Global Tunneling 31st May 2018

Deep Excavations and Cut and Cover Tunnels

Top – down and Bottom - up

John Endicott
AECOM Fellow

AECOM

80 floors Co-development Airport Railway Station below

Hong Kong has many Regulations and “Guidelines”

Building Control, Geotechnical Control

Individual responsibility of Professional Engineers,

Registered Geotechnical Engineers

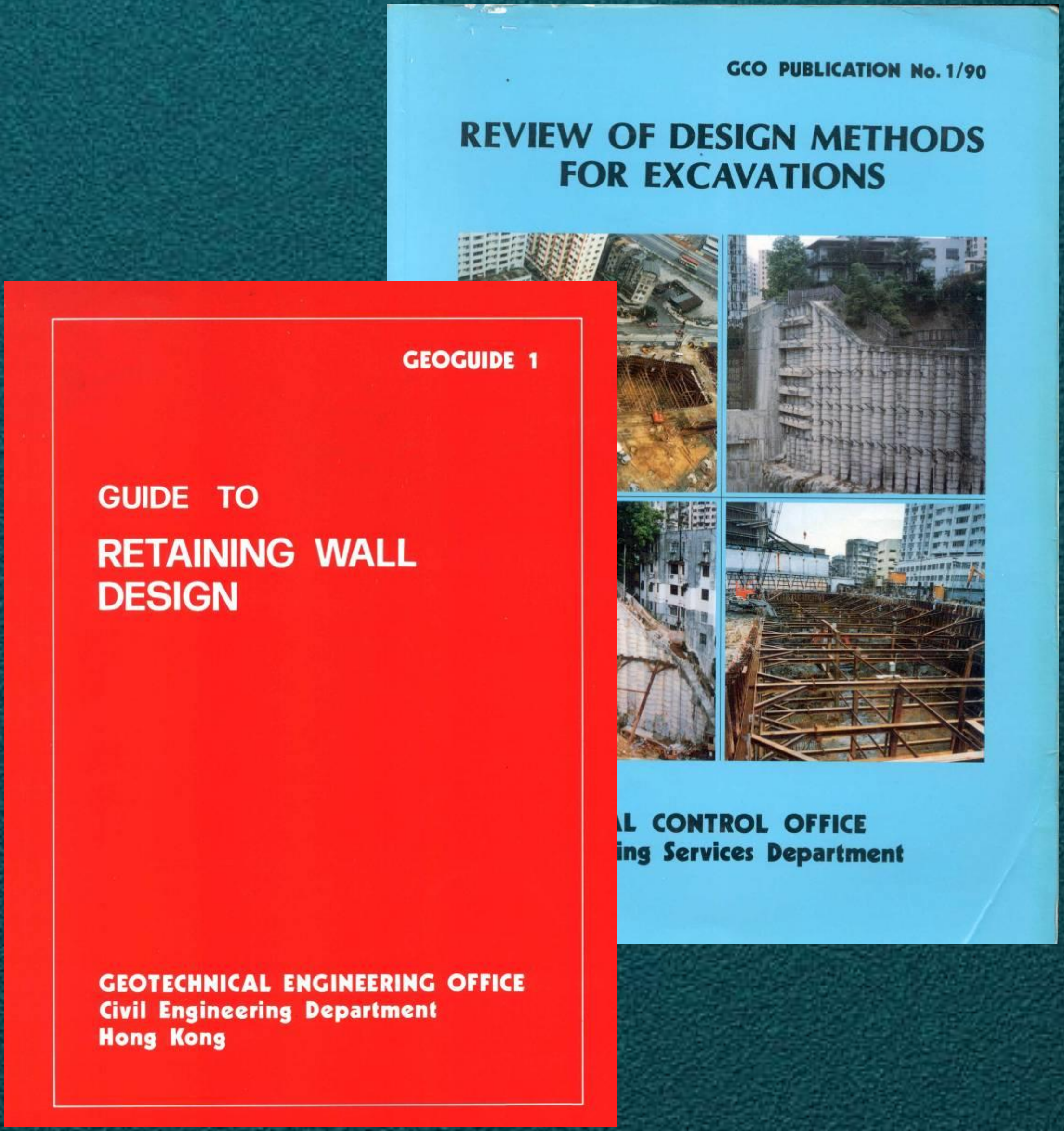
Imprisonment: custodial sentence

Not yet Registered Tunnel Engineers

Singapore has similar Building Control

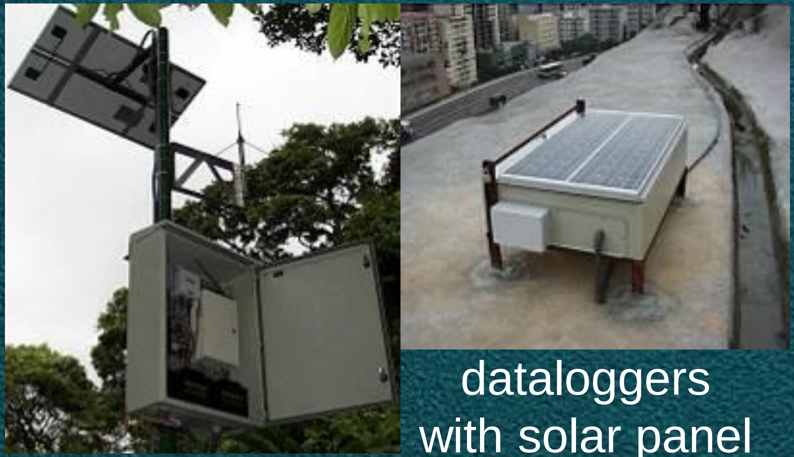
Design Codes and Guides

- CIRIA 104
- BS 8002
- DD ENV
- BD 42/00
- Piling handbook
- CIRIA R185
- CIRIA C517
- CIRIA SP95
- GEOGUIDE 1 2nd Ed.
- GCO Publication No. 1/90
- C 580 Limit State



Web-Based Real Time Reporting

Instruments (eg.strain gauges on struts)

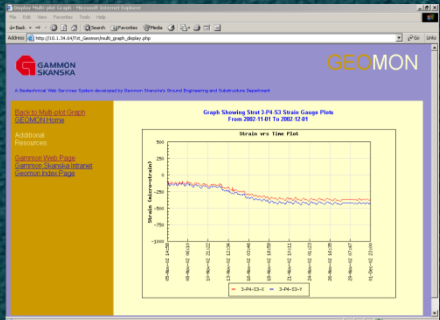


dataloggers with solar panel

Server

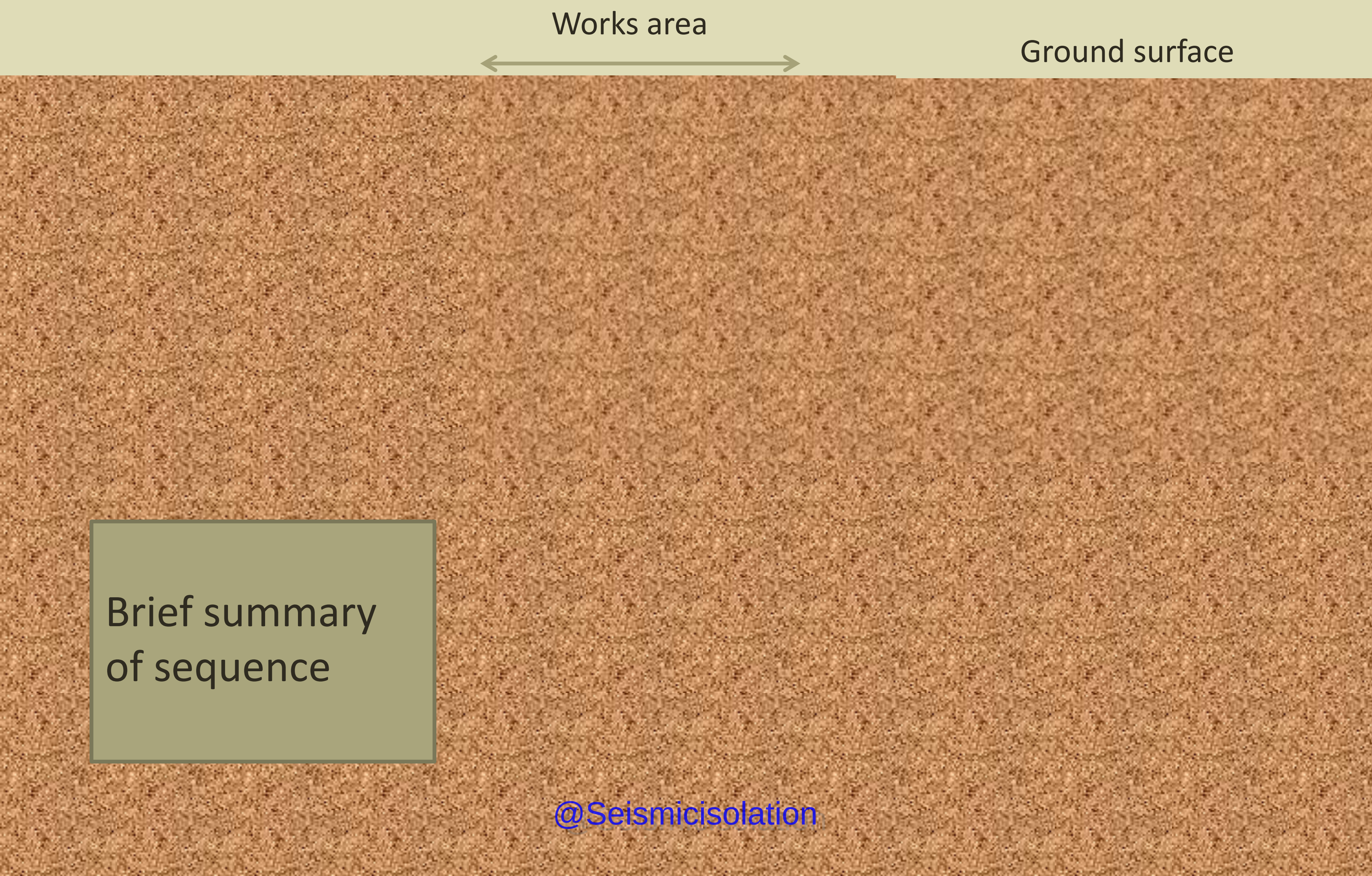
Internet

I-phones



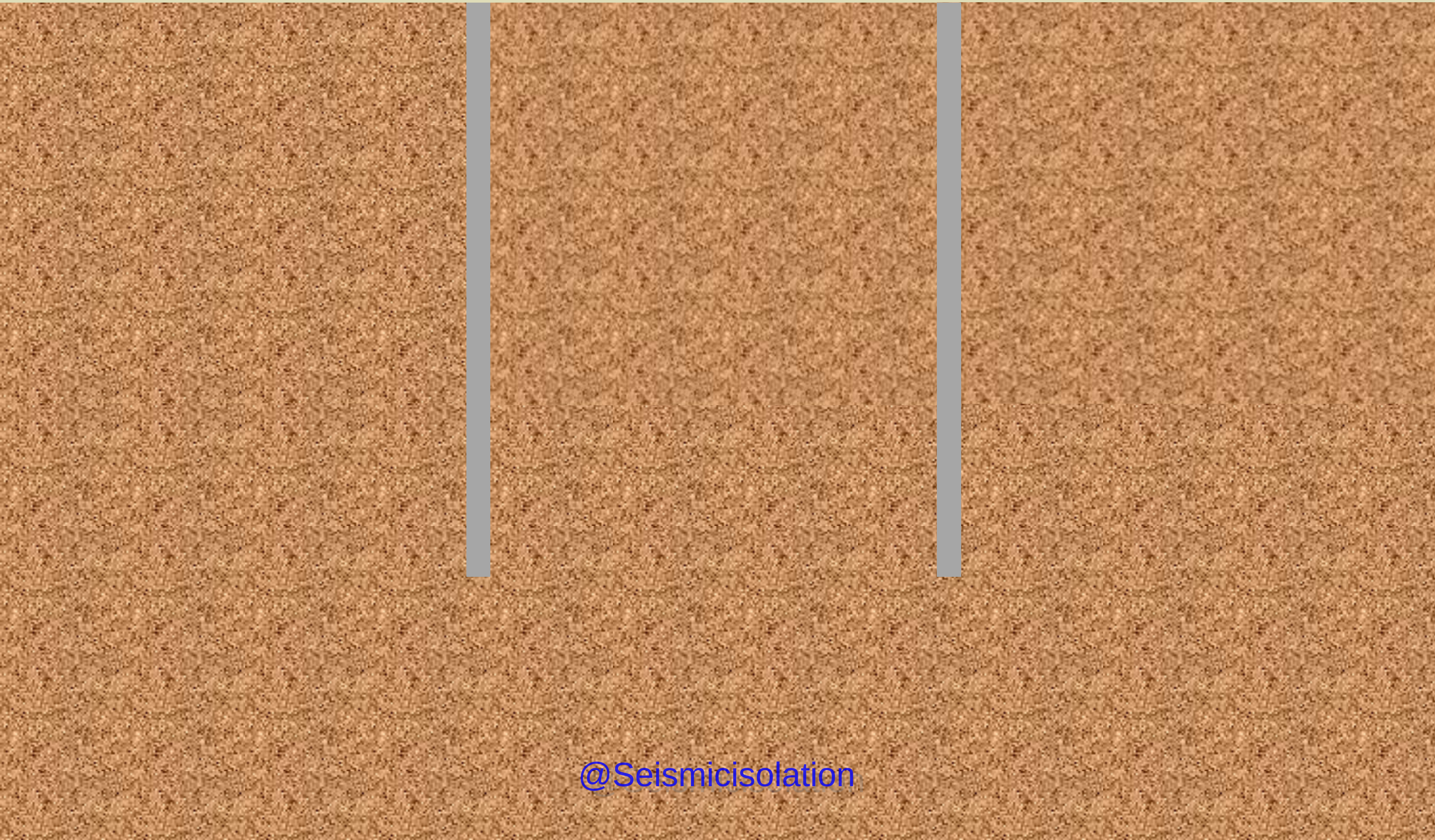
Real time monitoring and alerts

Top-Down Method of deep excavation and construction   Stage 0



Top-Down Method of deep excavation and construction Stage 1

Install diaphragm walls

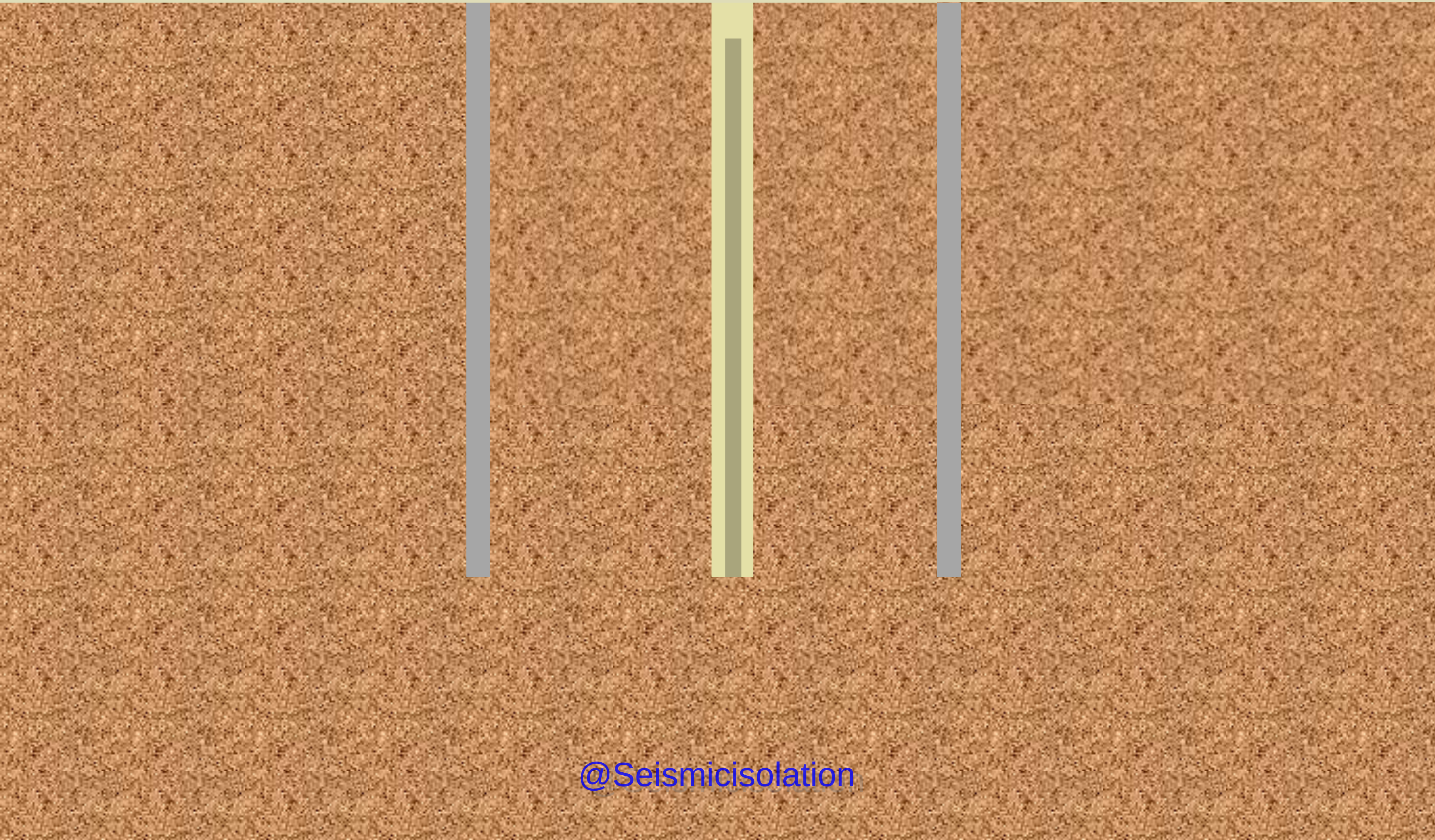


Cutter for excavating

Diaphragm Walls

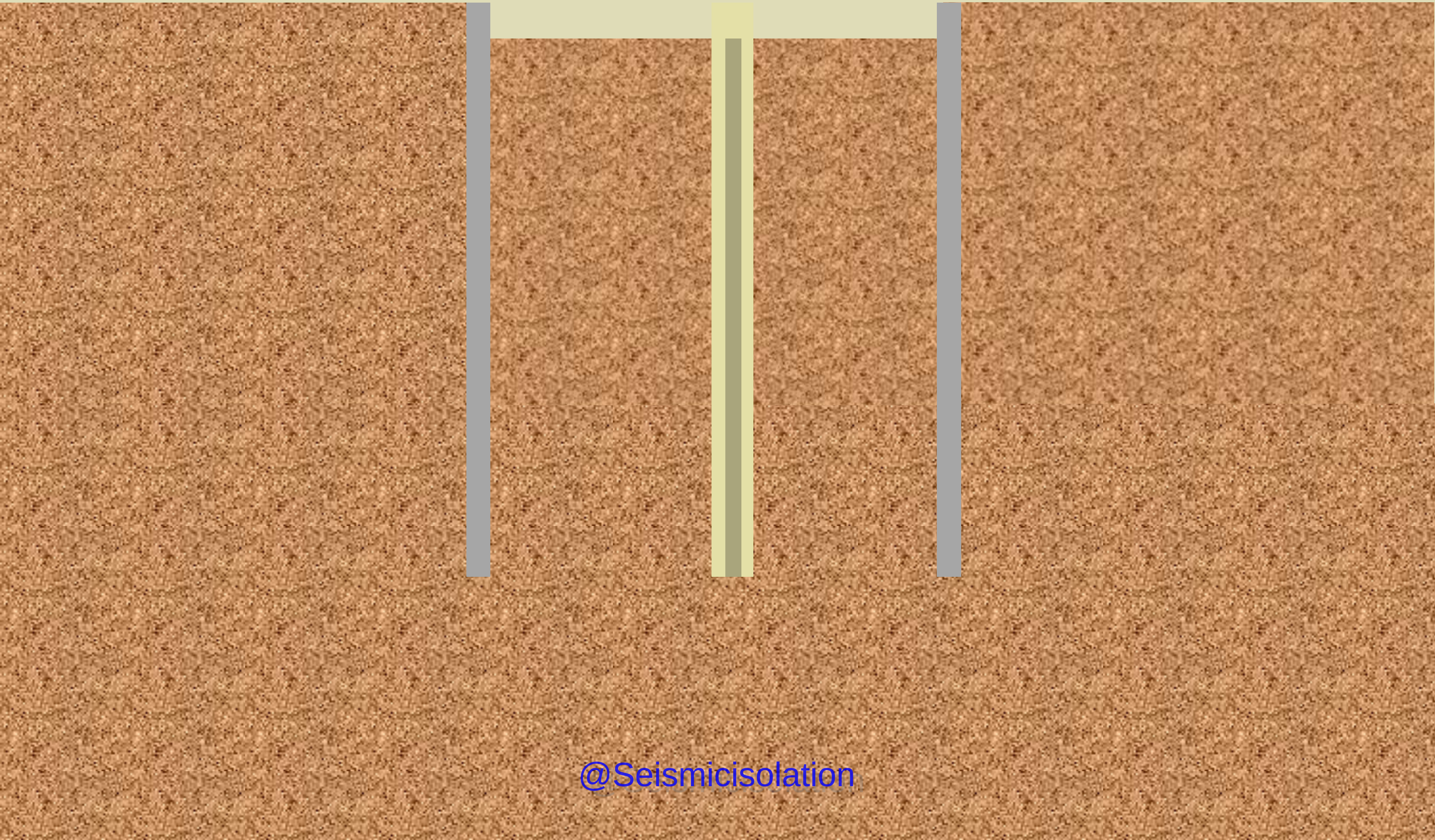
Top-Down Method of deep excavation and construction Stage 1

Install diaphragm walls and plunge columns



Top-Down Method of deep excavation and construction Stage 2

Excavate for top deck/slab



Sometimes the

top slab

is

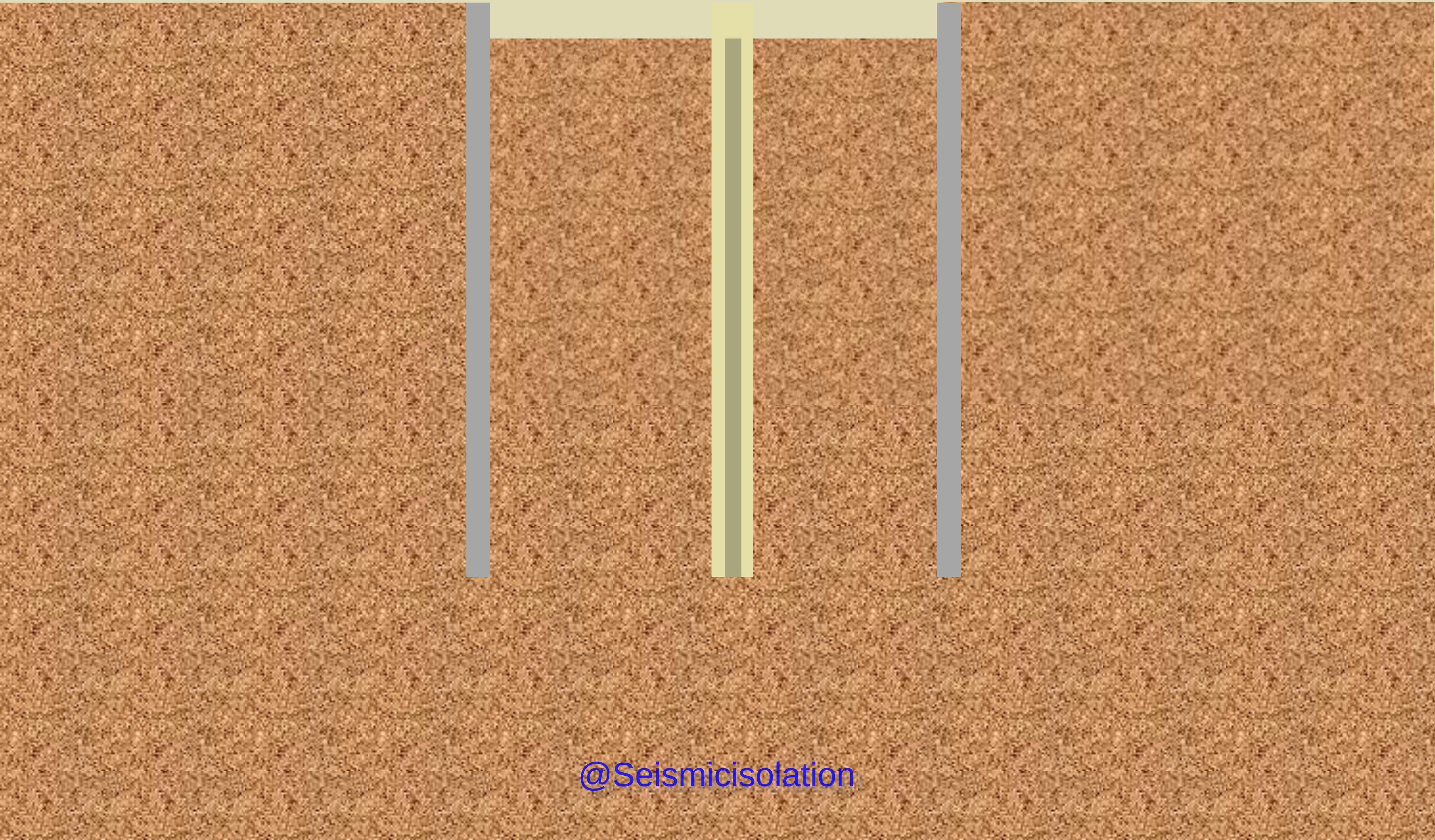
below ground

and is

later backfilled

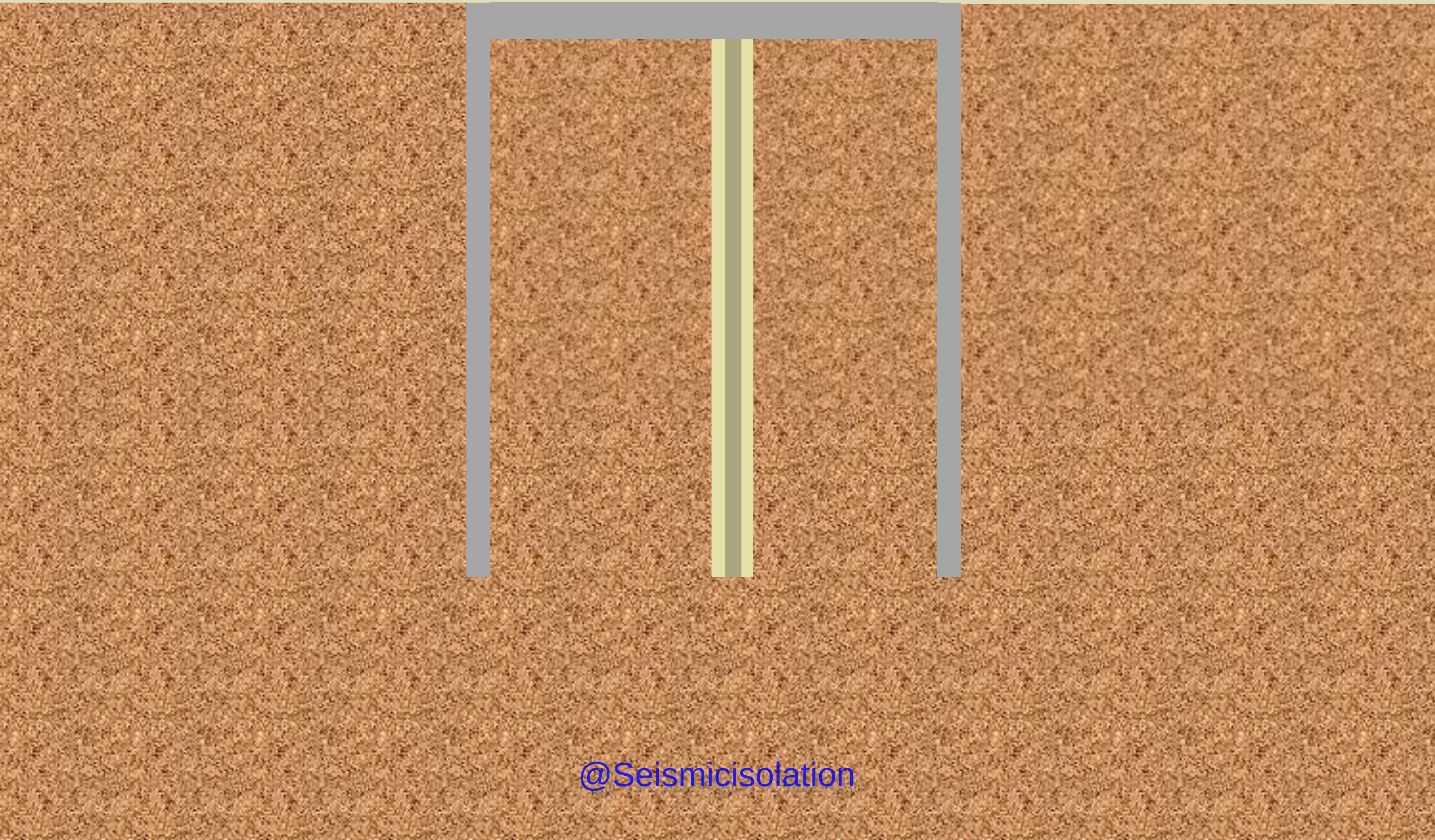
Top-Down Method of deep excavation and construction Stage 2

Excavate for top deck/slab



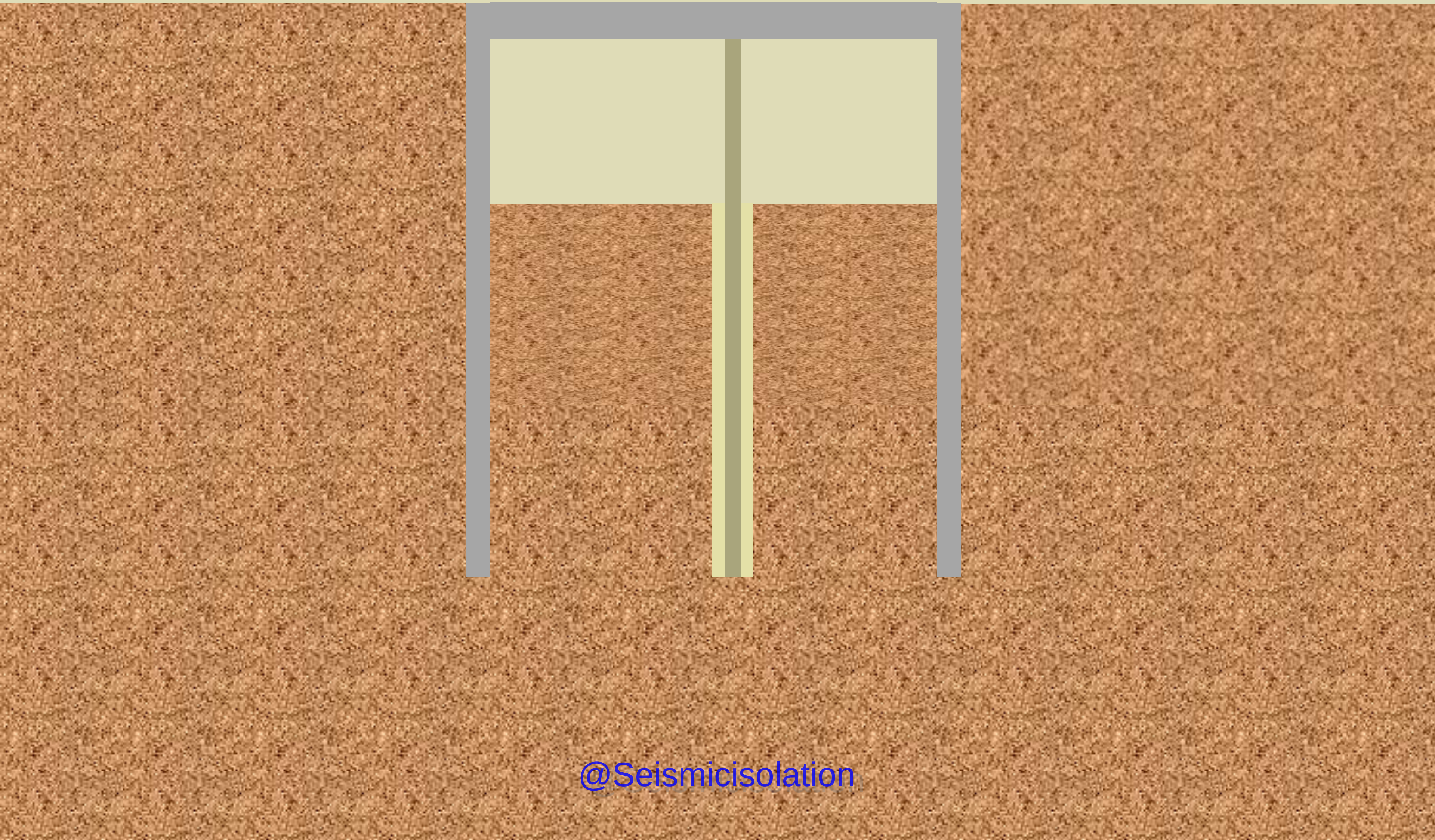
Top-Down Method of deep excavation and construction Stage 4

