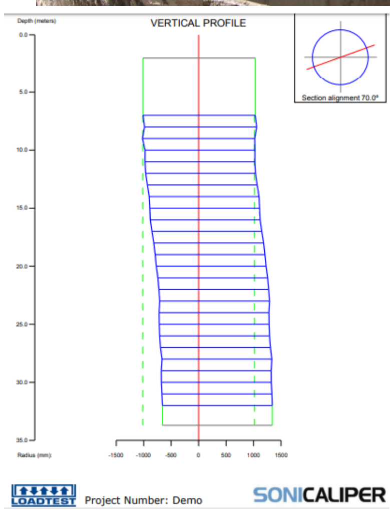


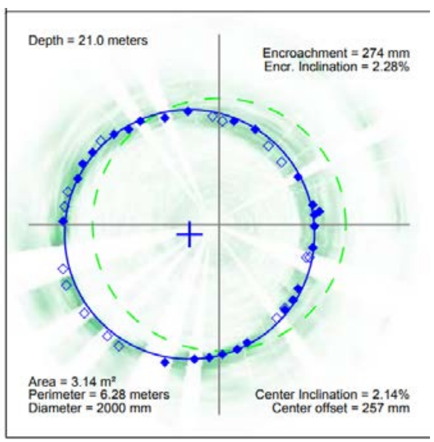
TYPICAL CROSS SECTION OF TEMPORARY HARD/SOFT SECANT PILE WALL
(PLAN VIEW)
NOT TO SCALE



CASE STUDIES - LIMESTONE

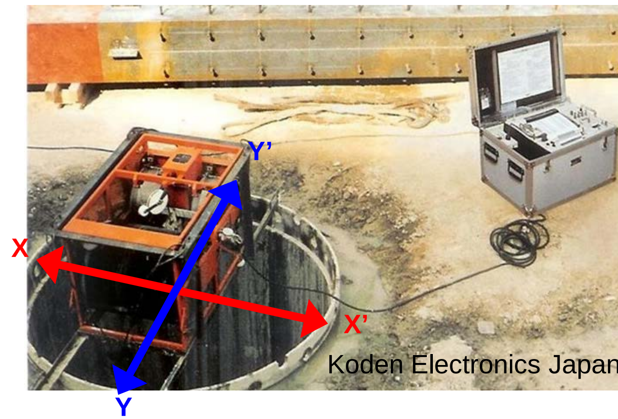
Sonic Caliper

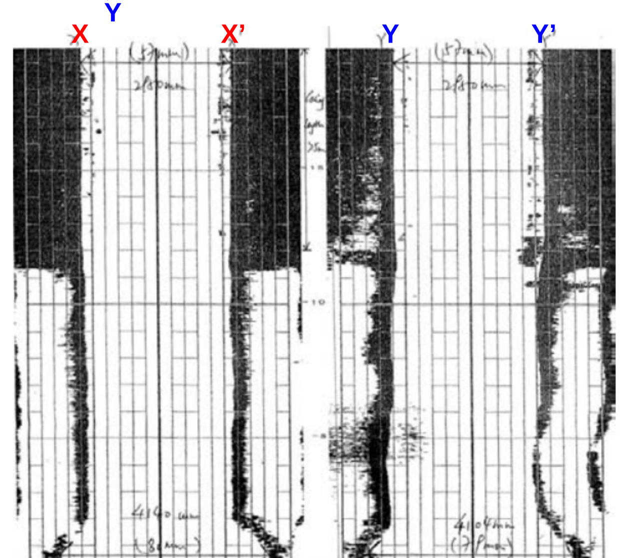




http://www.sonicaliper.com/soni/index.shtml

Koden Test





Dai & Lu (2009)

CASE STUDIES - LIMESTONE

CASE STUDIES - LIMESTONE

Typical Secant Pile Wall Elevation View

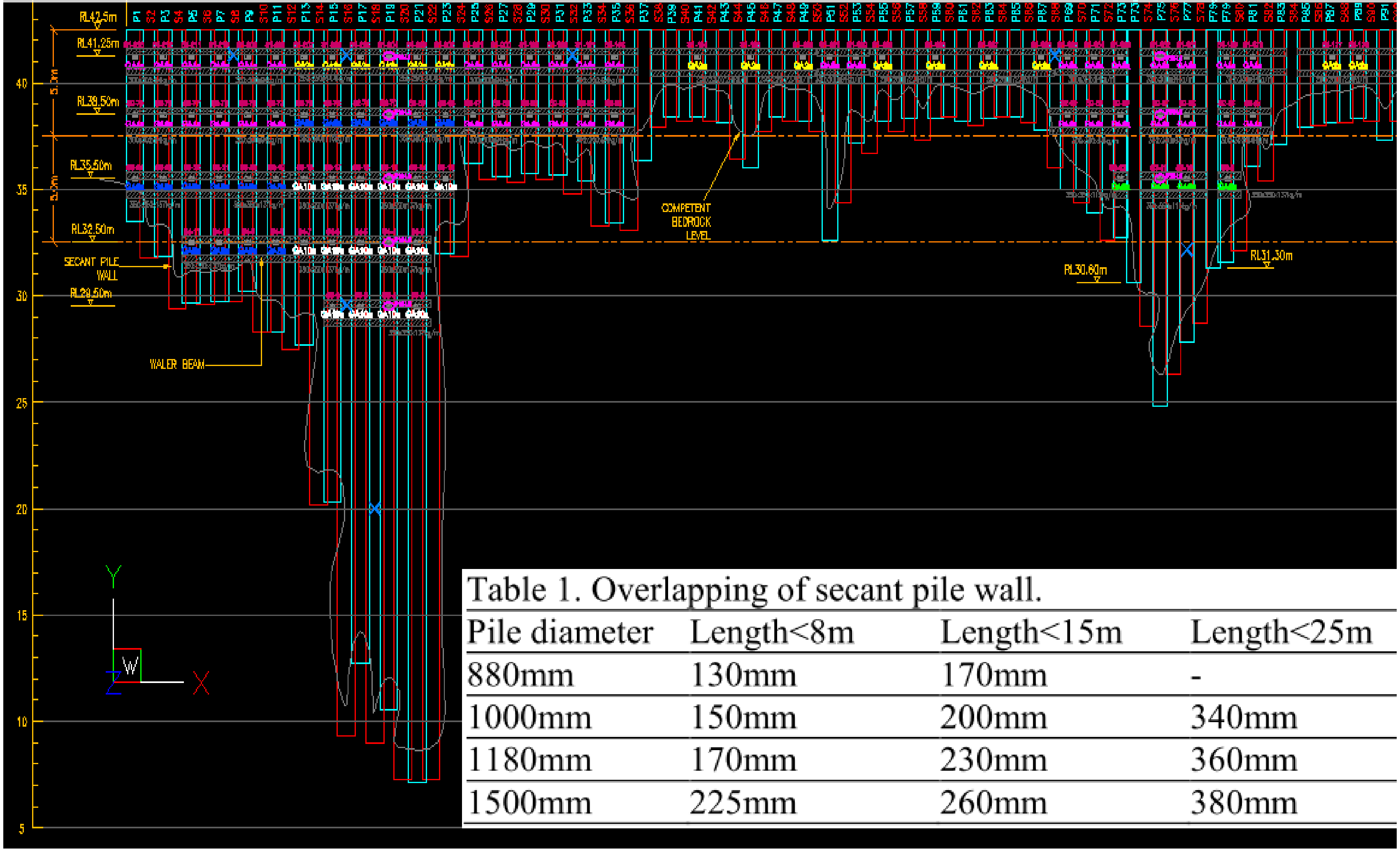
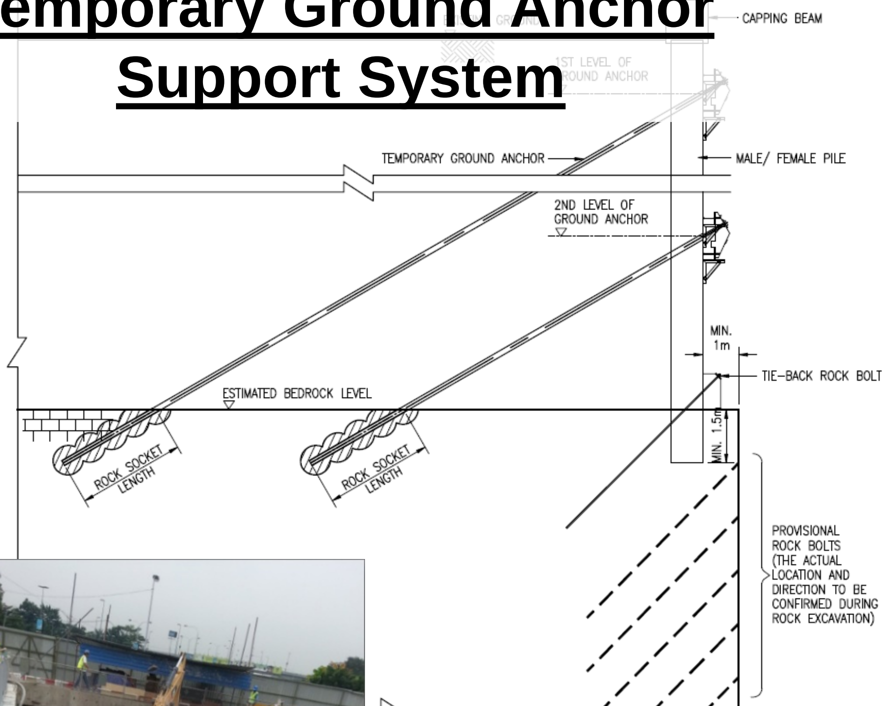


Table 1. Overlapping of secant pile wall.

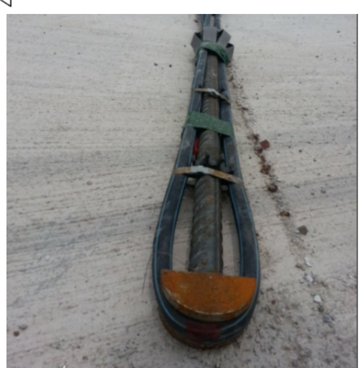
Pile diameter	Length<8m	Length<15m	Length<25m
880mm	130mm	170mm	-
1000mm	150mm	200mm	340mm
1180mm	170mm	230mm	360mm
1500mm	225mm	260mm	380mm

CASE STUDIES - LIMESTONE

Temporary Ground Anchor Support System



Description	Properties
Working loads (kN)	212; 424; 636; 848
No. of strand	2; 4; 6; 8
Strand diameter	15.24mm
Breaking load	260.7 kN
Factor of safety	1.6
Strand U-turn radius	47.5mm
Reduction factor	0.65
Drill hole diameter	175mm
Allowable bond stress	400 kPa (limestone)
Free length	Varies (until bedrock)
Bond length (m)	3; 3; 4.5; 6



