Lesson learnt from foundation failure cases in Singapore

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Building and Construction Authority

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Outline

Factors contributing to foundation failure

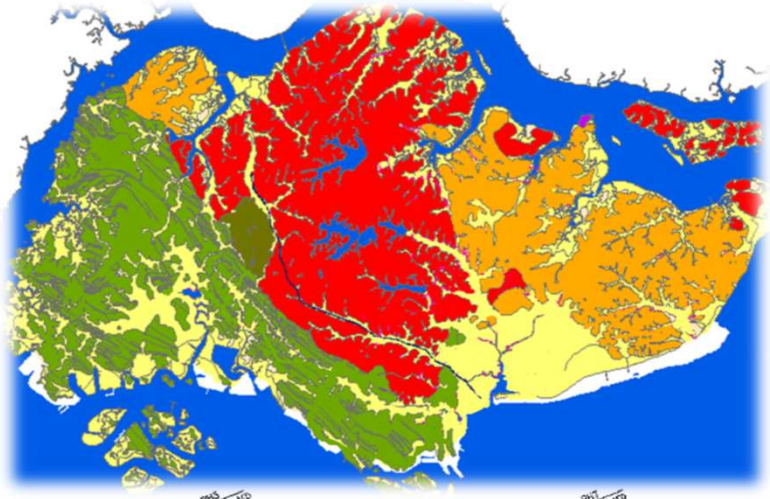
Sharing of local cases

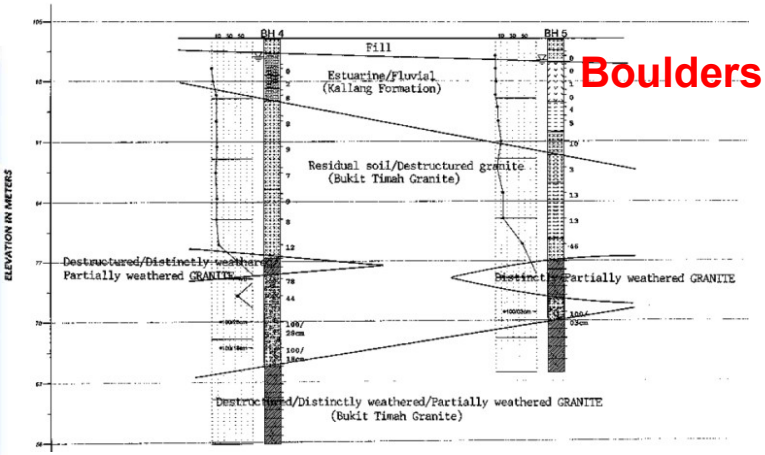
Factors contributing to foundation failures

1. Inadequate site investigation
2. Inappropriate use of pile design parameters
3. Poor construction workmanship

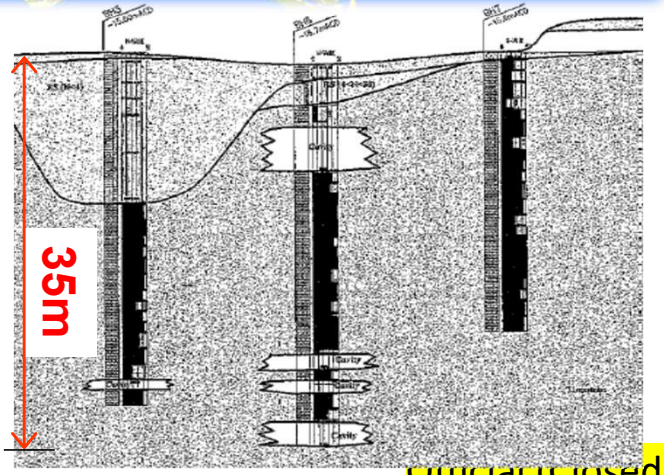
Complex geology

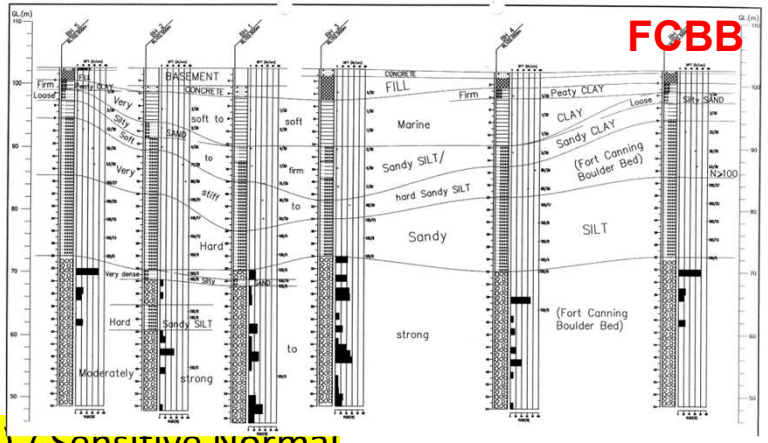
“The ground is full of surprises for the unwary.” *Karl Terzaghi*





Cavity





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1. Inadequate site investigation

- It is imperative to conduct **Adequate site investigation** to identify all ground formations and layers, to determine ground properties.
  - ❖Extent: Sufficient number of site investigation boreholes
  - ❖Depth : Sufficient exploration depth
- Success of any foundation work depends largely on adequate site investigation regime to fully understand the ground on which the foundation is located.
- When bored piles are required to reach or penetrate into bedrock, level of bedrock surface shall be determined.

Inadequate site investigation

- "Conservative" design & high quality construction may not be adequate to compensate for wrong understanding and interpretation of the ground.
- Unnecessary cutting down in site investigation cost may prove to be penny wise, pound foolish. It is a cost too hefty to pay.

Vigilance for difficult geological formations

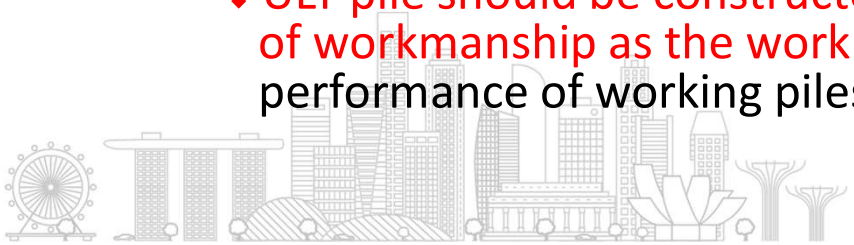
- Presence of cavities within soils / rock
  - ❖Pandan Formation, Boon Lay Formation
- Presence of boulders in the soil matrix
  - ❖Boulders misconstrued as the bedrock
- Presence of thick deposit of soft clay
  - ❖Negative downdrag
- Highly variable bedrock stratum, with steeply inclined bedrock

2. Inappropriate use of pile design parameters

- Could happen due to adoption of over-optimistic design parameters, and failure to recognize the execution condition e.g.
  - ❖Unrealistically high end bearing resistance for bored piles with soft toe
  - ❖Unrealistically high shaft resistance for large and deep bored piles with bentonite cake forming along shaft
- Essential to have good understanding of the local practices, recognizing the level of workmanship attainable/expected and specify them into the technical specification of the project, for compliance by the piling contractors.