Construct top deck/slab



Top-Down Method of deep excavation and construction Stage 6

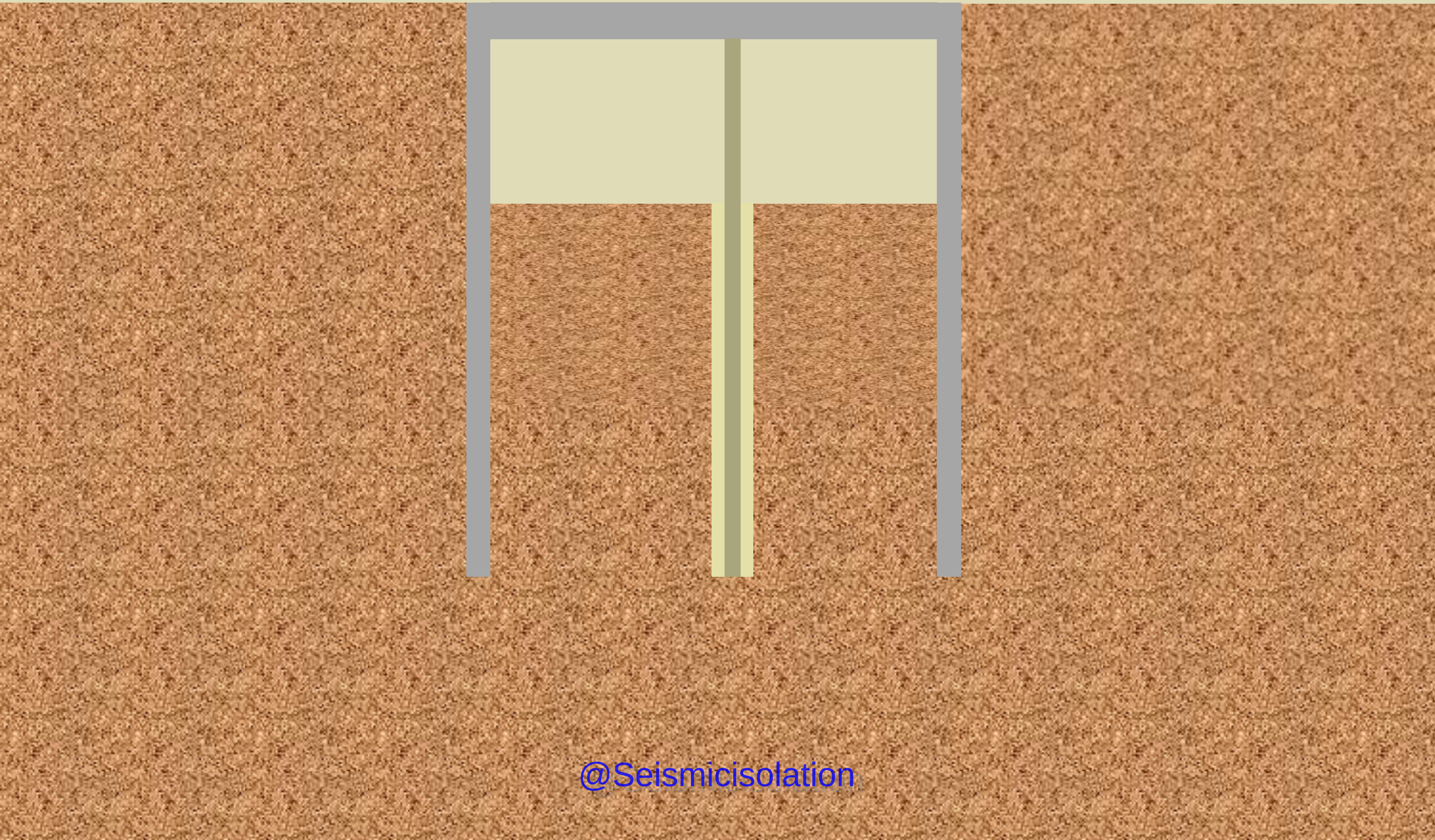
Excavate to First level



Top down creates a lot of protected space on site that is often under-utilised

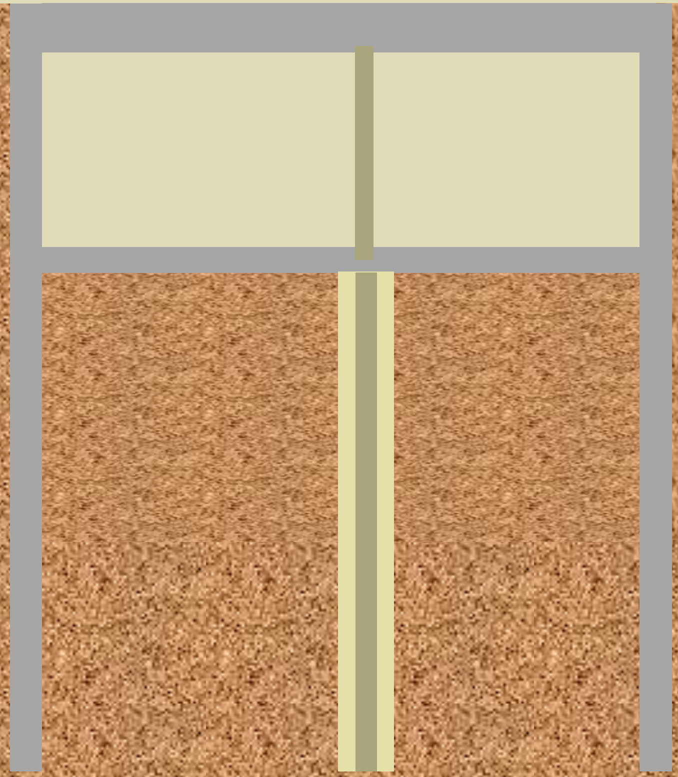
Top-Down Method of deep excavation and construction Stage 6

Excavate to First level



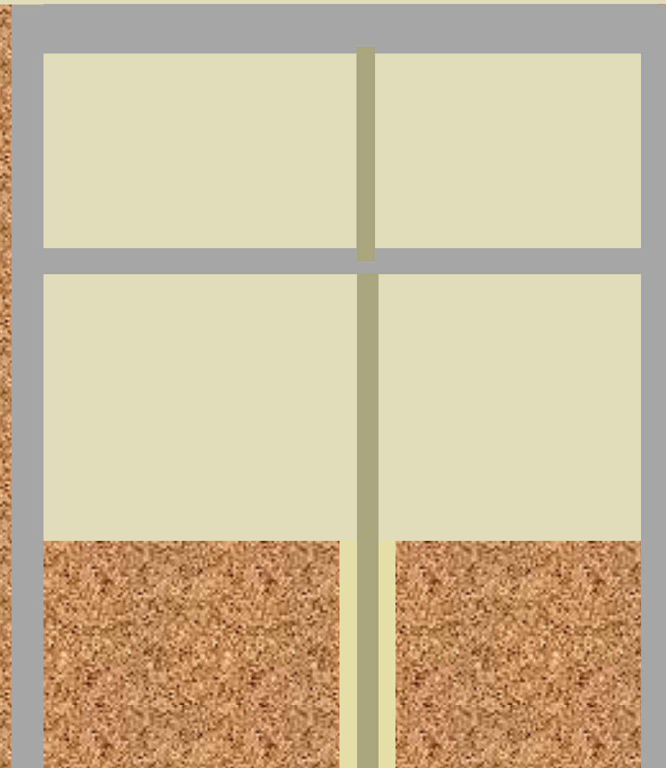
Top-Down Method of deep excavation and construction Stage 6

Construct first level deck/slab



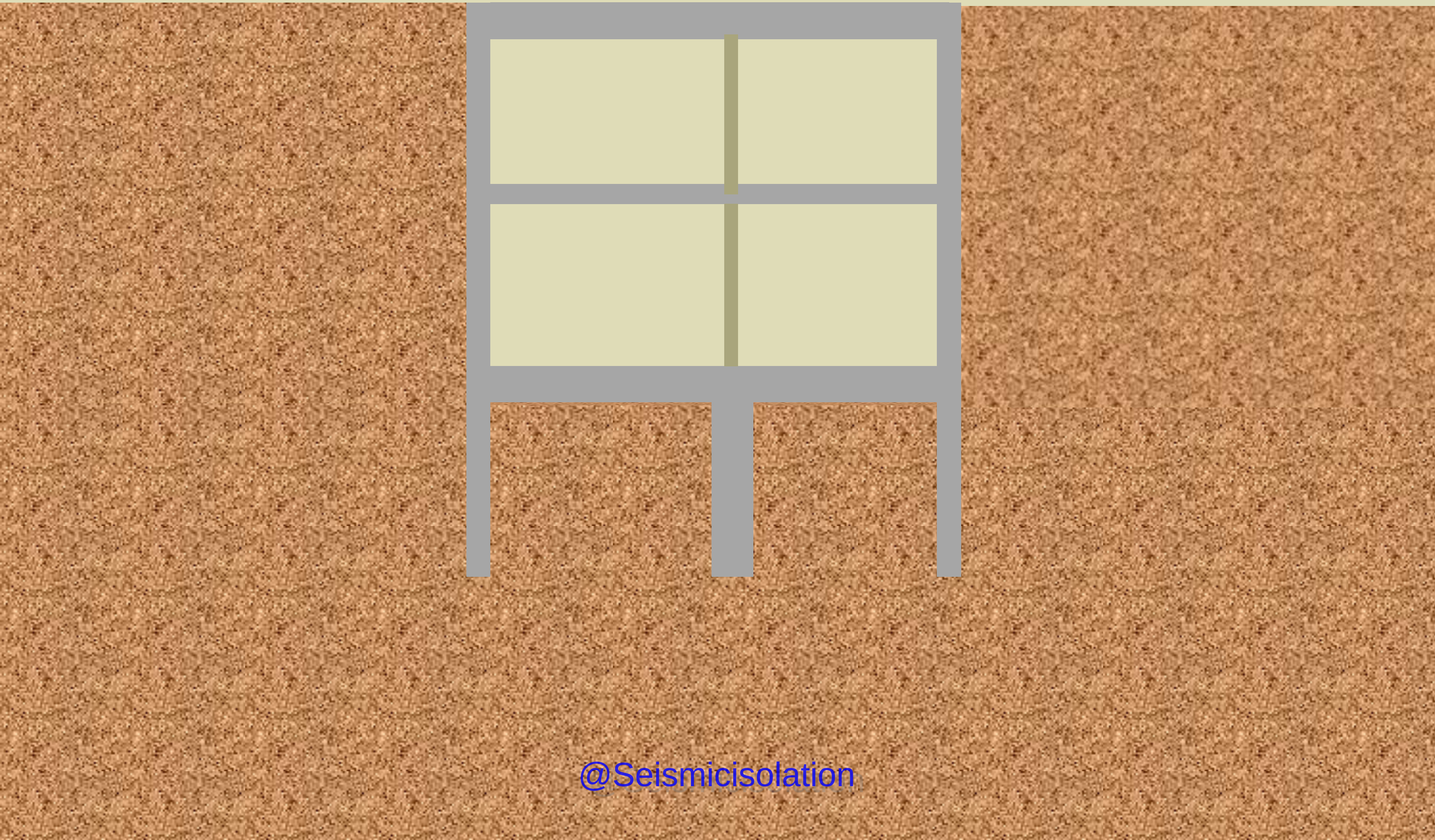
Top-Down Method of deep excavation and construction Stage 6

Construct first level deck/slab



Top-Down Method of deep excavation and construction Stage 8

Construct bottom slab



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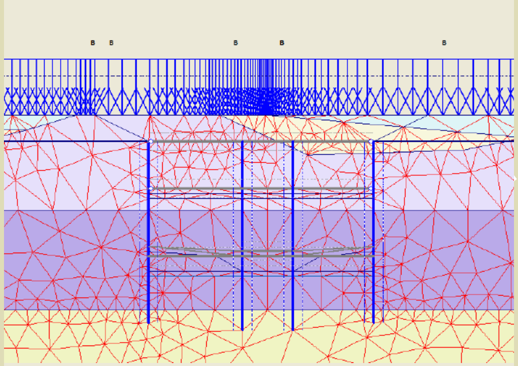
Top-down: Permanent Diaphragm wall and Skin wall

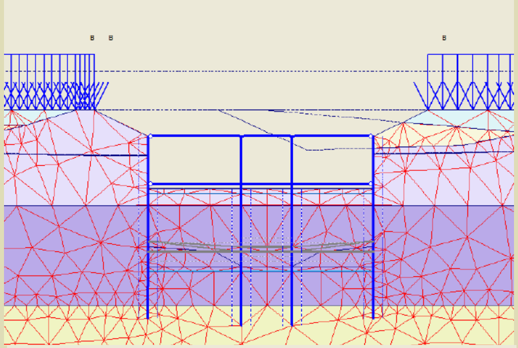
PLAXIS and others

can model the sequence in many stages for you

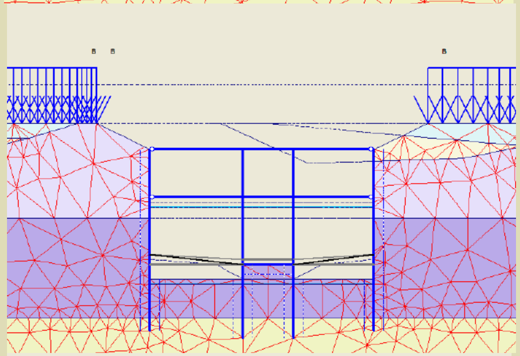
Excavate to top slab level and install top slab



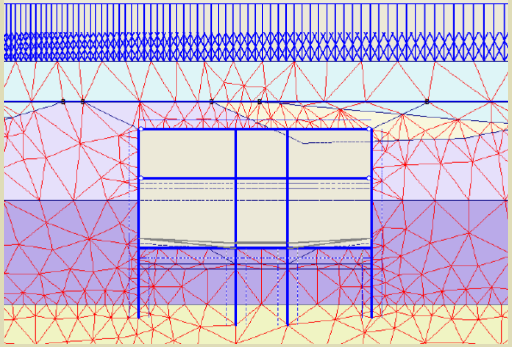
Excavate to first level and construct first slab



Excavate to final level and construct bottom slab

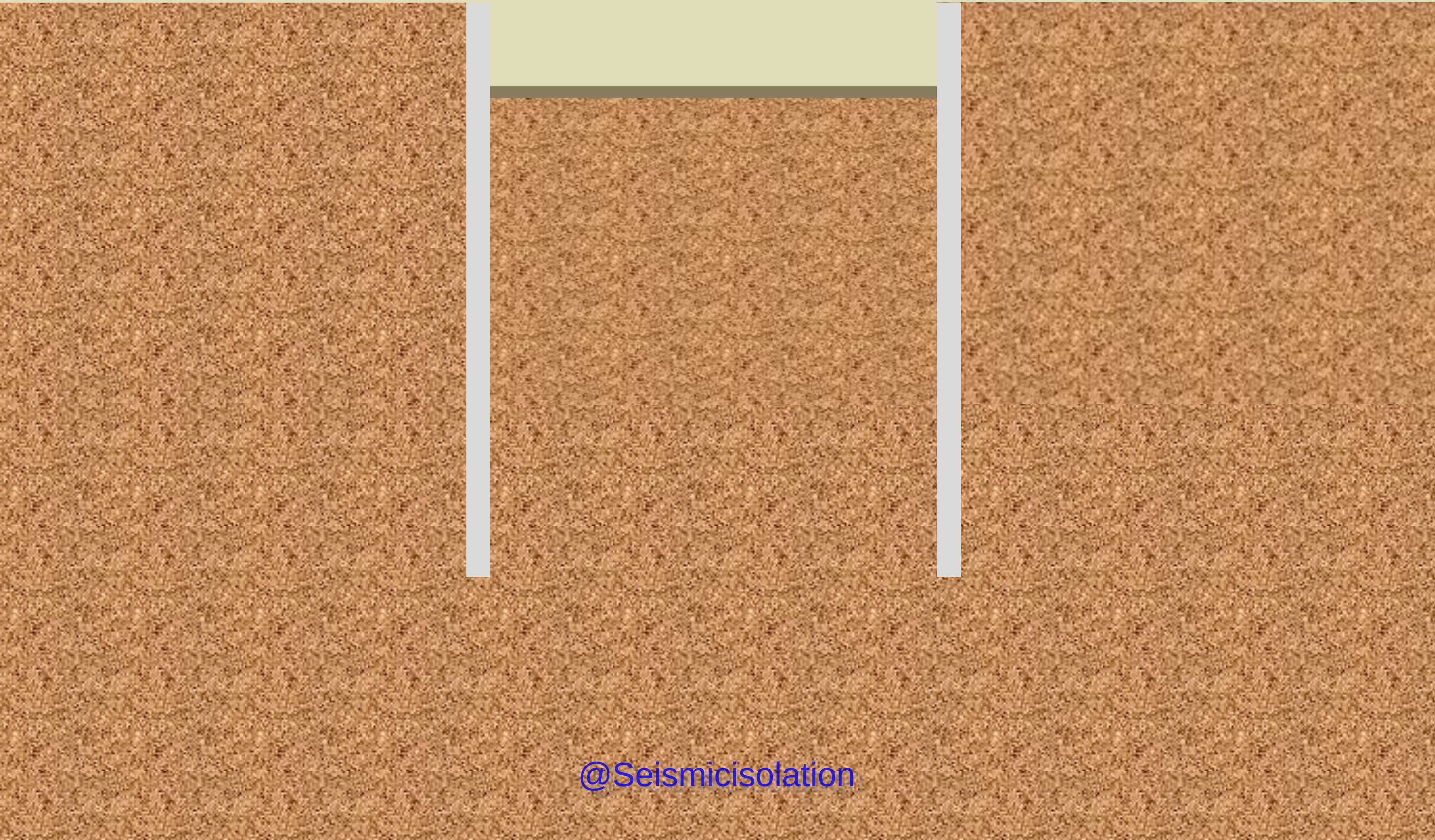


Backfill on roof



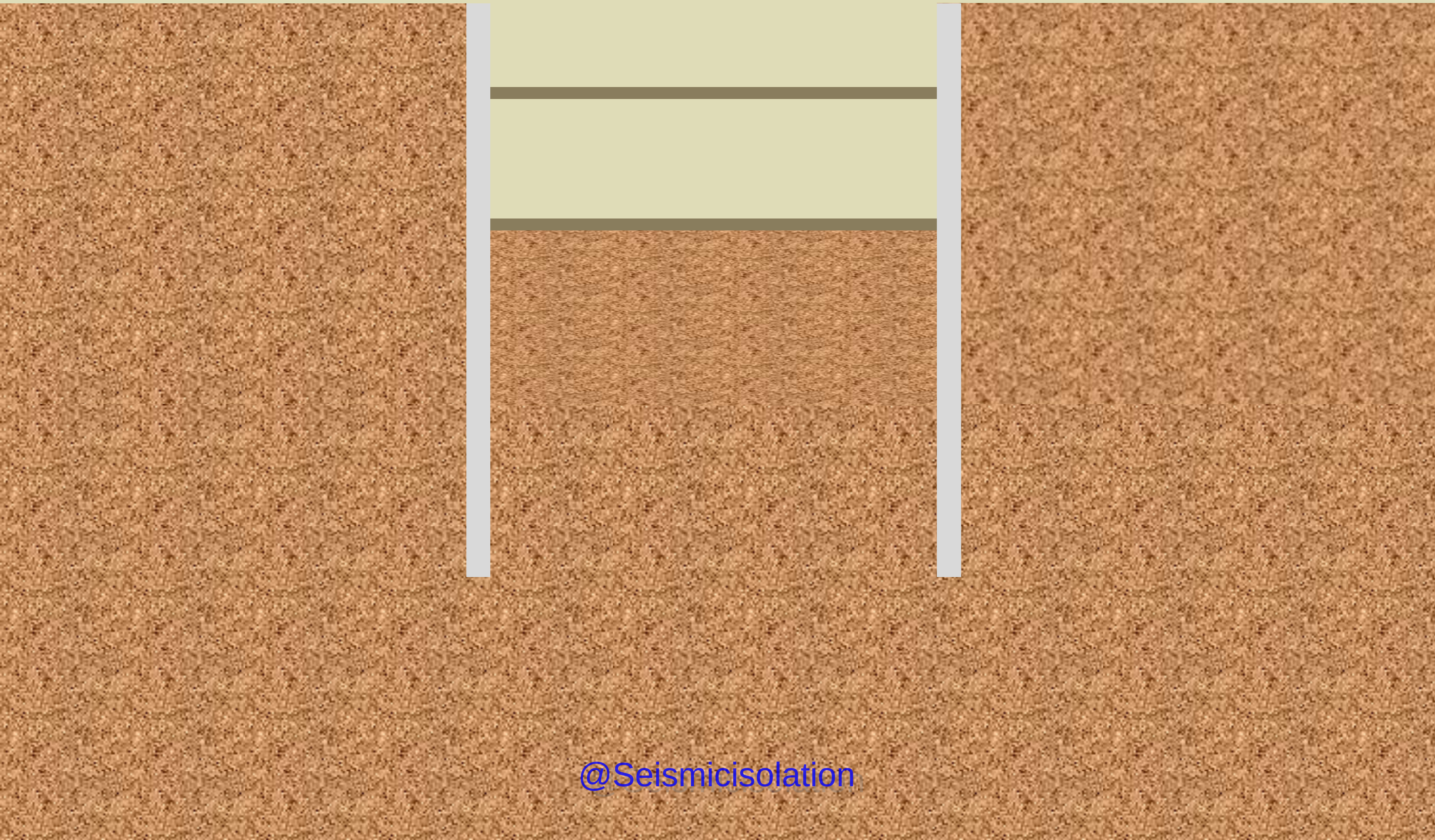
Bottom-up Method of deep excavation and construction Stage 3

Install temporary walls, excavate for, and install top temporary strut.



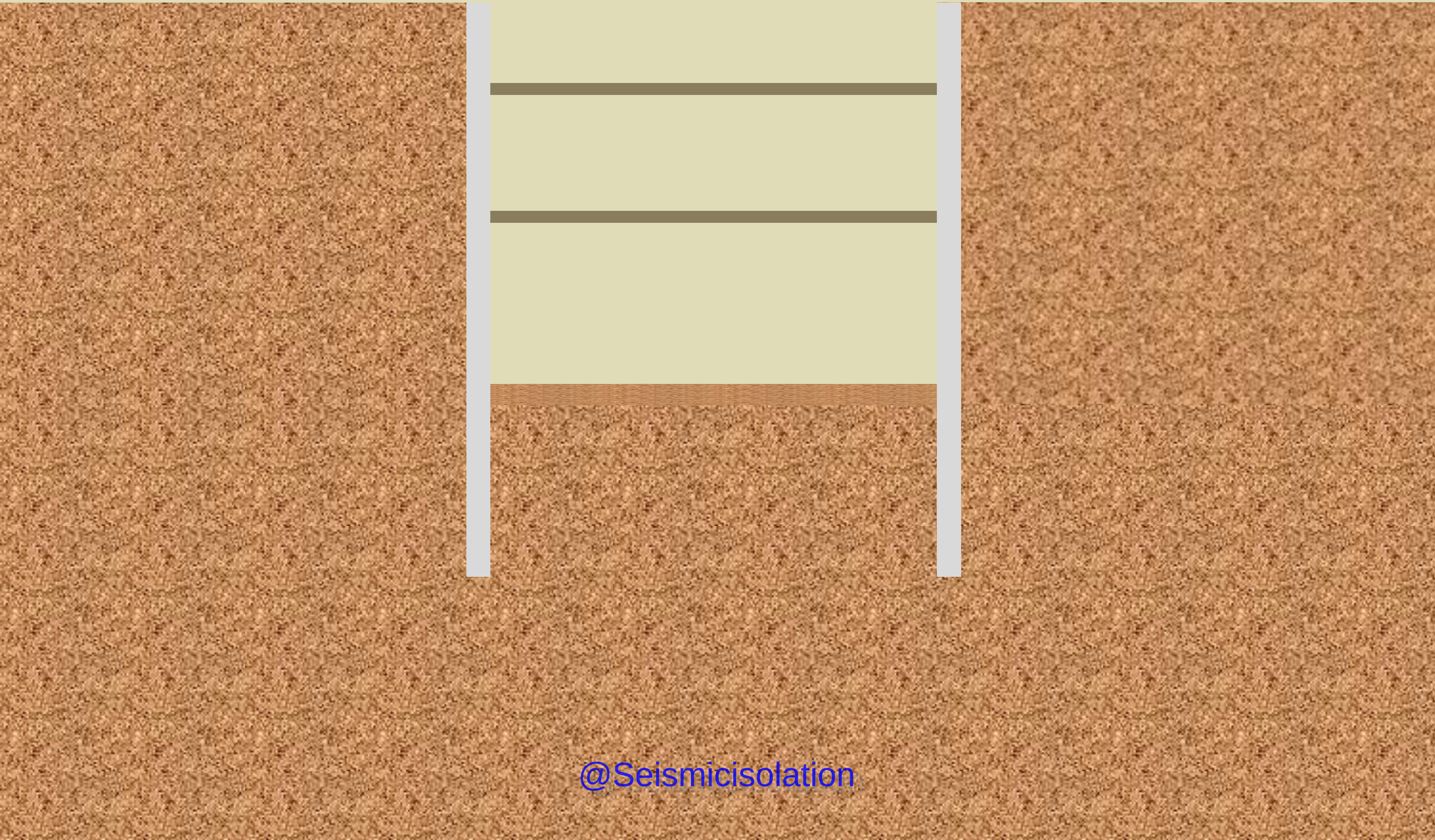
Bottom-up Method of deep excavation and construction Stage 5

Excavate to second level and install second level temporary strut



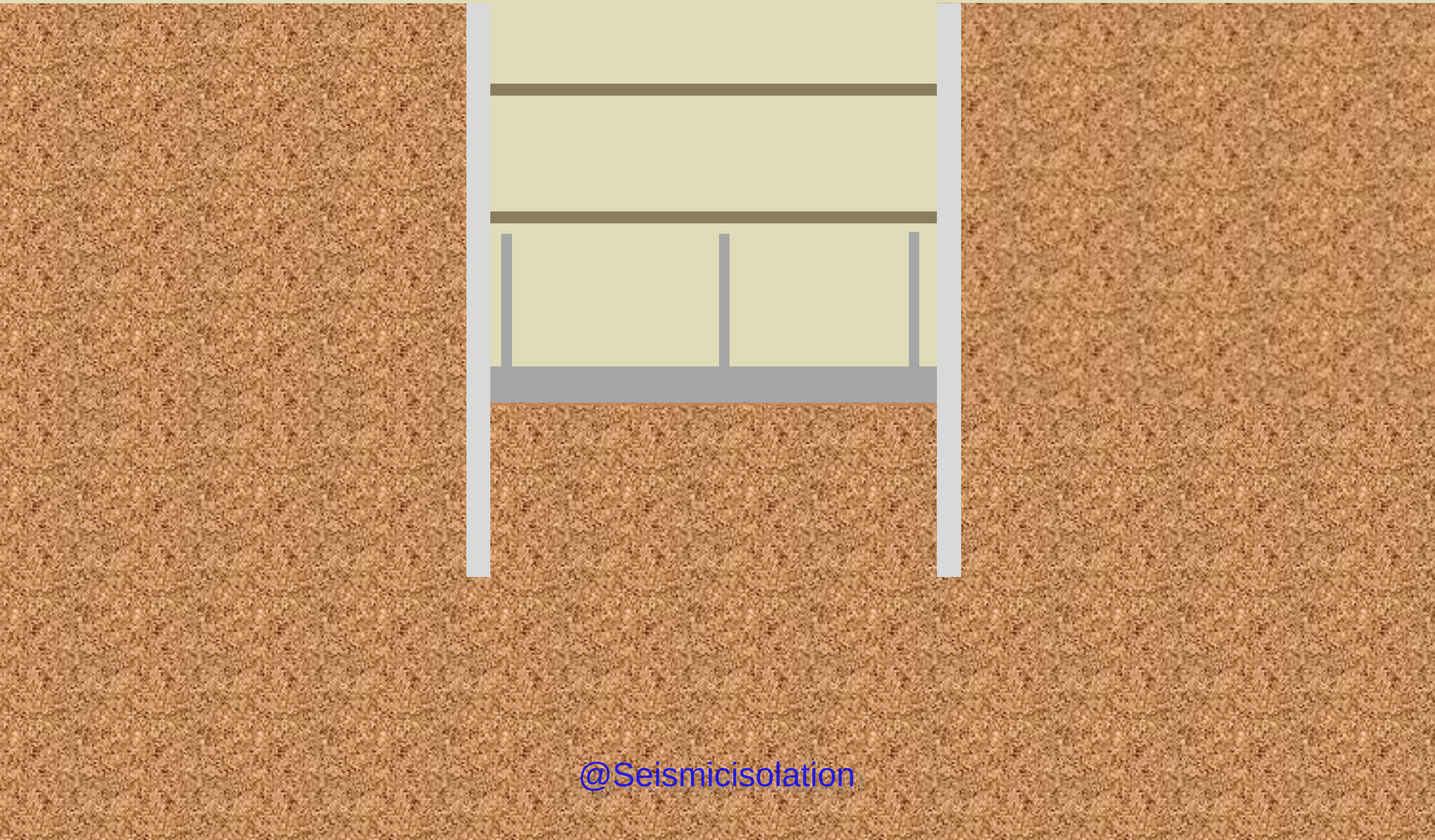
Bottom-up Method of deep excavation and construction Stage 8

Excavate to final level



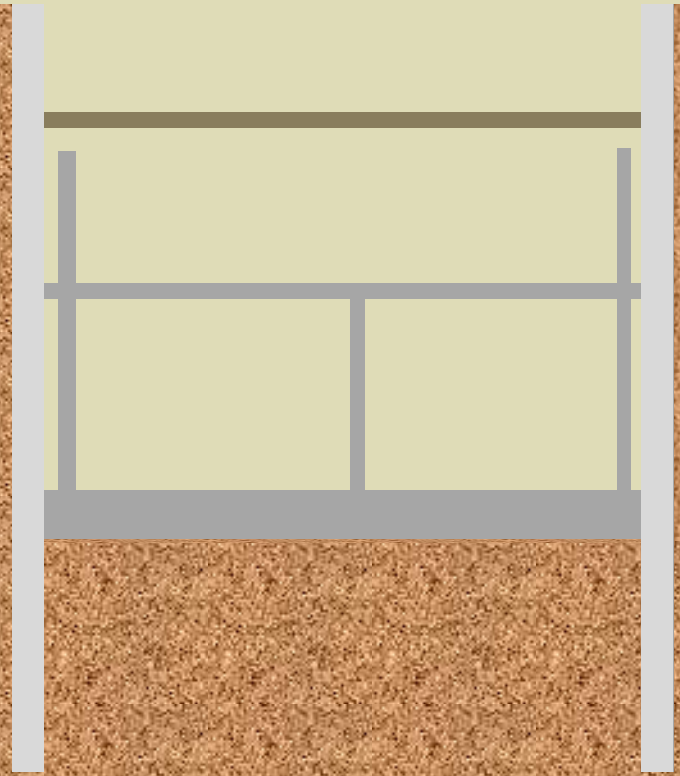
Bottom-up Method of deep excavation and construction Stage 9

Cast base and first lift of permanent walls and columns



Bottom-up Method of deep excavation and construction Stage 11

Remove second strut, cast concourse floor and second lift of permanent walls.



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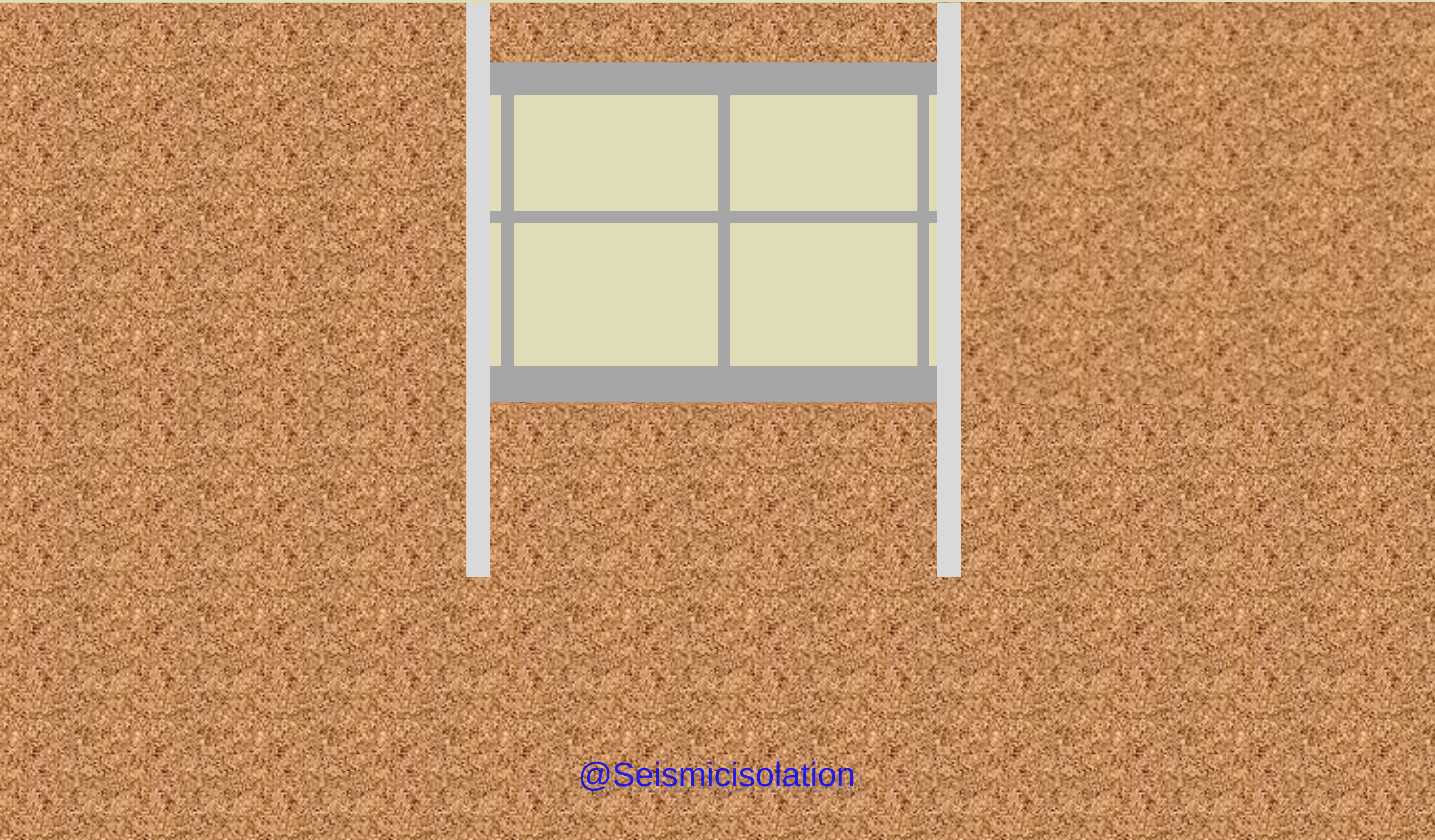
Bottom-up Method of deep excavation and construction Stage 13

Remove top strut, cast walls, columns and roof and backfill.