CASE STUDIES - LIMESTONE

Curtain & Base Grouting to seal the Limestone Karstic Features

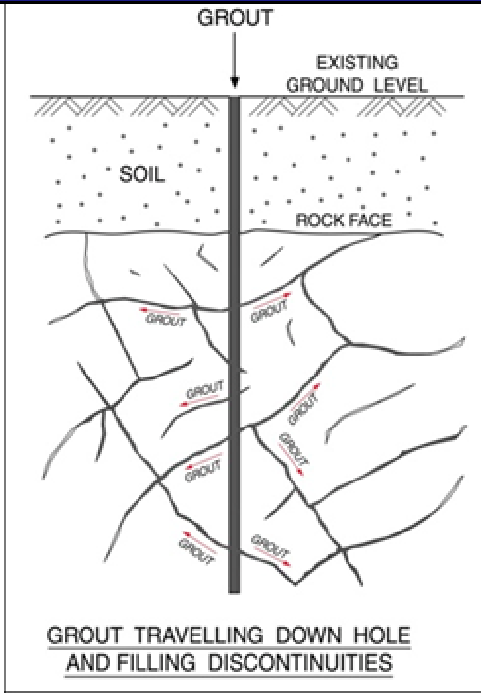


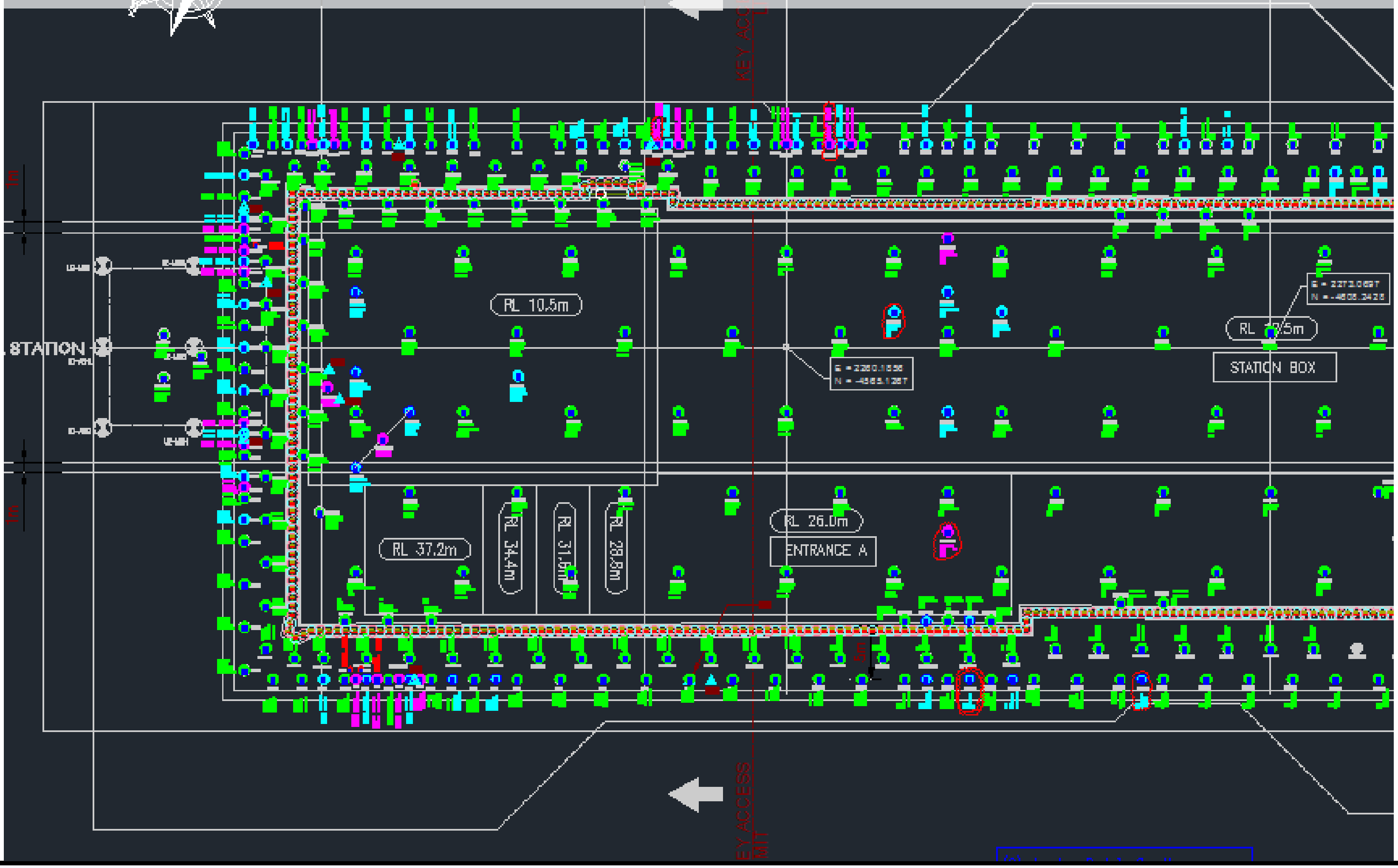
Table 3. Holding pressure for fissure grouting.

Depth (m)	Holding pressure (Bar)
0 to 10	2 to 4
10 to 20	6 to 8
20 to 30	10 to 12
30 to 40	14 to 16
40 to 50	18 to 20
>50	>22

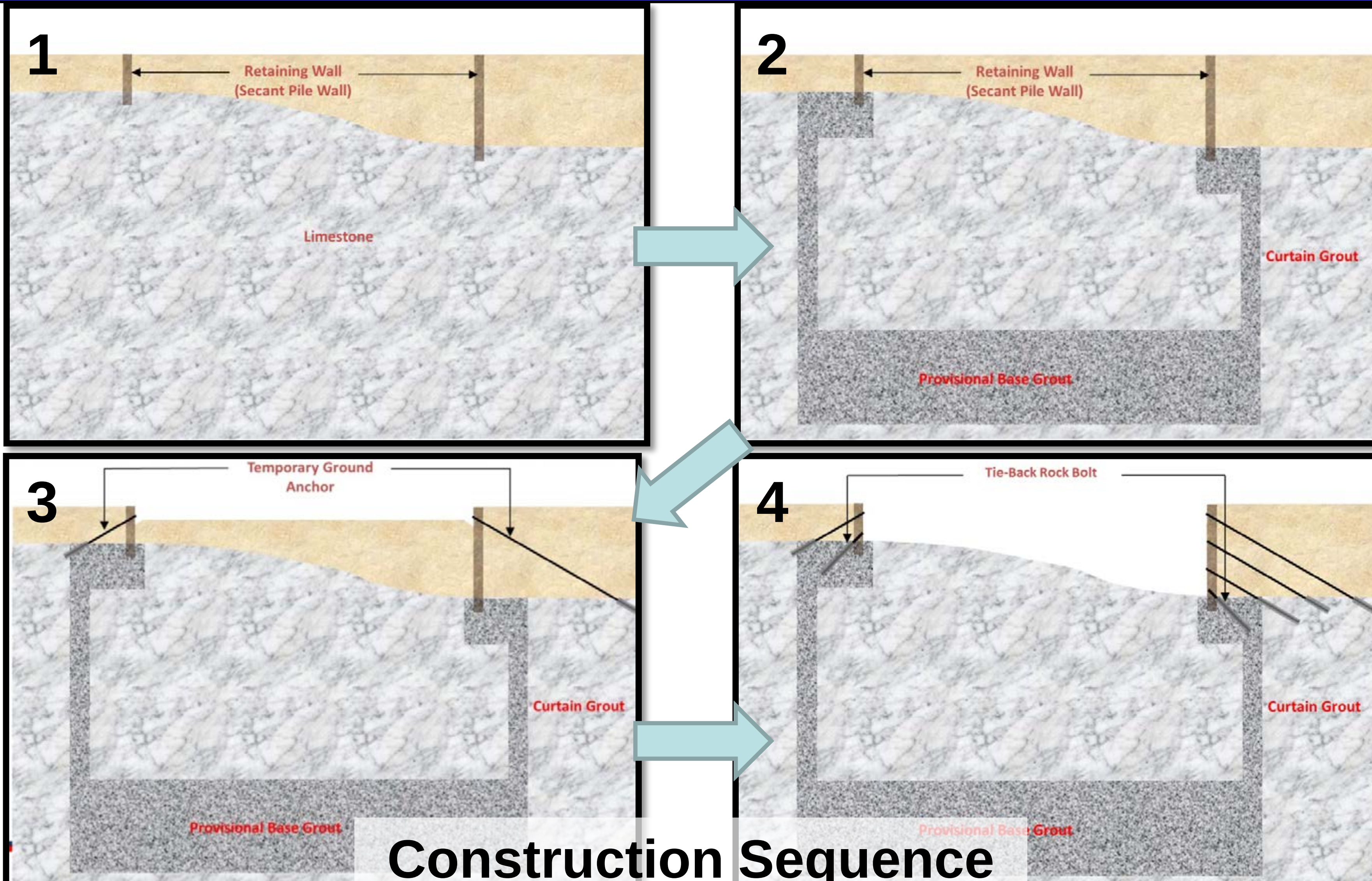
Note: Termination criteria shall be satisfied with flow rate less than 2 liters per minute or grout volume reaches 10m^3 for every grouting zone in 5m depth.

CASE STUDIES - LIMESTONE

Typical Curtain & Base Grouting Holes Layout

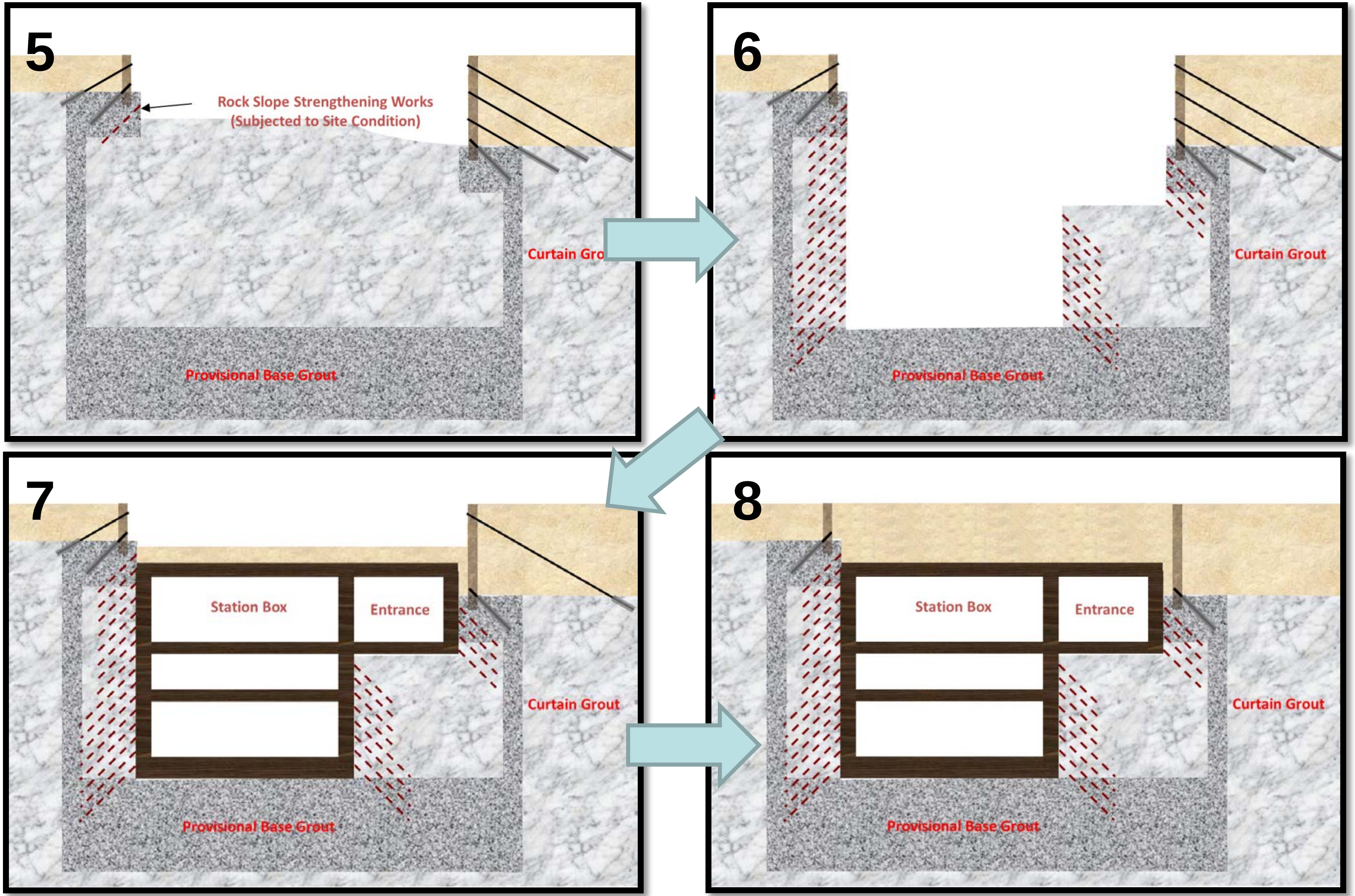


CASE STUDIES - LIMESTONE



Construction Sequence

Constrution Sequence (con’t)