Conduct of Ultimate load tests to verify design

- It is important to conduct ultimate load test to verify the design parameters, before installation of working piles
  - ❖ To derive fs and qb for each layer of soil
  - ❖ Based on a specified method of construction and level of workmanship
- Due to variable workmanship and construction method, designers may assess the probable range of design parameters & submit several design sets using performance-based pile design method for approval.
  - ❖Parameters can range from most pessimistic to most optimistic
  - ❖Verify the suitable design set by testing on the most optimistic ULT pile
  - ❖ULT pile should be constructed using the similar construction method and similar level of workmanship as the working piles, to obtain representative results that reflect performance of working piles



3. Poor construction workmanship

- Defects of bored piles can include:
  - ❖ Loss of continuity along the pile length or necking, due to intrusion of soil or ground water
  - ❖ Defective concrete with low concrete strength, due to segregation, channelization, bleeding, concrete contamination
  - ❖Cavities within the piles, due to lack of concrete workability
- **Pile defects are hidden underground** and could not be seen or detected. Tests to assess the structural integrity of completed piles include:
  - ❖Sonic logging test
  - ❖PDA / PIT test
  - ❖Full coring / interface coring test

Bored pile issues

- **Stability of pile bore**
  - ❖ Stabilizing fluid – need to be dense enough to prevent soil along the entire shaft from collapse
  - ❖ Steel casing – need to be extended to below the soft clay layer
- **Soft toe issue**
  - ❖Caused by sedimentation of contaminated stabilizing fluid **or** collapsed soil deposited at pile base, without being removed before concreting
  - ❖Tool need to be deployed to clean the pile toe before concreting

Driven/ jacked piles issues

- **Pile heave**
  - ❖ Pile capacity may be reduced / damaged structurally if it heaved due to installation of adjacent piles
  - ❖ Pro-active measures like pre-boring, relief wells need to be put in place
  - ❖It is important to have pile heave being monitored during piling work
- **Short piles**
  - ❖ May arise due to encounter of boulders or intermediate hard soil layer
  - ❖Amendment plan submission needed if piles are shorter by more than 20%
  - ❖The capacity of short piles can be substantiated by working load test or additional boreholes

Sharing of Local cases

1. Tilt of 2-storey landed house on Shallow foundation
2. Excessive settlement of highrise building on piles
3. Short piles resting on inclined bedrock
4. Adverse effect of displacement piling on adjacent building

Case 1
Tilt of 2-storey house on shallow foundation

Tilt of 2-storey building on shallow foundation

- Reconstruction of a 2-storey house from a single-storey corner terrace – nearing completion
- Founded on raft foundation on bakau piles
- Building settles excessively by 655mm, and move laterally by 236 mm
- Severe damage to adjoining terrace house, with cracks as large as 200mm wide

Tilt of 2-storey building on shallow foundation

Reasons

- **Unsuitable foundation type** – raft with short bakau piles not embedded into stiff soil stratum is unsuitable.
- **Additional surcharge** acting on the founding soft marine clay due to land backfill to raise the platform level by 1.5m – not taken into design, inducing consolidation settlement.
- Excessive settlement causes the shared intermediate boundary wall to tilt & separate itself from adjacent terrace house, inducing large cracks

Tilt of 2-storey building on shallow foundation

Post incident activities

- Near completed 2-storey house was assessed to be not habitable, and has to be demolished and rebuilt
- Adjacent intermediate terrace house was also demolished due to the extent of damage
- Both buildings were rebuilt on RC pile foundation

Lesson learnt

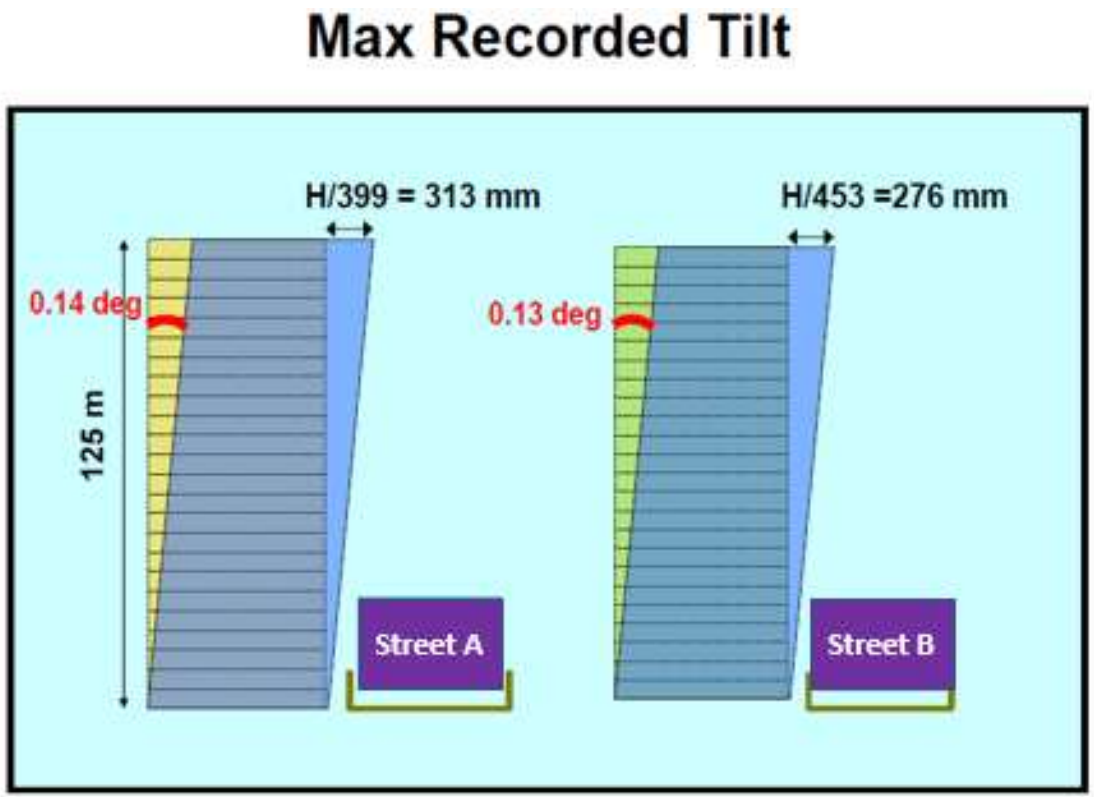
- Shallow foundation using raft is unsuitable for a building with soft marine clay
- Foundation design need to consider any additional surcharge loading, e.g. due to backfill