Examples

A variety of applications

The methods are **not new**

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Bottom-up construction

Temporary steel sheet pile walls and

Struts or Tie-back anchors

1976

Bottom-up construction

Permanent diaphragm walls, temporary strutting

Re-usable hired struts from Yong Nam

Top-down:

Permanent primary roof beams at every plunged column position

Hand excavated caisson walls

1976

Primary roof beams

used as casting beds for pre-tensioned Tee-beams to be placed between primary beams.

Top-down or bottom-up, Benefits?

Top-down

Early completion and access at ground level

No temporary shoring (or only a little)

No formwork for floors and roof

Cheaper to construct

Contractor's alternative

Bottom-up

Easier to design

Better waterproofing

More access for cranes   Reference design

Top-down or bottom-up, **Dis-Benefits?**

Top-down

Less access below slabs during excavation

Plunge columns

More complicated to design

Contractor’s alternative

Bottom-up

More expensive to construct

Usually slower

Reference design

Case 1

Top-down Basement

5 level basement provided a ground level slab with large site works area at ground level and

Bottom-up Superstructure

Simultaneous construction

Wynn's casino, Macau.

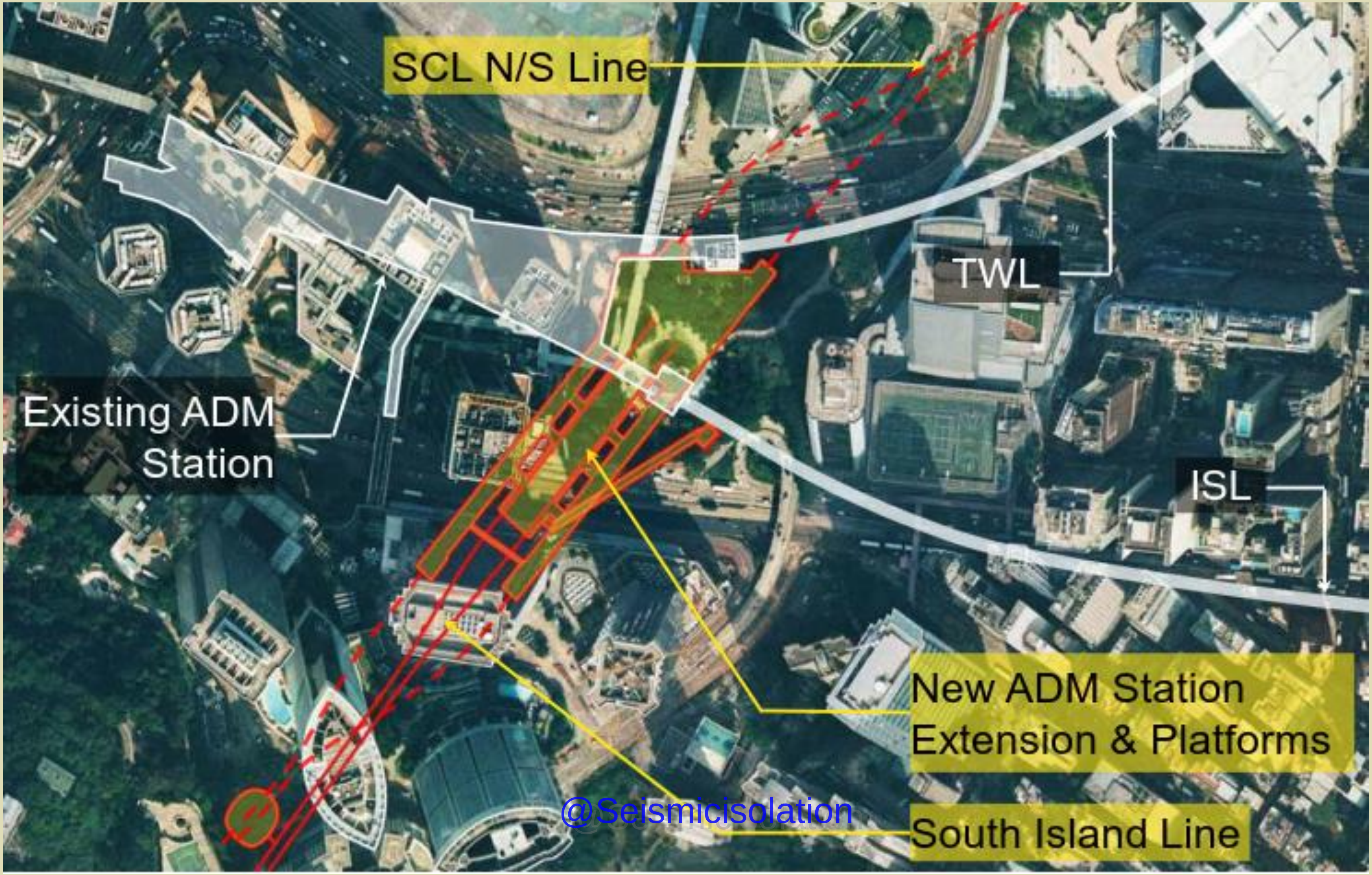
Large ground level platform with several openings for access to basement

Mucking out basement

5th basement

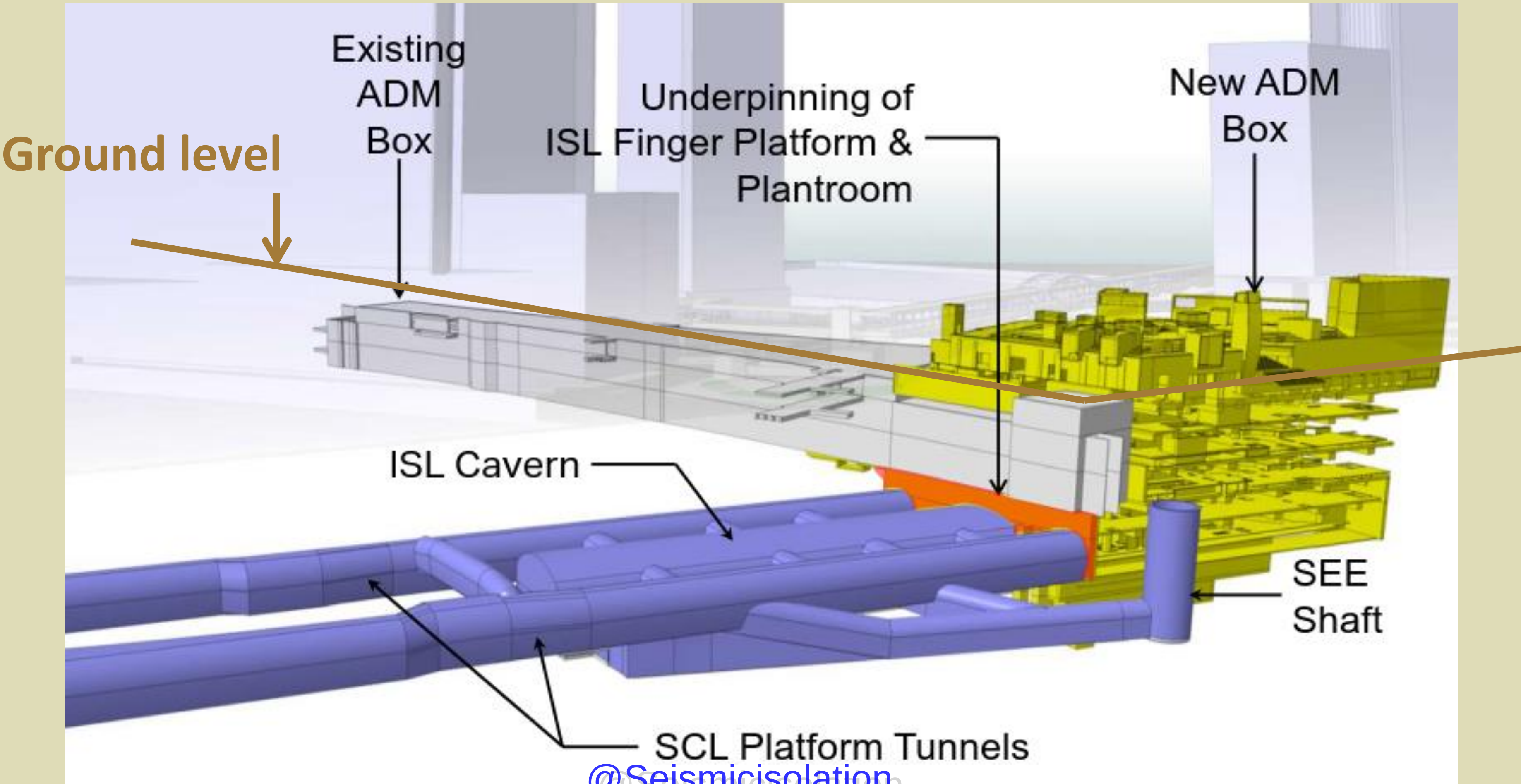
Case 2 SIL at Admiralty Station - 3 Lines

Undermining two lines and end of junction station

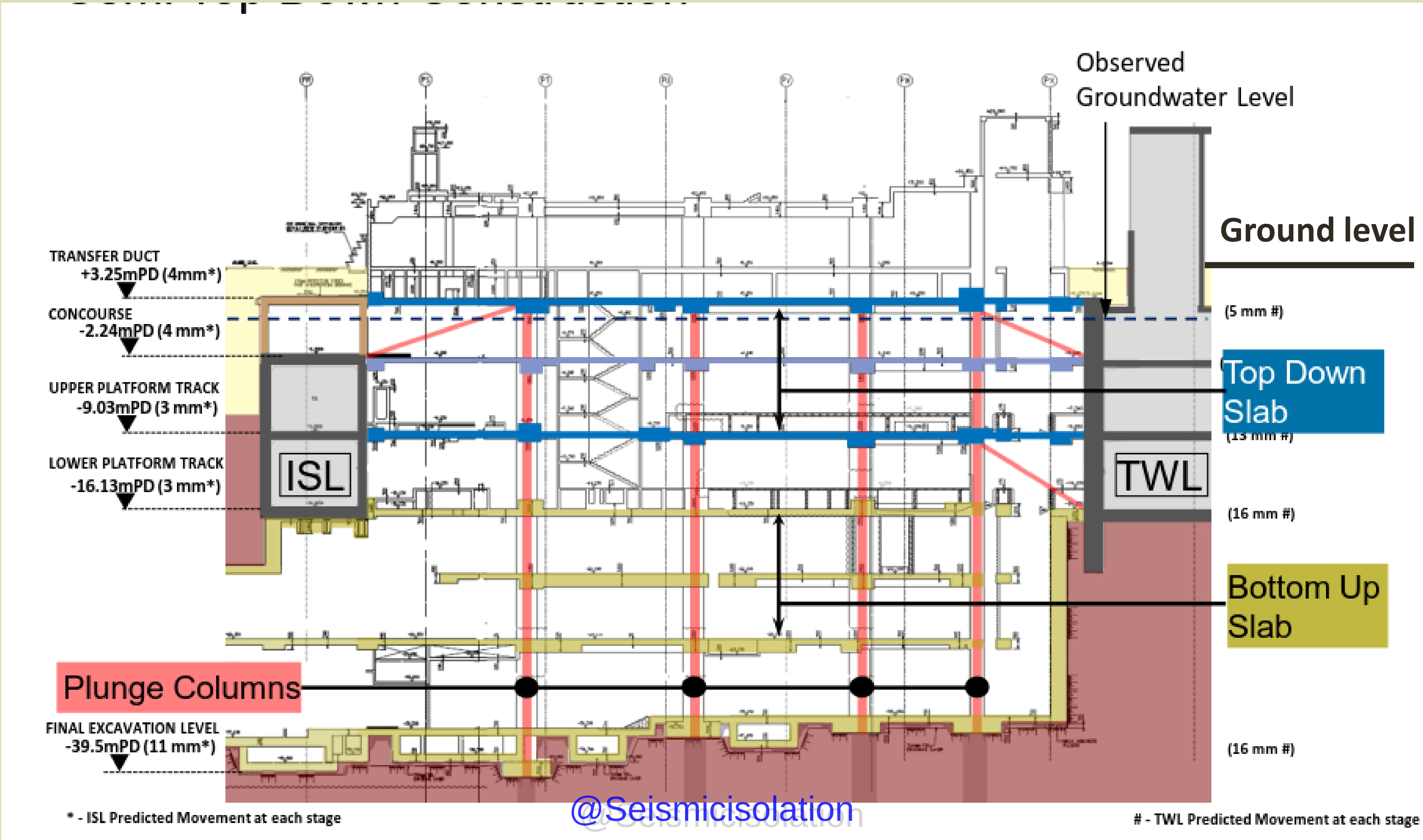


Complexity

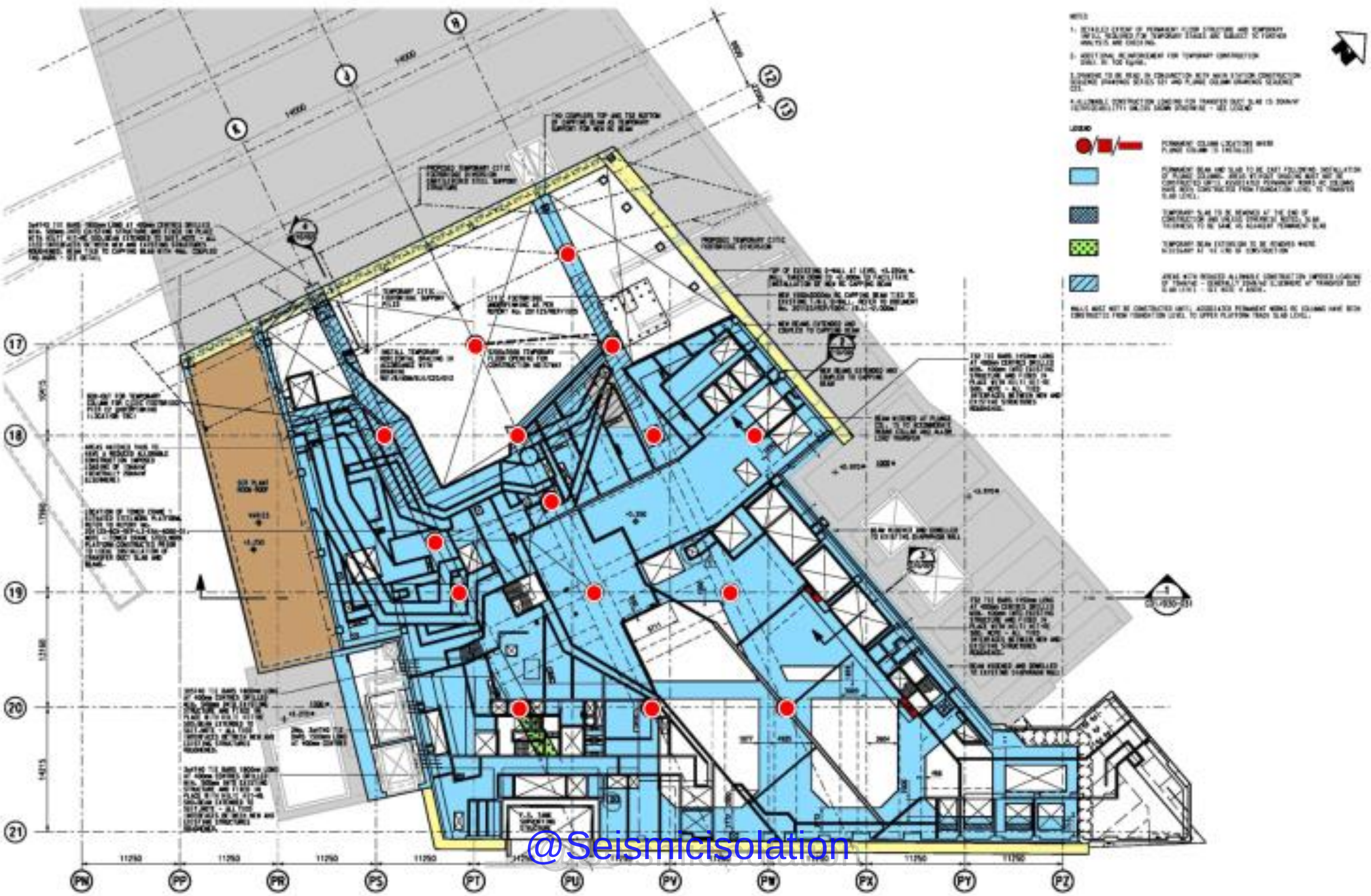
Schematic of physical interfaces



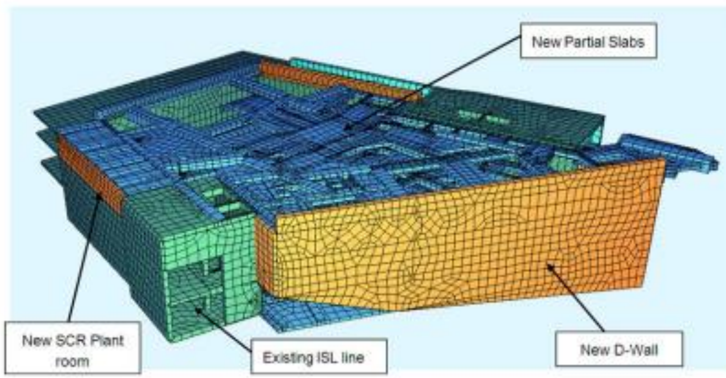
Hybrid:
3 floors top-down then 4 floors bottom-up



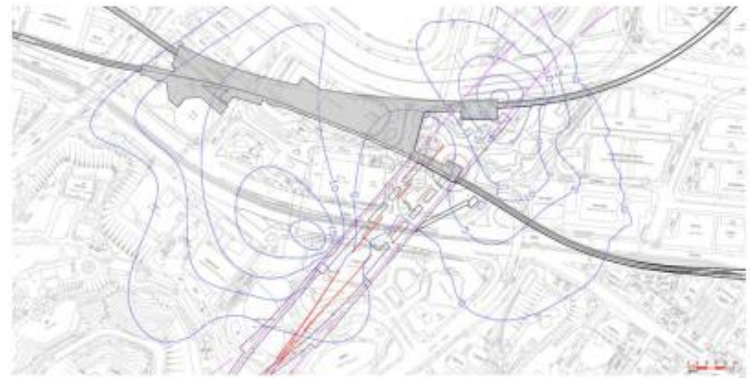
Top-down involves incomplete slabs for access

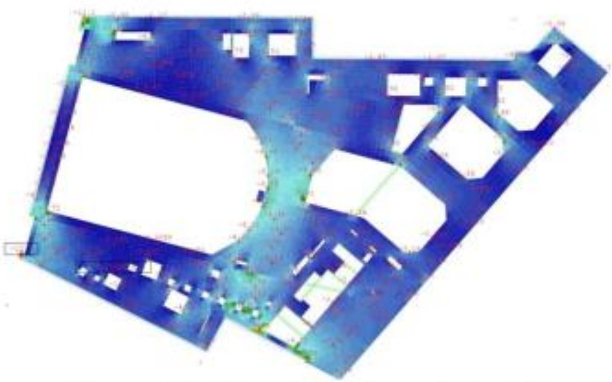


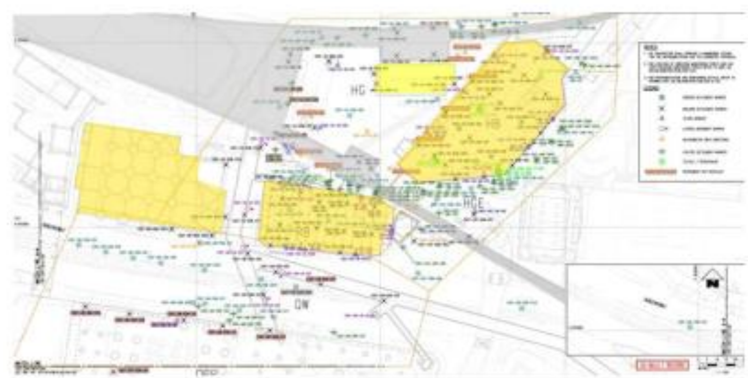
3-D modelling of structure at several stages



Soil Structure Interaction FE Models


Ground Settlement Predictions


Operational Infrastructure Verification


AAA / Instrumentation & Monitoring

Top-down first then Bottom-up

Permanent structural elements used for temporary lateral bracing

Plunged columns and blinding for Bottom-up construction

The excavation is quite big

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Underpinning for excavation beneath live tracks.

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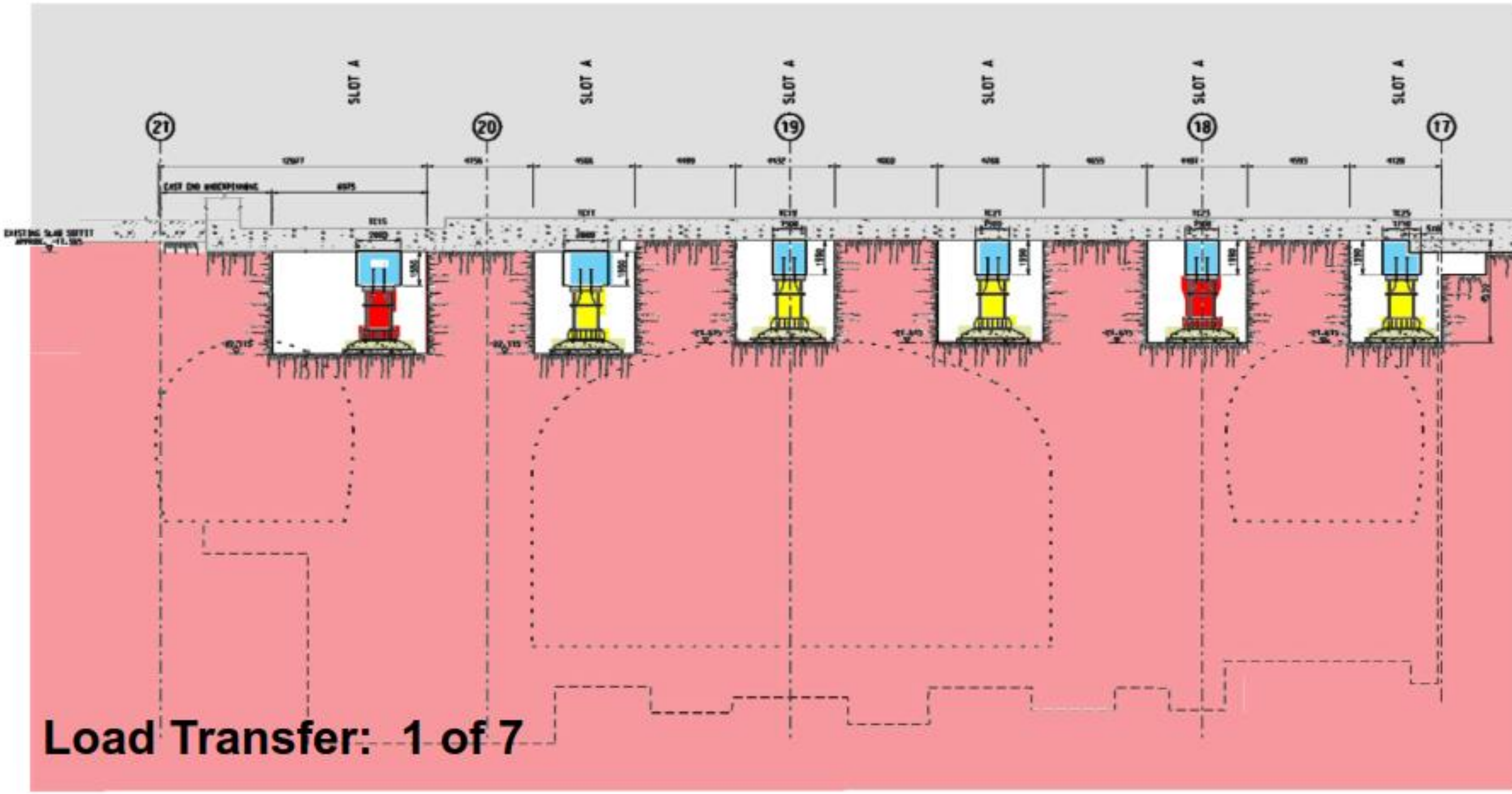
Admiralty Station Expansion

Step 1 of 12

Underpinning for excavation beneath live tracks.



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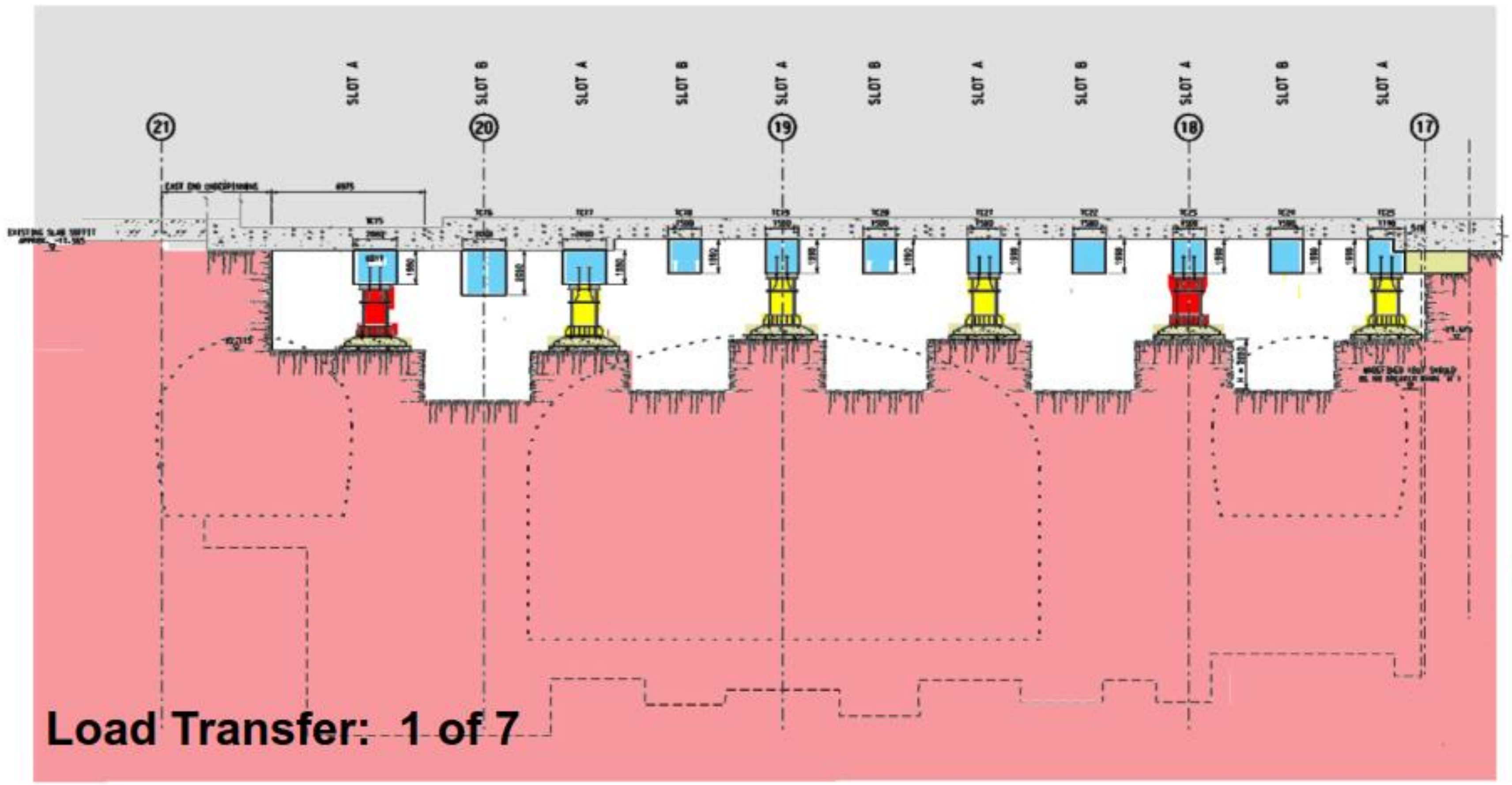
Underpinning ISL Finger Platform Tunnel