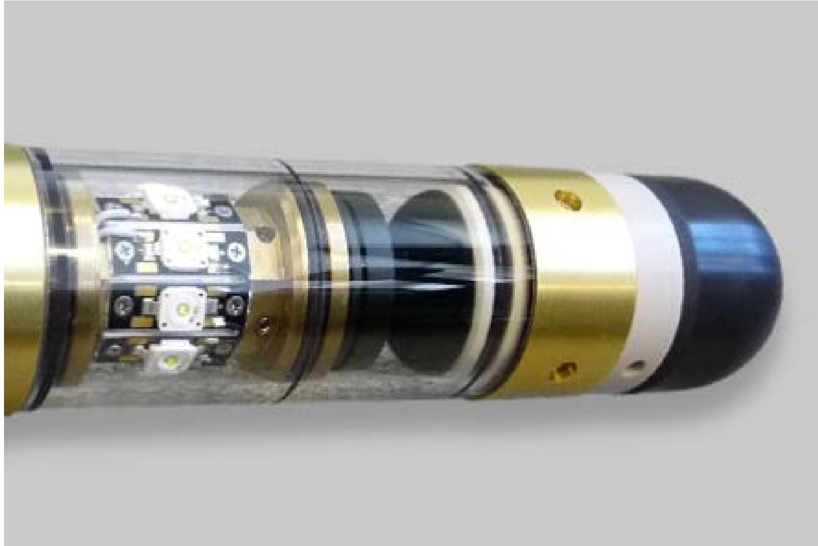
CASE STUDIES - LIMESTONE

Exposed Vertical Rock Face of the Excavation

BOREHOLE TELEVIEWER

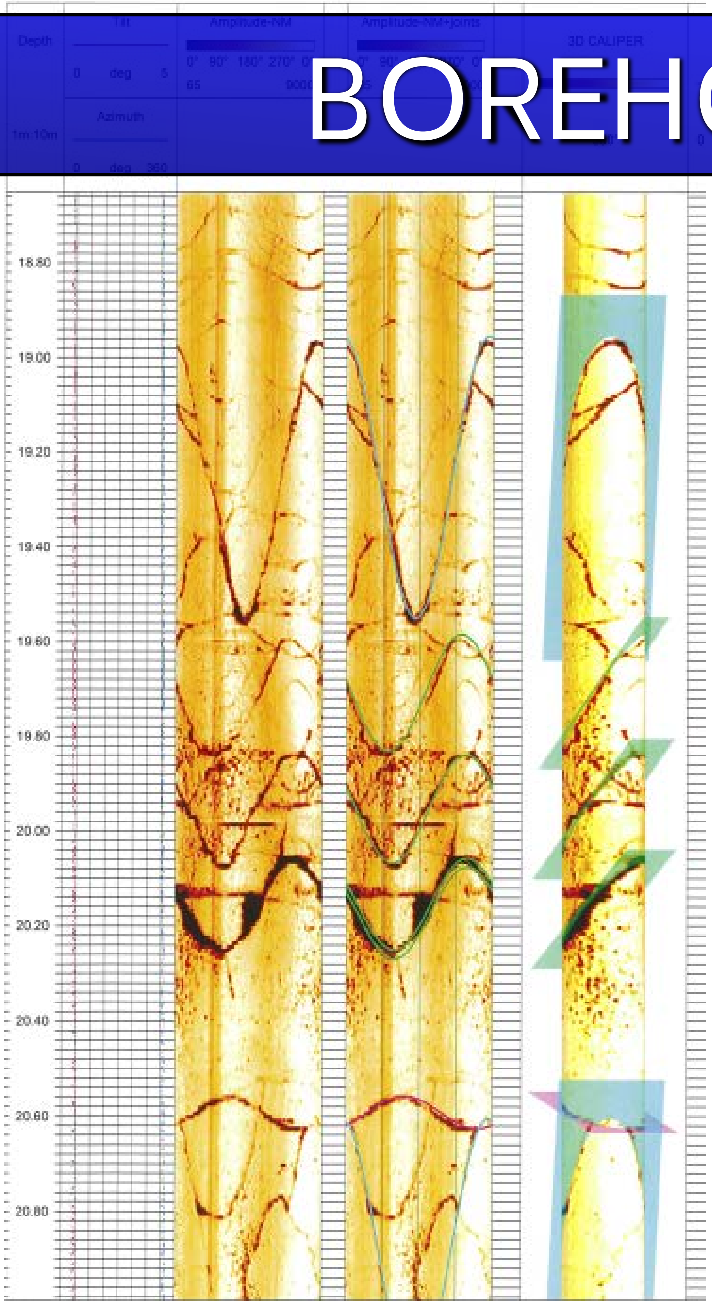
Borehole Televiewer - Ultrasonic logging device

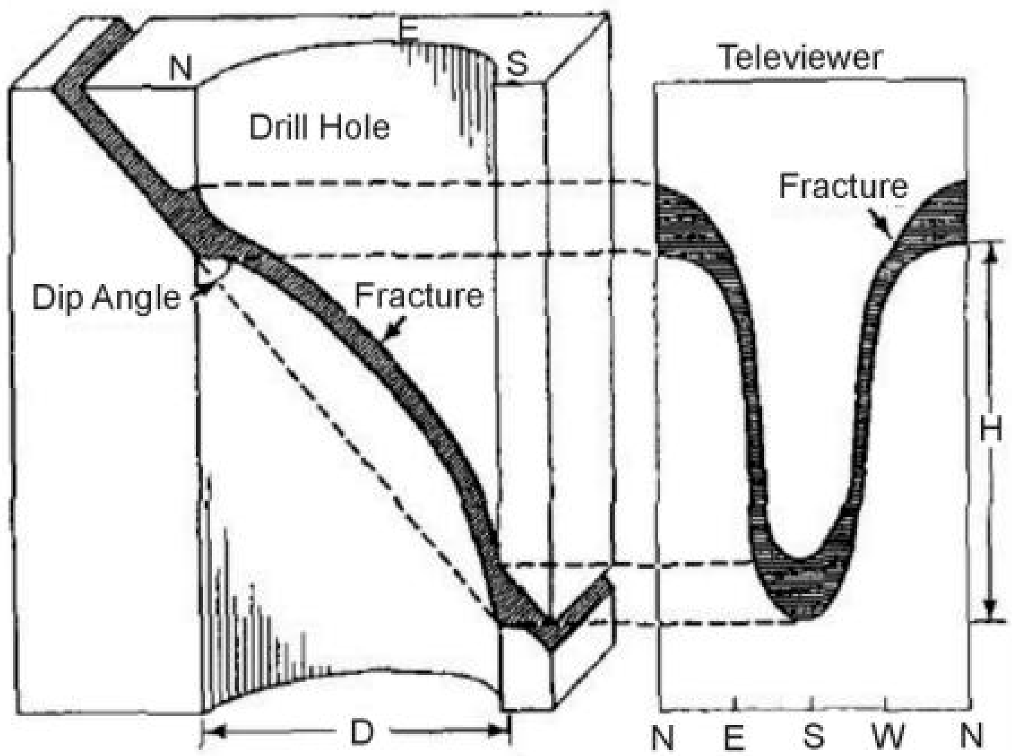
Radially mounted rotating transducer to scan borehole wall – Identify dip, fractures, bedding, etc.



Info from Advanced Logic Technology (ALT)

BOREHOLE TELEVIEWER





Info from clu-in.org

CASE STUDIES - LIMESTONE

Maluri Portal

Table 2. Partial load factors.

Load case	EL	DL	LL	TL	IL
Working condition	1.4	1.4	1.6	1.2	NA
Accidental impact	1.05	1.05	0.5	NA	1.05
One-strut failure	1.05	1.05	0.5	NA	NA

Note:
EL – Earth pressure and groundwater
DL – Dead load
LL – Live load
TL – Tempreture effect
IL – Accidental impact load
NA – Not applicable

CASE STUDIES - LIMESTONE

Steel Decking for the Traffic diversion above @ Maluri

CASE STUDIES - LIMESTONE

CASE STUDIES - LIMESTONE

Conchrane Station (Excavation Stage)

CASE STUDIES - LIMESTONE

Conchrane Station (Launching of 2^{nd} TBM)

Maximum 35m deep

CASE STUDIES – CIRCULAR SHAFT

Case History 2:
Circular Shaft for Launching of TBM in Kuala Lumpur

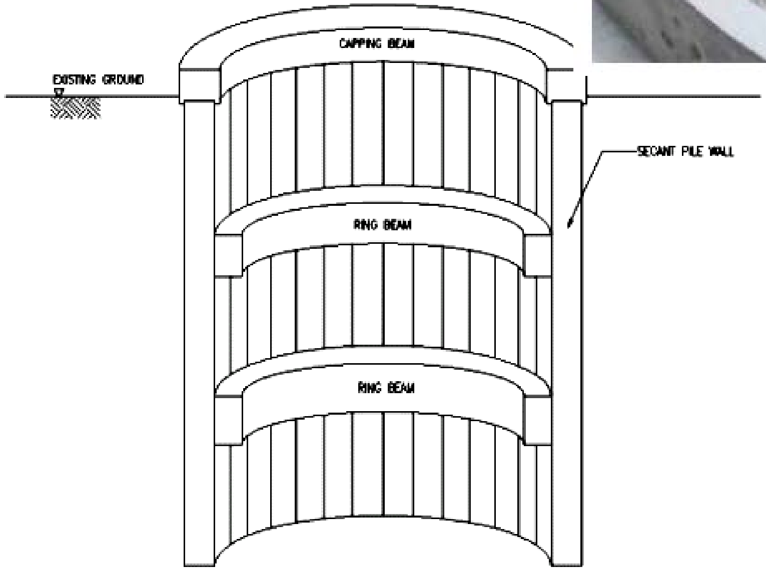
- KVMRT Line 1, Sungai Buloh to Kajang

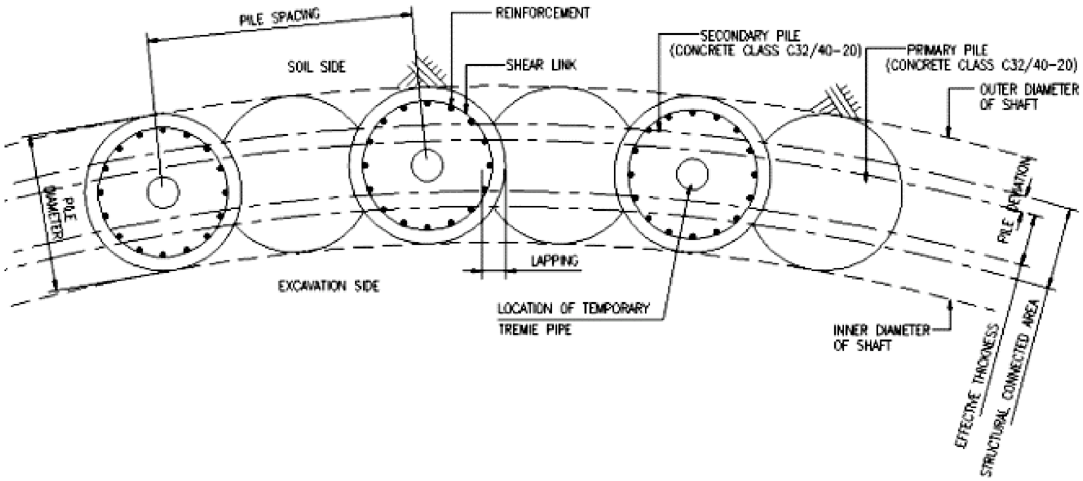
CASE STUDIES – CIRCULAR SHAFT

Circular TBM Launching Shaft

CASE STUDIES – CIRCULAR SHAFT

Circular Shaft during Excavation





Sectional view of circular shaft with ring beams.