Case 2

Excessive settlement of a highrise building during construction

Tilt of highrise building during construction

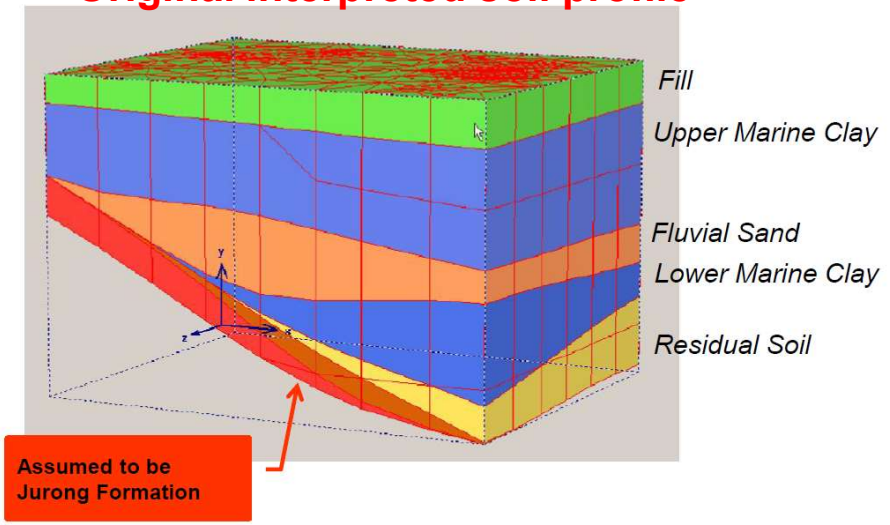
- A 30-storey building nearing completion experiencing settlement at 3-4 mm/week, posing stability concern
- QP discovered that building was tilting during installation of curtain walls
- Building was found to have tilted, with **measured lateral displacement** at roof level at 313mm in one direction and 276mm in the other direction, which translates to a tilt of to **1:399** and **1:453** respectively. This has exceeded 1:500 limit.
- Cracks of width upto 1mm were detected on some structural members (*floor slabs and core walls).*



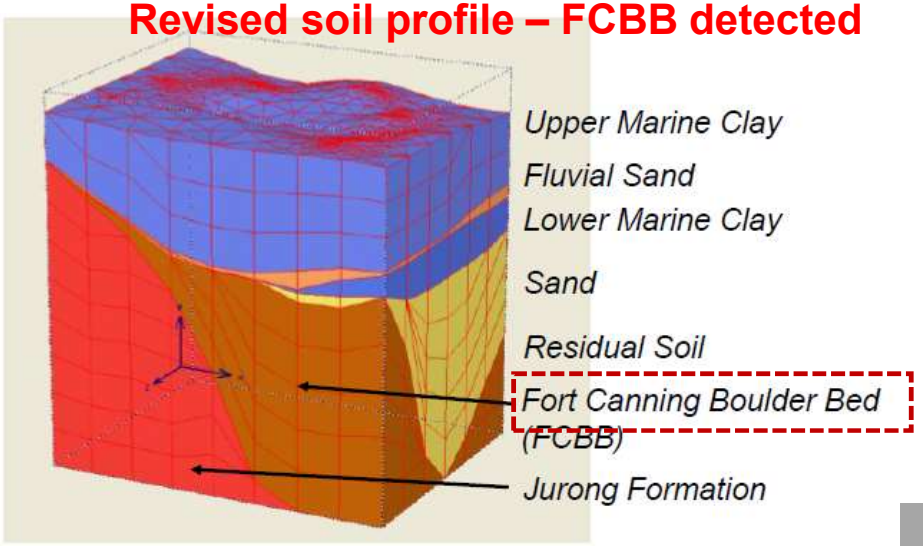
Investigation into cause of excessive settlement

- Original site investigation report has limited number of boreholes and exploration depth – the ground was mis-interpreted as **Kallang Formation underlain by Jurong Formation**
- Additional site investigation revealed :
  - ❖ Presence of **Fort Canning Boulder Bed overlying the Jurong Formation**.

Original interpreted soil profile

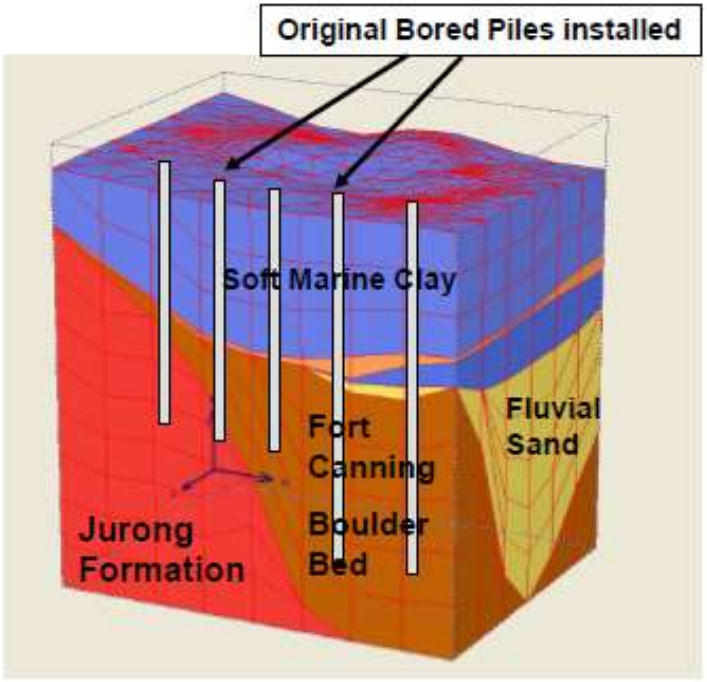


Revised soil profile – FCBB detected



Possible causes of the tilt

- Many piles were terminated in boulders within soft soil matrix of Fort Canning Boulder Bed
  - ❖not socketed a minimum 5 m into Jurong Formation with SPT>100 as per original design intent
- Piles were not sufficiently founded into Jurong Formation
- Highly varying pile founding stratum – result in pile depth varies greatly from one side to the other side of building.
- Excessive differential settlement caused building to tilt.