Sequence of Works

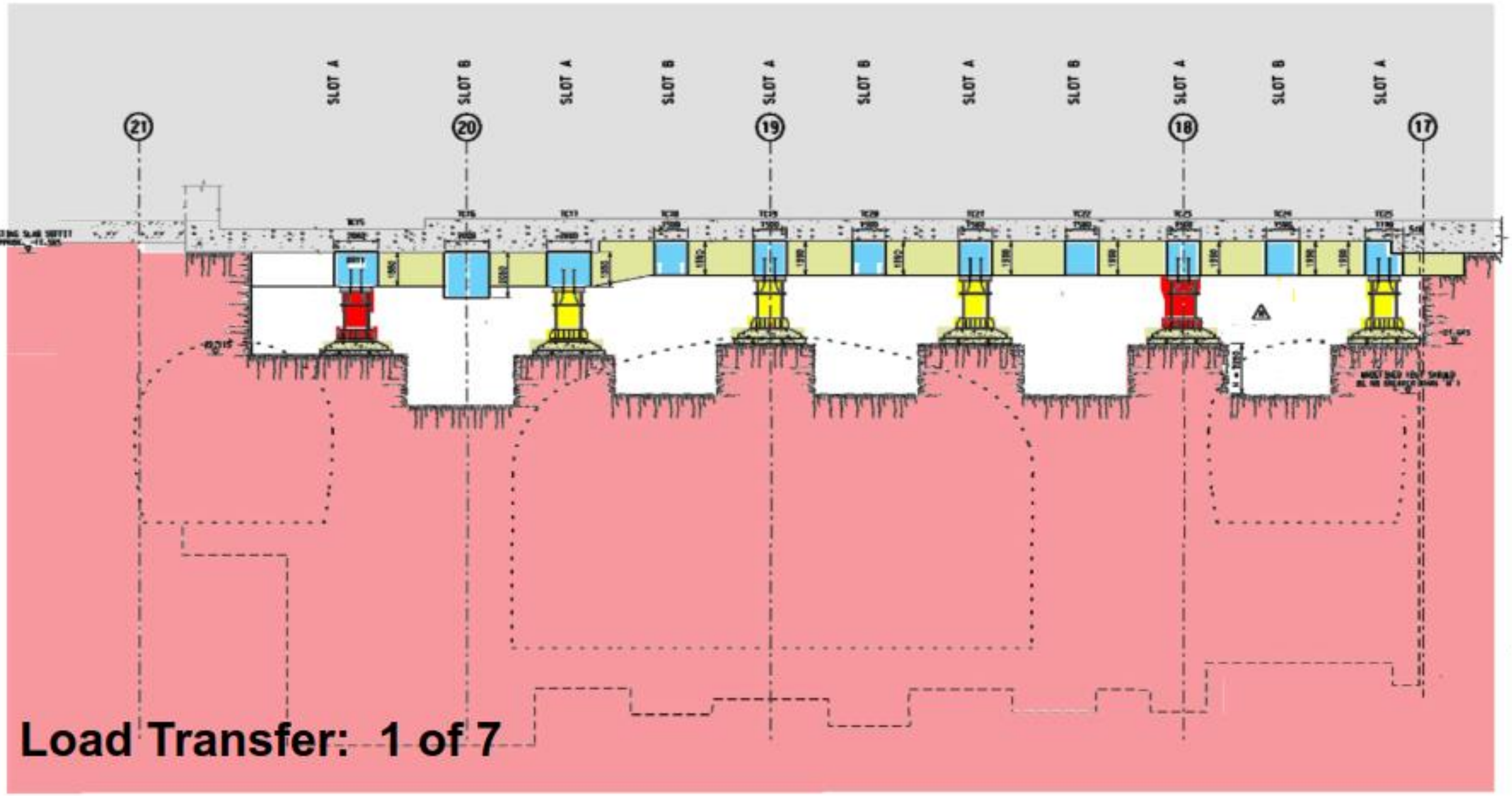
Step 2 of 12



benaim

Underpinning ISL Finger Platform Tunnel

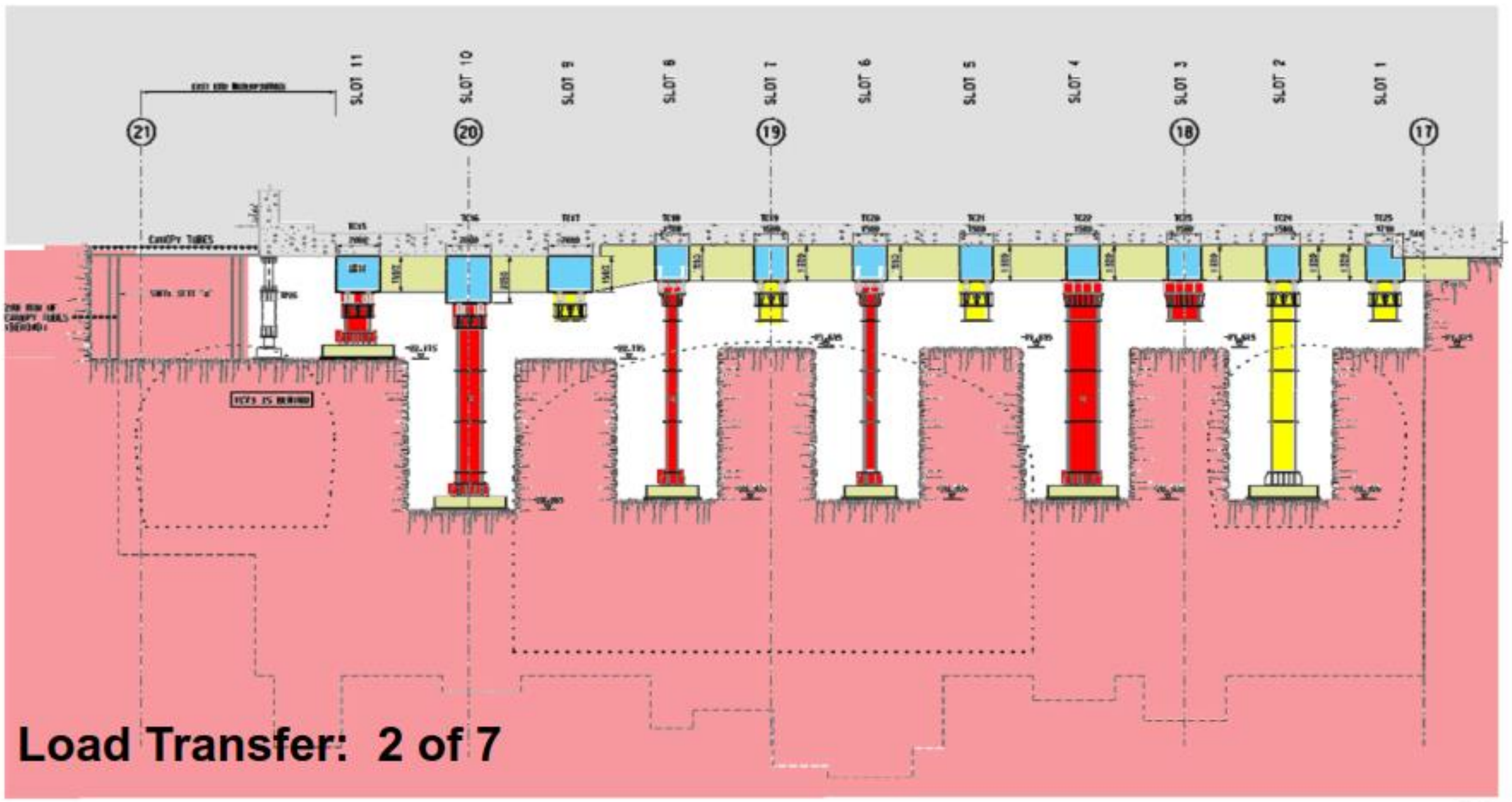
Sequence of Works



benaim

Underpinning ISL Finger Platform Tunnel

Sequence of Works



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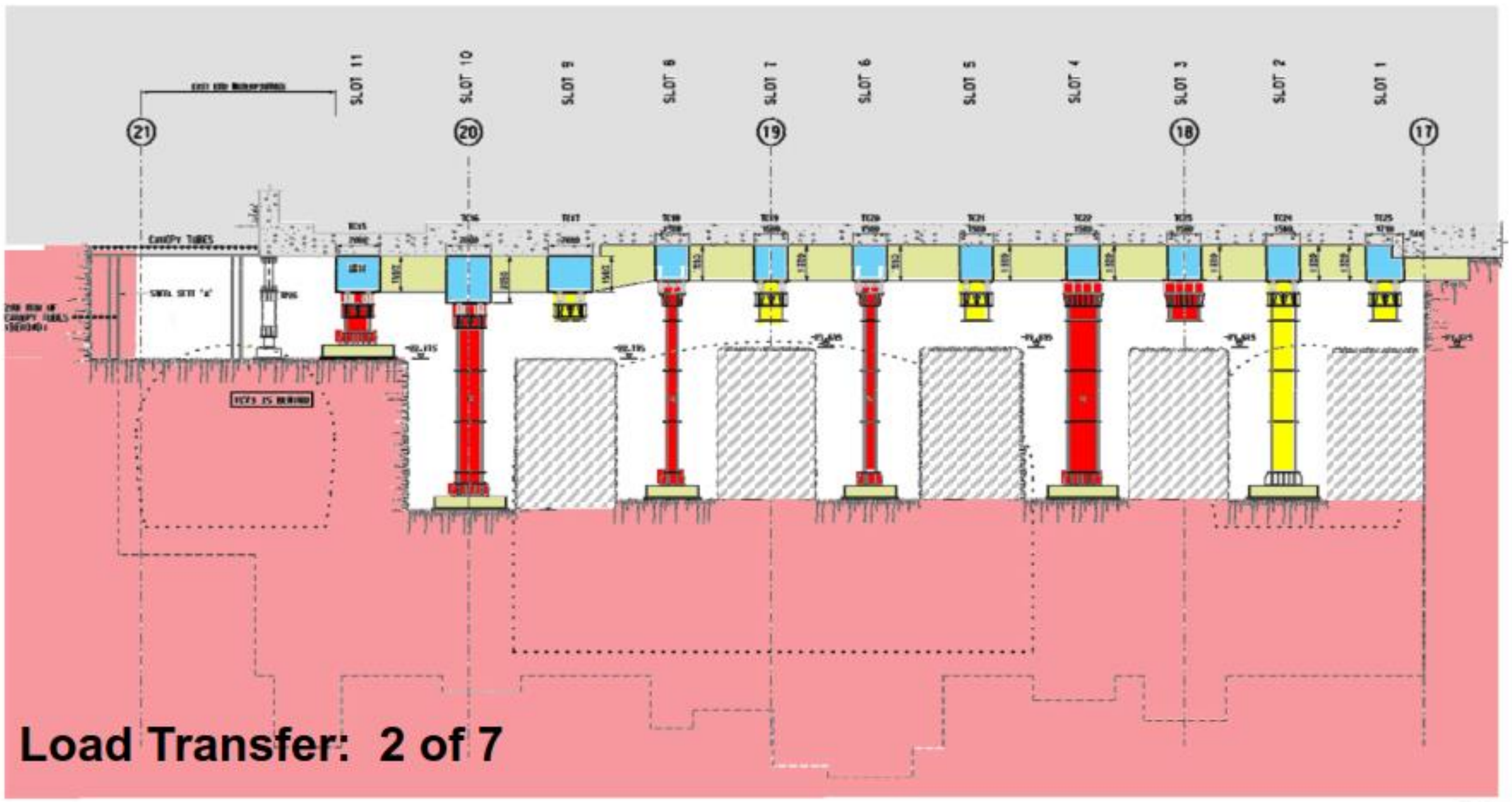
Underpinning ISL Finger Platform Tunnel

Sequence of Works

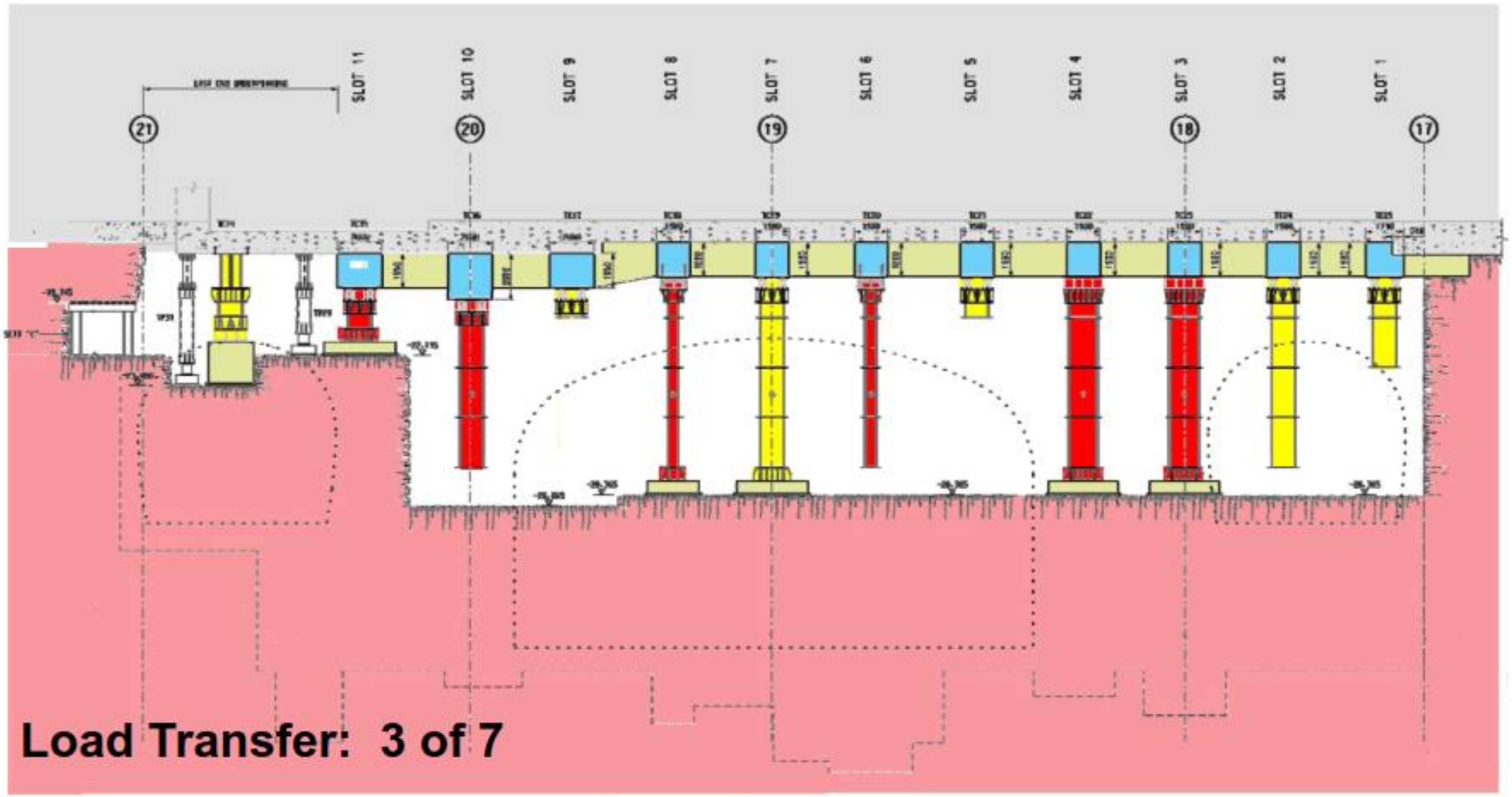
Step 5 of 12



Underpinning ISL Finger Platform Tunnel

Sequence of Works

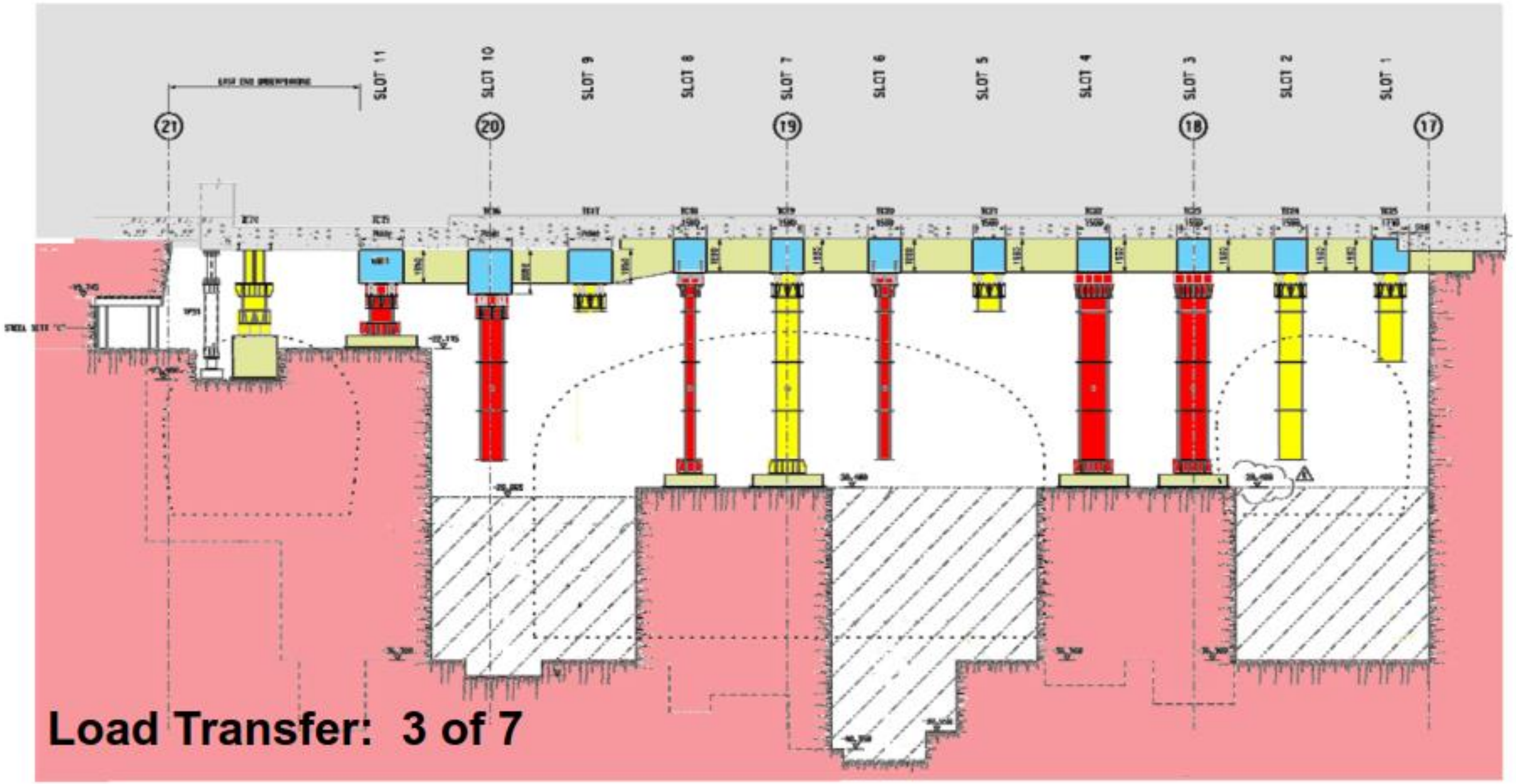
Step 6 of 12



Underpinning ISL Finger Platform Tunnel

Sequence of Works

Step 7 of 12



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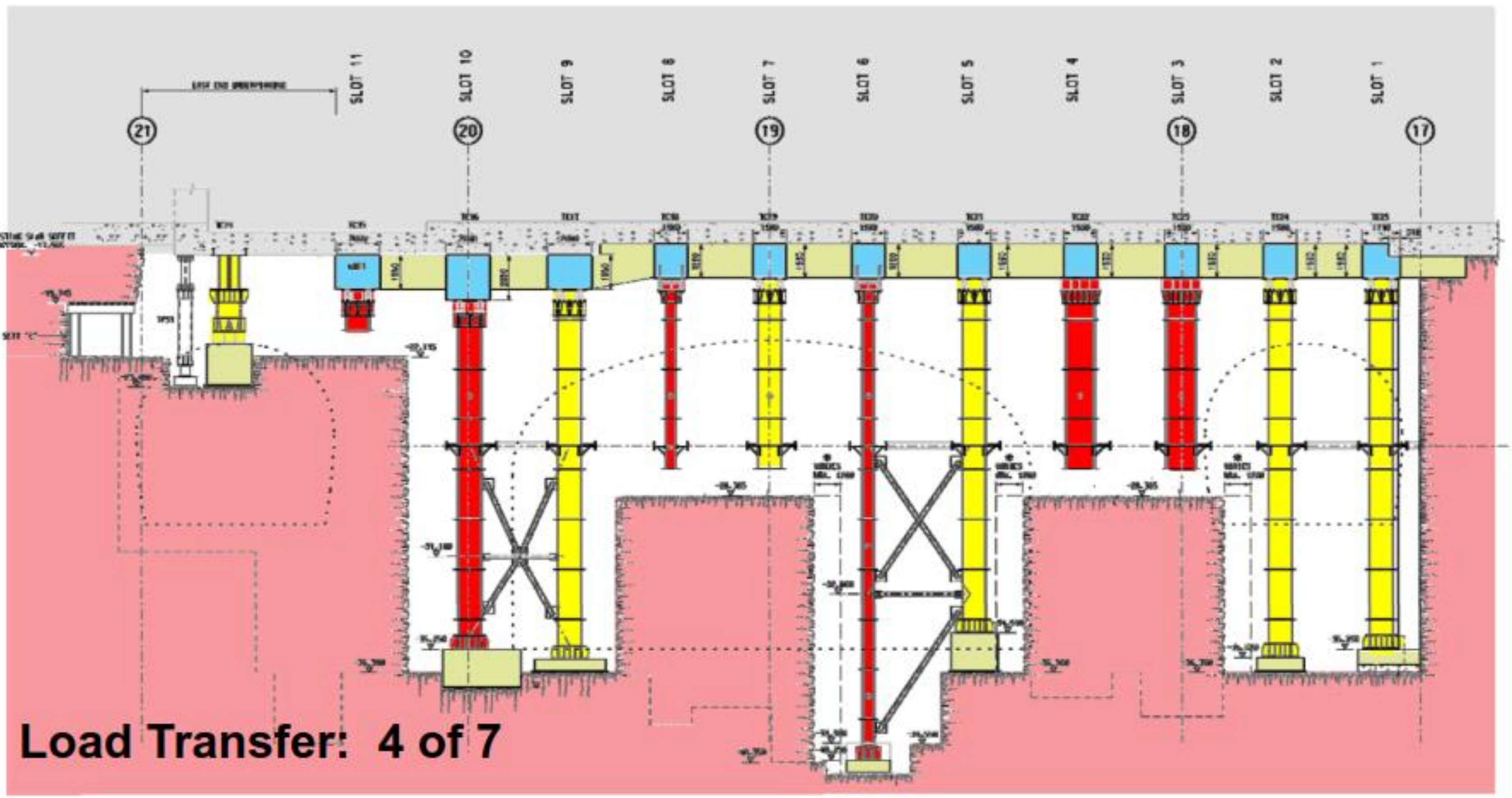
Underpinning ISL Finger Platform Tunnel

Sequence of Works

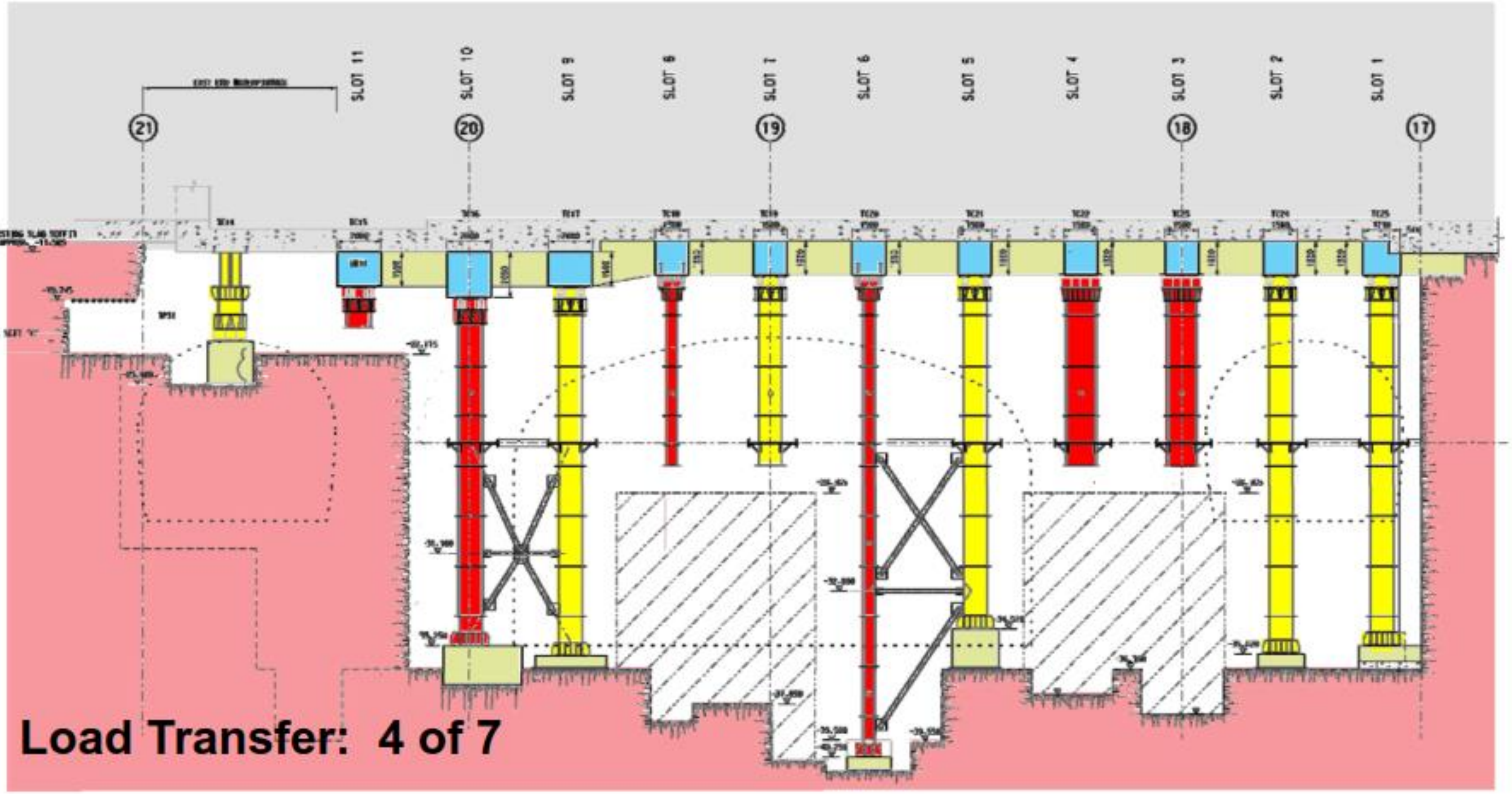
Step 8 of 12



Underpinning ISL Finger Platform Tunnel

Sequence of Works

Step 9 of 12



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Underpinning ISL Finger Platform Tunnel

Sequence of Works

Step 10 of 12

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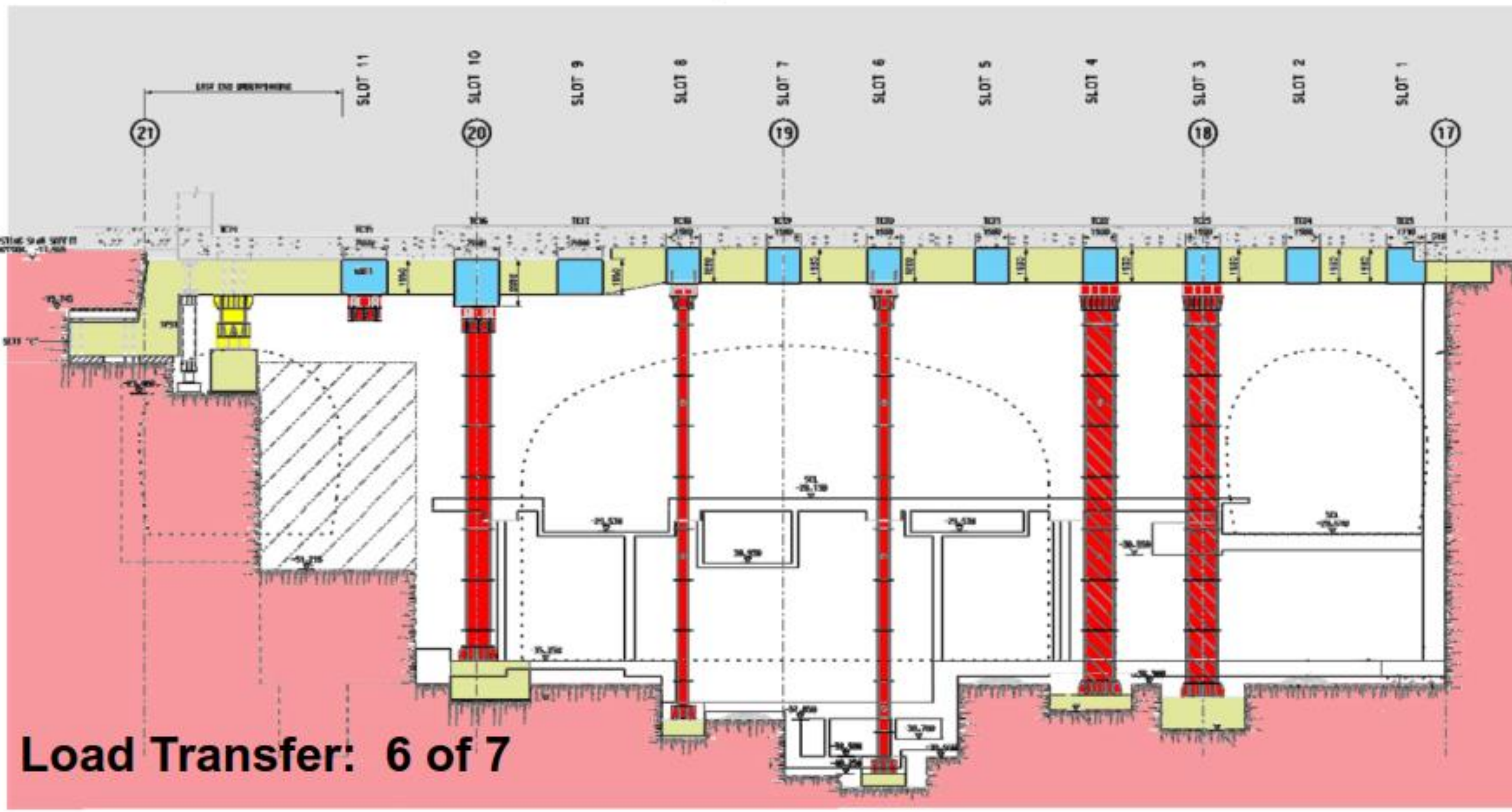
Underpinning ISL Finger Platform Tunnel

Sequence of Works

Step 11 of 12



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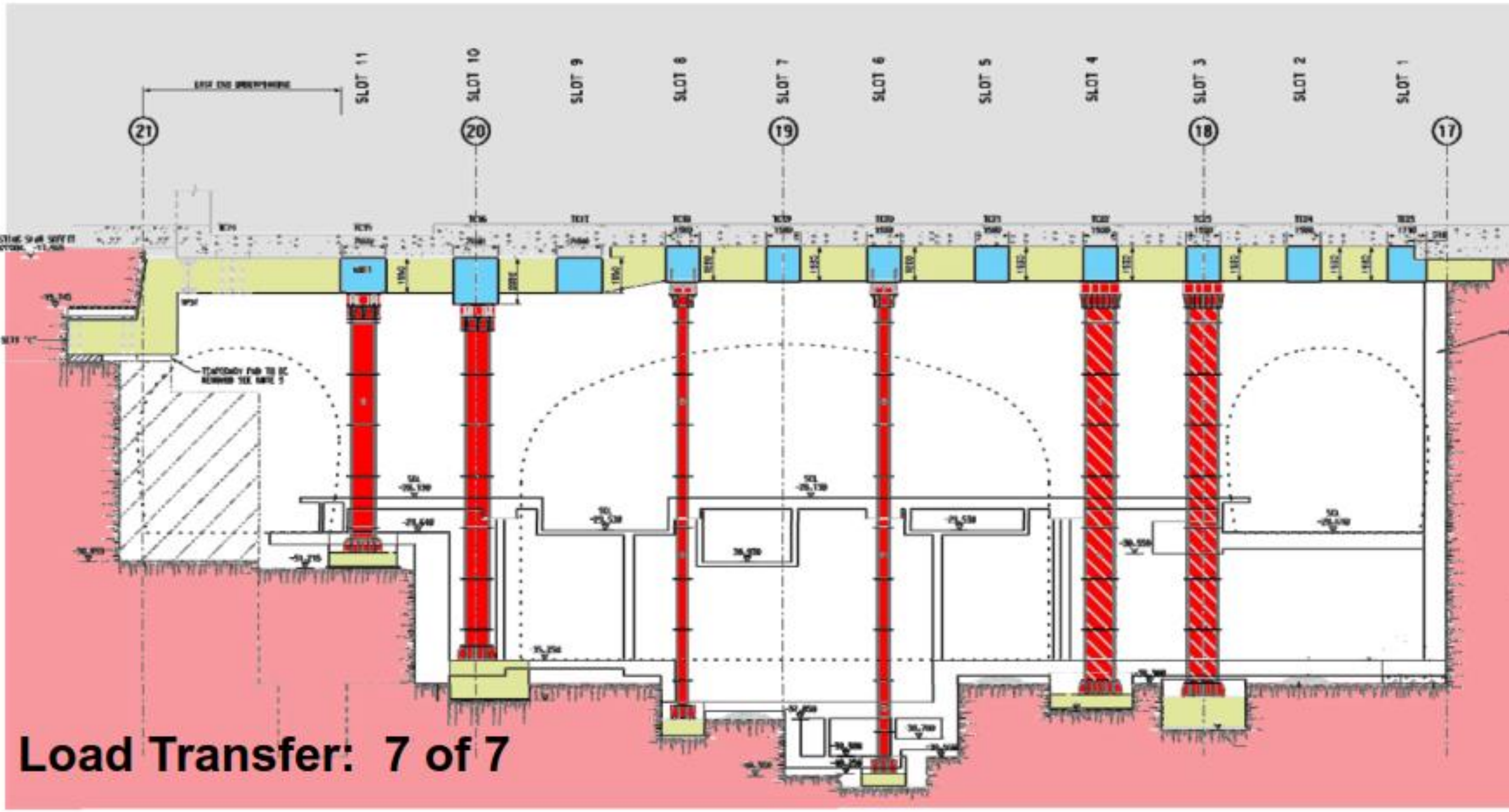
Underpinning ISL Finger Platform Tunnel

Sequence of Works

Step 12 of 12



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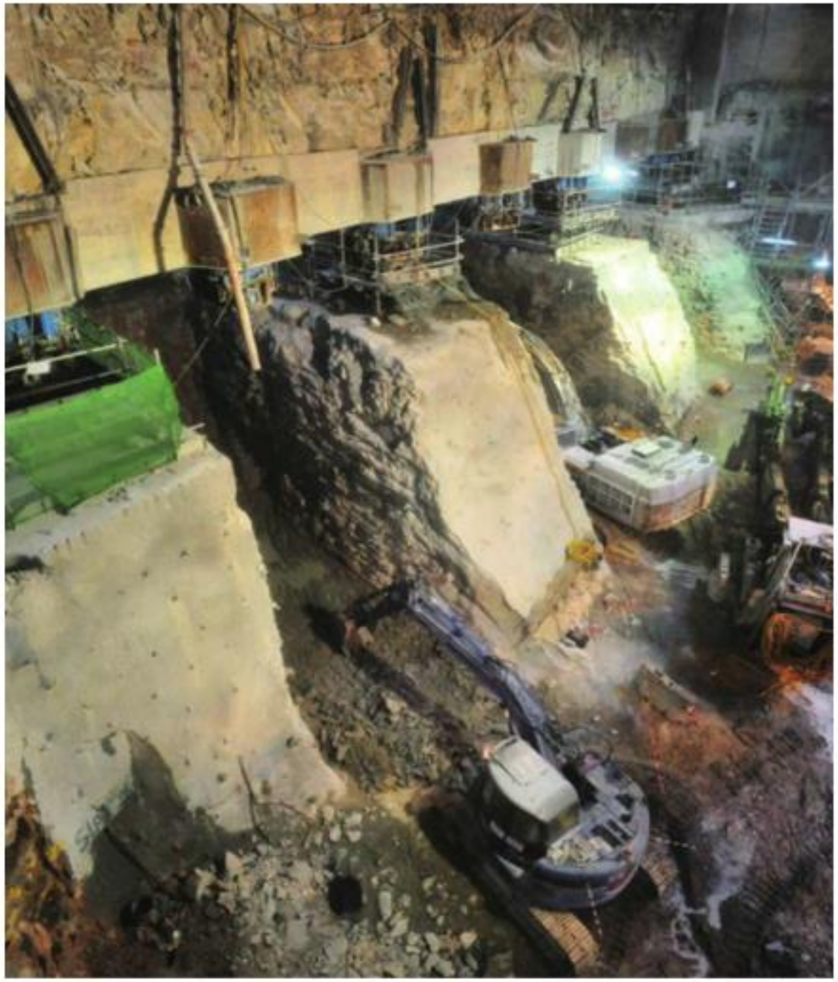
Underpinning ISL Finger Platform Tunnel