CASE STUDIES – CIRCULAR SHAFT

Design Based on Hoop Force

$$\textit{Allowable compressive stress of concrete} \geq \frac{\textit{Critical hoop force in wall}}{\textit{Effective thickness of wall}}$$

where

Critical hoop force (kN per meter)
= (Maximum lateral pressure) x (0.5 of circular shaft outer diameter)

Effective thickness (m)
= (structurally connected area of retaining wall) – (pile deviation and verticality at critical depth during installation)

Allowable compressive stress of concrete (kPa)
= 0.25 of concrete design strength

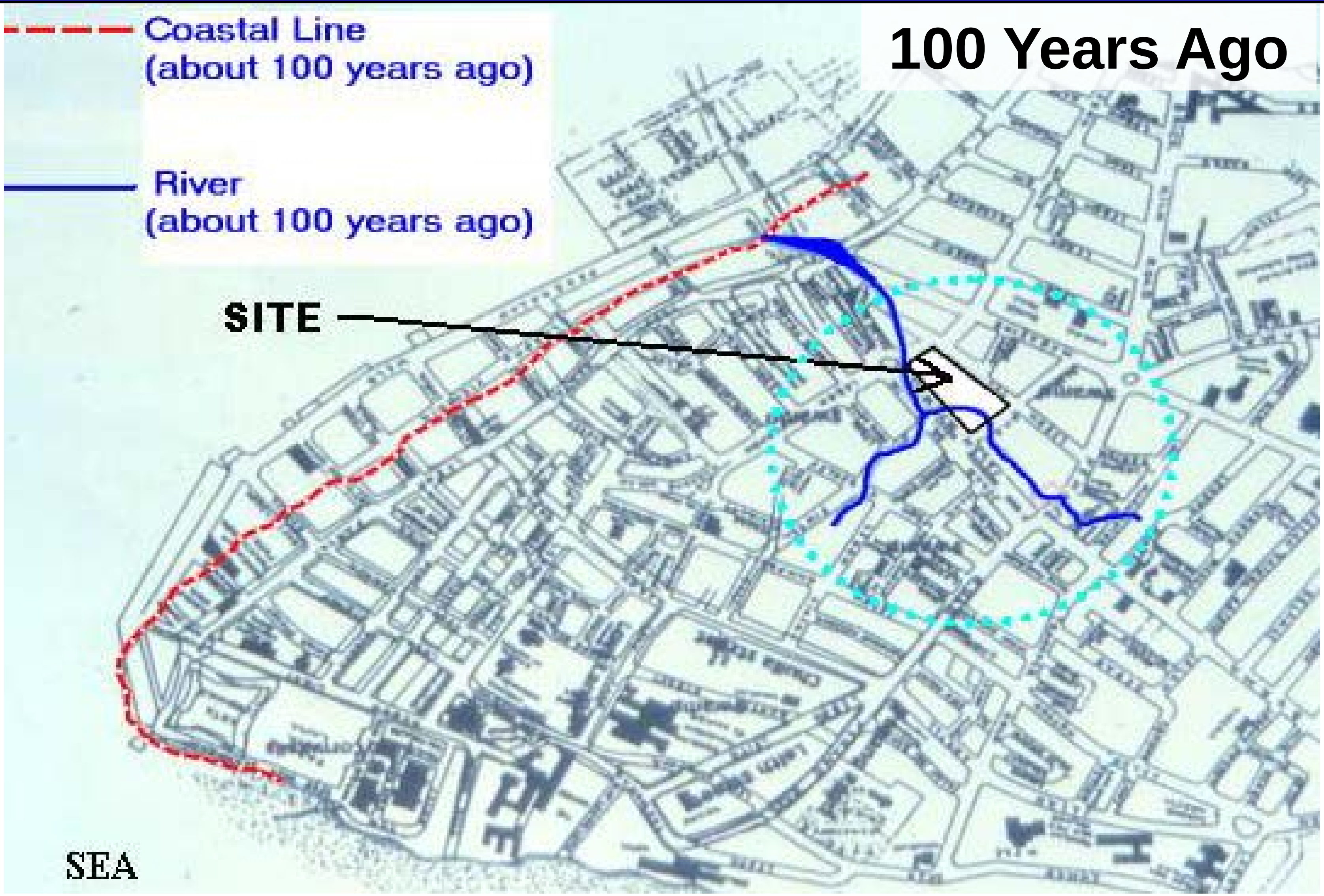
CASE STUDIES - ALLUVIUM

Case History 3:

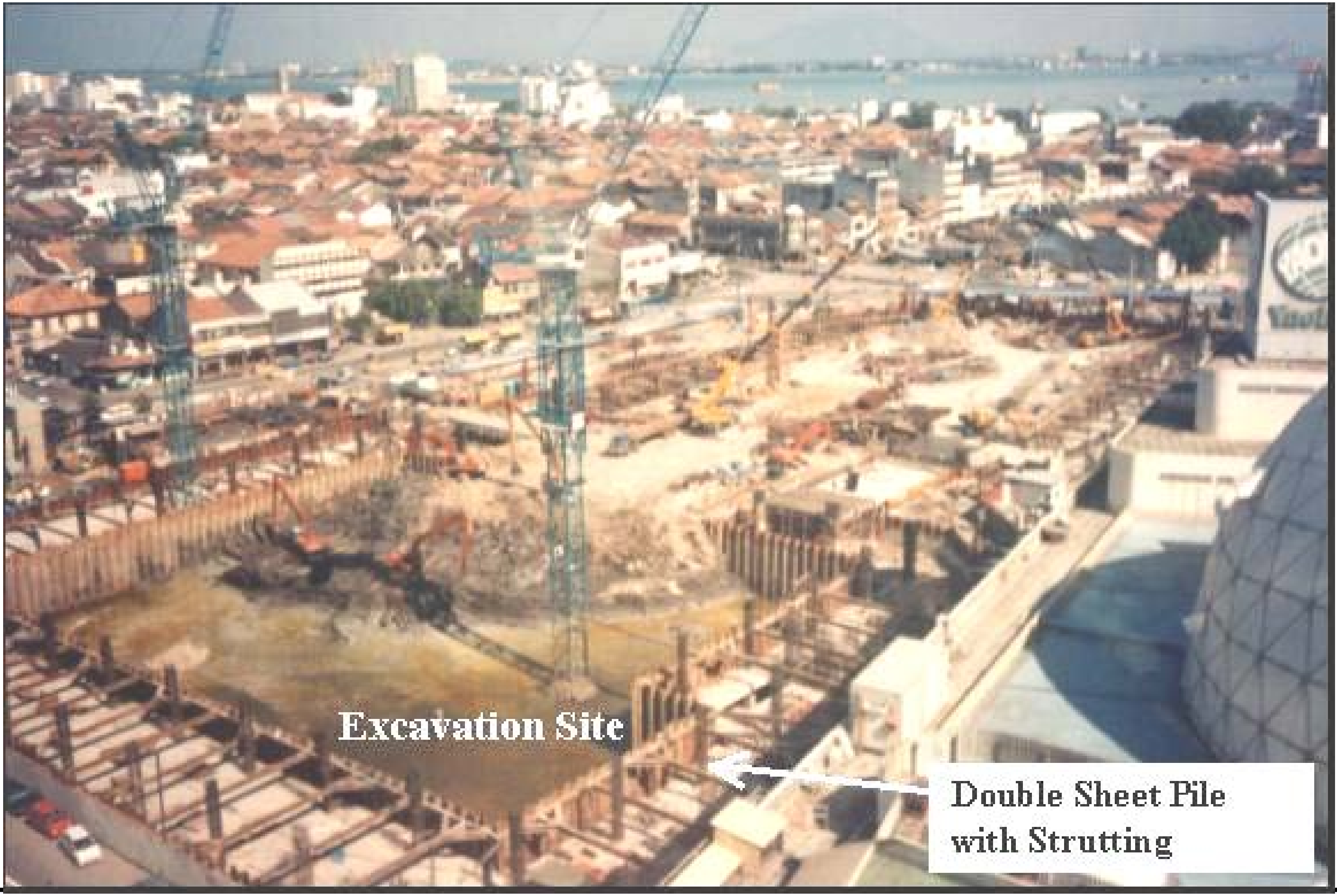
Hydraulic Failure @ Penang in

Alluvium with High Ground Water Table

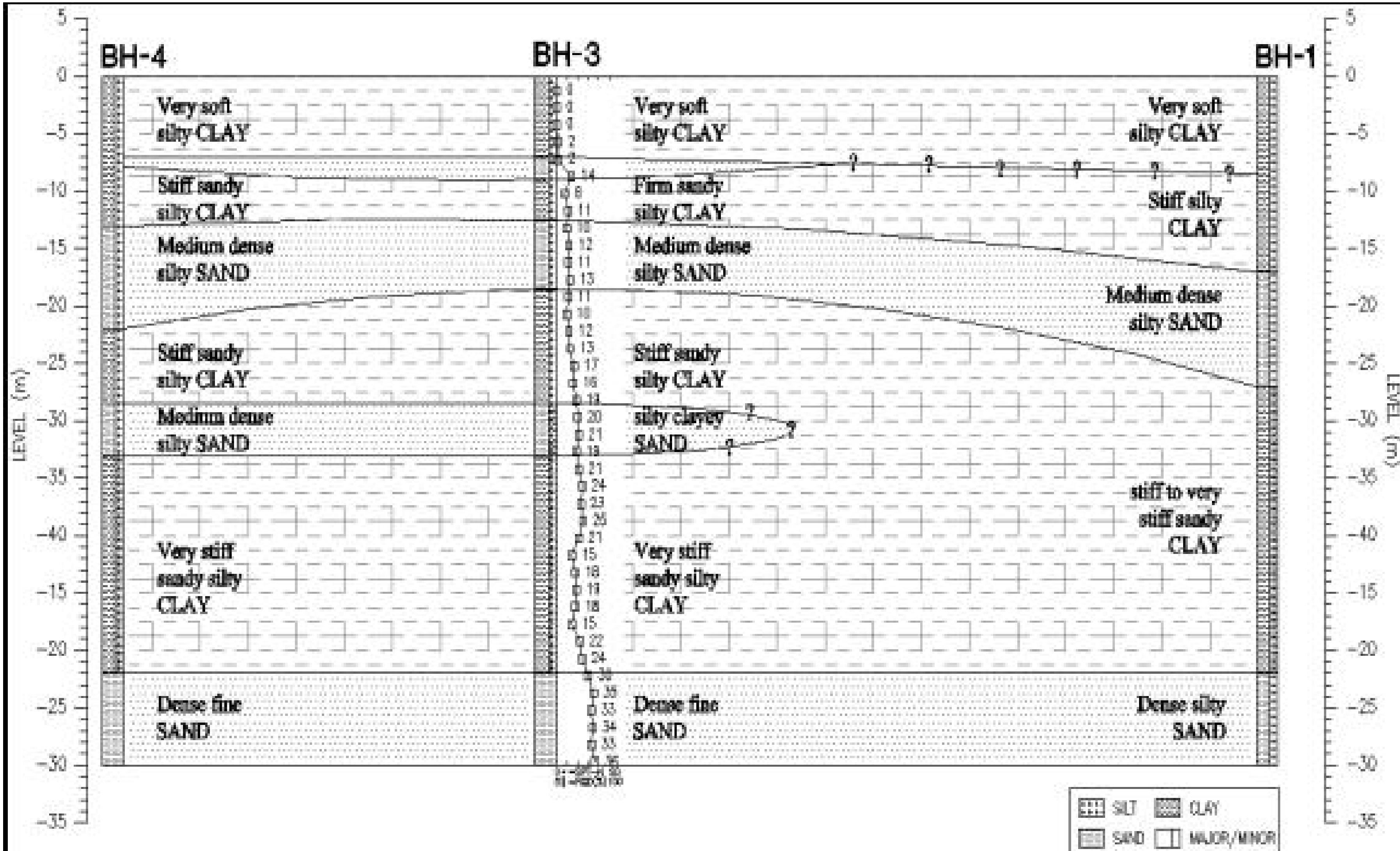
CASE STUDIES - ALLUVIUM



CASE STUDIES - ALLUVIUM



CASE STUDIES - ALLUVIUM



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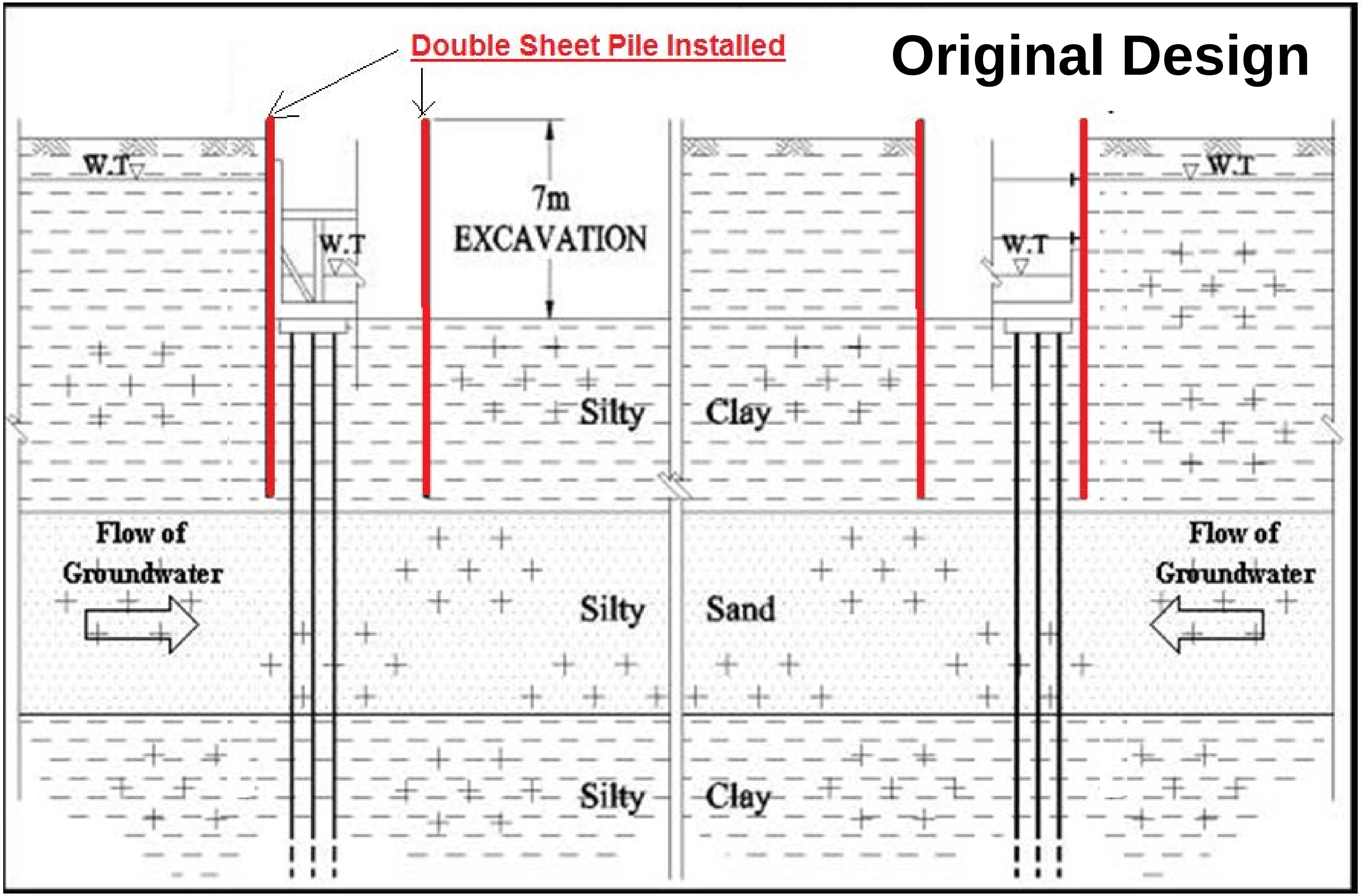
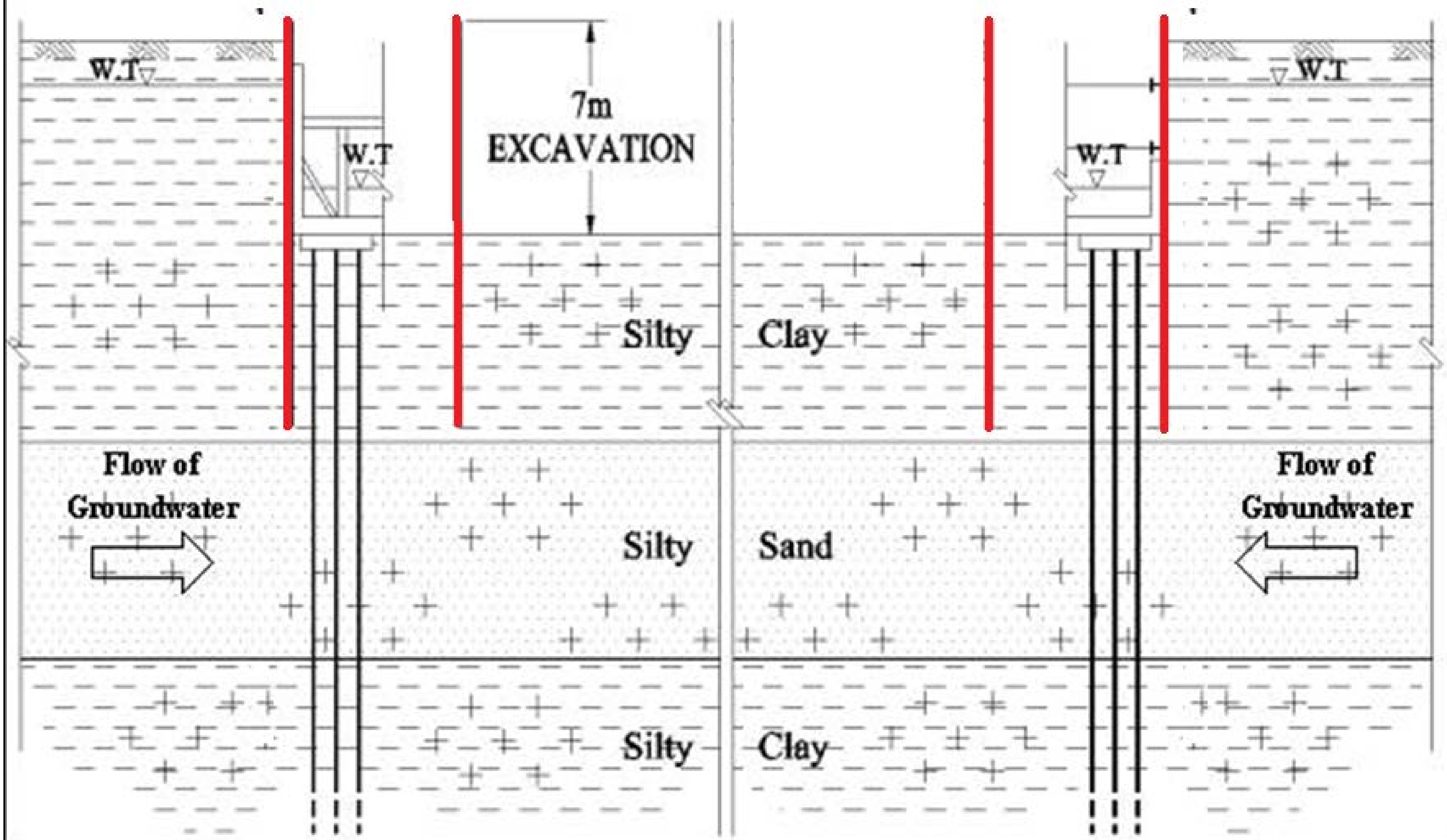


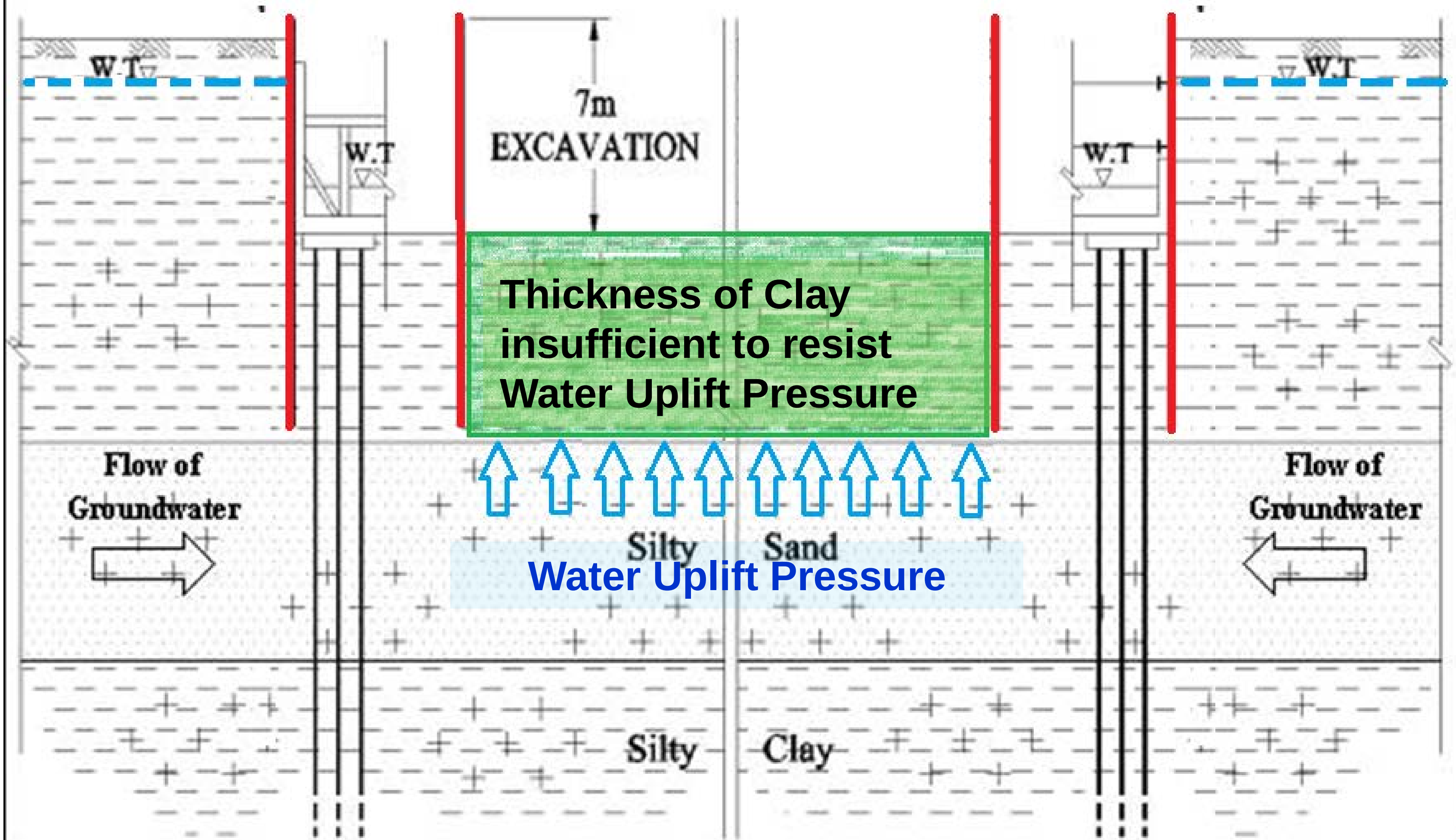
CASE STUDIES - ALLUVIUM

Original Retaining Wall (Insufficient Depth)