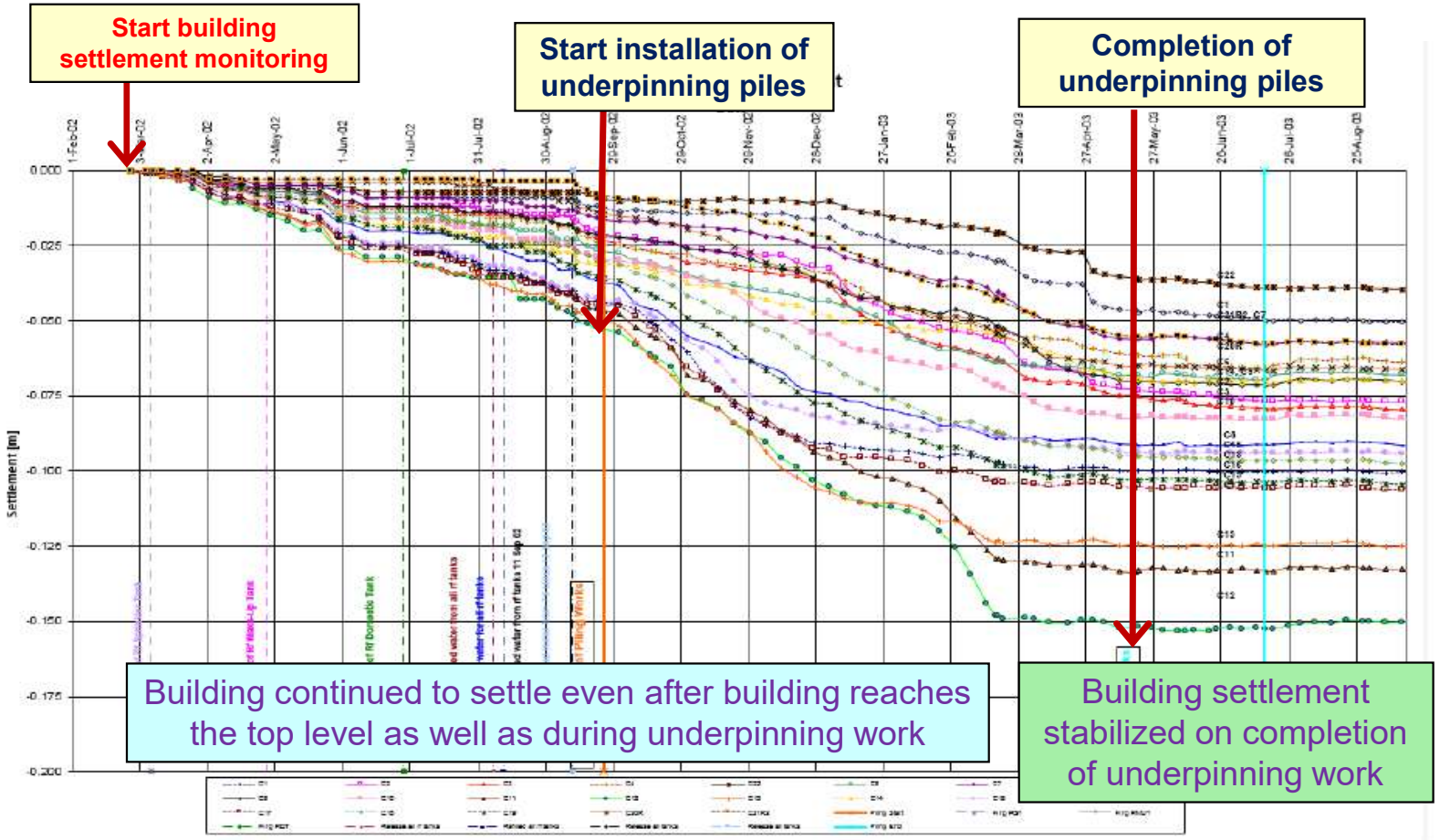
Rectification by Underpinning work

- To arrest continuing building settlement, the foundation of this nearly completed building need to be **underpinned**.
- A total of 86 steel micropiles were installed, by deploying special piling rig. Down-the hole hammer was used to core through the boulders.

Close monitoring & Contingency plan

- Contingency plan would be to demolish the building should the building became unstable during underpinning work.
  - ❖Close monitoring of trend of building settlement and tilt
  - ❖Daily inspection of building
- During underpinning work, there was additional settlement of 2 mm/week observed
- Building settlement was stabilized upon completion of underpinning work.

Settlement monitoring



Costly rectification work

- Besides underpinning work, extensive repair and strengthening work carried out:
  - ❖To columns, beams and slab;
  - ❖To curtain wall
- Cost of rectification is almost the same as the original construction cost !

Other costs

- Loss of use of the building due to delayed occupancy by more than 3 years !
- Loss of time and money in lawsuits.
- Loss of confidence in the construction industry.

Lessons Learnt

- Adequate soil investigation is essential to determine and establish pile founding stratum prior to design

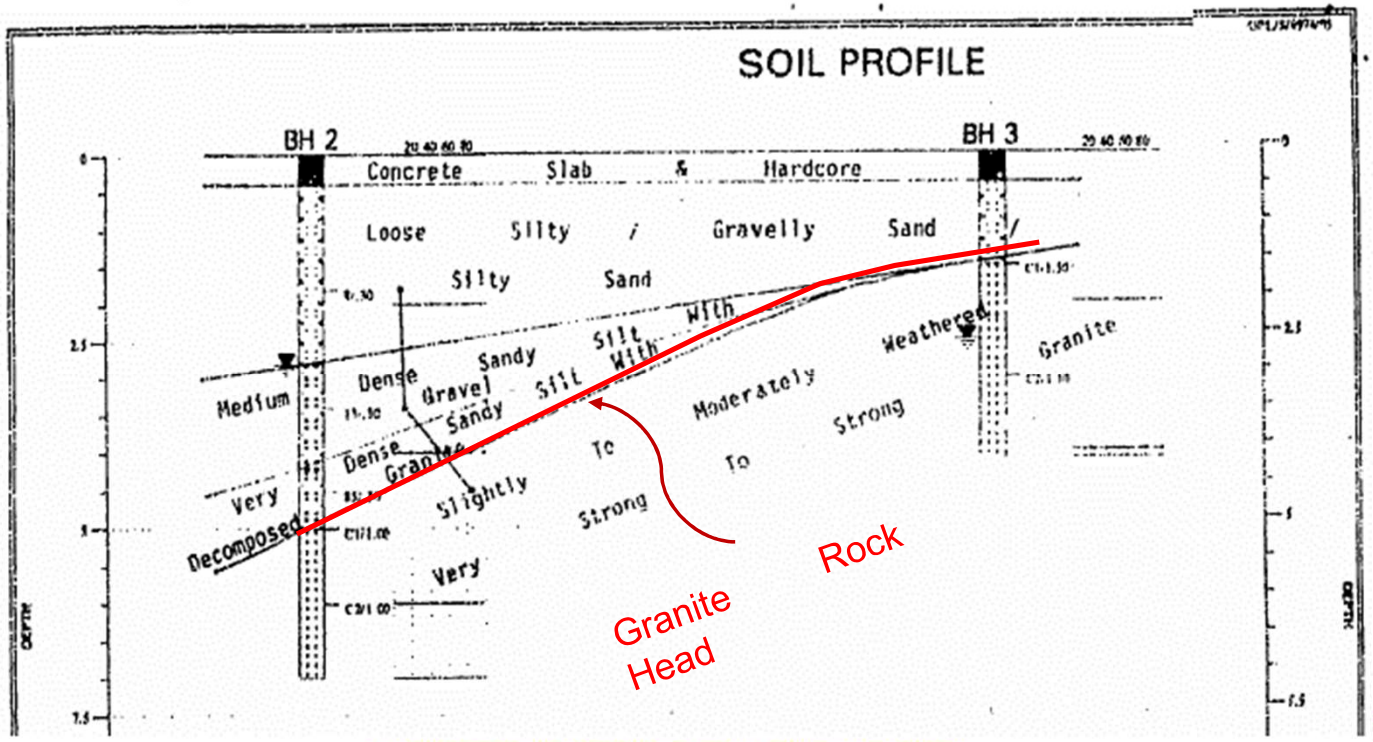
- Important to have reliable pile load test results

- Important to have building settlement monitoring during superstructure erection

Case 3
Short piles resting on steeply inclined bedrock

Short piles on steeply inclined bedrock gradient

- Project involved construction of 2 blocks of 10-storey residential building, supported on bored piles in Bukit Timah Formation.
- Boreholes show the presence of granitic bedrock at shallow depth. Pile design depth was about 10m, with 4m to 7m in rock socket.