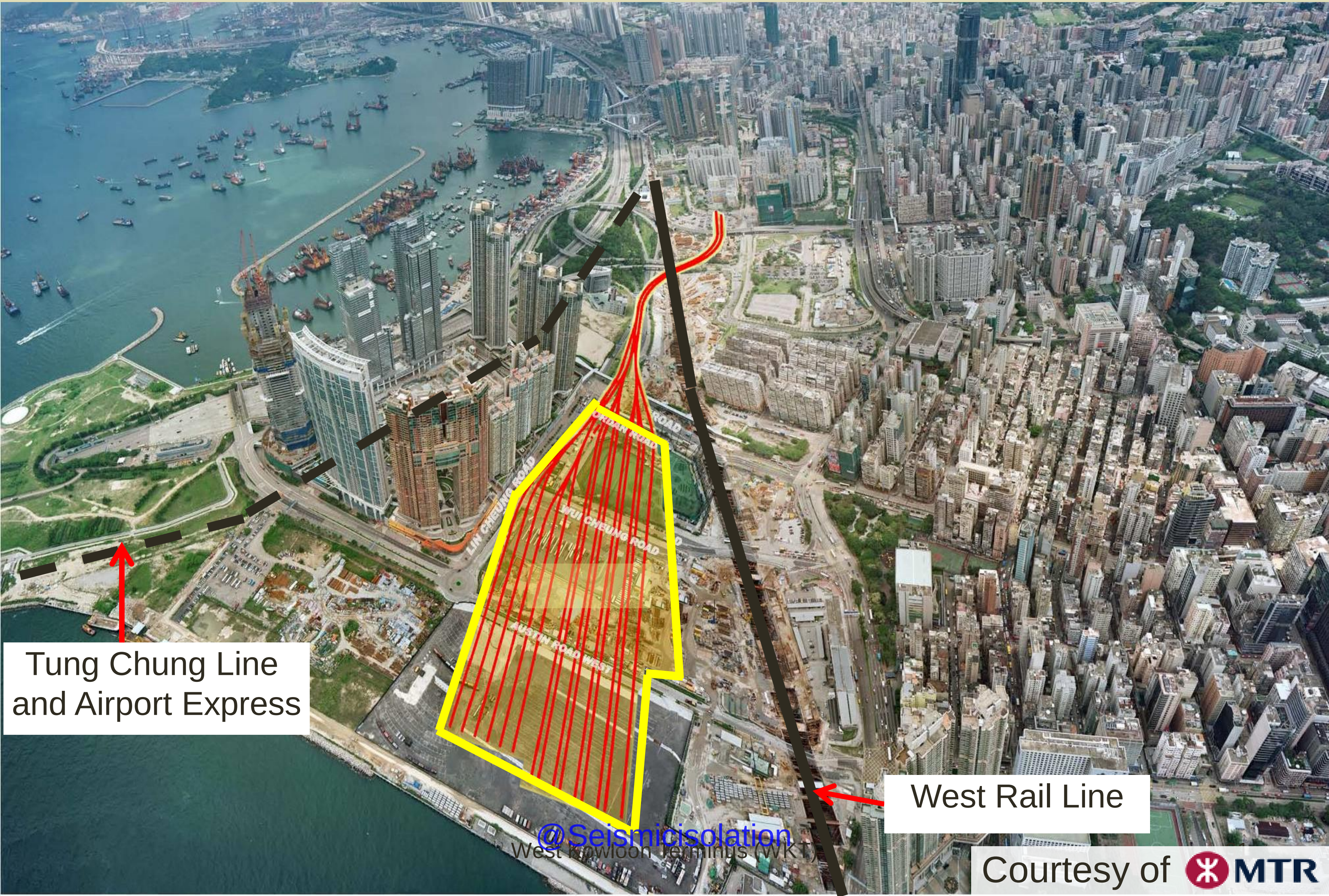
Jack / Load Cell Station

Underpinning ISL Finger Platform Tunnel
Excavating Slots



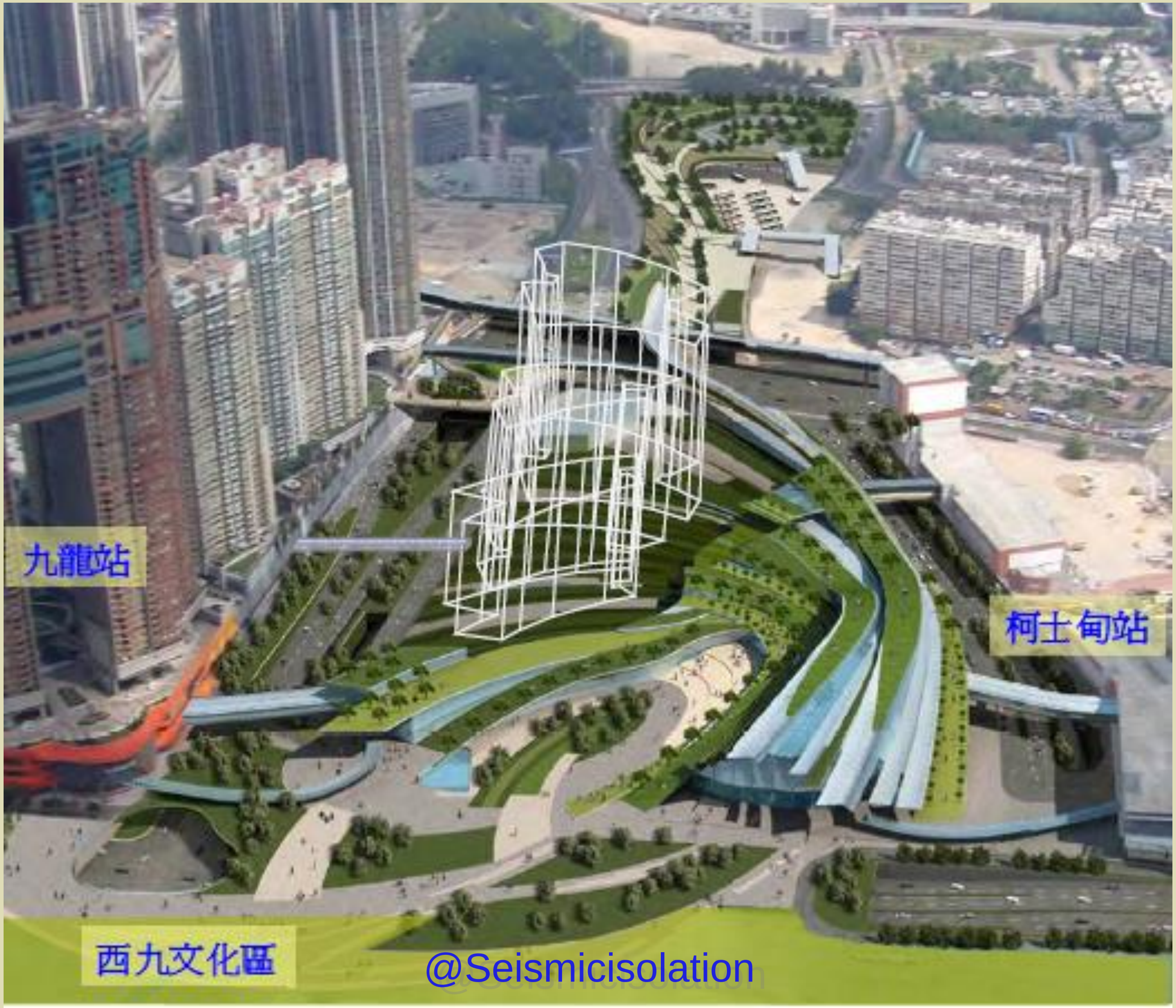
Underpinning ISL Finger Platform Tunnel
Break Through

Case 3: West Kowloon High Speed Railway Terminus



Entrance Building West Elevation

Planned Co-development



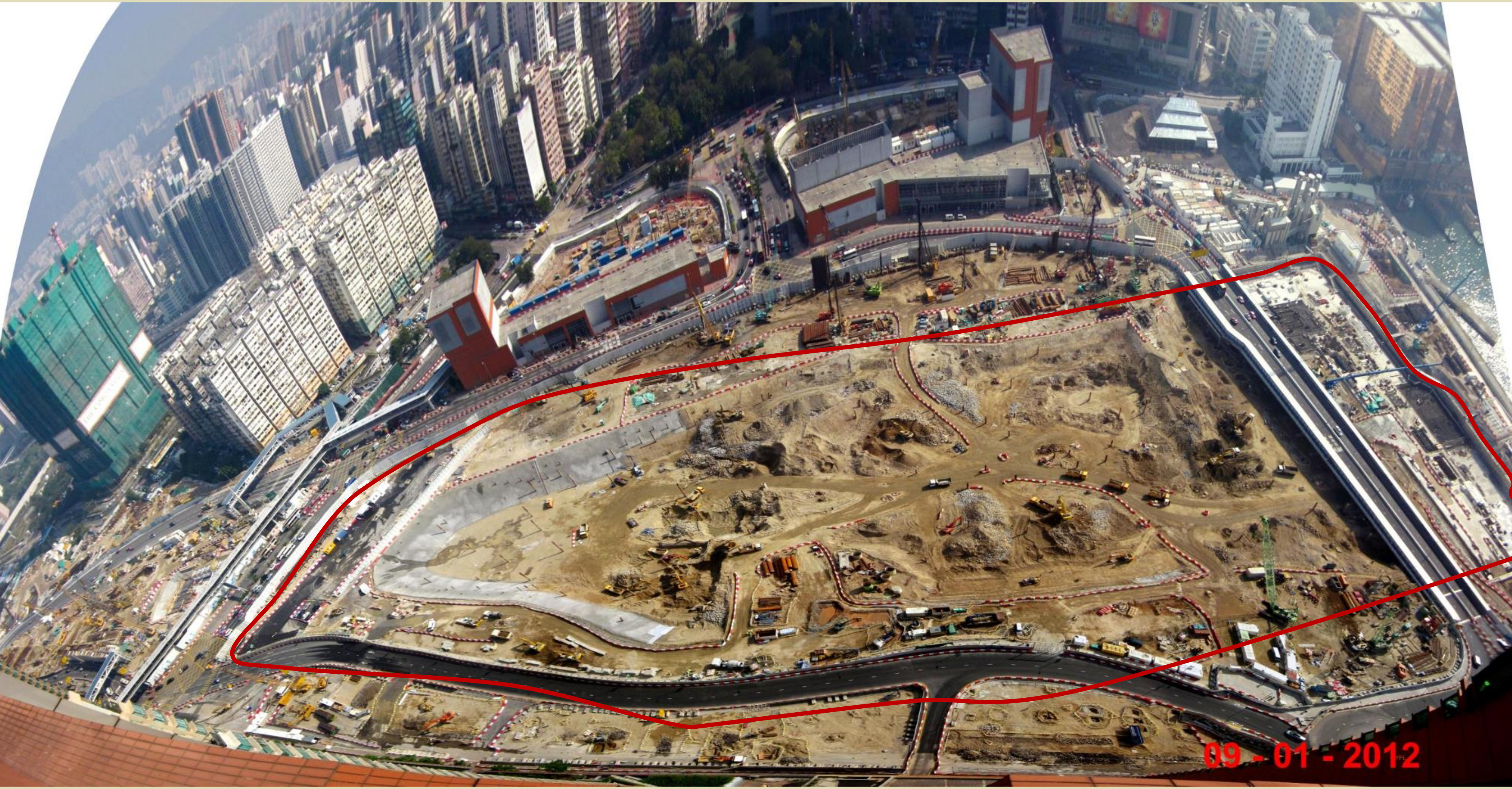
Reference Scheme

The technical challenge: a deep and extensive excavation in an intensively developed district.

11 hectares of site area

(1 million square feet)

3.5 M cubic yd. excavation volume



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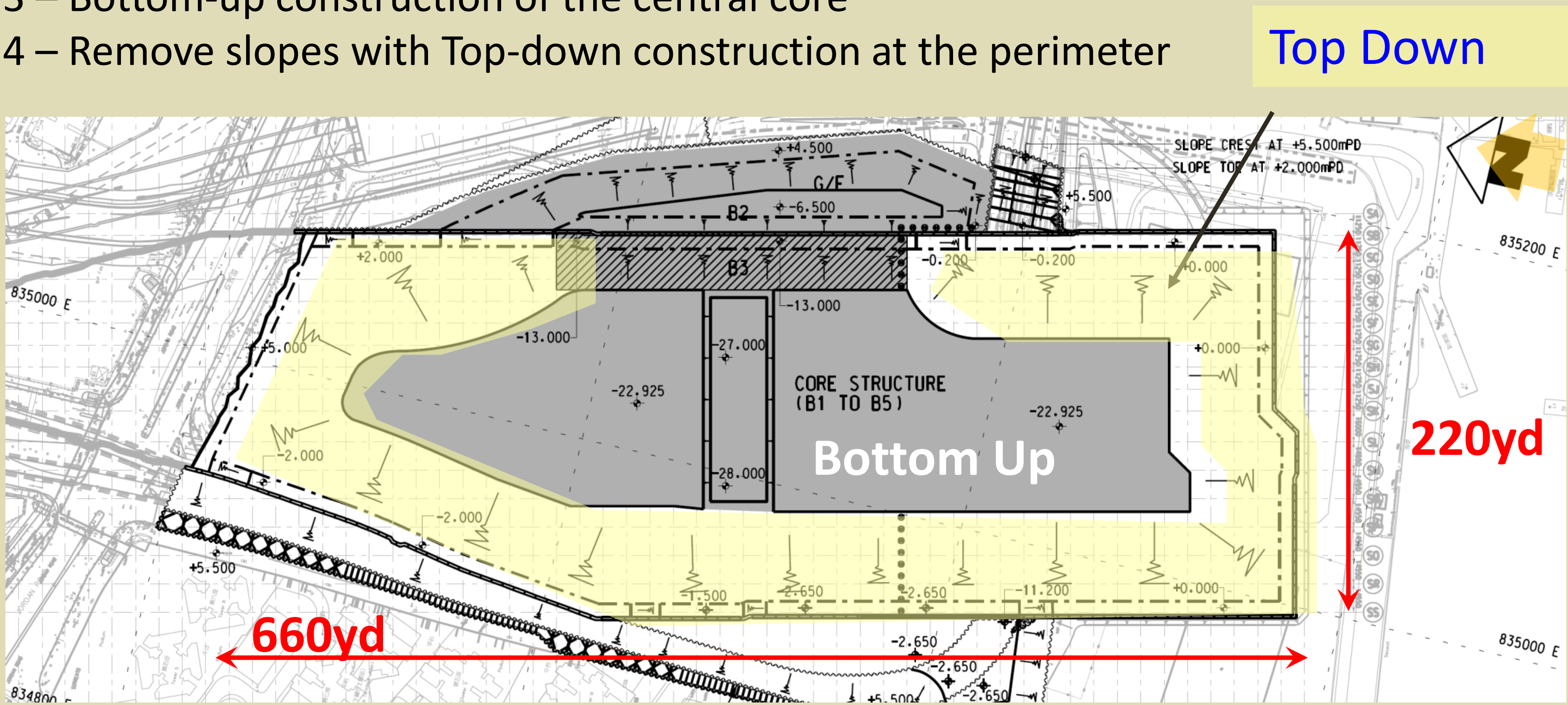
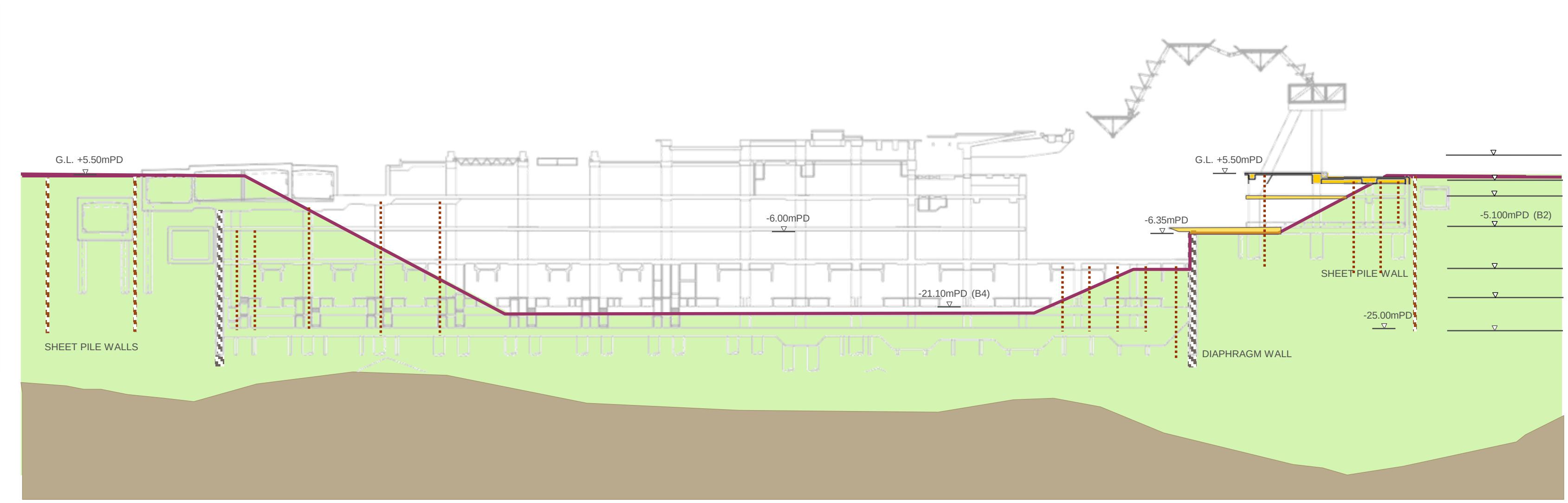
Concept: Big Dig and Bottom-up in the middle then Top-down around the perimeter.

1 – Diaphragm Walls and Foundations
2 – Rapid Open Bulk Excavation with Temporary cut slopes
3 – Bottom-up construction of the central core
4 – Remove slopes with Top-down construction at the perimeter



Excavate to -21mPD (B4)

Construct B1 and B2



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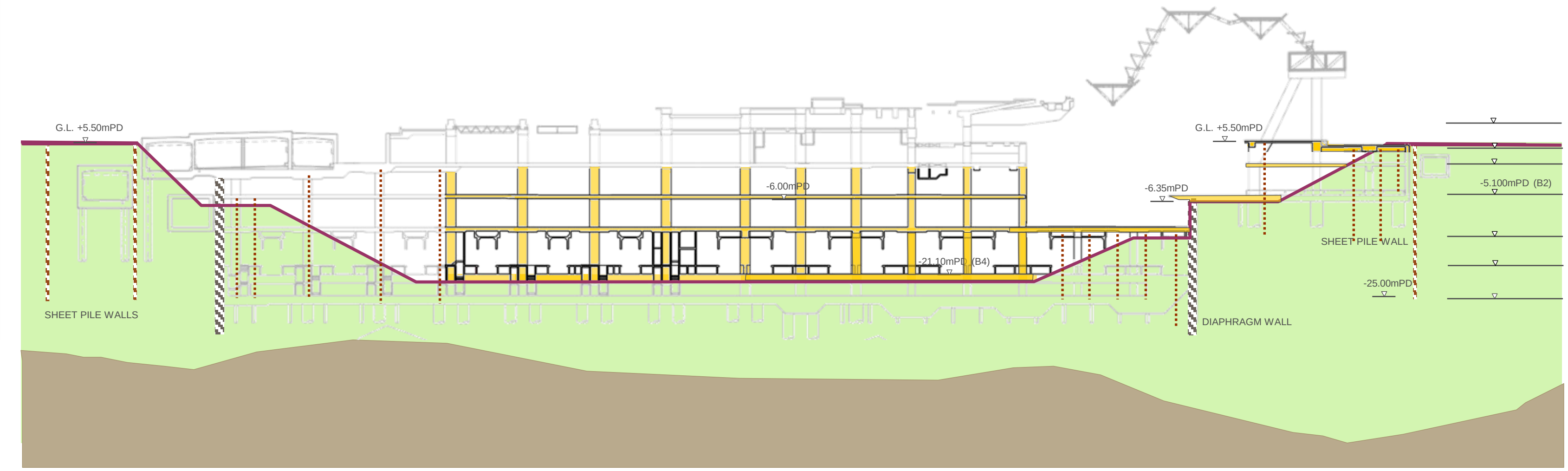
Bottom-up construction in the middle



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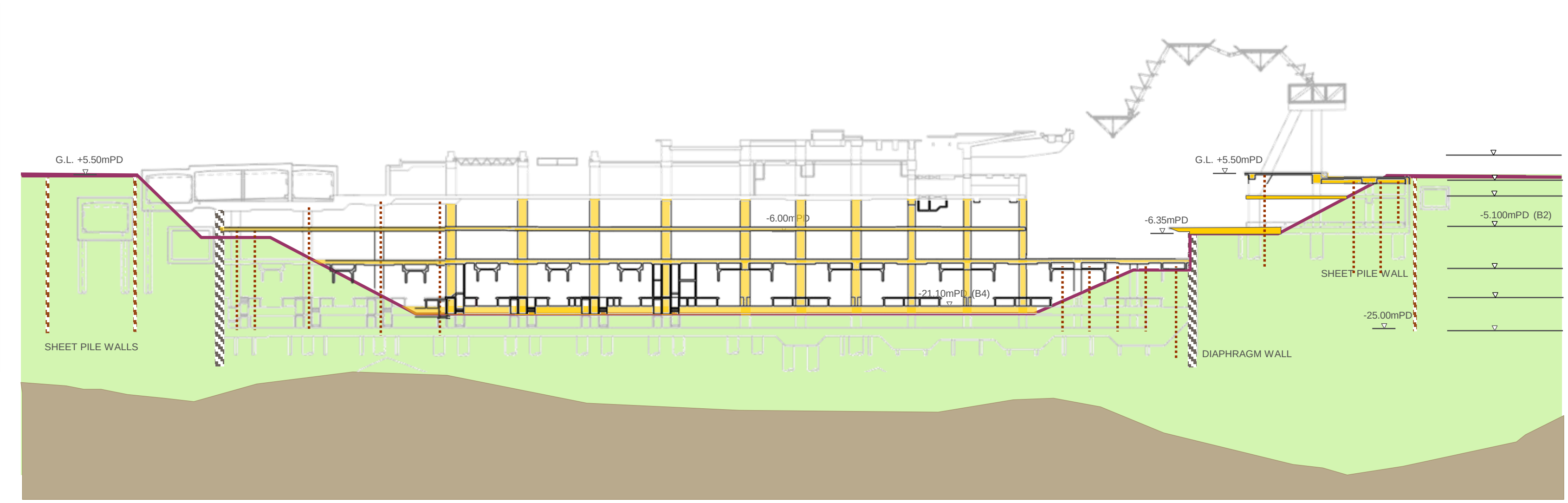
Construct B3, B2 in the middle



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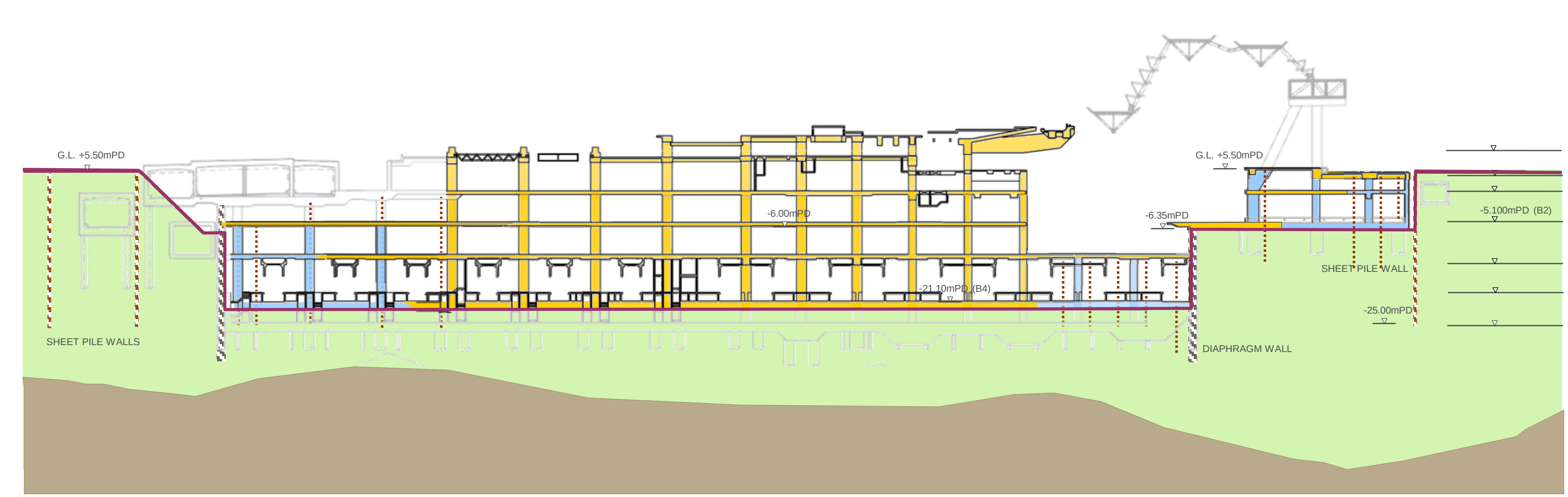
Partial Top-down on eastern and western sides

Continue Bottom-up B1 and G/F on middle part



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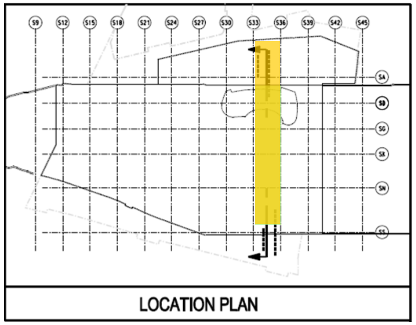
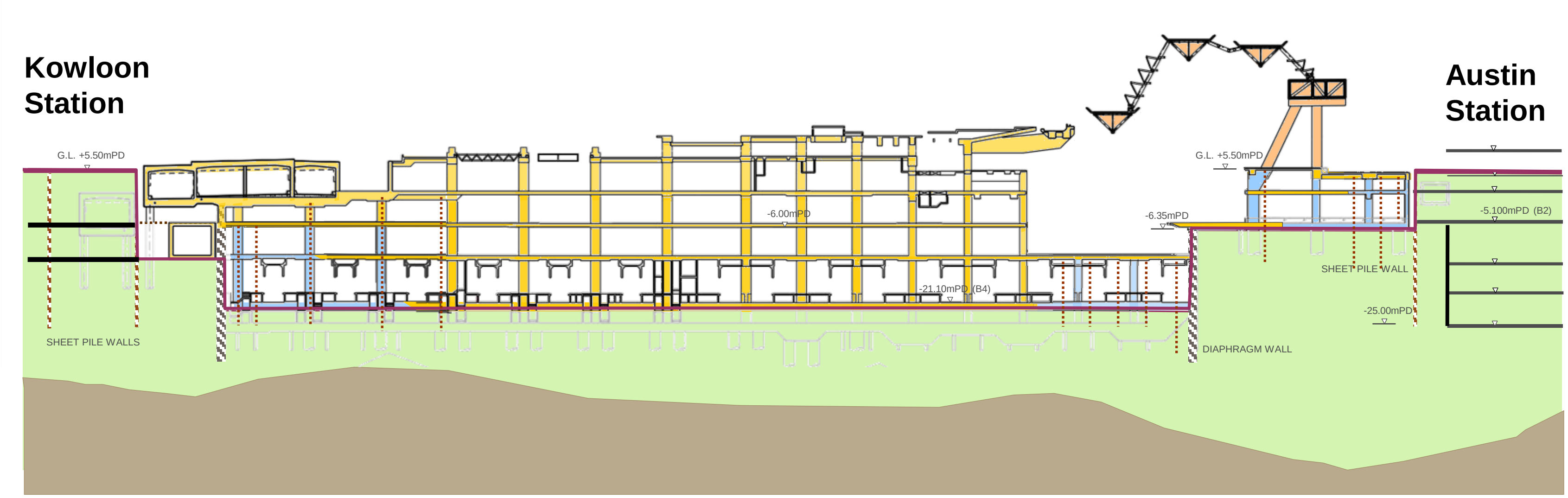
Construct western underpass and roof structures

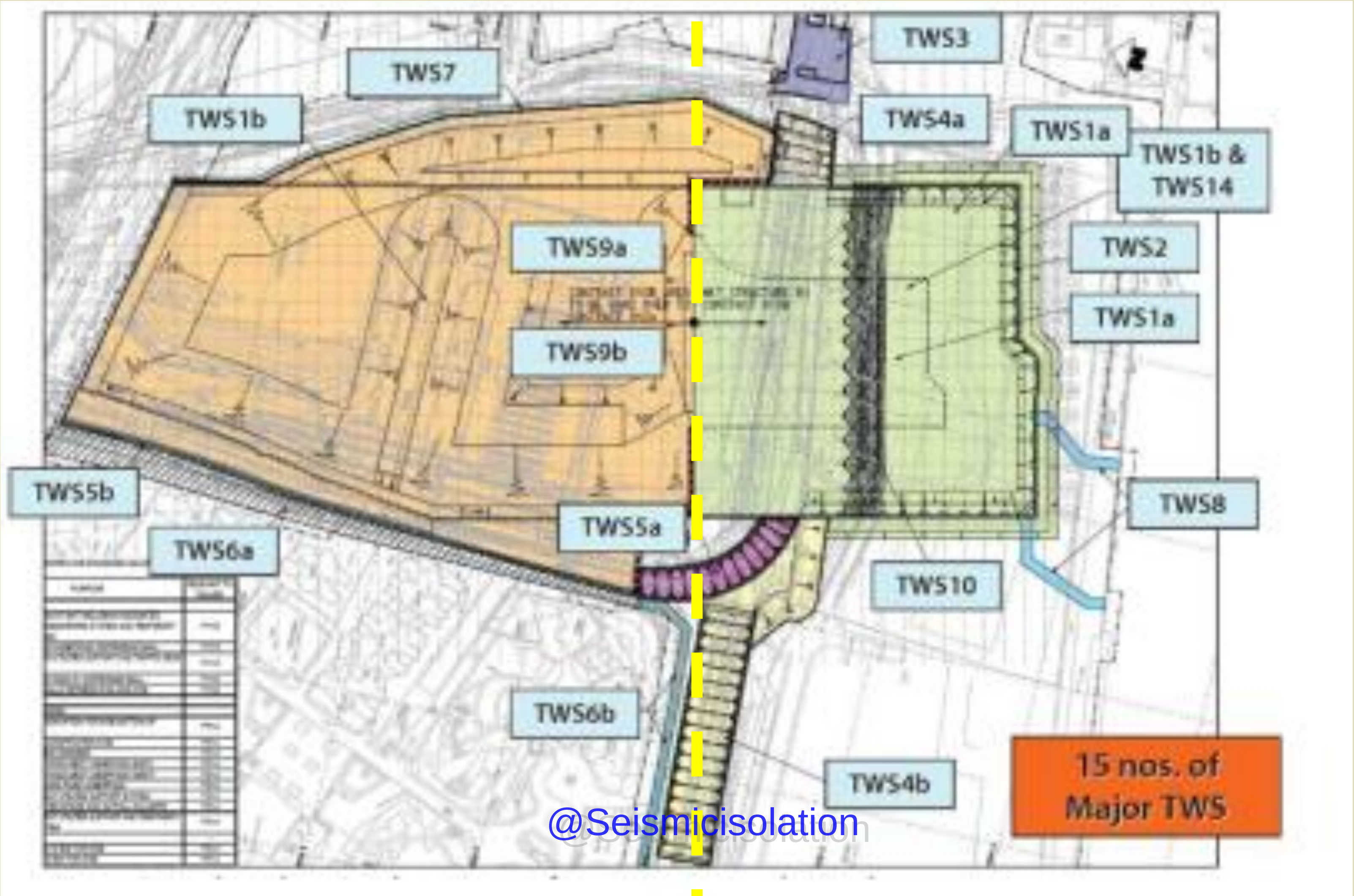




Separate Contracts :