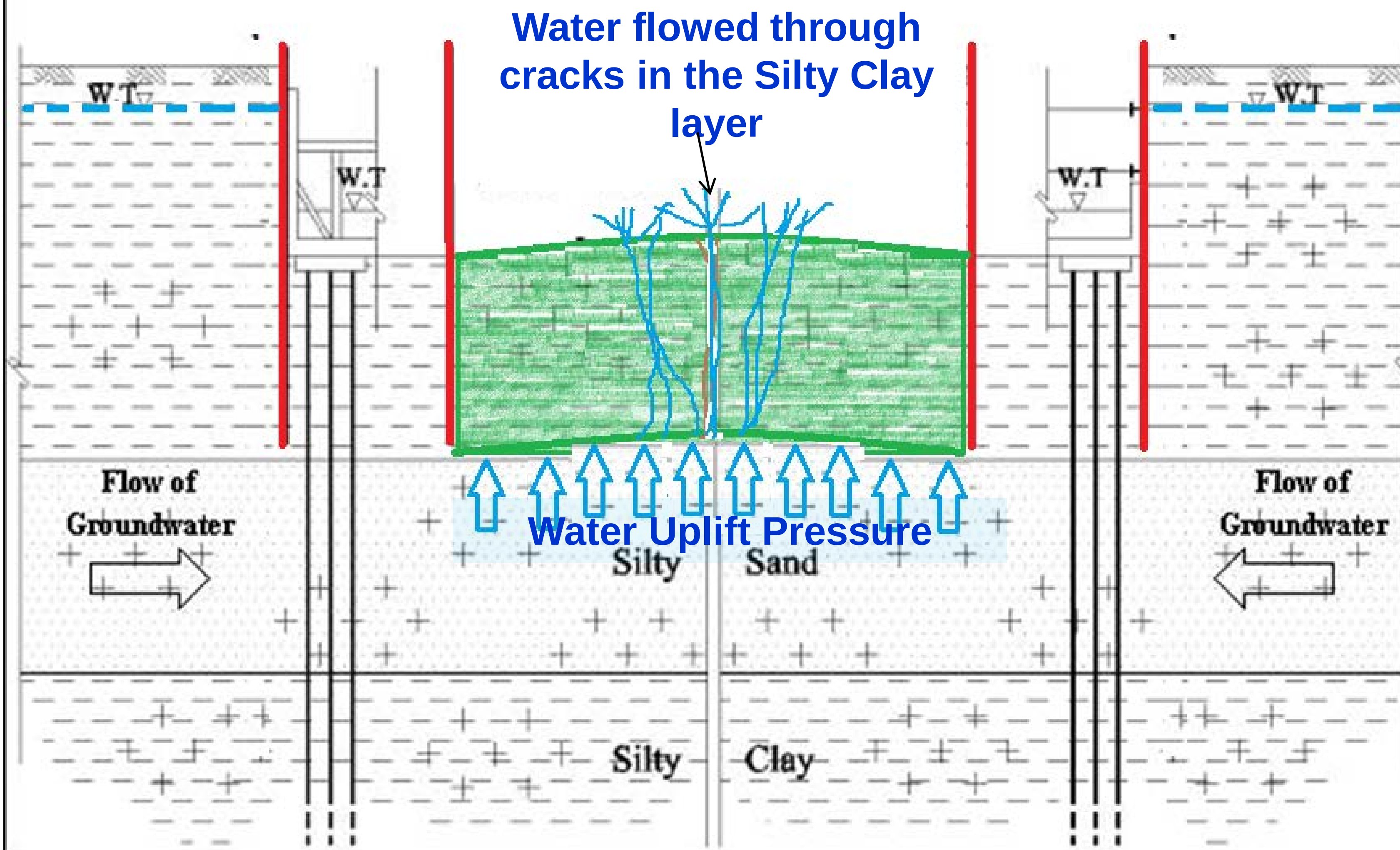
CASE STUDIES - ALLUVIUM

Original Retaining Wall (Insufficient Depth)



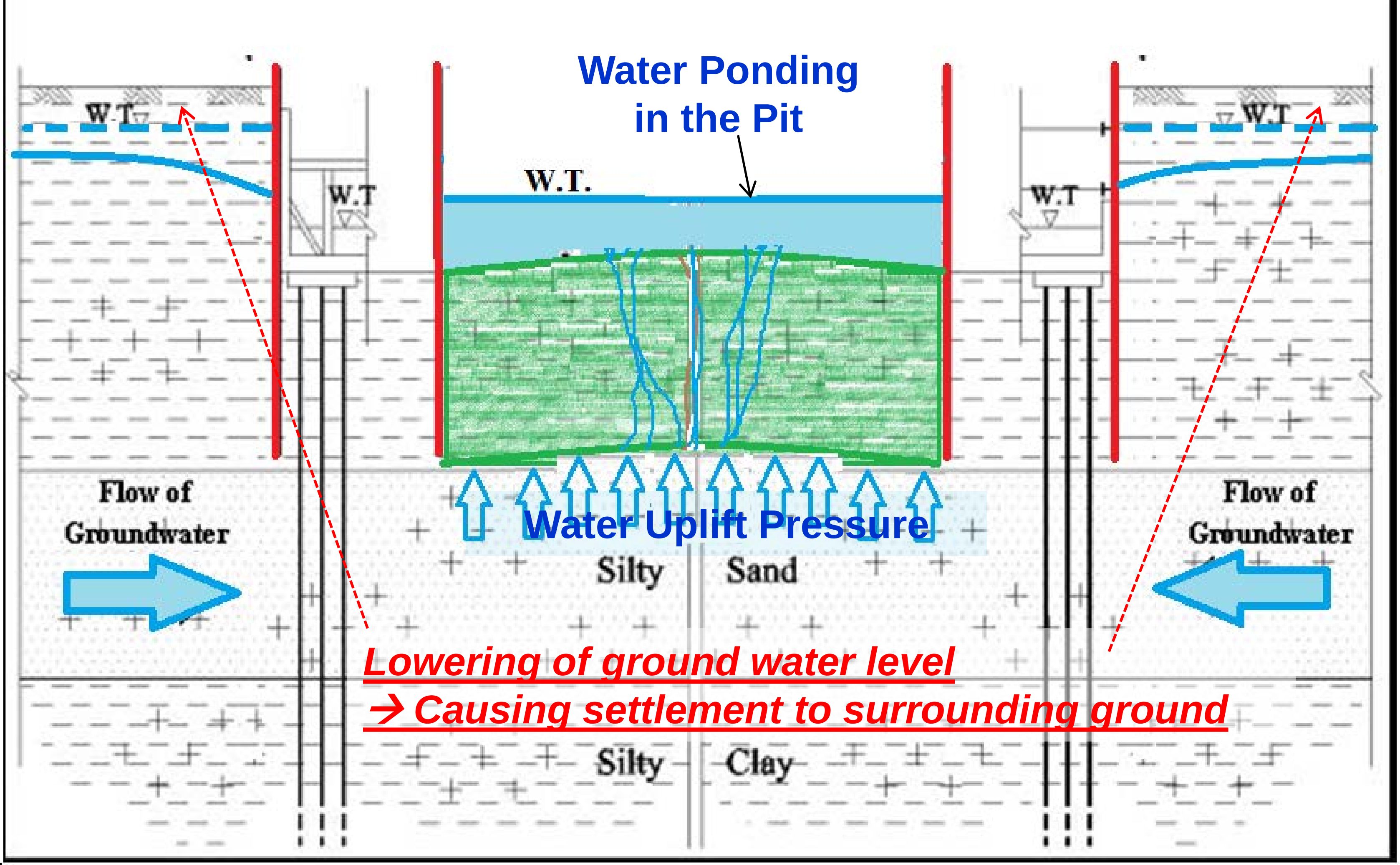
CASE STUDIES - ALLUVIUM

Original Retaining Wall (Insufficient Depth)



CASE STUDIES - ALLUVIUM

Original Retaining Wall (Insufficient Depth)