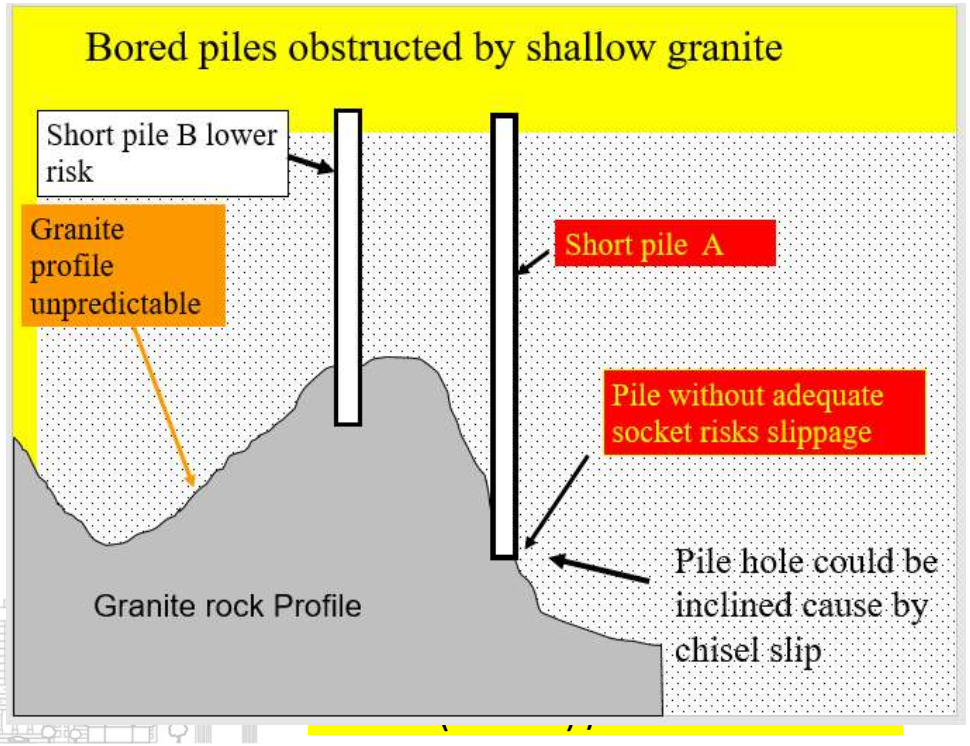
Short piles on steeply inclined bedrock gradient

- It was found that bored piles installed were abnormally short of 3m to 5m, which is more than 50% shorter than the original designed depth
- Investigation revealed that piles were installed without any socket into granitic bedrock, and merely rest on the steeply inclined bedrock.

Pile resting on inclined slope

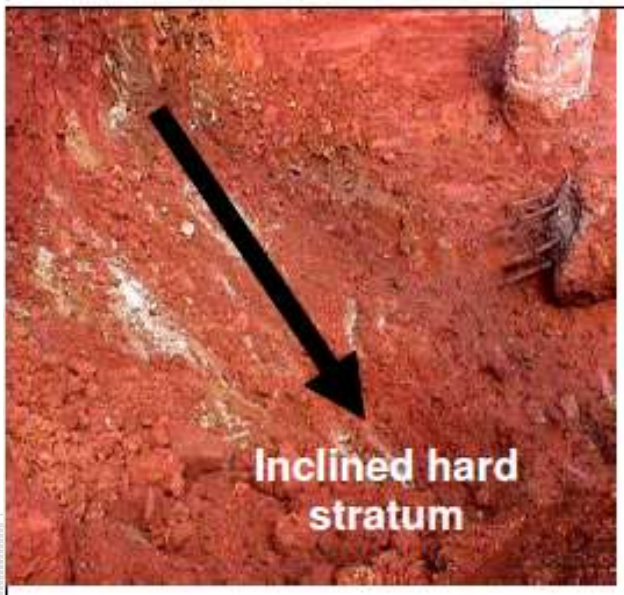
Concerns of pile installation on steeply inclining and undulating rock head

- Piles without adequate rock socket has a higher risk of slippage on rock surface
- Problem exacerbated if (i) chiselling slip occurs (ii) presence of rock joints that dip towards slope surface



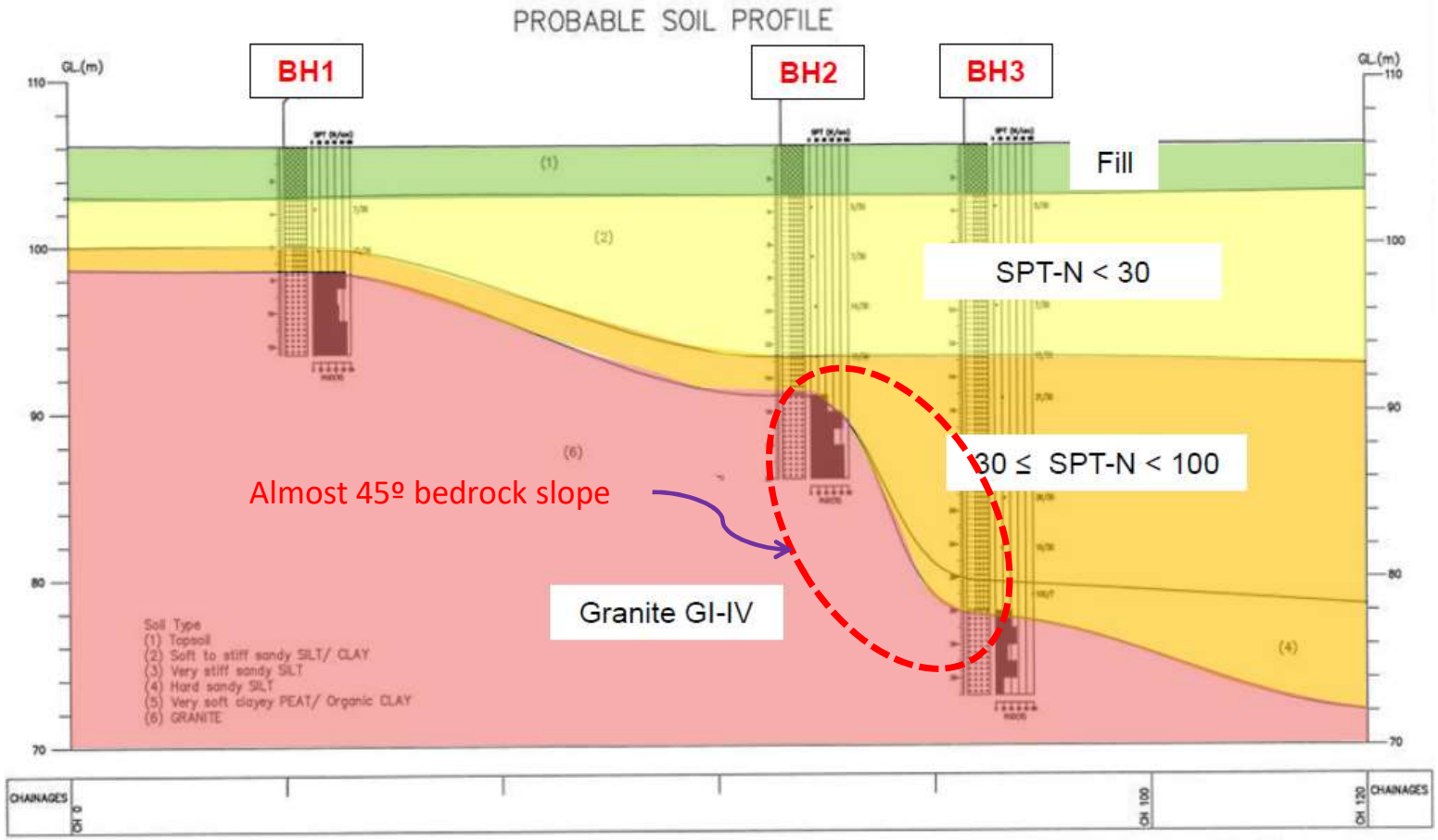
Investigation of Short piles on steeply inclined bedrock