Reference Scheme
with shared haul road

All Top-down



Deep Excavation at West Kowloon High Speed Rail Terminus

Excavation for Bottom-up G/f construction Top-down

Courtesy of MTR

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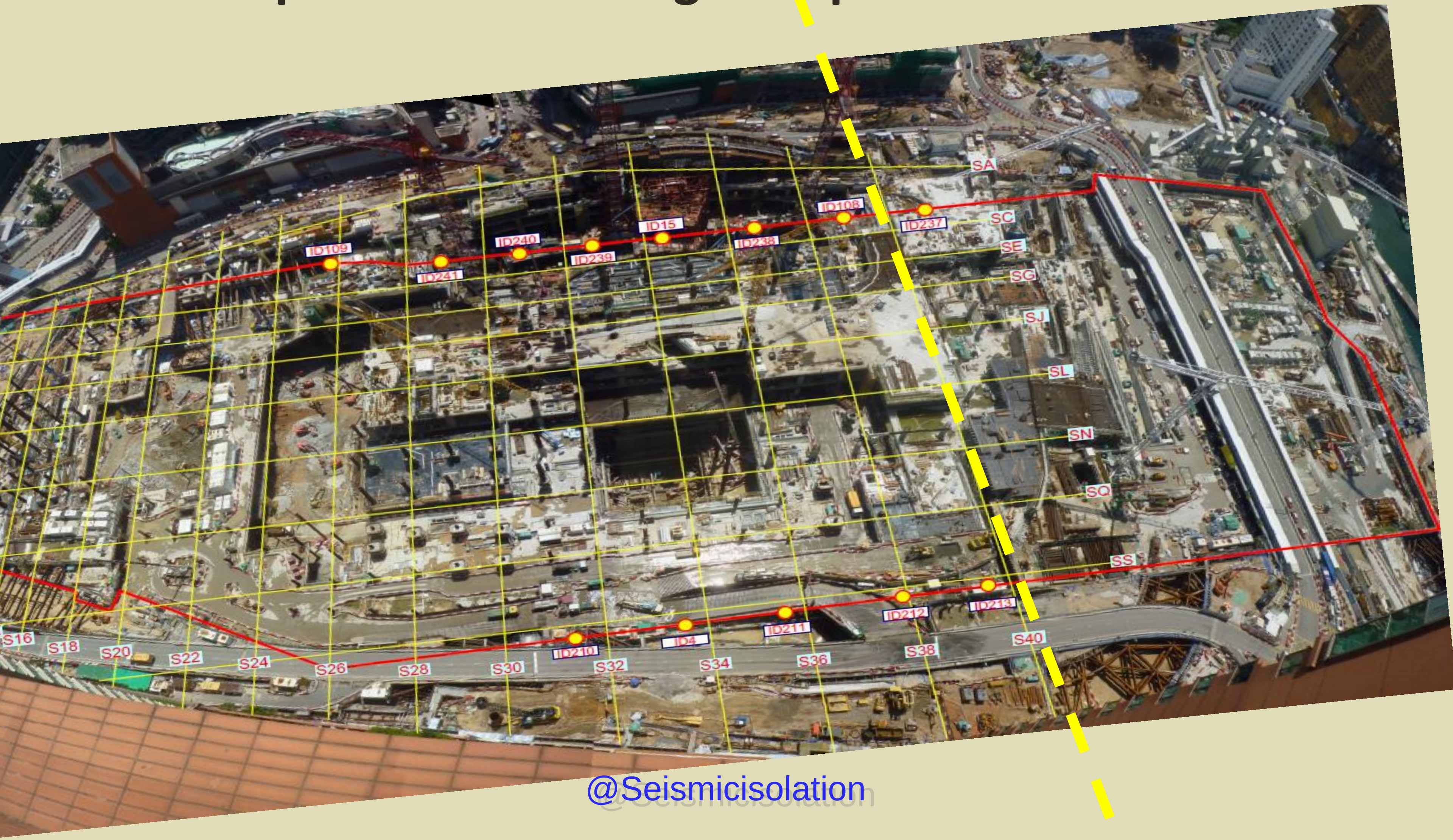
Later stage of construction

Bottom-up structure linking to Top-down



Top-down

Bottom-up construction below ground

30m deep

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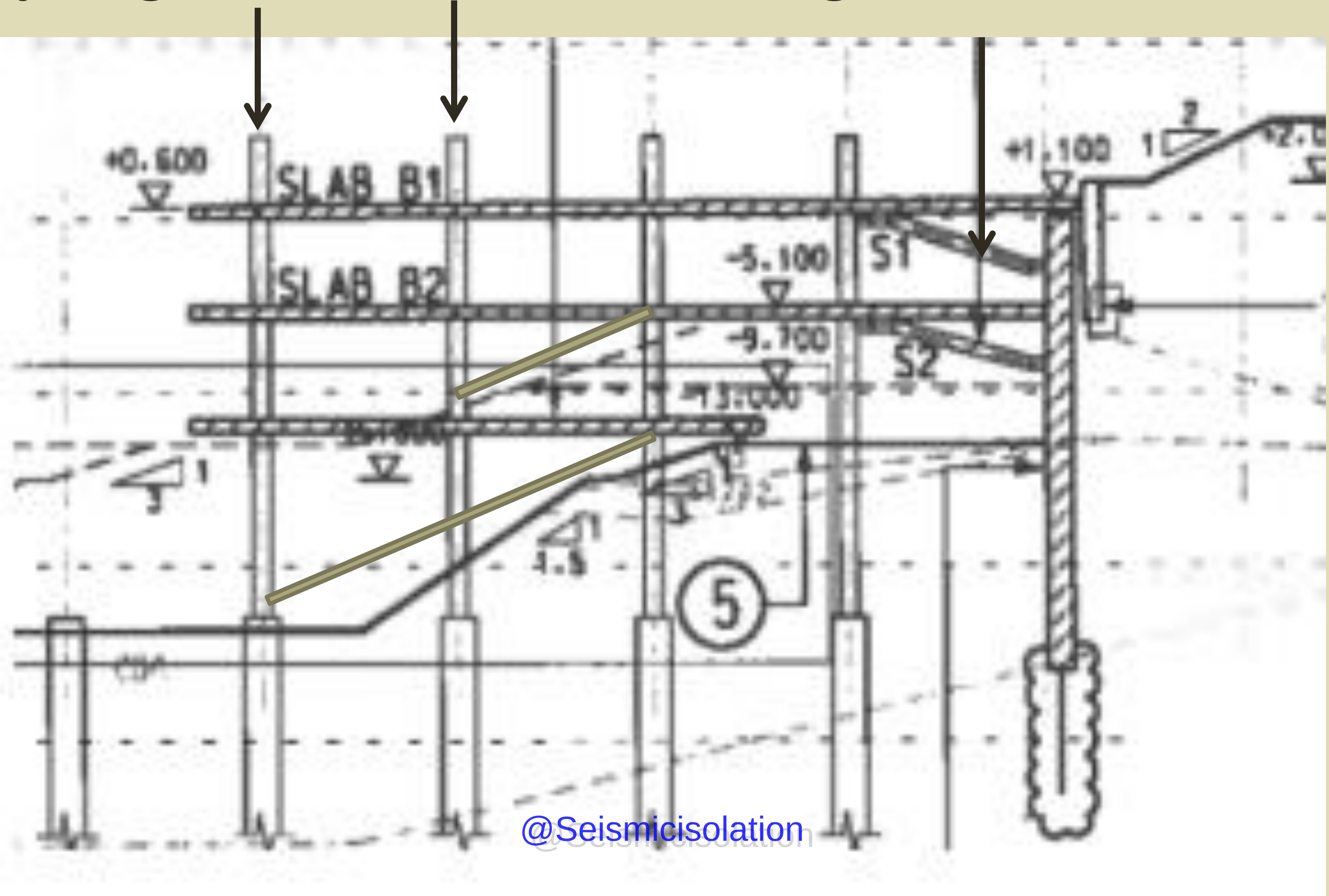
Shared haul road

Top-down

Bottom-up

Top-down:

plunged columns and raking shores



Top-down:

Plunged steel columns to be encased as permanent columns

Top-down:

Permanent columns cast around plunged columns and raking shores

Bottom-up:
In situ columns with steel cores for capacity

P

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Bottom-up:

Steel core for heavy load columns for future buildings.

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Bottom-up
in-situ columns

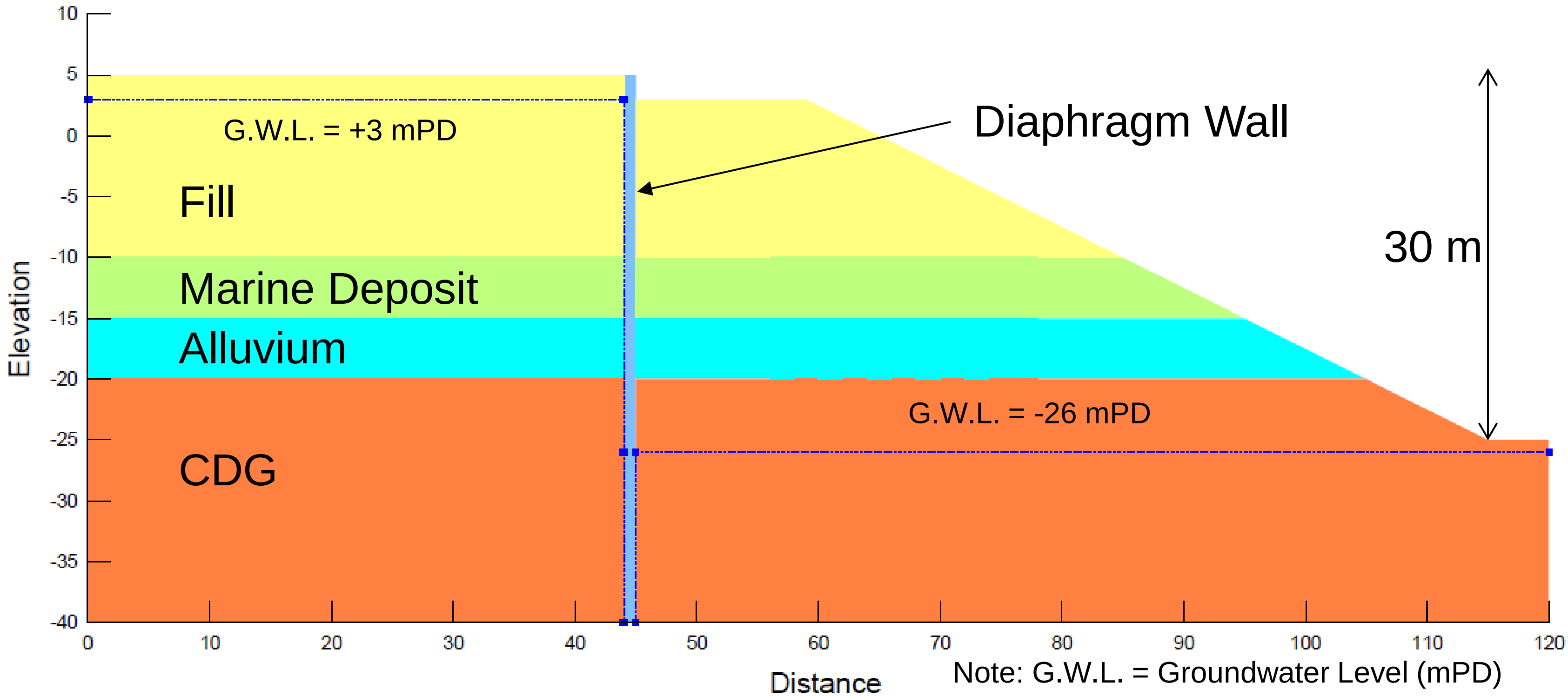
Top-down
Encased plunged columns

Unusual numerical modelling

1. Stability of temporary side slopes
   - Open cut excavation supported by temporary slopes (finite element vs limit equilibrium)
   - Modelling of ground treatment to enhance overall stability

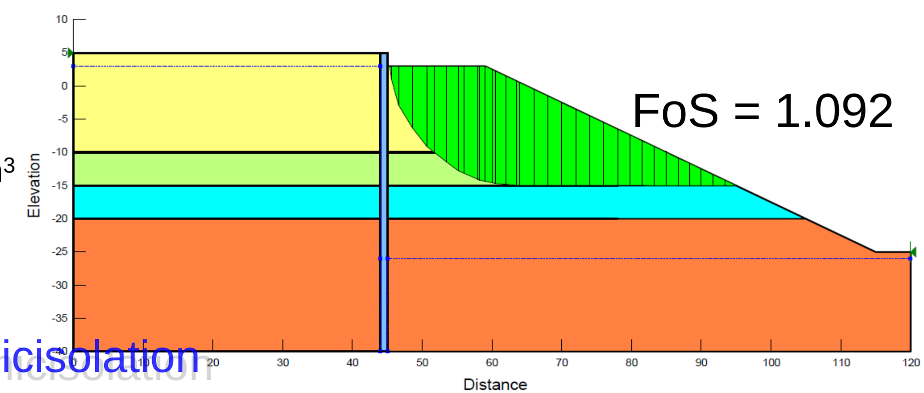
2. 3-D modelling of adjacent diaphragm wall movements
   - Different construction sequences may induce 3-D wall movements
   - Modelling of panel connections

Slope Stability Assessment – Limit Equilibrium Method

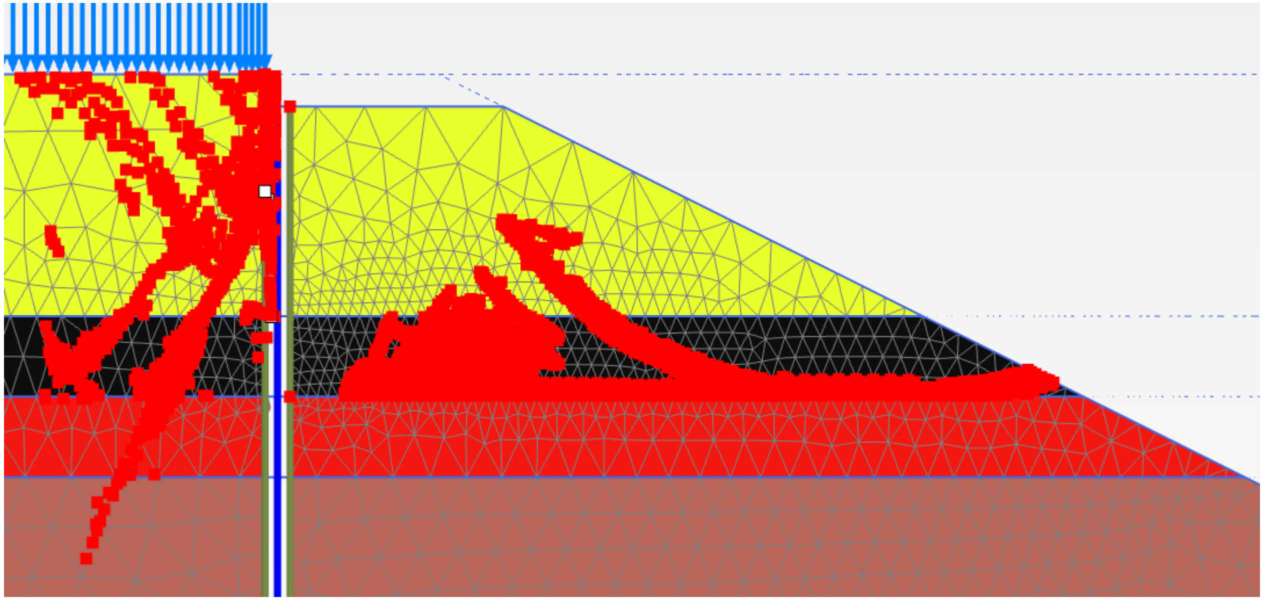


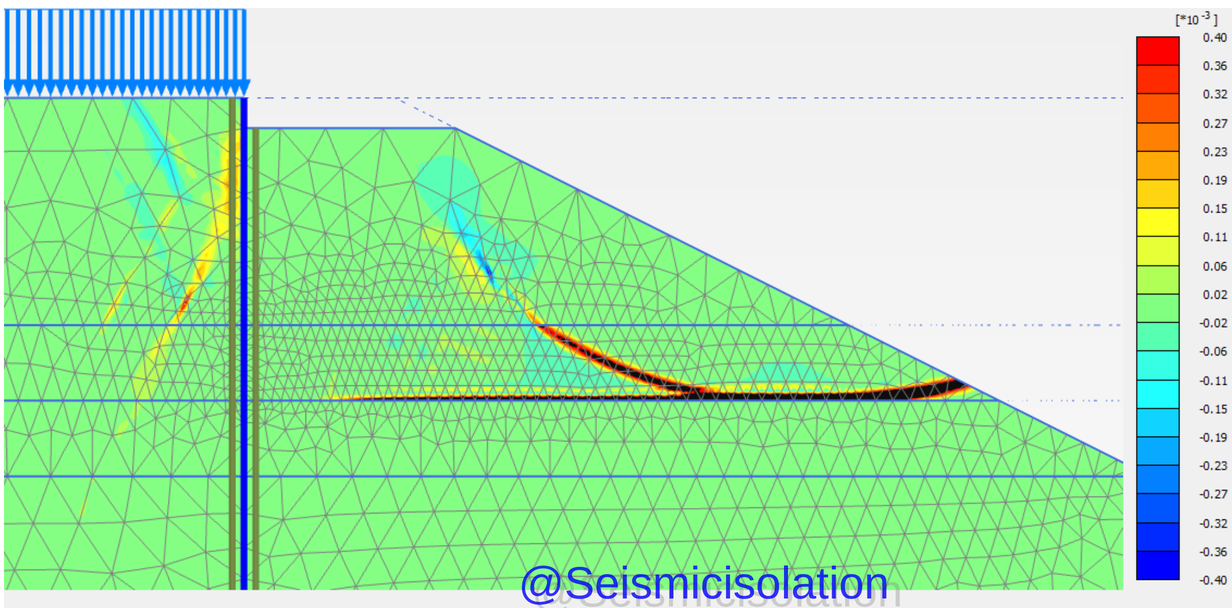
Input Parameters:

Fill	Marine Deposit	Alluvium	CDG
$\gamma = 19$ kN/m^3	$\gamma = 17$ kN/m^3	$\gamma = 19.5$ kN/m^3	$\gamma = 19$ kN/m^3
c = 0 kPa	c_u = 40 kPa	c = 0 kPa	c = 5 kPa
$\phi = 36^o$		$\phi = 36^o$	$\phi = 35^o$

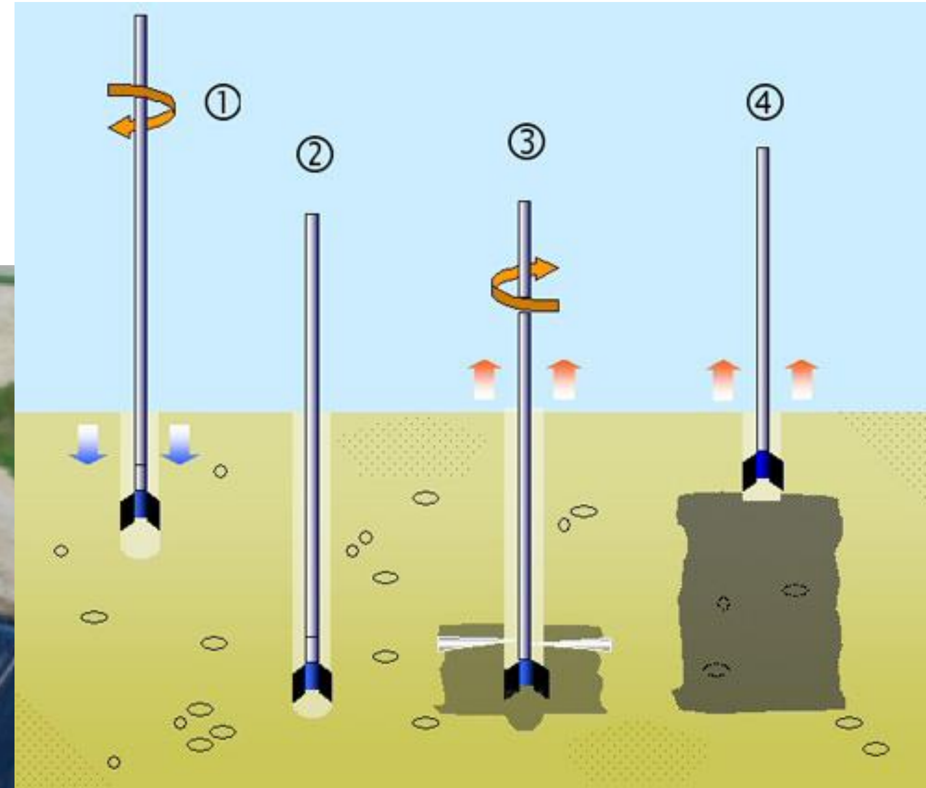


Finite Element Modelling – Plaxis

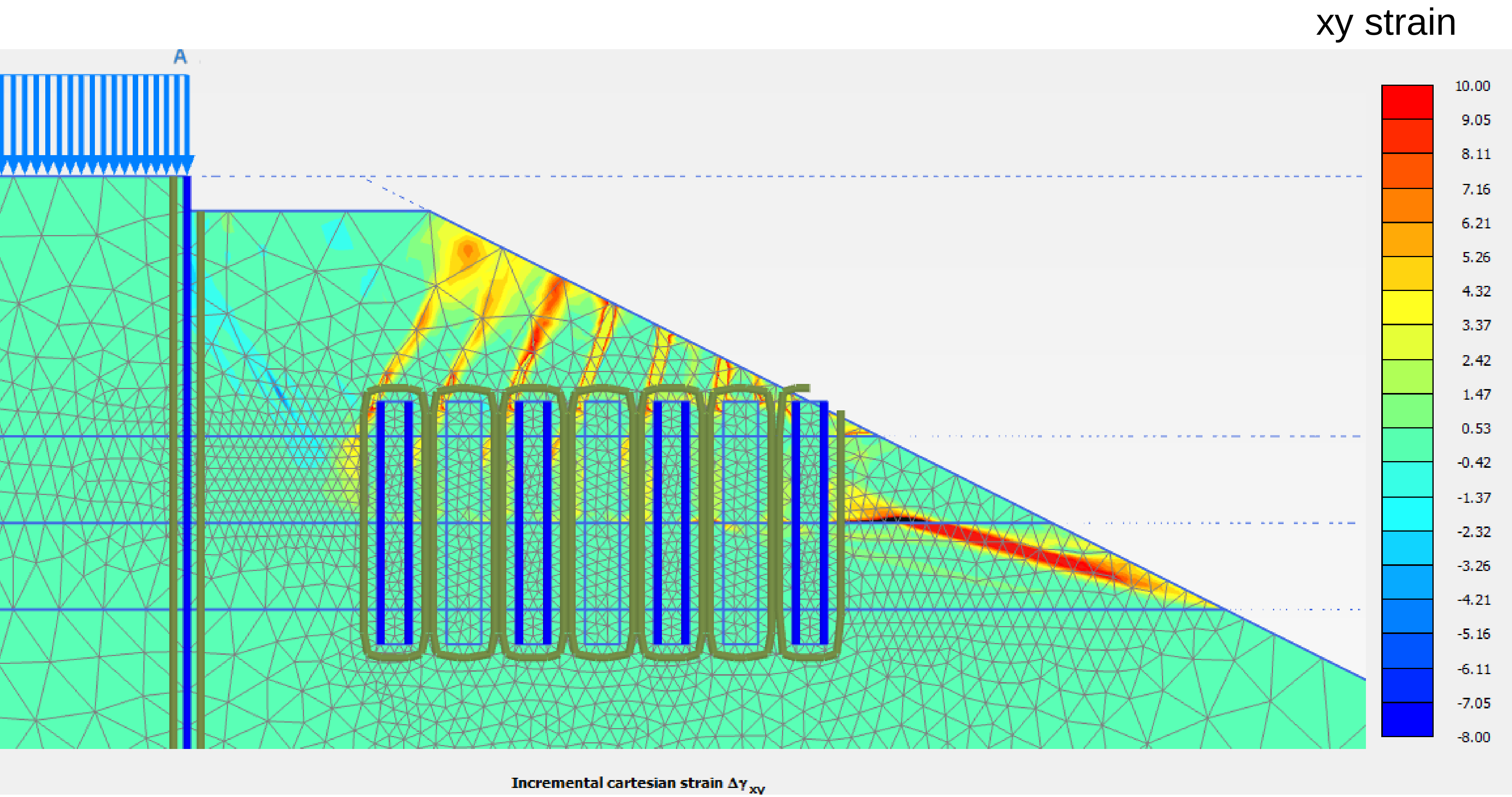




Ground Treatment – Jet Grouting



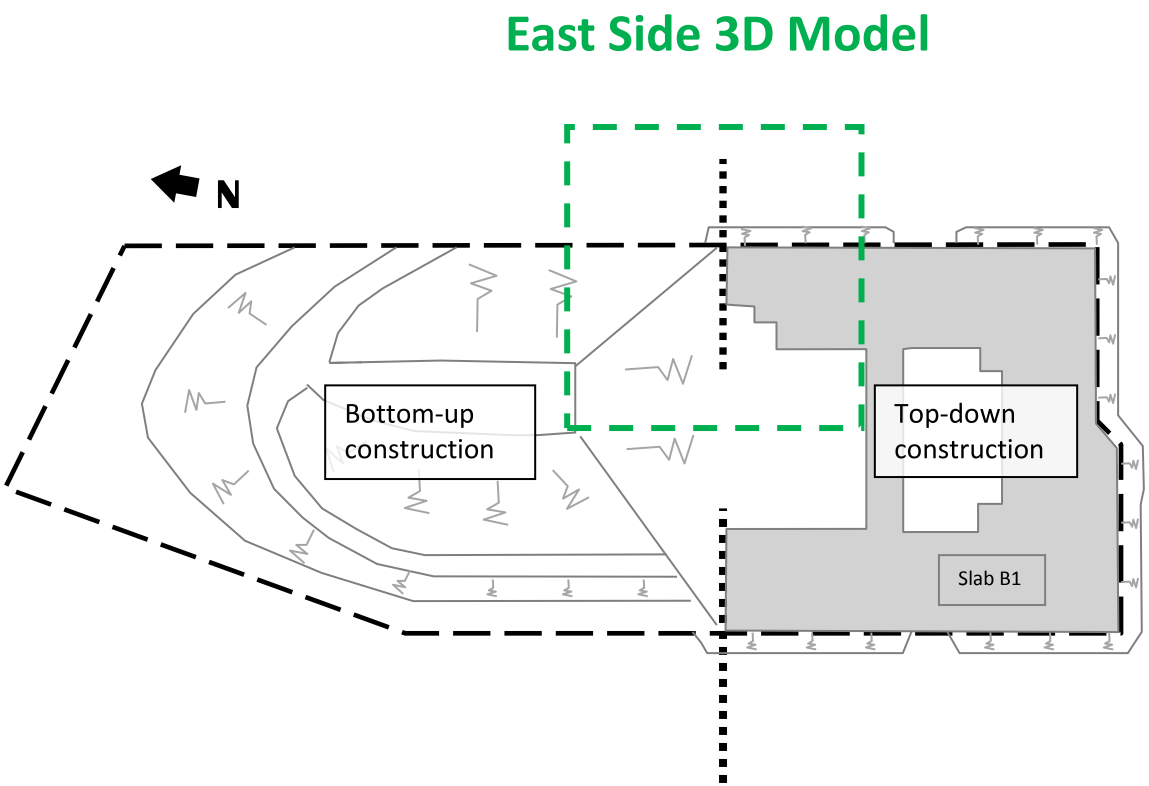
Finite Element Modelling of Jet Grouting

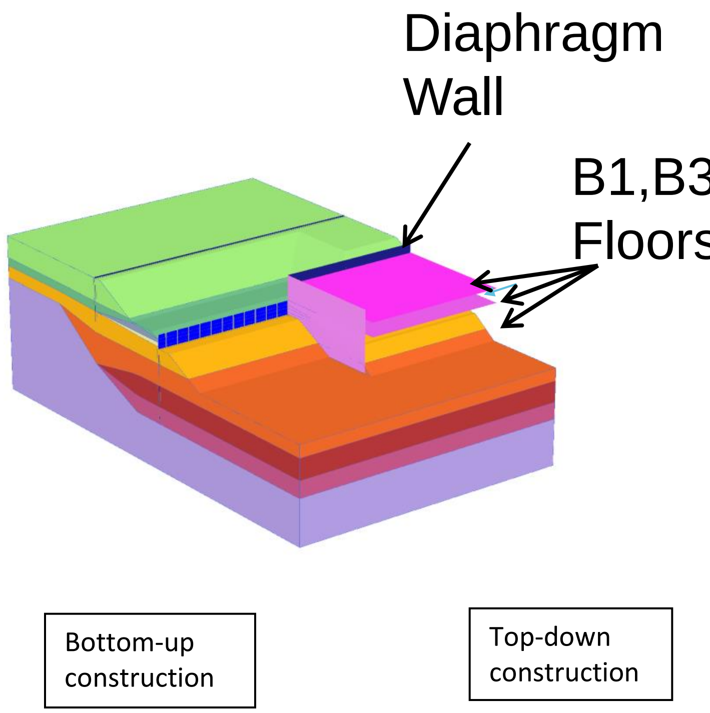


Slip elements between JGP columns

AECOM

Bottom-up/Top-down interface



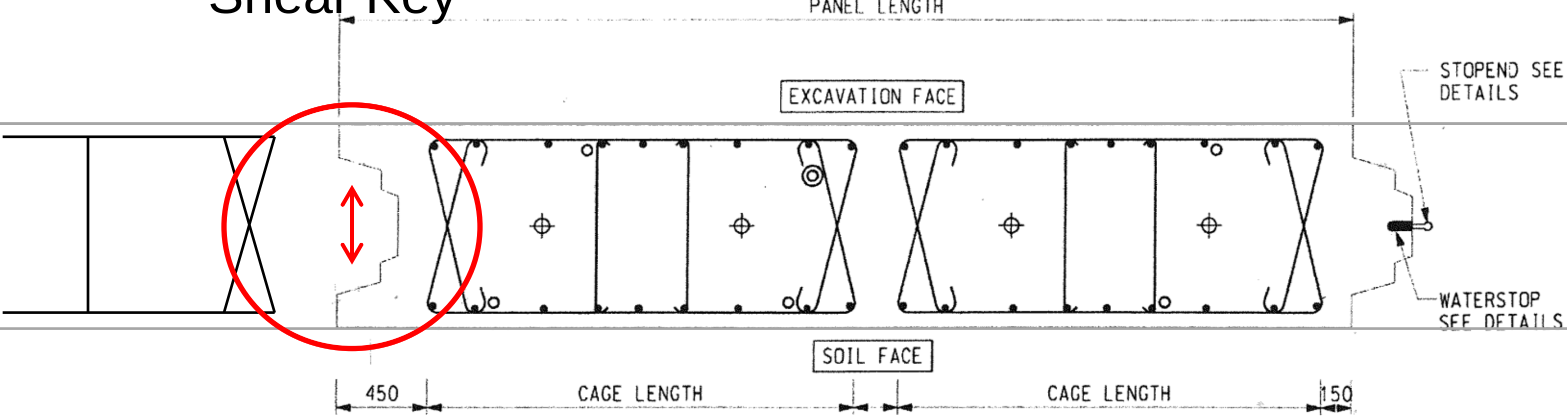


Details of Actual Panel-Panel Connections

No reinforcement across the shear key :-

- Bending moments cannot be transferred between D-wall panels
- Shear forces can be transferred by plain concrete

Shear Key



Can rotate = no bending moment
Resists shear

AECOM

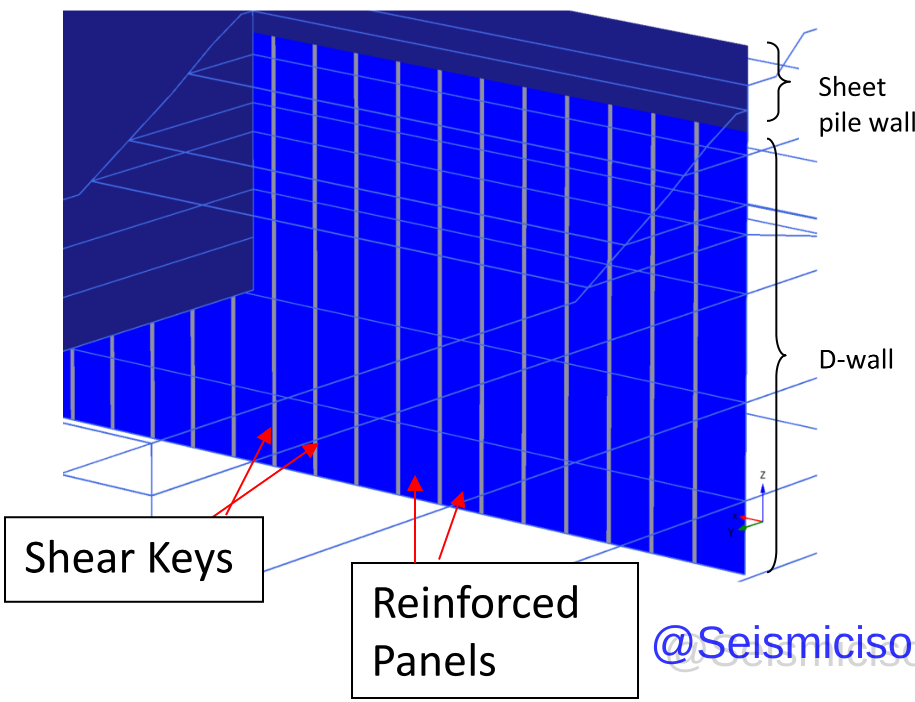
Modelling of Diaphragm Wall

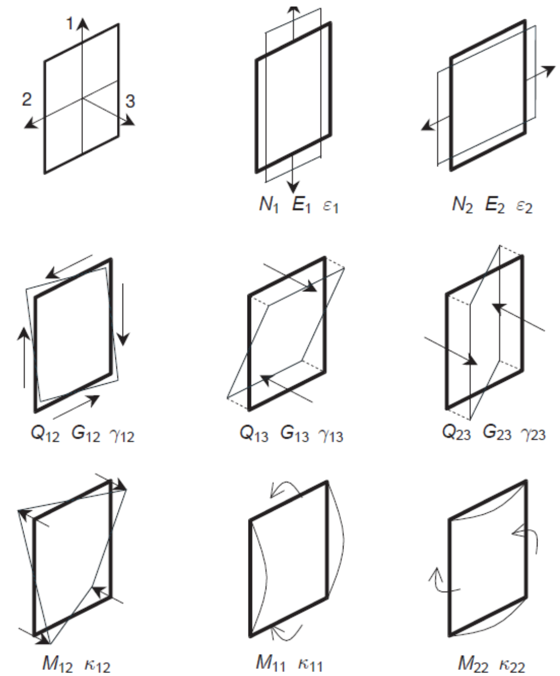
- Isotropic reinforced concrete properties for the reinforced blue panels
- Anisotropic properties for grey shear keys, with E_2 (Young's modulus in lateral direction) close to zero, and shear modulus unchanged in both directions

$$\begin{bmatrix} N_1 \\ N_2 \end{bmatrix} = \begin{bmatrix} E_1 d & \nu_{12} E_2 d \\ \nu_{12} E_2 d & E_2 d \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix}$$

$$\begin{bmatrix} Q_{12} \\ Q_{13} \\ Q_{23} \end{bmatrix} = \begin{bmatrix} G_{12} d & 0 & 0 \\ 0 & kG_{13} d & 0 \\ 0 & 0 & kG_{23} d \end{bmatrix} \begin{bmatrix} \gamma_{12} \\ \gamma_{13}^* \\ \gamma_{23}^* \end{bmatrix}$$

$$\begin{bmatrix} M_{11} \\ M_{22} \\ M_{12} \end{bmatrix} = \begin{bmatrix} \frac{E_1 d^3}{12} & \frac{\nu_{12} E_2 d^3}{12} & 0 \\ \frac{\nu_{12} E_2 d^3}{12} & \frac{E_2 d^3}{12} & 0 \\ 0 & 0 & \frac{G_{12} d^3}{12} \end{bmatrix} \begin{bmatrix} \kappa_{11} \\ \kappa_{22} \\ \kappa_{12} \end{bmatrix}$$