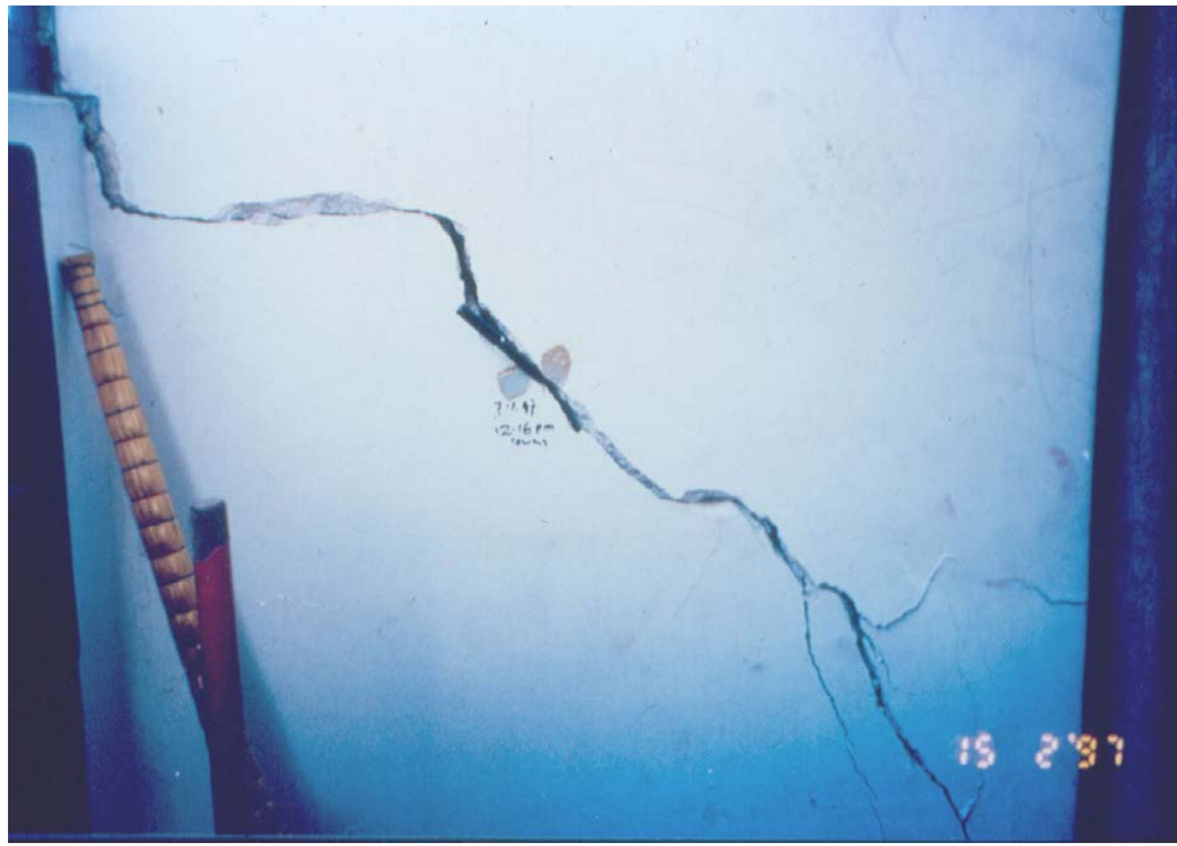


CASE STUDIES - ALLUVIUM

The Site after Failure

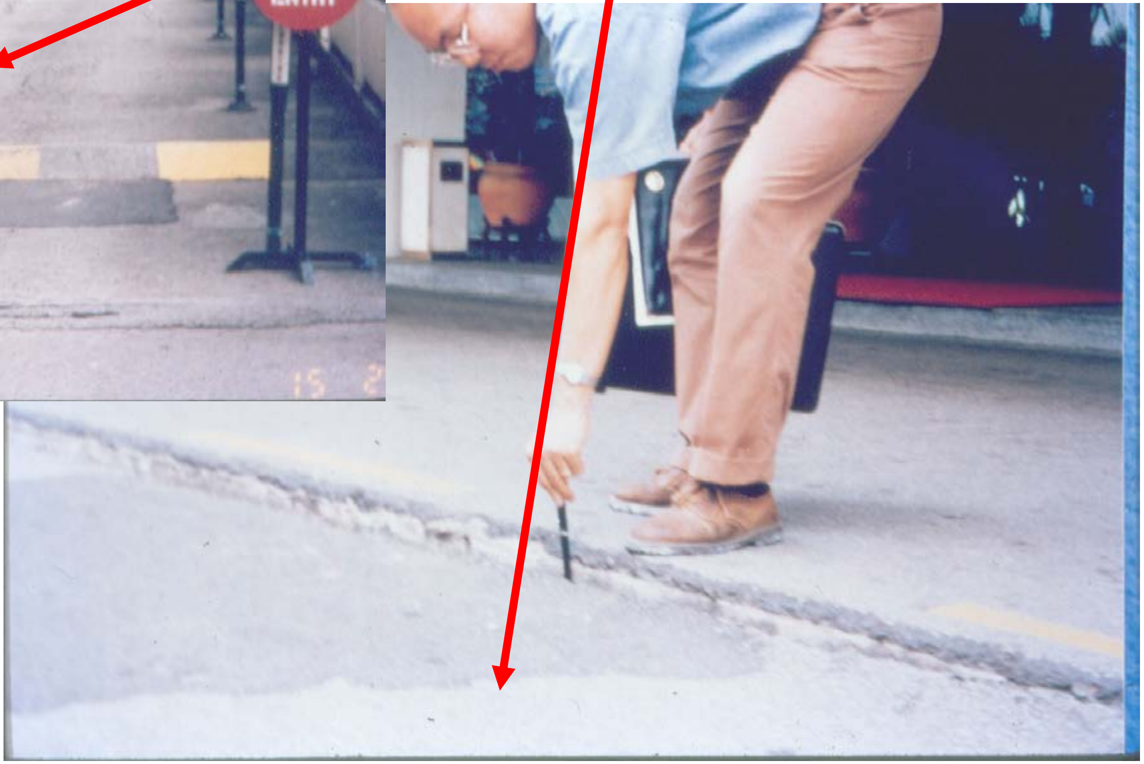
CASE STUDIES - ALLUVIUM

Cracks of Houses – about 120 m away excavation

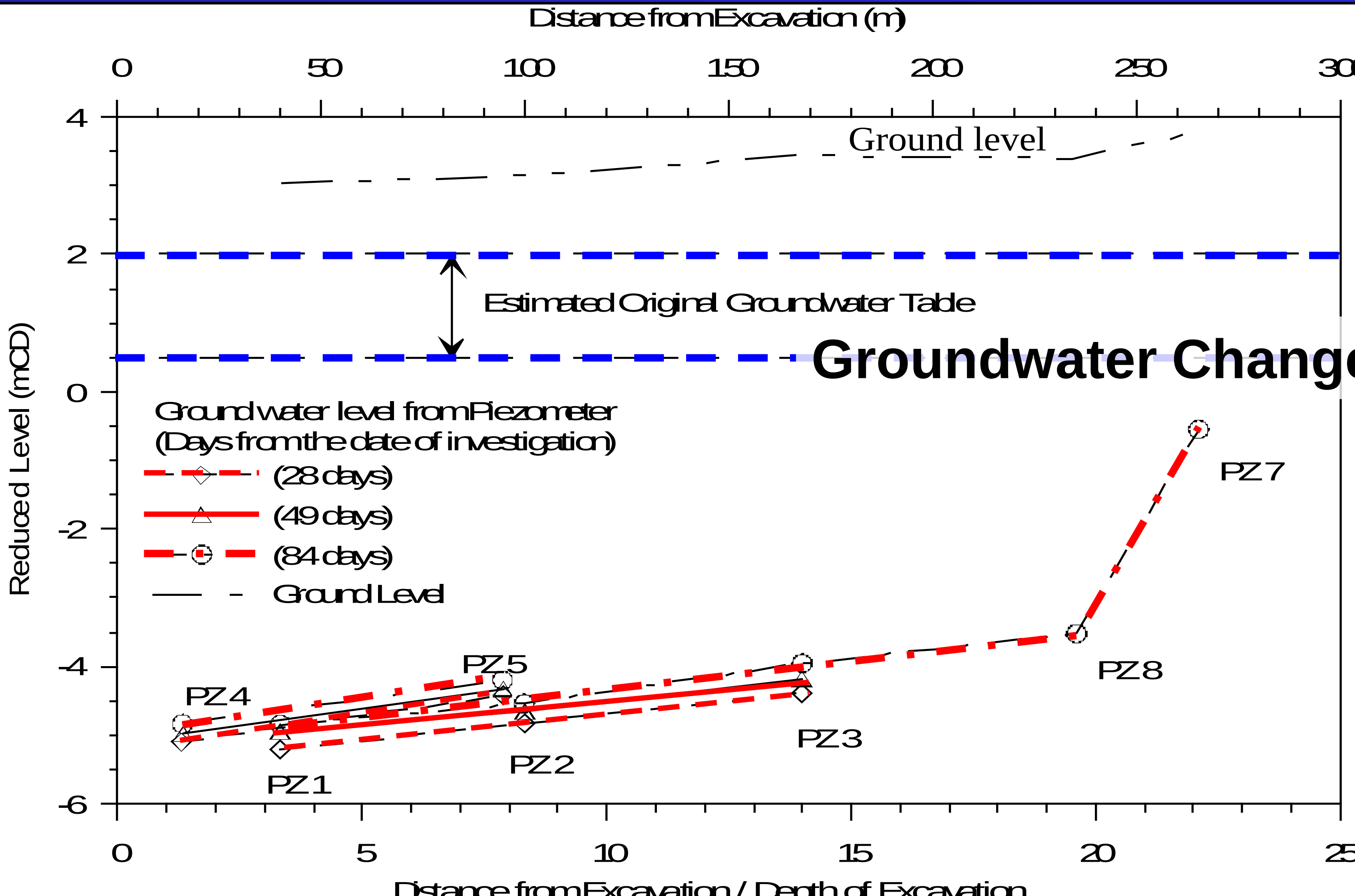


CASE STUDIES - ALLUVIUM

Settlement of Ground

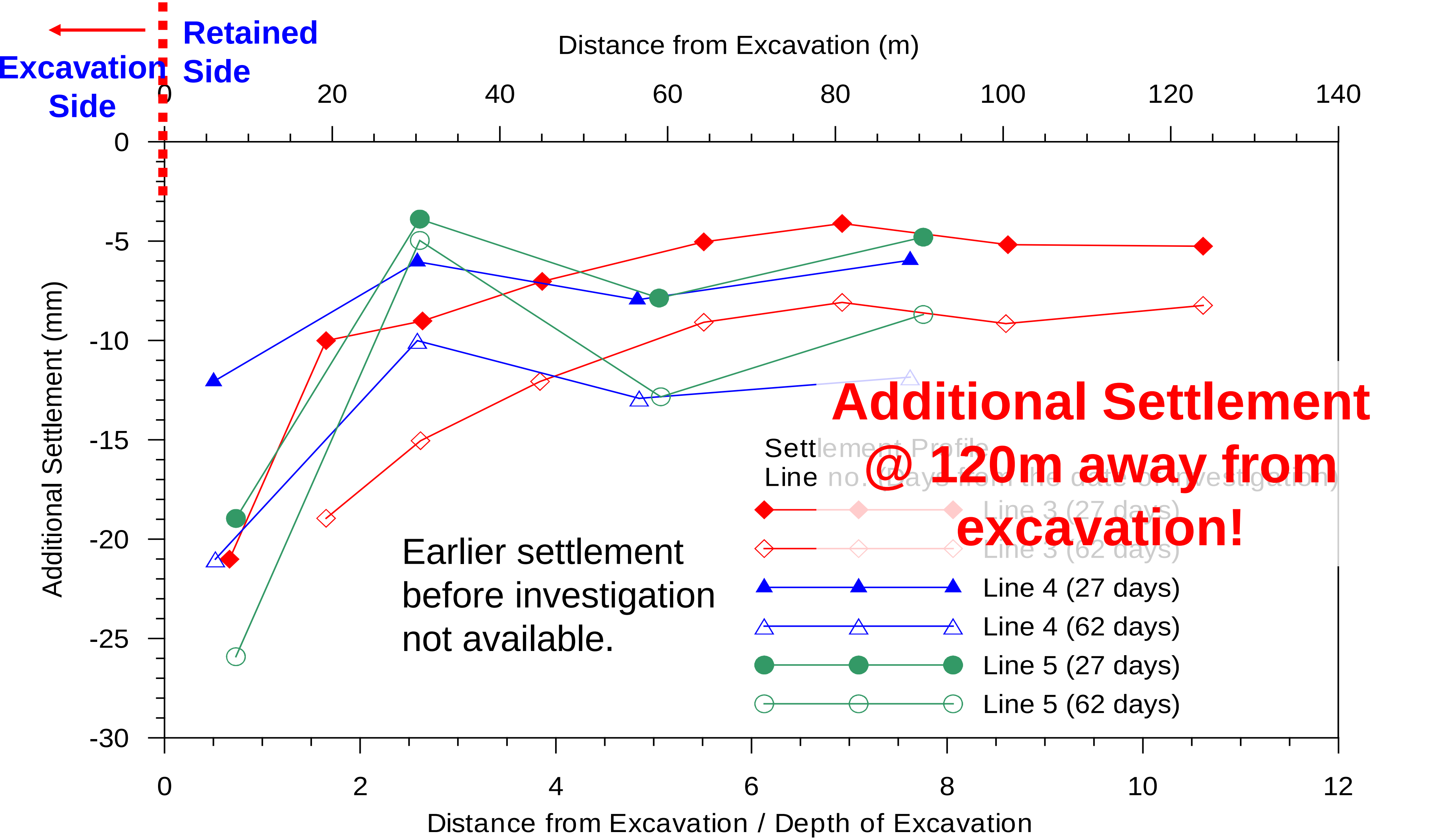


CASE STUDIES - ALLUVIUM

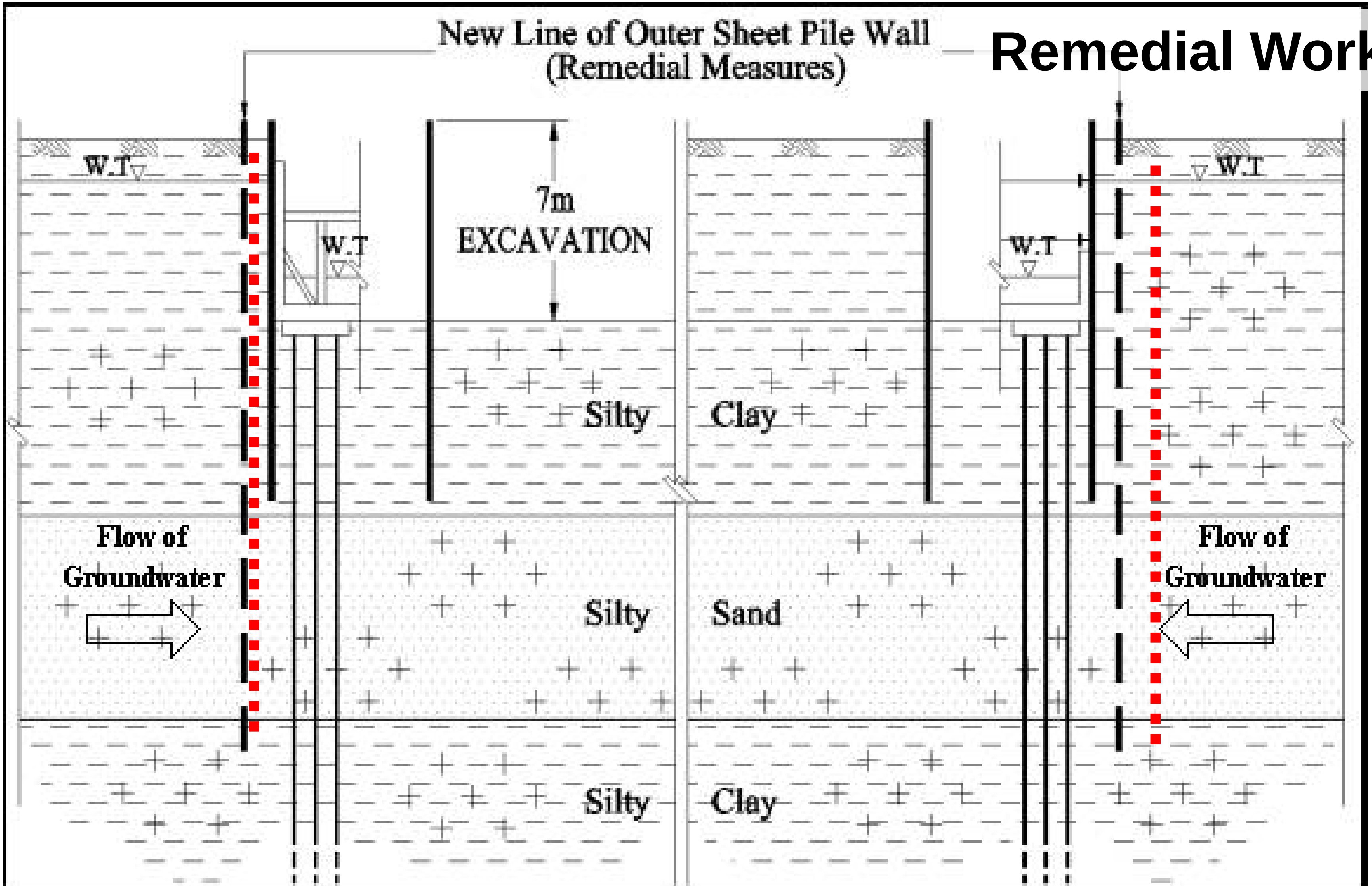


Groundwater Changes

CASE STUDIES - ALLUVIUM



CASE STUDIES - ALLUVIUM



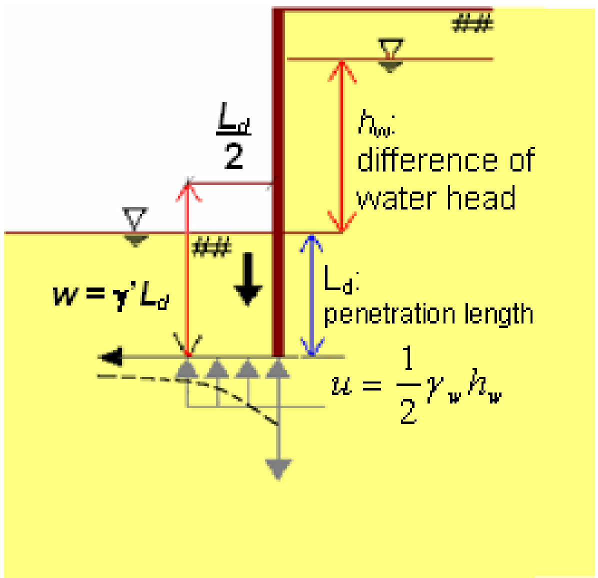
CASE STUDIES - ALLUVIUM

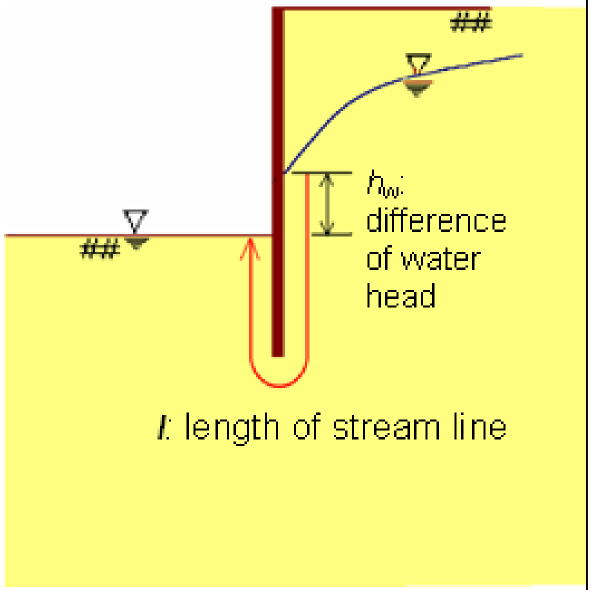
Hydraulic Failure

- Base instability caused by piping
  - **Seepage** due to high groundwater level
- Available methods
  - **Terzaghi's method**
  - **Critical hydraulic gradient method**

CASE STUDIES - ALLUVIUM

Hydraulic Failure Checks

<table>
<tr><th></th><th>Terzaghi's method</th><th>Critical hydraulic method</th></tr>
<tr><td>Diagram</td><td>

γ':submerged unit weight of soil
γ_w: unit weight of water</td><td>

G_s: specific gravity of soil particle
e : void ratio</td></tr>
<tr><td>Equation</td><td>FOS = $w / u = \dfrac{2\gamma' L_d}{\gamma_w h_w}$
FOS ≥ 1.2 (temporary works)
FOS ≥ 1.5 (permanent works)</td><td>FOS = $i_c / i = \dfrac{G_s - 1}{1+e} \cdot \dfrac{l}{h_w} = \dfrac{\gamma' l}{\gamma_w h_w}$
FOS ≥ 2.0</td></tr>
</table>

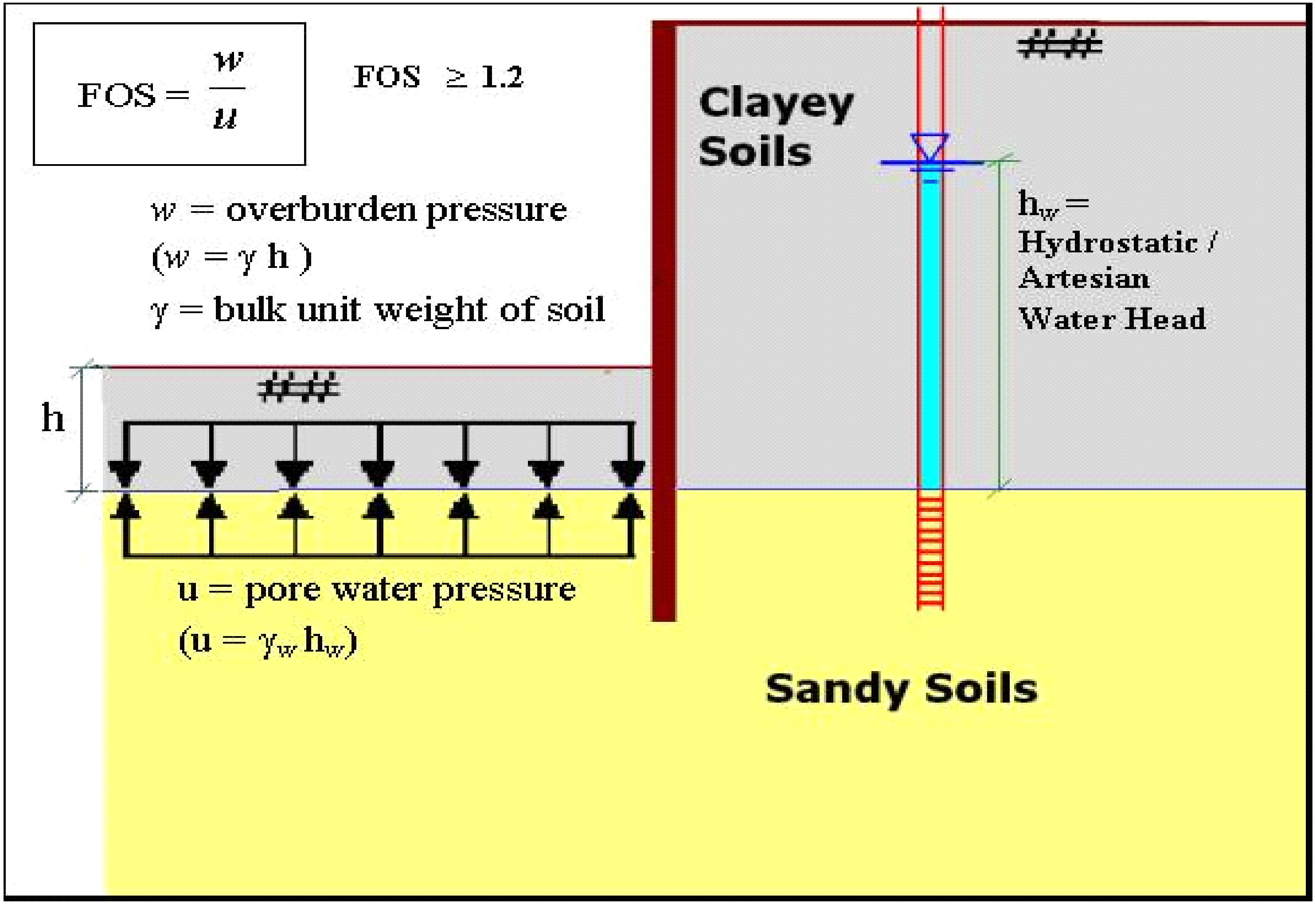
CASE STUDIES - ALLUVIUM

Hydraulic Failure

- **Terzaghi's method recommended**