- 3 bored piles with installed depth of only 3 m were excavated for investigation, which revealed:
  - ❖ Very steeply inclined granite rock surface below the pile toe
  - ❖ Poor quality of concrete at pile toe, which dislodged and expose rebar



Poor quality concrete at pile toe, which dislodged and exposed steel rebars

Another example of steeply inclined bedrock



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Lessons Learnt

- Adequate soil investigation needed to determine the variability and undulating rock head level for Bukit Timah Formation

- Deploy suitable piling rig and tools that are capable of drilling into rock, e.g. rock auger

- Specify minimum rock socket to ensure the entire pile toe is embedded into rock

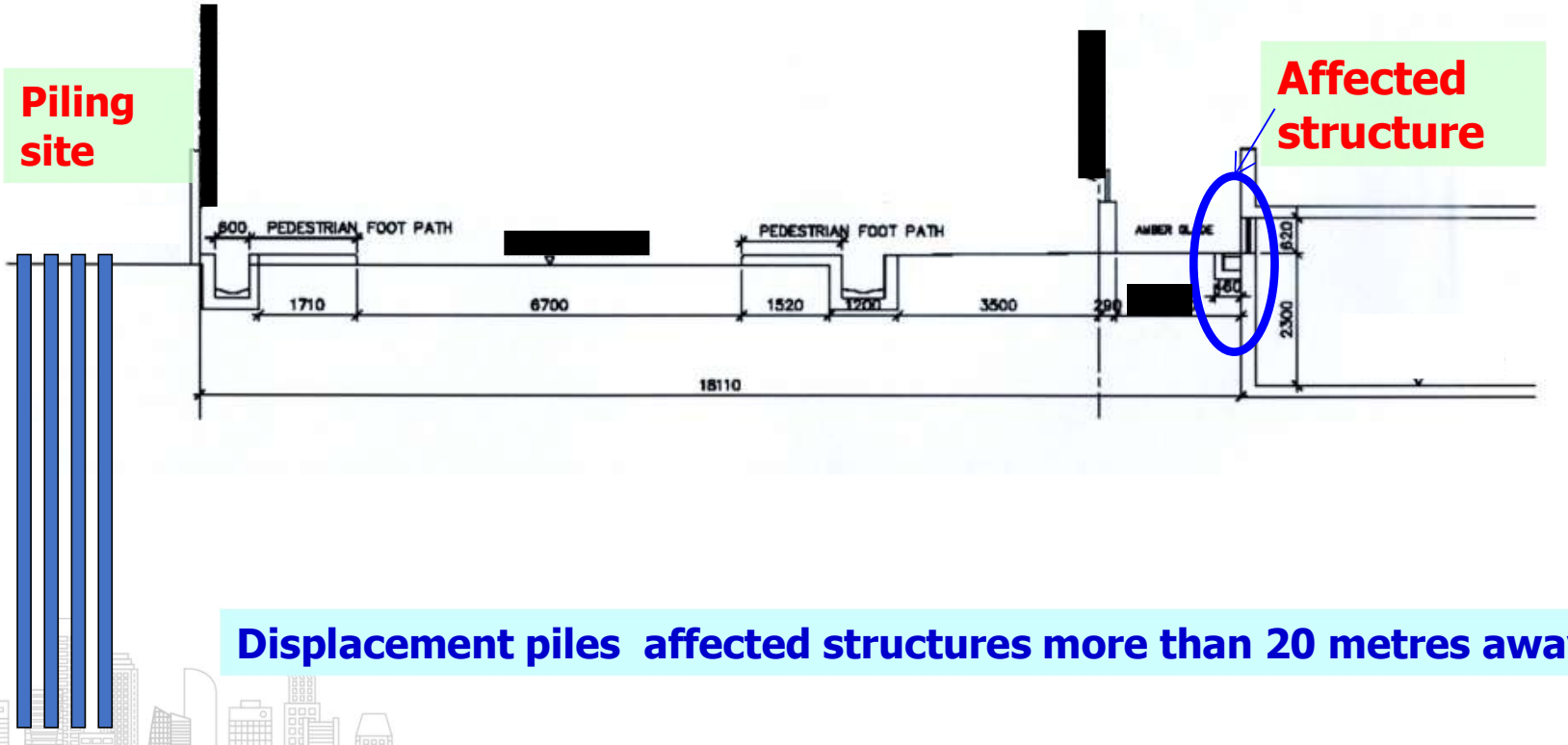
Case 4

Adverse effect of large displacement piling on adjacent building

Effect of large displacement piles on adjacent buildings

- In this project, large diameter prestressed concrete spun piles were used (300mm to 600mmΦ) to support several blocks of 20-storey buildings
- Pile depth ranges from 40m to 50m
- Piles were installed by jack in through a thick layer of marine clay, using 800-tonne piling machine
- *Soil displacement due to pile installation has resulted in cracks to a neighbouring building, located more than 20 metres away*

Section through piling site and affected structures



Displacement piles affected structures more than 20 metres away.

Very severe diagonal shear cracks at external column

What happens when pile is forced into soft clay ?