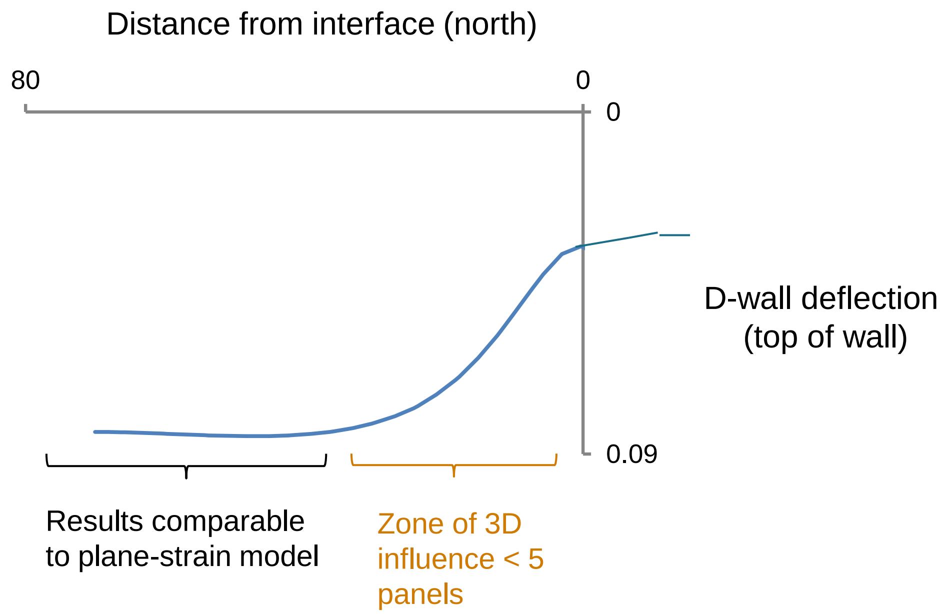


(PLAXIS 3D manual)

Lateral Influence Zone

- Bending moments not transferred between panels, so they rotate freely with respect to each other
- Shear forces are transferred between panels (G_{23} unchanged), mimicking the function of shear key
- Axial forces in lateral direction cannot be transferred between panels

- 3-D modelling allows the potential influence zone to be identified.
- Outside the influence zone, wall deflection is comparable to 2-D estimates

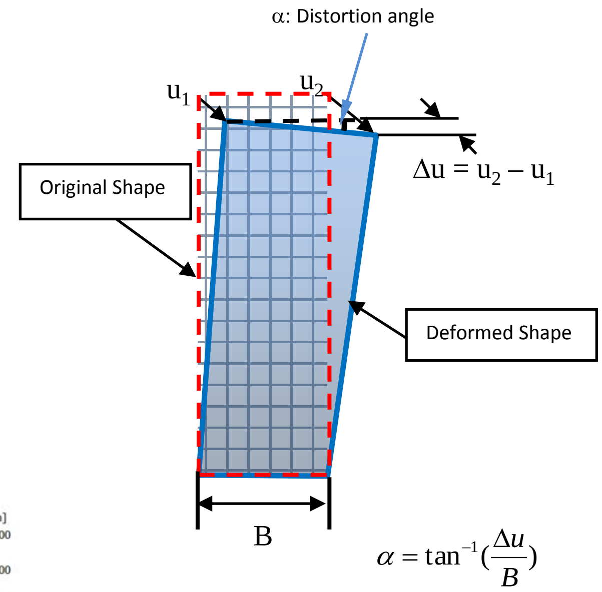


AECOM

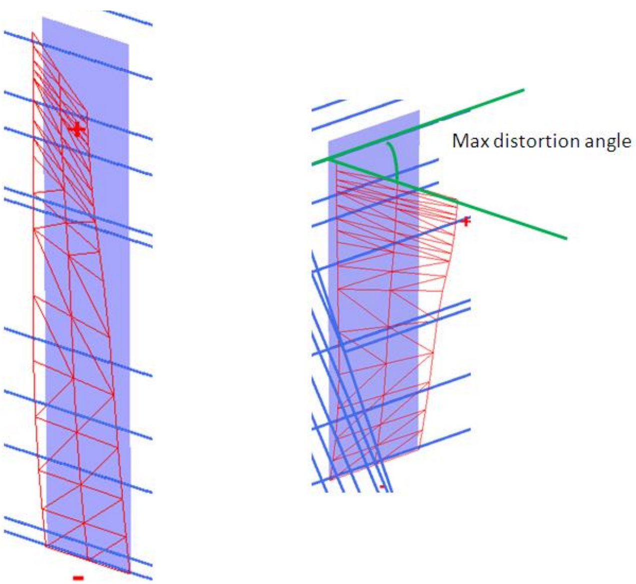
3-D Movement Pattern of the Diaphragm Wall

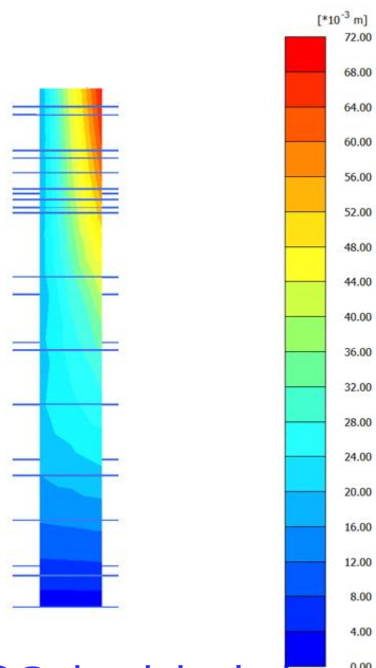
- Difference in construction sequences can lead to distortion of D-wall panels near the interface, which cannot be captured in 2-D models

- Modelling of individual panels allows evaluation of this distortion for each panel



Deformed Shape (exaggerated)





New Topic:

Back Analyses

Fundamental to "Observational Method'

Useful for understanding how the ground and structures are behaving

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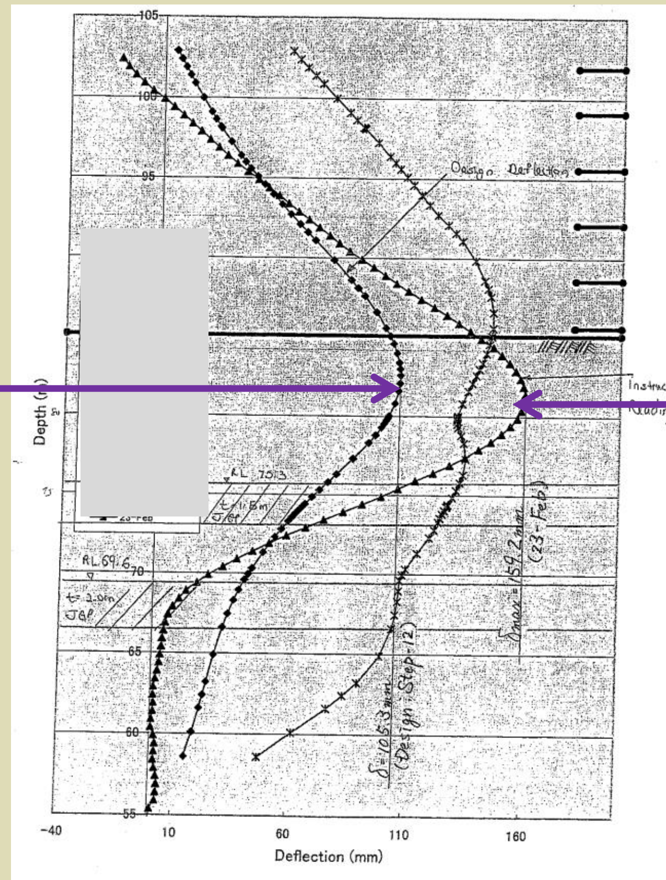
At a given stage of construction a “Stop Work” limit was exceeded

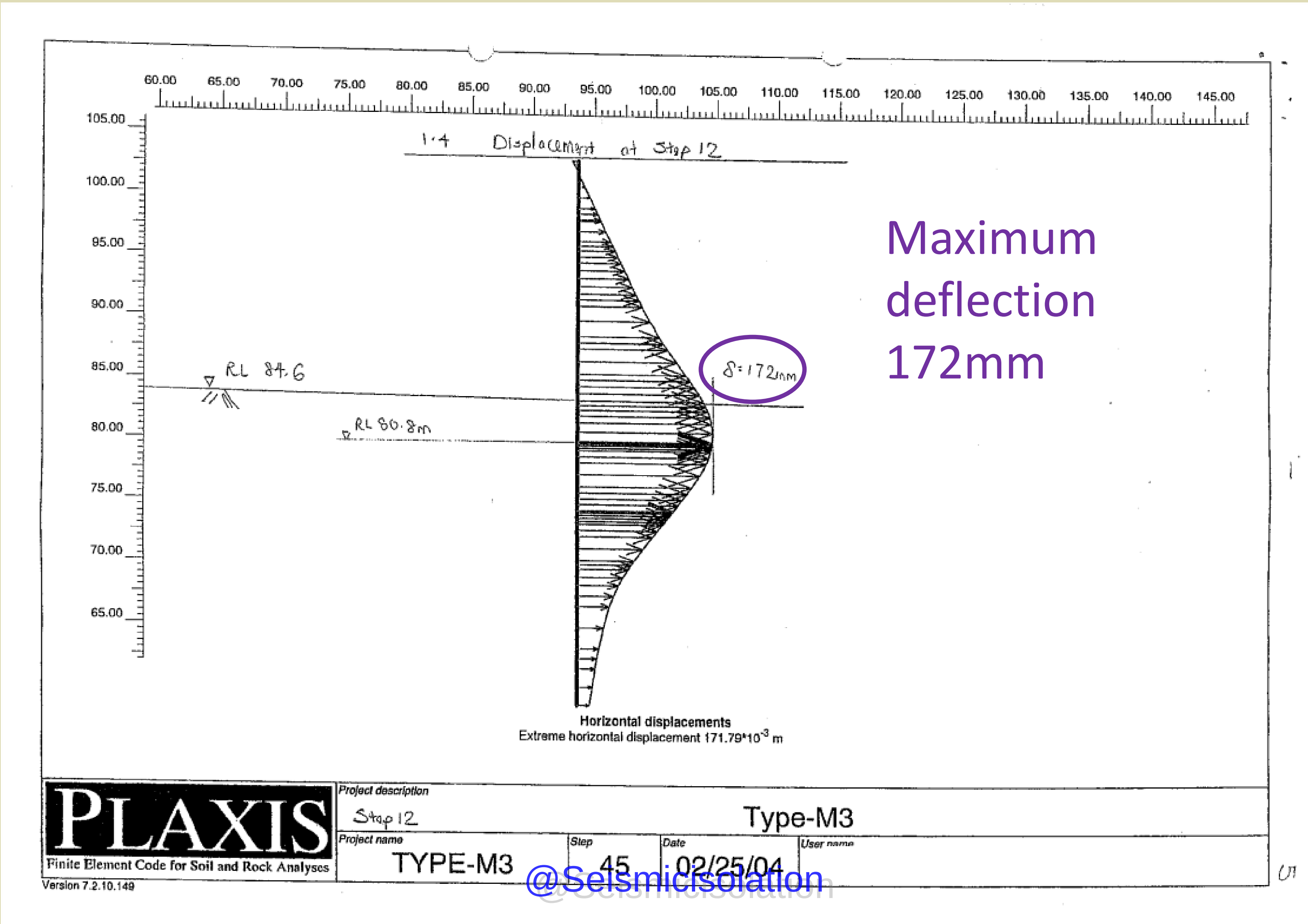
Designer’s prediction at this stage 105.3mm



Monitored Maximum deflection 159.2mm

Inclinometer at cut and cover tunnel excavation, Singapore

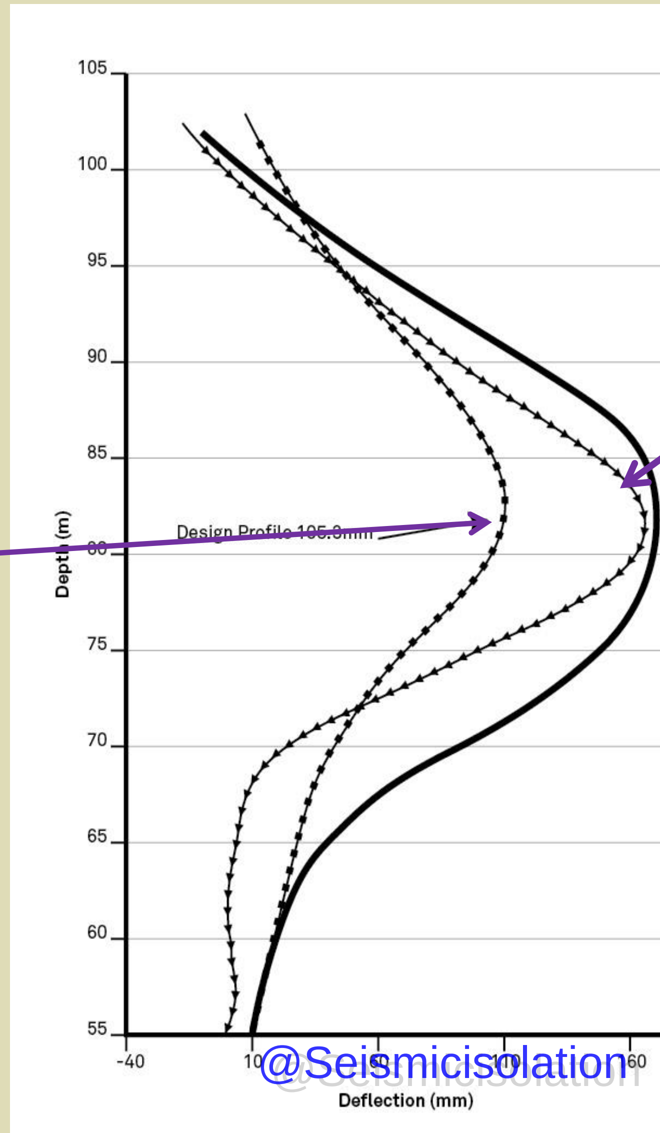
Back analysis for this stage :



Maximum deflection 172mm

Back analysis showed wall was within limits so the Stop Work limit was increased to 300mm

Design Profile 105.3mm



Monitoring 159.2mm

Back analysis 172mm

Bending moment = “EI”/Radius

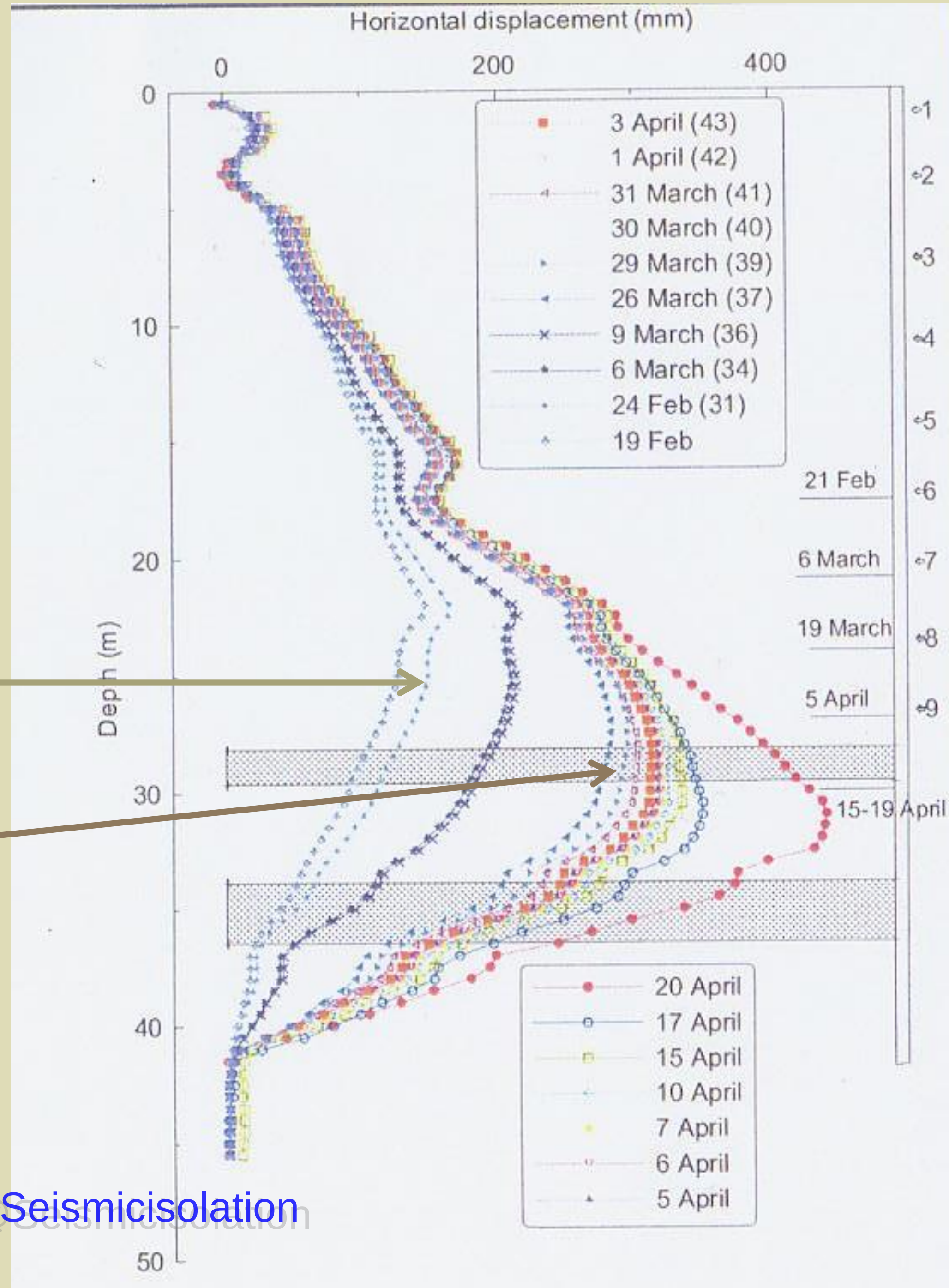
Later the wall moved more than300mm

A second back analysis was required

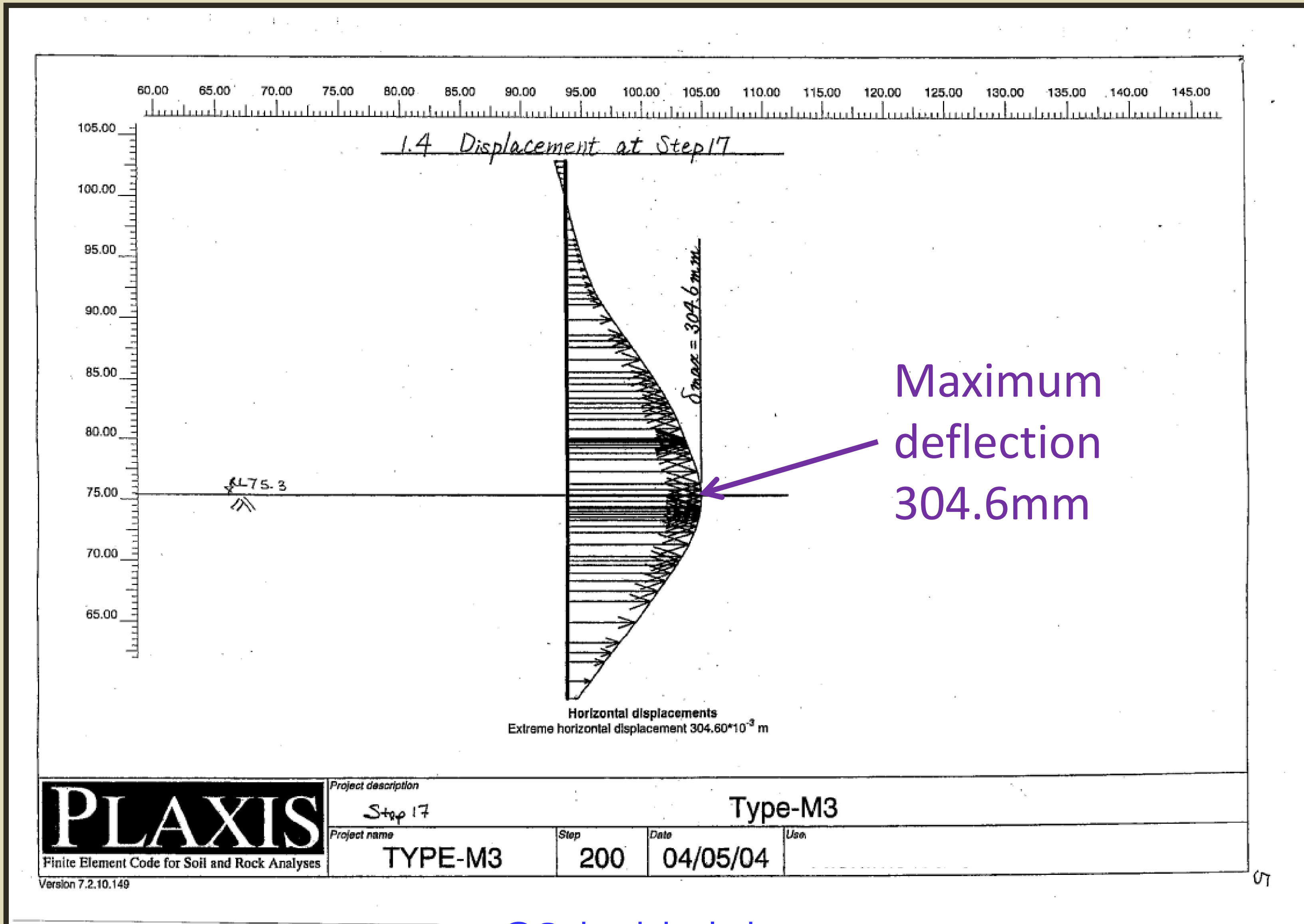
First back analysis 23 February 159.2mm

Second back analysis 3 April 300mm

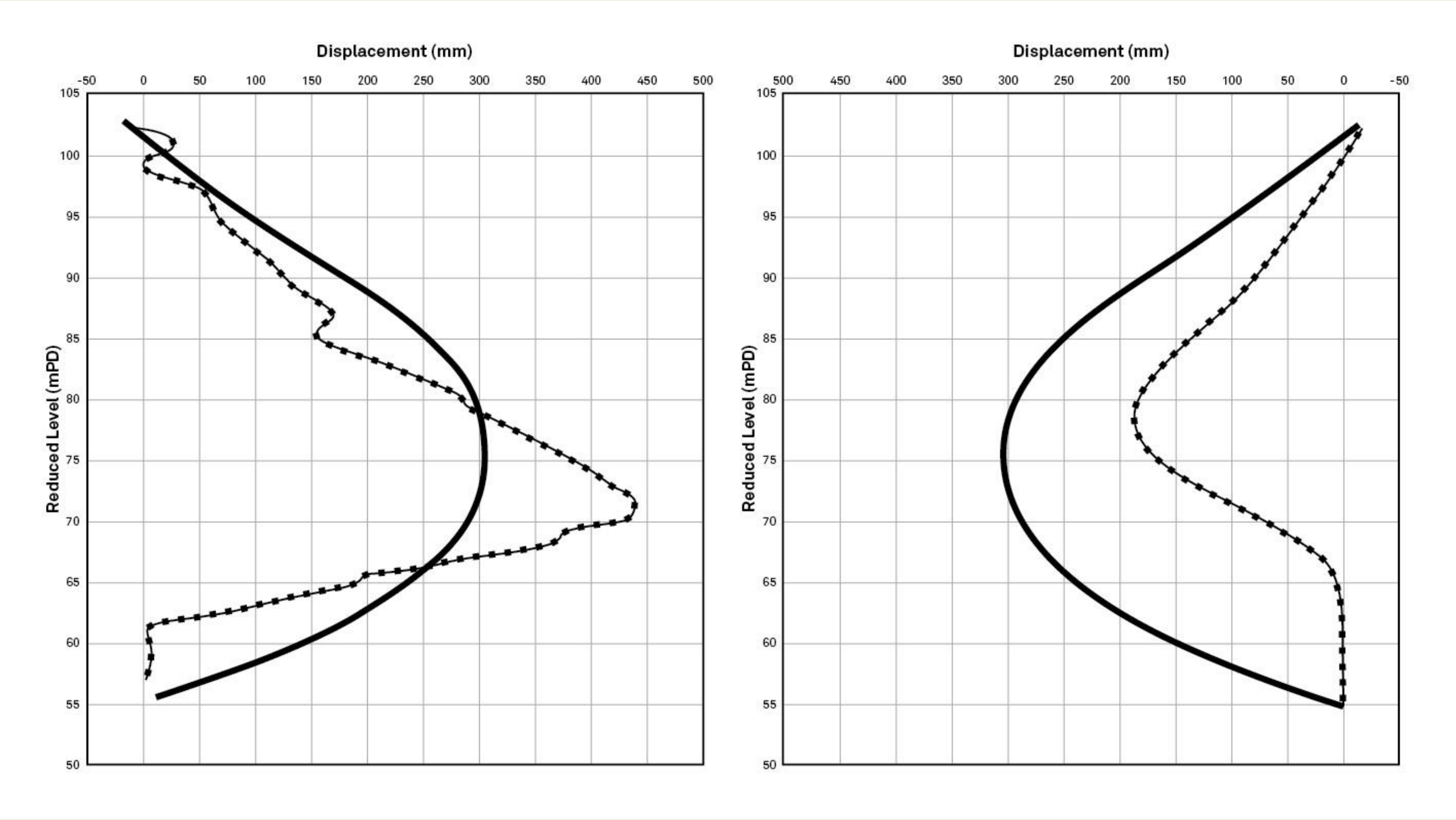
Work continued Deflection reached 400mm 20 April



Second Back Analysis

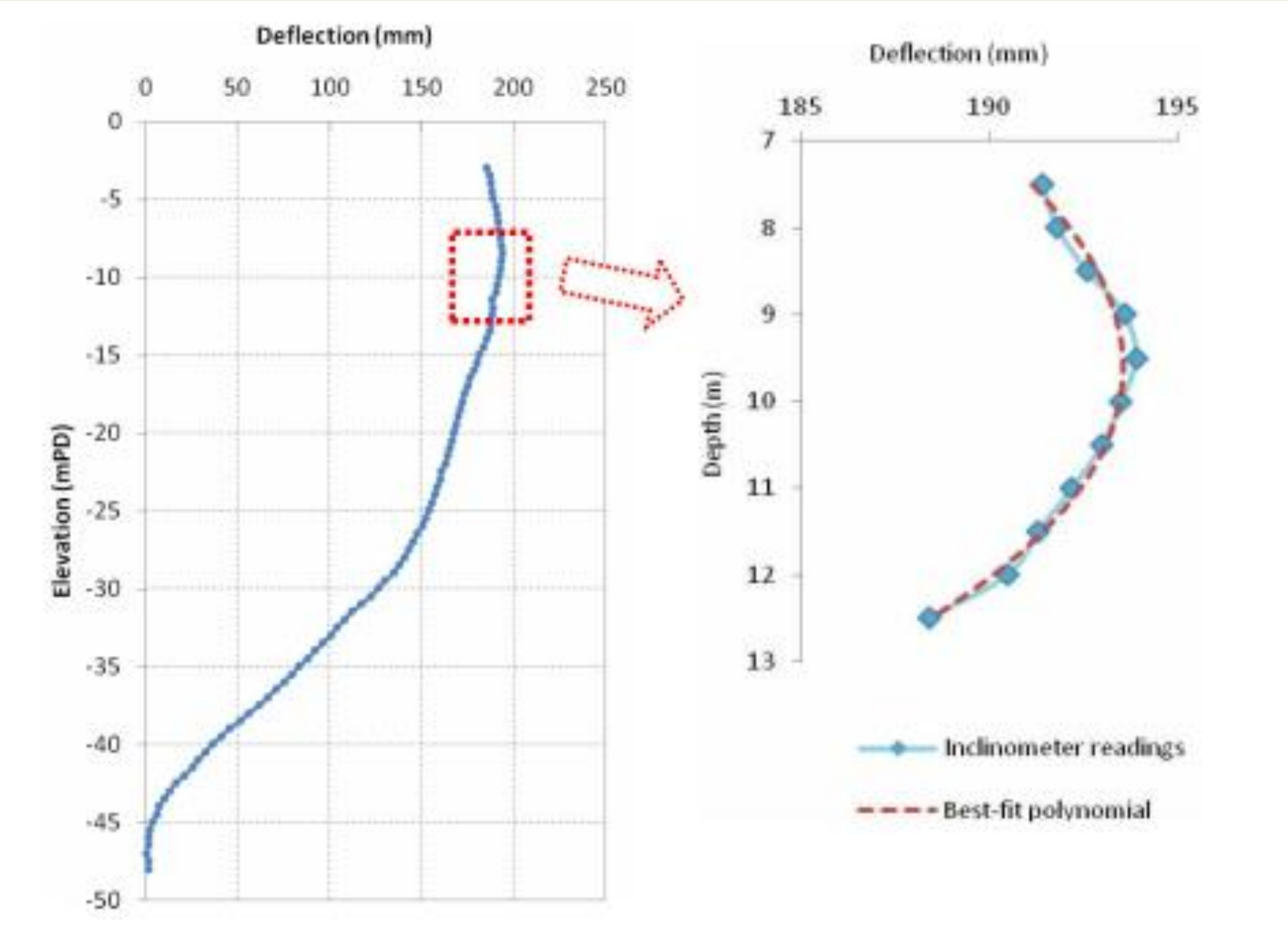


The back analysis profile did not fit either inclinometer profile



Bending moment = “EI”/Radius

Back analyses of deflections: Fourth order difference

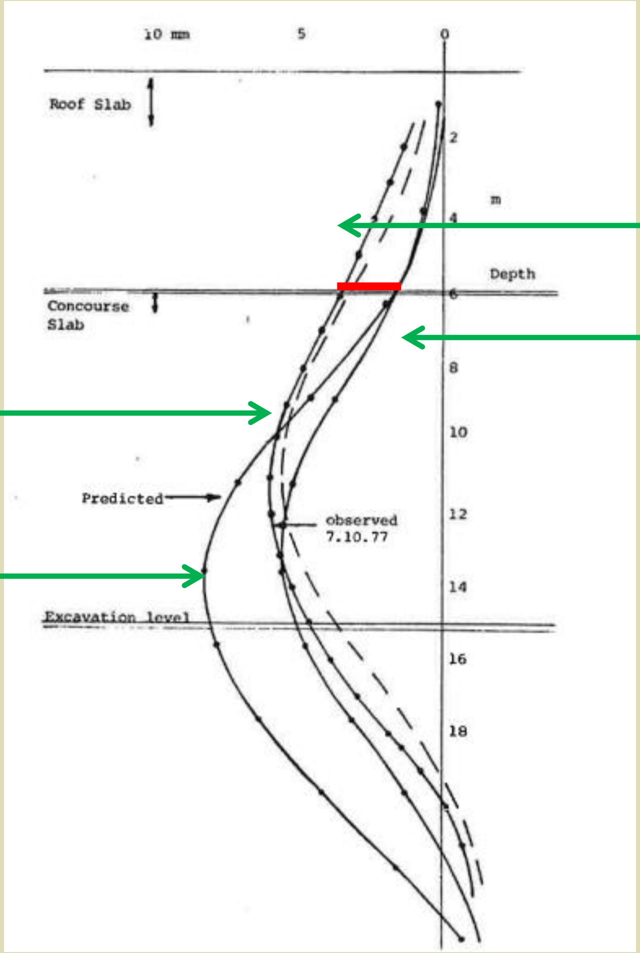


Another project

Back analysis at pre-final stage allowed deletion of lowest strut

Actual Deflection

Design Deflection



Lessons:-

1.High shrinkage of concrete resulted in twice estimated compression of concourse slab

2. Lateral earth pressure less than estimated and reduced by de-watering.

Observational Method allowed omission of lowest strut

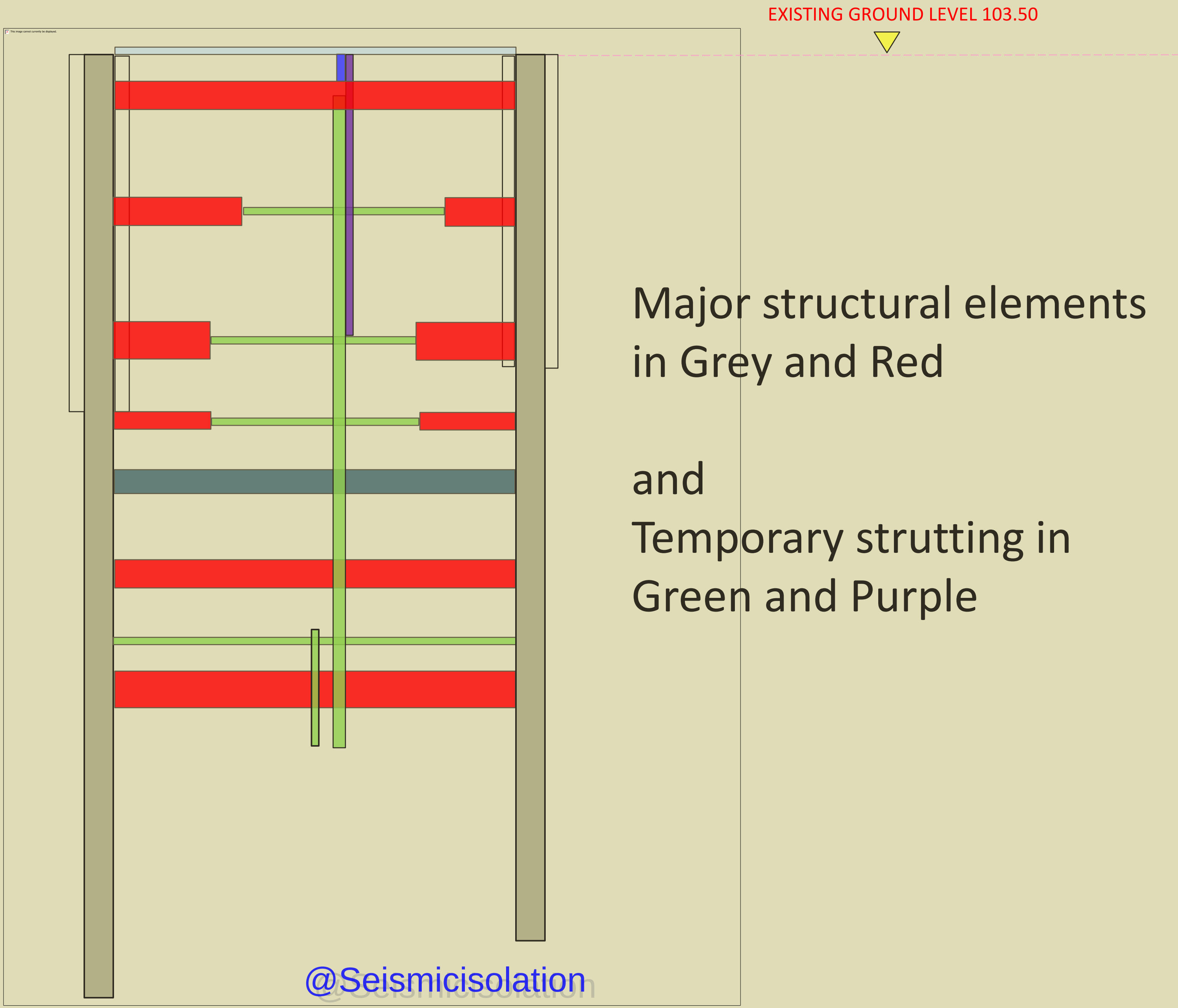
<u>Note the headroom</u>

Plunged permanent RC columns supported by steel stools for connection to base slab.