  - Based on latest research by Tanaka & Verruijt (1999)
  - Factor of safety required – **1.2 to 1.5**

CASE STUDIES - ALLUVIUM

HEAVING DUE TO ARTESIAN PRESSURE



CASE STUDIES - ALLUVIUM

Hydraulic Failure

- **Heaving due to artesian pressure**
  - Factor of safety – **1.1 to 1.2**
  - Smaller FOS sufficient as it did not consider shear strength or adhesion strength of the ground and retaining wall

Video of Hydraulic Failure

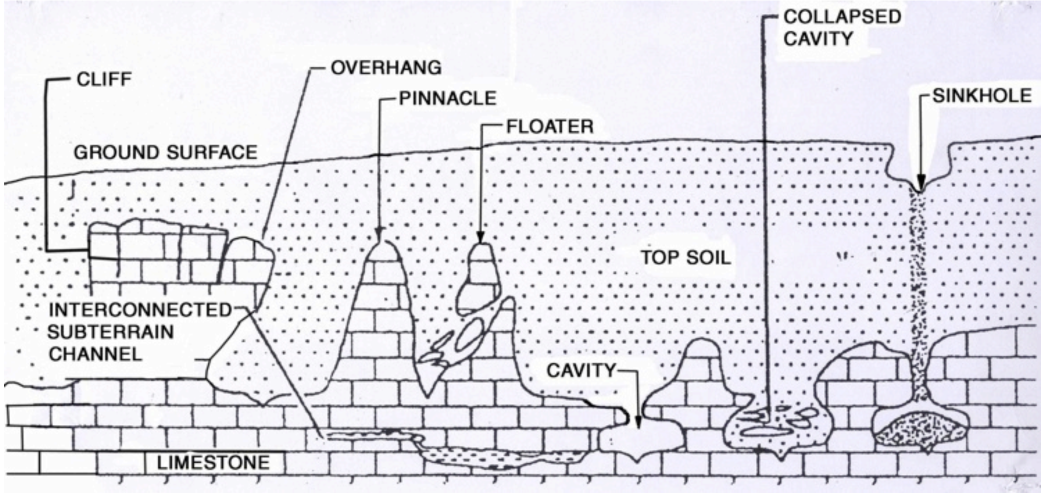
SUMMARY

SUMMARY

Successful deep excavation depends on:

- Proper SI, Subsoil Profile, Parameters & calibrations
- Proper Constitutive models & Analyses
- Beware of Impact of lowering water table & Mitigation measures

SUMMARY



- Construction of deep excavation **in erratic and complex Limestone** formation requires multiple retaining systems and treatments together with strict control of vertical alignment with verification during construction

SUMMARY

- Manage to use **controlled blasting** for the station construction **with live traffic above the blasting level**. The vibration is within the permissible limit of 25mm/s.

SUMMARY

Cracks of Houses – about 120 m away excavation

- Deep excavation in **Alluvium** with **sand layer lowered the water table** to a distance of **over 40 times** the **depth of excavation** & induced **settlements up to 120m away from excavation!**

ACKNOWLEDGMENT

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- Ir. Dr. GUE Chang Shin
- Dr. GUE Chang Ye


THANK YOU