- **Alteration of soil properties**

  High excess pore pressure

  Shear strength reduced

  Clay remoulded

- **Lateral soil movement and heave**

  Lateral movement and eventually manifested as heave

  May affect piles driven earlier

  May affect adjacent foundation and adjacent structures

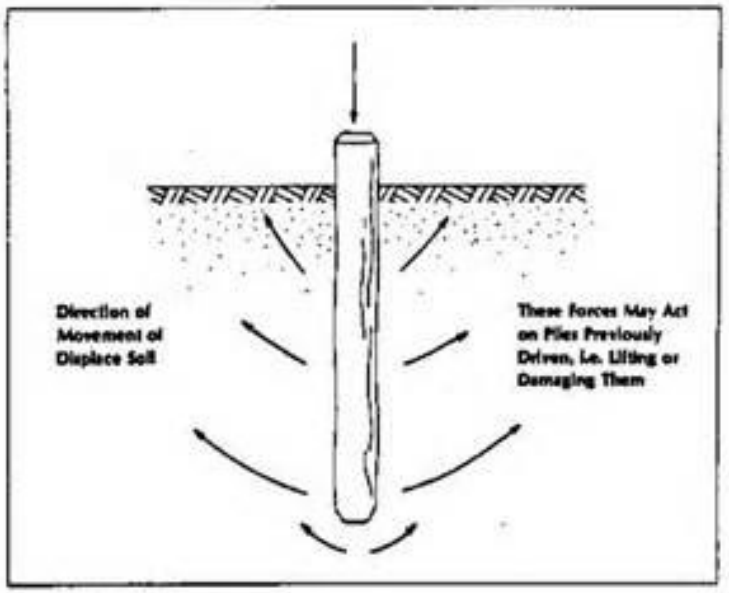
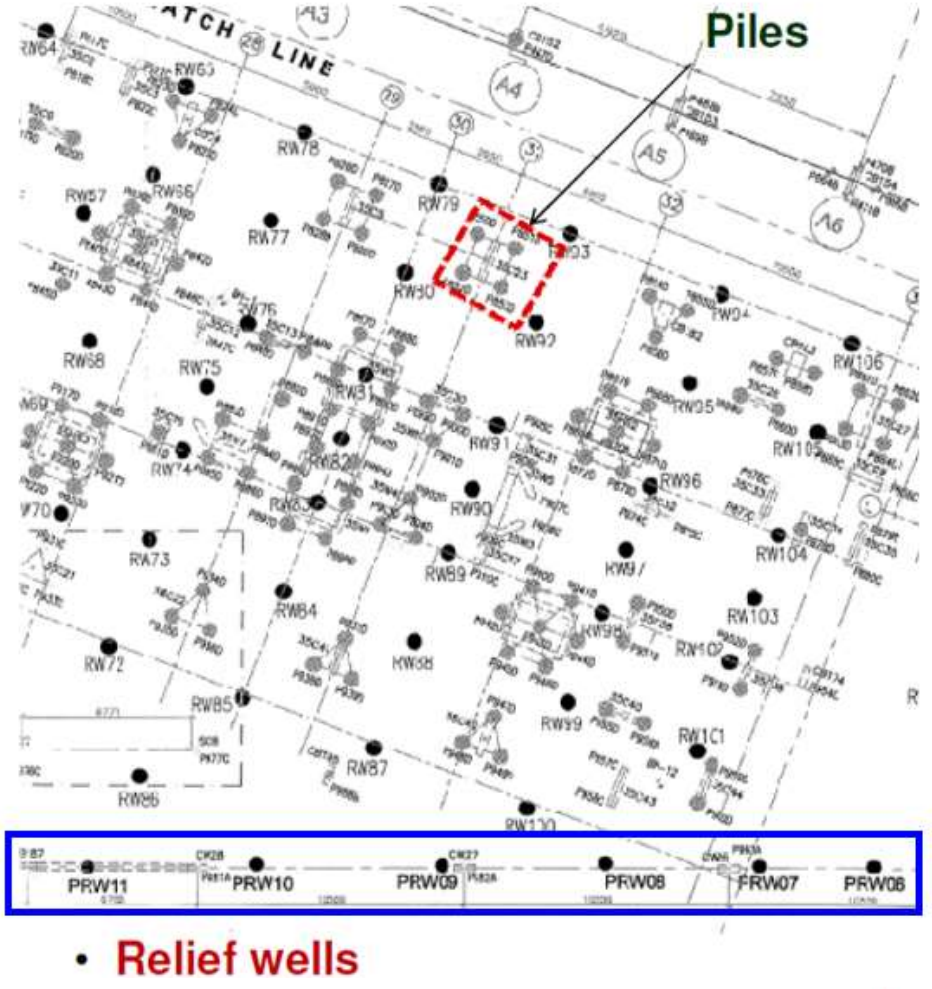


Figure 6-5 Pile action on the soil

Initial measures taken

- Pre-boring at every pile location
- 3 temporary relief wells around every pile
- Permanent relief wells around the boundary
- Volume of soil displaced by pile and volume of soil taken out of relief wells are closely monitored.



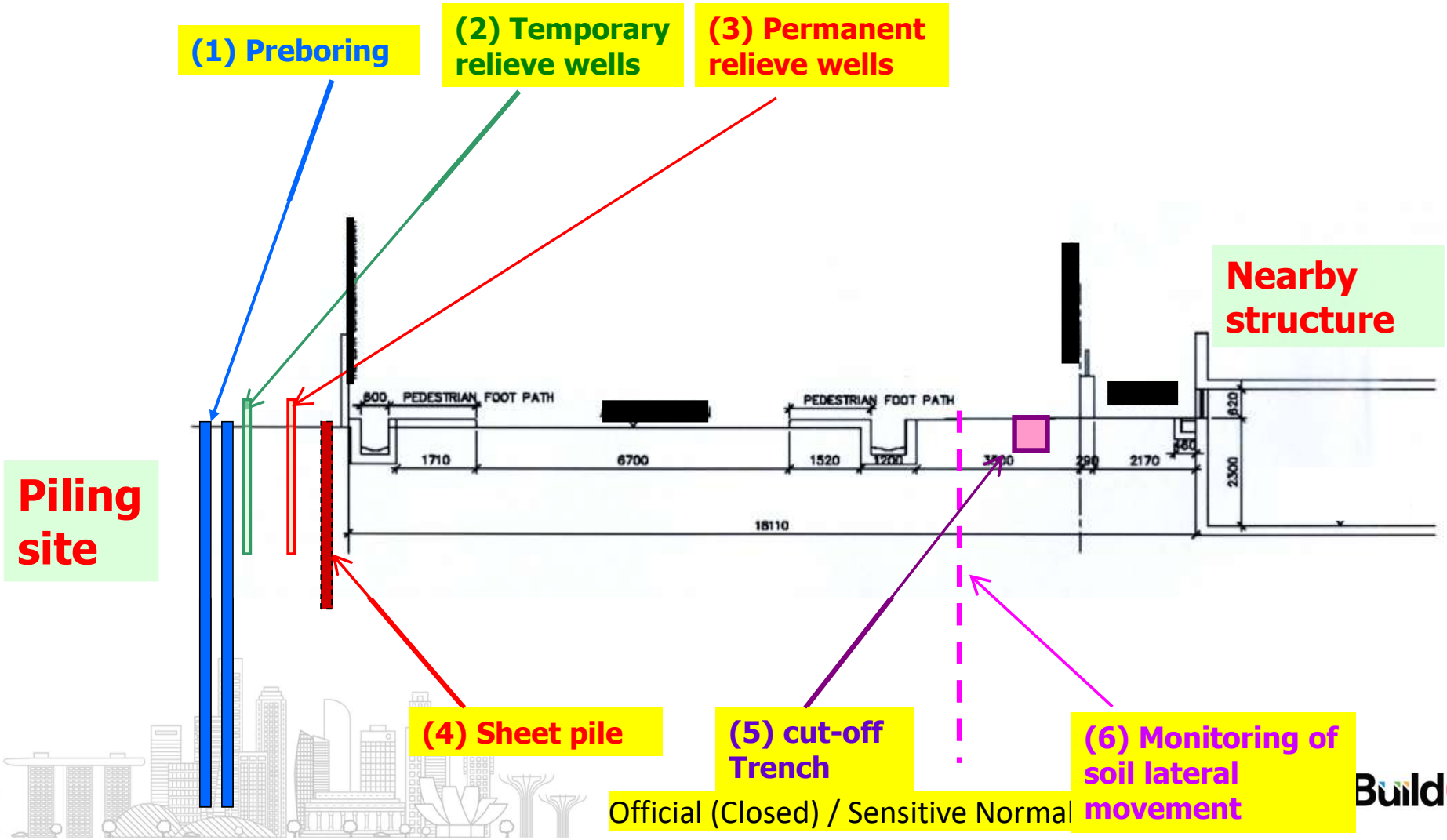
Preboring at pile location

Relief wells around pile location

Additional measures taken to prevent further damage

- Install sheetpile to reduce the migration of soil outside the boundary
- Reduce piling speed to allow time for soil movement to stabilise
- Increased monitoring, and additional instruments installed near to critical structures
- Digging trench near to critical structures

Precautionary measures taken for installation of displacement piles



Lesson learnt

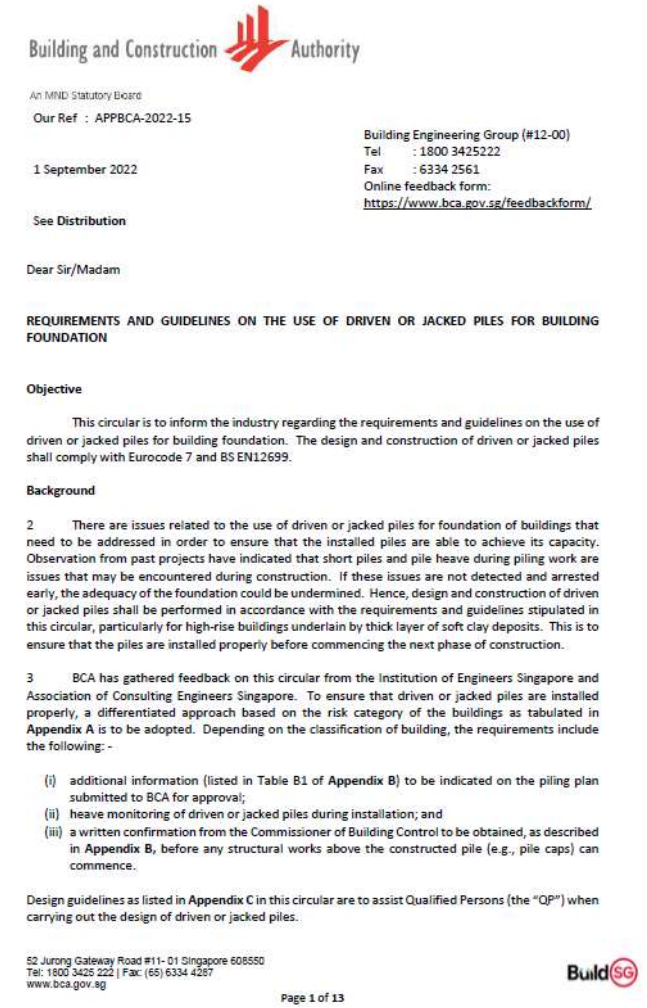
- The effect caused by soil displacement during installation of large displacement piles could be difficult to control, particularly where thick layer of soft clay is present.
- QP need to assess carefully before deciding to use such piling method. The installation may cause (i) heave of earlier installed piles (ii) damage to adjacent structures.
- For displacement piling, it is important to put in place **pro-active measures** like preboring and relief wells, to minimise the soil movement.
- If mitigation measures are ineffective to prevent damage to adjacent buildings, **non-displacement piles** would be a preferred option.

Circular on jacked / driven piles

- Issued to industry on 1 Sep 2022
  - ❖Inform the industry regarding the **requirements and guidelines on the use of driven or jacked piles** for building foundation
- Circular requires :

(i) pile heave monitoring (For Type A & B buildings)

(ii) written confirmation from CBC for commencement of structural work above the constructed piles (for Type A building only)



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1 September 2022

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Dear Sir/Madam

REQUIREMENTS AND GUIDELINES ON THE USE OF DRIVEN OR JACKED PILES FOR BUILDING FOUNDATION

Objective

This circular is to inform the industry regarding the requirements and guidelines on the use of driven or jacked piles for building foundation. The design and construction of driven or jacked piles shall comply with Eurocode 7 and BS EN12699.

Background

2 There are issues related to the use of driven or jacked piles for foundation of buildings that need to be addressed in order to ensure that the installed piles are able to achieve its capacity. Observation from past projects have indicated that short piles and pile heave during piling work are issues that may be encountered during construction. If these issues are not detected and arrested early, the adequacy of the foundation could be undermined. Hence, design and construction of driven or jacked piles shall be performed in accordance with the requirements and guidelines stipulated in this circular, particularly for high-rise buildings underlain by thick layer of soft clay deposits. This is to ensure that the piles are installed properly before commencing the next phase of construction.

3 BCA has gathered feedback on this circular from the Institution of Engineers Singapore and Association of Consulting Engineers Singapore. To ensure that driven or jacked piles are installed properly, a differentiated approach based on the risk category of the buildings as tabulated in **Appendix A** is to be adopted. Depending on the classification of building, the requirements include the following: -

(i) additional information (listed in Table B1 of **Appendix B**) to be indicated on the piling plan submitted to BCA for approval;
(ii) heave monitoring of driven or jacked piles during installation; and
(iii) a written confirmation from the Commissioner of Building Control to be obtained, as described in **Appendix B**, before any structural works above the constructed pile (e.g., pile caps) can commence.

Design guidelines as listed in **Appendix C** in this circular are to assist Qualified Persons (the "QP") when carrying out the design of driven or jacked piles.

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Classification & Requirements of buildings with jacked or driven piles

High risks → Low risks

	Type A Buildings	Type B Buildings	Type C Buildings
Classification of building	• All buildings that are 11 storeys or more (*excluding basement*) • Buildings that are 4 to 10 storeys and with soft clay[a] of thickness[b] exceeding 10m *(excluding all landed properties)*	• Buildings that are 4 to 10 storeys and with soft clay[a] of thickness[b] up to 10m *(excluding all landed properties)*	• All landed properties • All buildings up to 3 storeys • Buildings that are 4 to 10 storeys and without soft clay[a]
Pile-heave monitoring[c,d]	• **100% of working piles**	• 50% of working piles	For independent Type C Building • Optional For Type C Building that cannot be demarcated from Type A or/and Type B Building • 50% of working piles
Written confirmation to allow the structural work above the constructed piles (e.g., pile caps) to commence	• **Required**	• Not required	• Not required

Compliance with BS EN 12699 & Eurocode 7

Design of displacement piles shall comply with Eurocode 7.
Execution of displacement piles shall comply with BS EN 12699.

BSEN 12699 Execution of special geotechnical work – displacement piles

9.2.2 The pile construction process shall be monitored including behaviour of previously installed piles and all relevant data indicated in Clause 10 and when required those indicated in 10.3 shall be recorded.

9.2.4 Frequency of monitoring shall be specified and agreed before commencement of piling work.

9.2.10 Where heave or lateral displacements are likely to be detrimental to pile integrity and performance, pile top level and plan location readings with respect to a stable reference level mark should be taken before and after driving of neighbouring piles and/or after possible excavations.

Moral of the story

It takes a wise man to learn from his mistakes, but an even wiser man to learn from others.

It is too hefty a cost from to learn from your own mistake!

Summary

1. Adequate site investigation – to understand the ground
2. Design diligently – with consideration of execution conditions
3. Construct vigilantly – with good workmanship using appropriate tool

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Thank you

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