Case 3

Mixture, top-down, bottom up, attached shaft

Case 4: Fashionable to have open ceilings



Major structural elements in Grey and Red

and

Temporary strutting in Green and Purple

Heavy structures around openings

Topic 2: Plunge Piles

These are ‘plunged’ into the ground at the beginning in order to support top-down construction

Some are only temporary and some are incorporated into the permanent works

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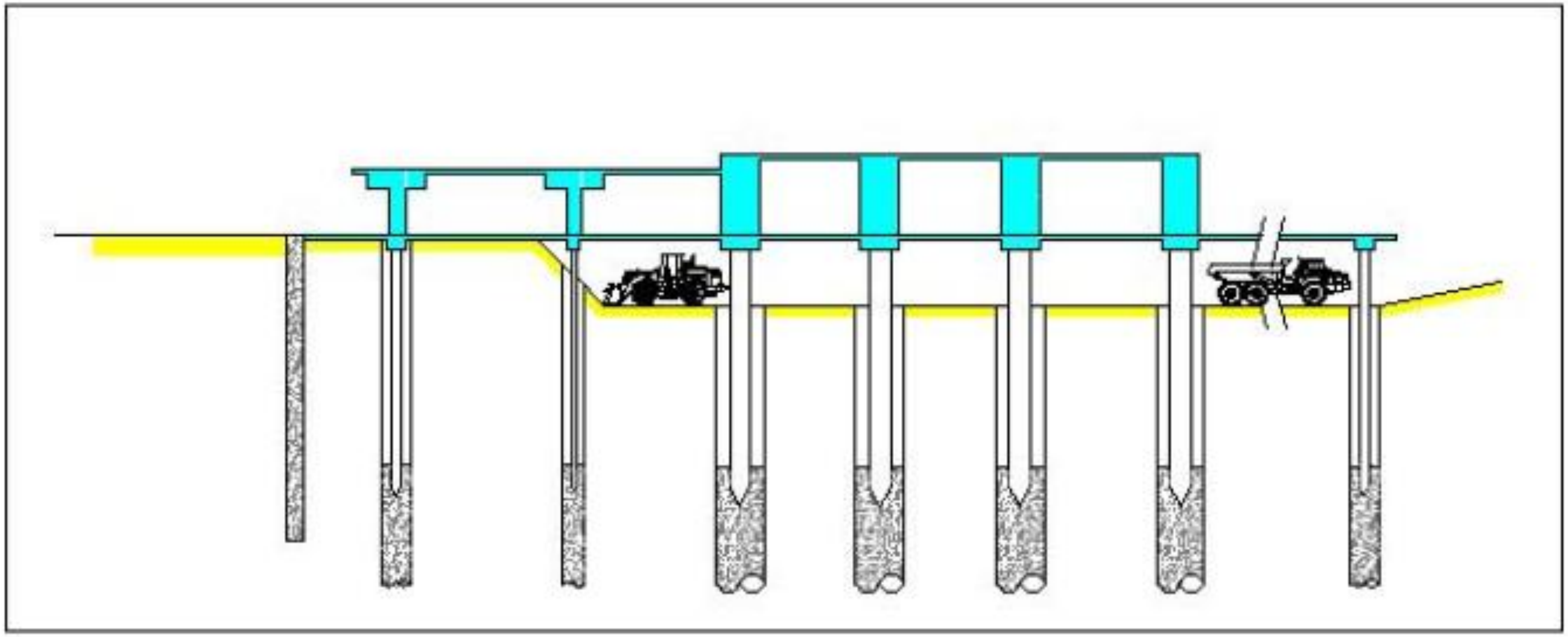
Wynn's Resort, Macao

Construction Sequence

benaim



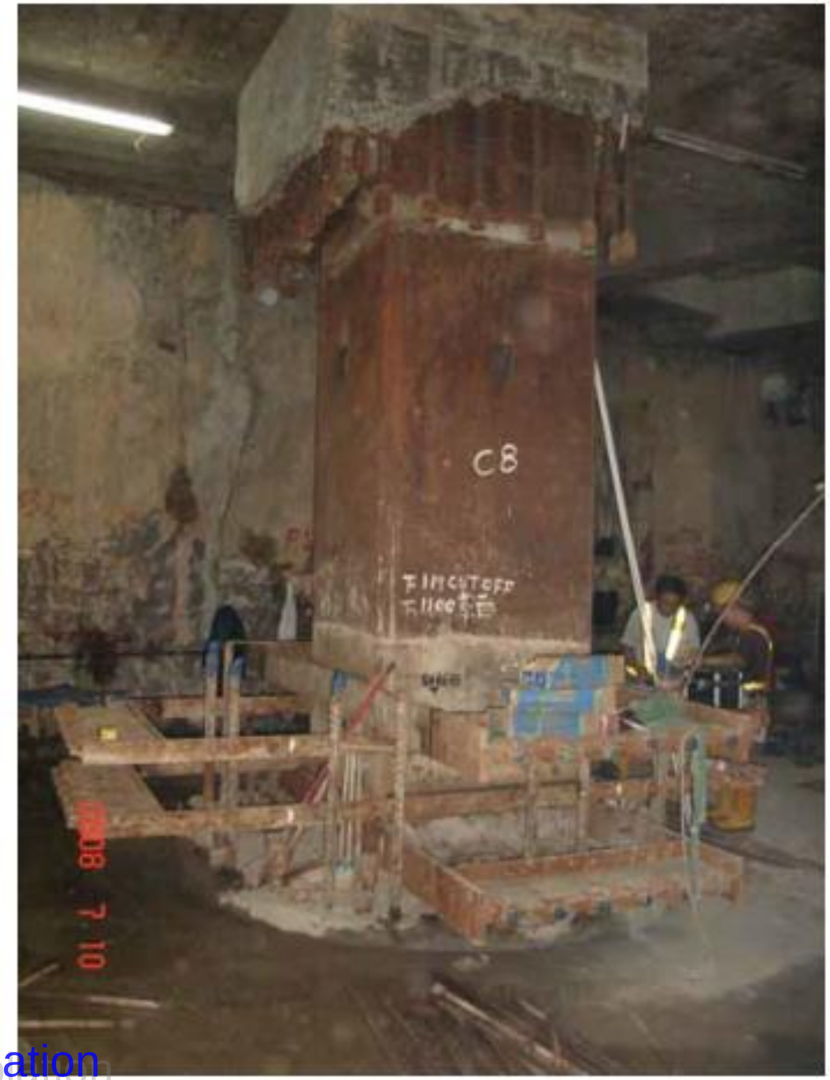
- 1. Complete Construction of Lower Ground Floor Slab
- 2. Start Excavating below Slab to U/S of Basement B1
- 3. Start Construction of Ground Floor Slab

Plunged columns

Voids in B Floors for access

Cast into in situ

Lots of detailed design required



Building limited to 8 floors until plunged columns are cased when B5 is reached

- 1. Complete Construction of External Walls and Internal Columns
- 2. Bottom-Up Construction of Superstructure Continues

Case 4: Partial Top-Down…example

Multiple roadways and access for hoisting

Case 5: Hong Kong Zuhai Macau Bridge

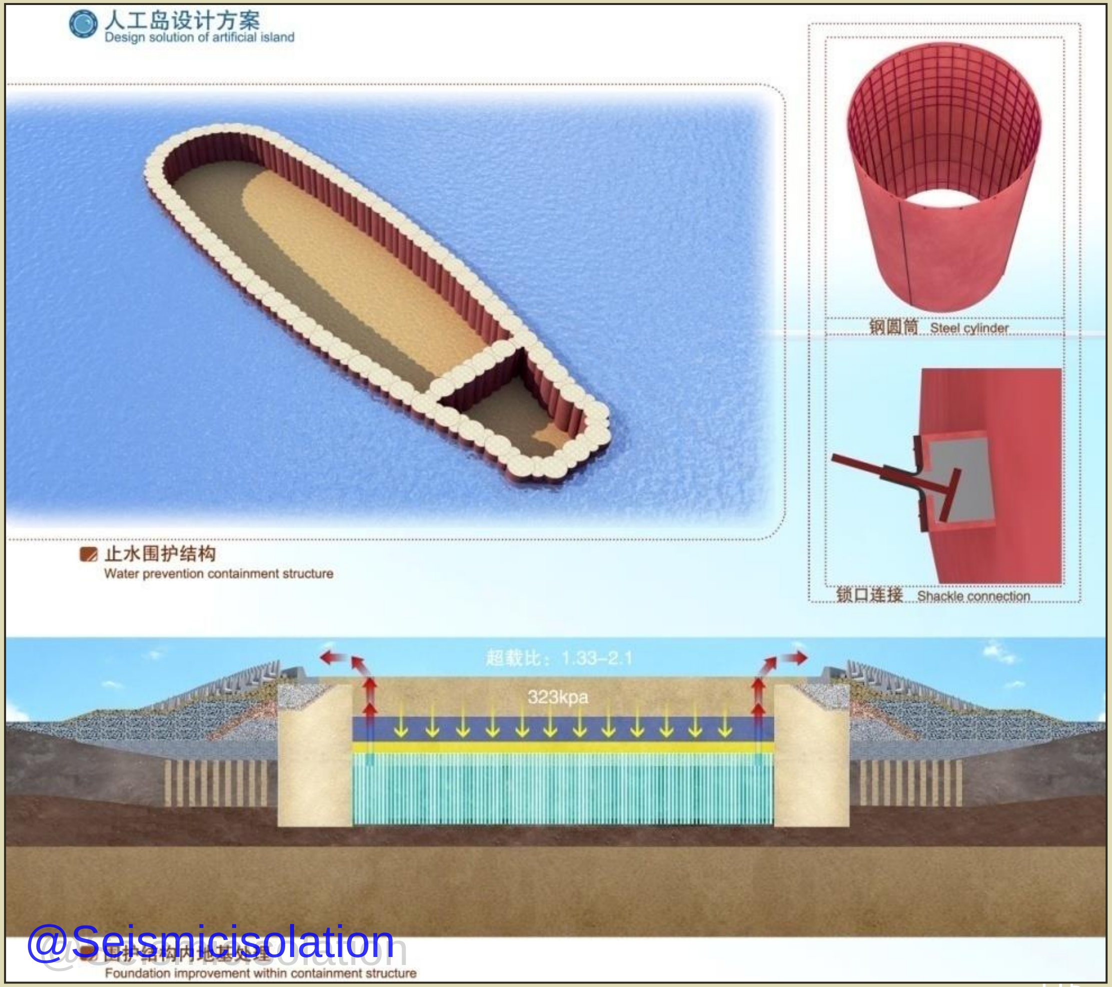
Man-made islands are portals for immersed tube tunnel

The Two man-made islands of about **100,000 m2. (1 million square feet)**

Water depth is about **10m**.

Thickness of soft soil layer is **20 ~ 30m**.

Retaining structure is a cellular cofferdam **22m** diameter, average depth **45m** and filled with sand.



Fabrication of Steel Cofferdam

Assembly of Steel Tubes

Combining Steel Tubes

Transporting

Installing by self-weight and six vibrators

Filling

Closing the retaining walls

Filling the Island

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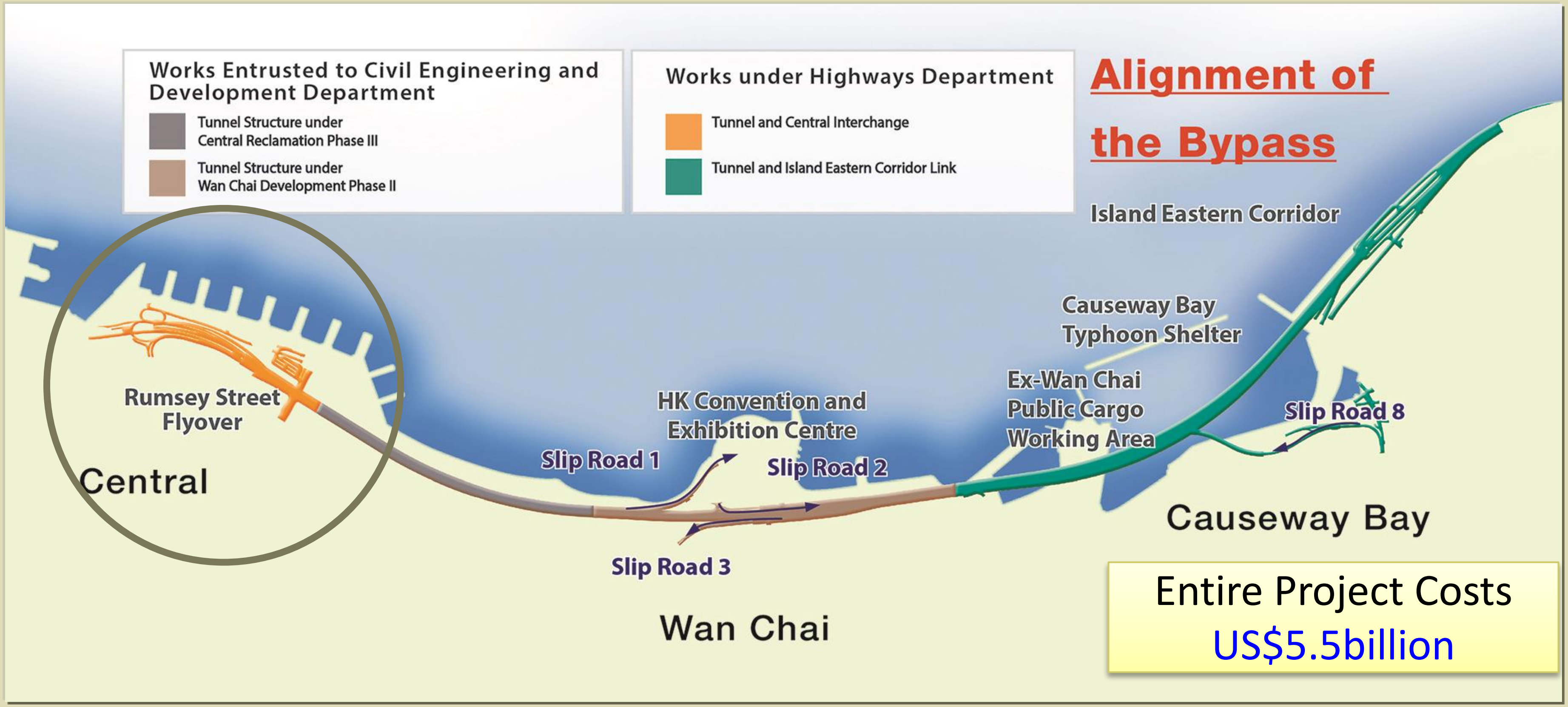
Case 6: Central - Wan Chai Bypass and Island Eastern Corridor Link

3km dual lane dual carriageway in cut and cover tunnels



Entire Project Costs
US$5.5billion

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Central District Portal

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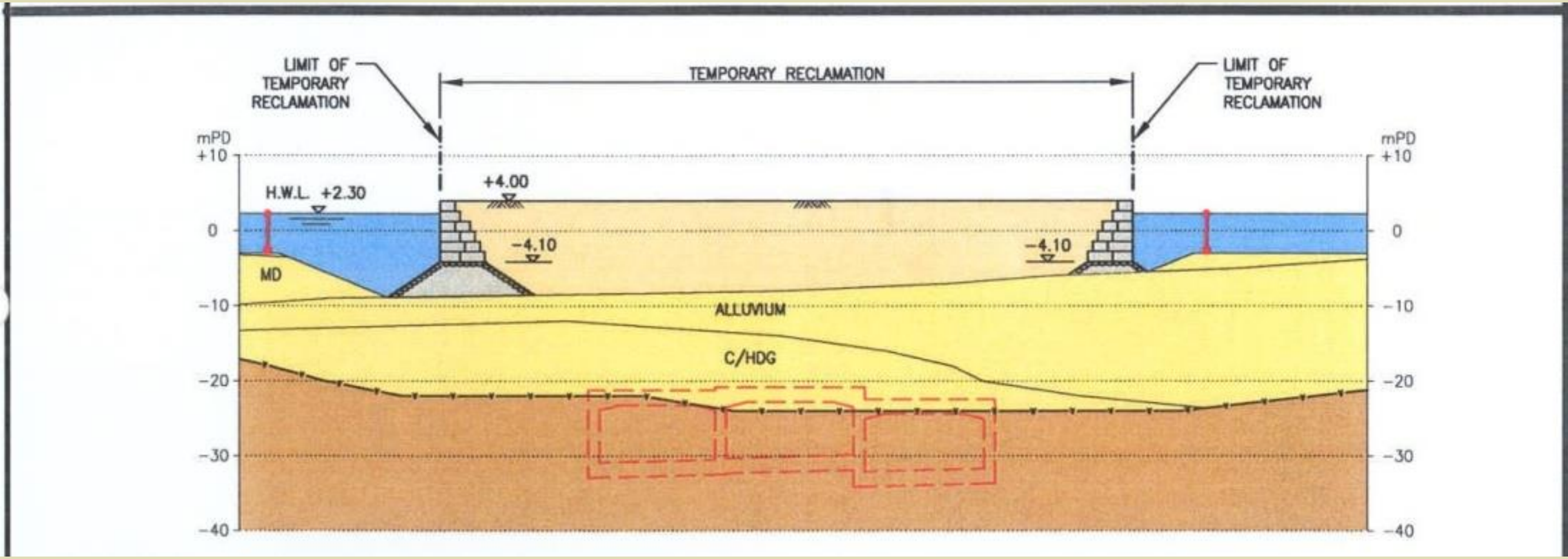
Central - Wan Chai Bypass and Island Eastern Corridor Link

Central - Wan Chai Bypass Middle Section

Crossing yacht basin with man-made islands

Temporary sea walls

Construction of man-made island



Temporary block sea walls and sand fill island

Excavation in the dry

Complexity

Tunneling below existing road tunnel and new railway tunnel

Mining in rock

Case 7:

Re-use of 35 years old “Temporary Walls”

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1975 Requirements

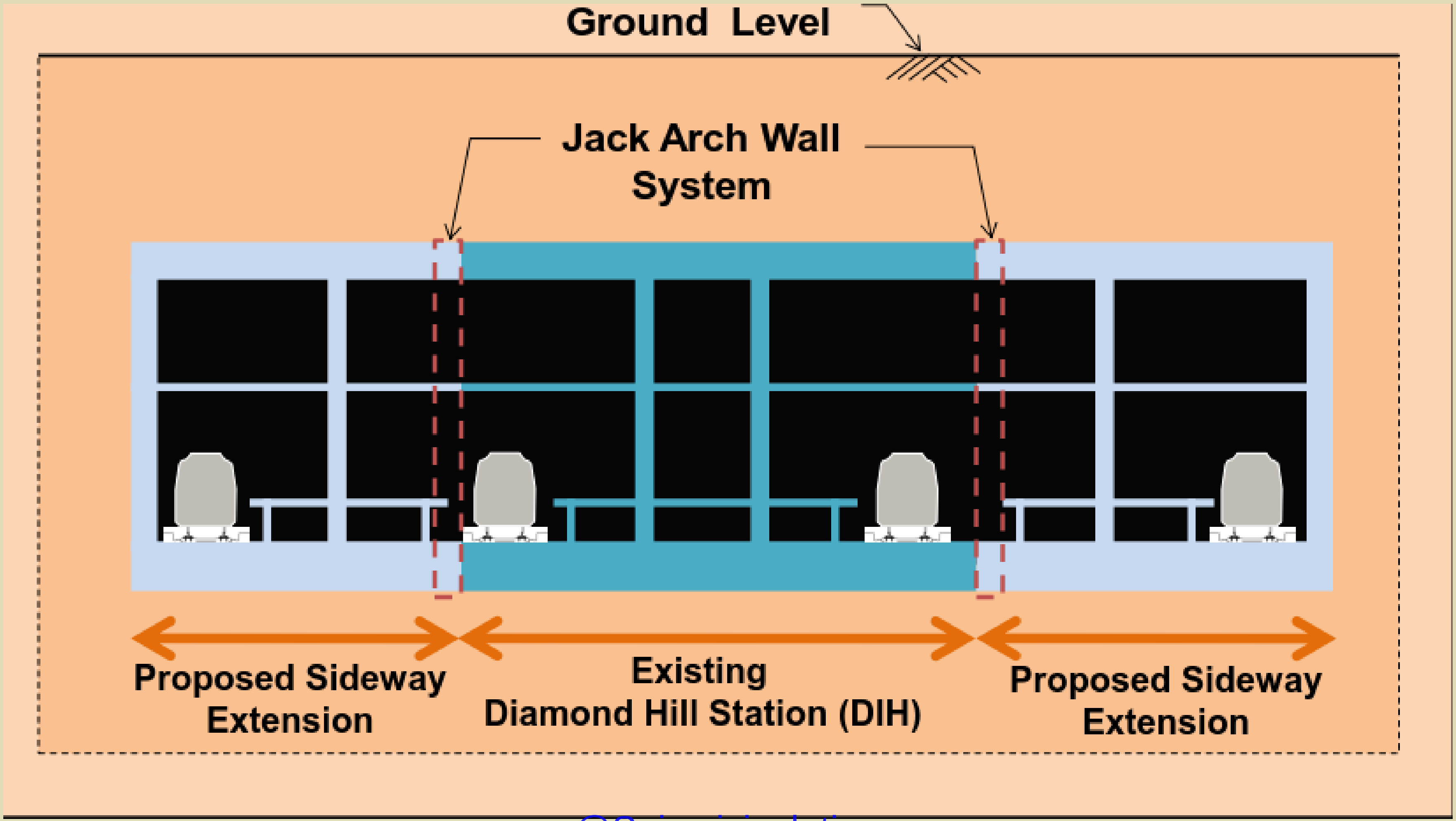
Short Term

- Central platform, two lines (standard) layout underground station.

Future

- Provision for future extension on both sides to provide a junction station with cross platform connections.
- Long side walls shall be easy to dismantle under normal operation of the lines (3 hours night time working)

1975 Intended future expansions



Contractor’s design for temporary walls for uncertain duration

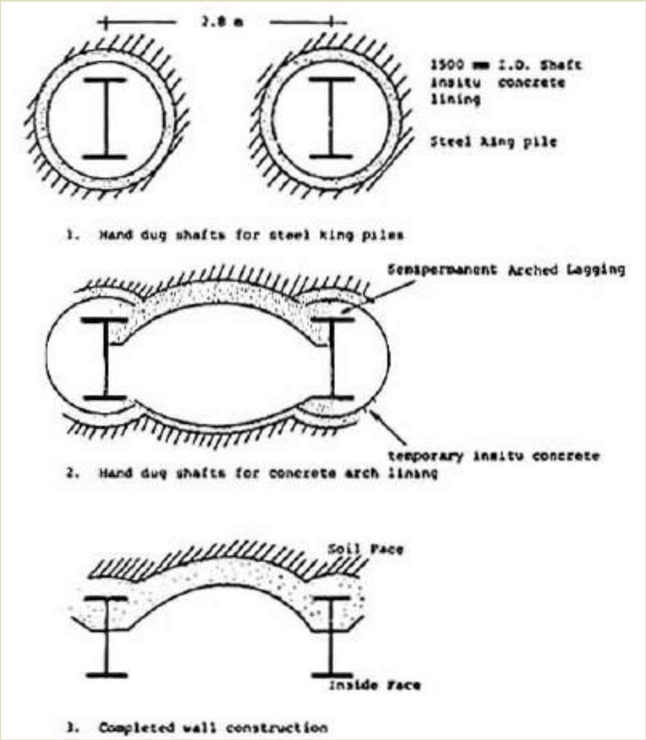
Jack Arch Wall with King Posts

Plan view, stages of construction

1 Hand dug shafts for plunged rolled steel sections (U.B. 911 x 418 mm). 1

2 Hand dug shafts for concrete lagging between steel U.B.s 2

3 plain concrete arches 3



Top down construction with dewatering as the shafts are sunk reducing lateral earth pressure.

Hand excavated shaft

Discarded options

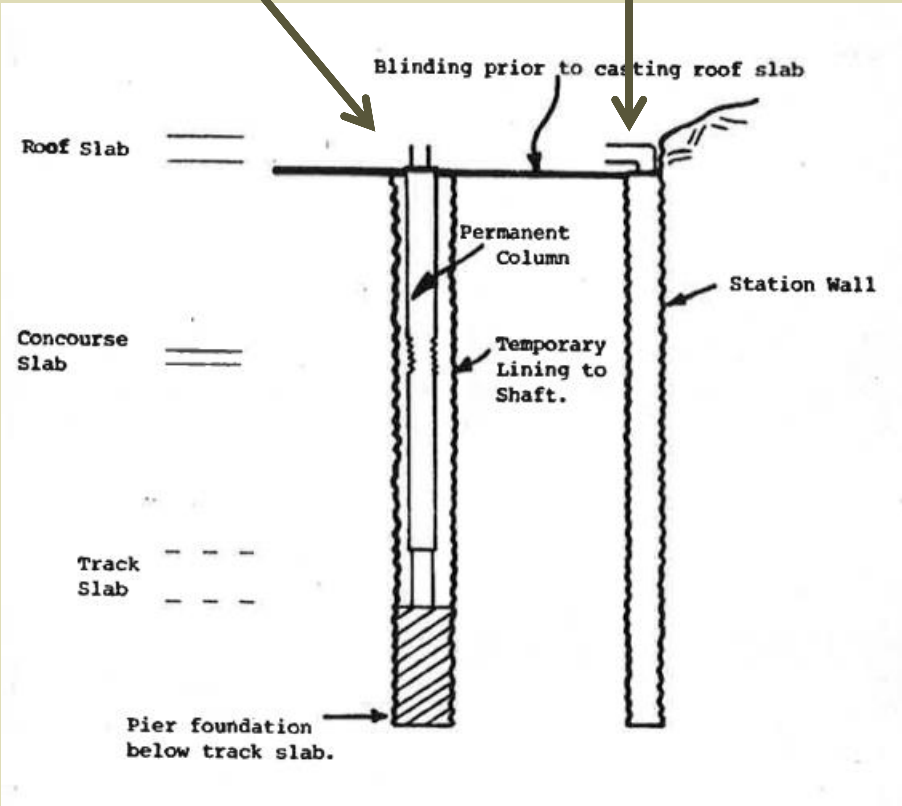
– Diaphragm walls would require a long time to break out whereas steel can be cut readily

– Heavy steel sheet piles would require driving past 3m dia. Boulders

– Sheet piles are insufficient in bending capacity over large spans.

Hand excavated shafts for plunge columns

Hand excavated shafts for walls



200 shafts excavated concurrently

Perimeter walls constructed in 80 days

North Wall

Plunged Columns

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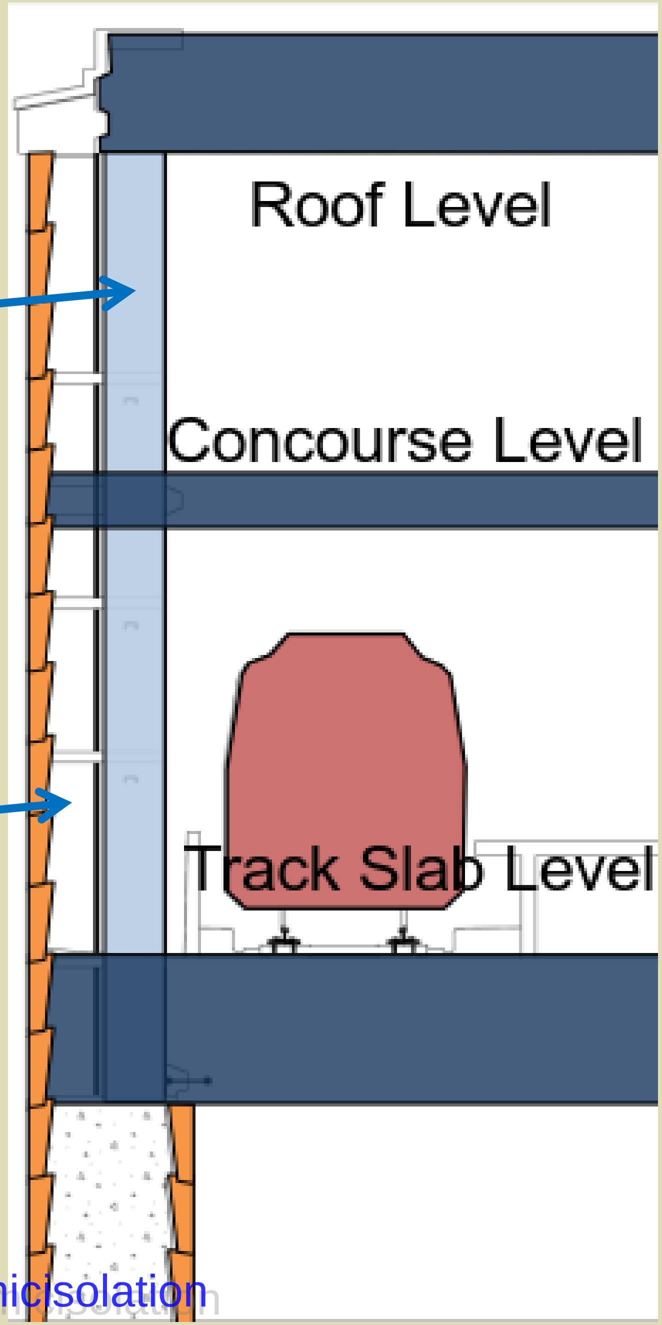
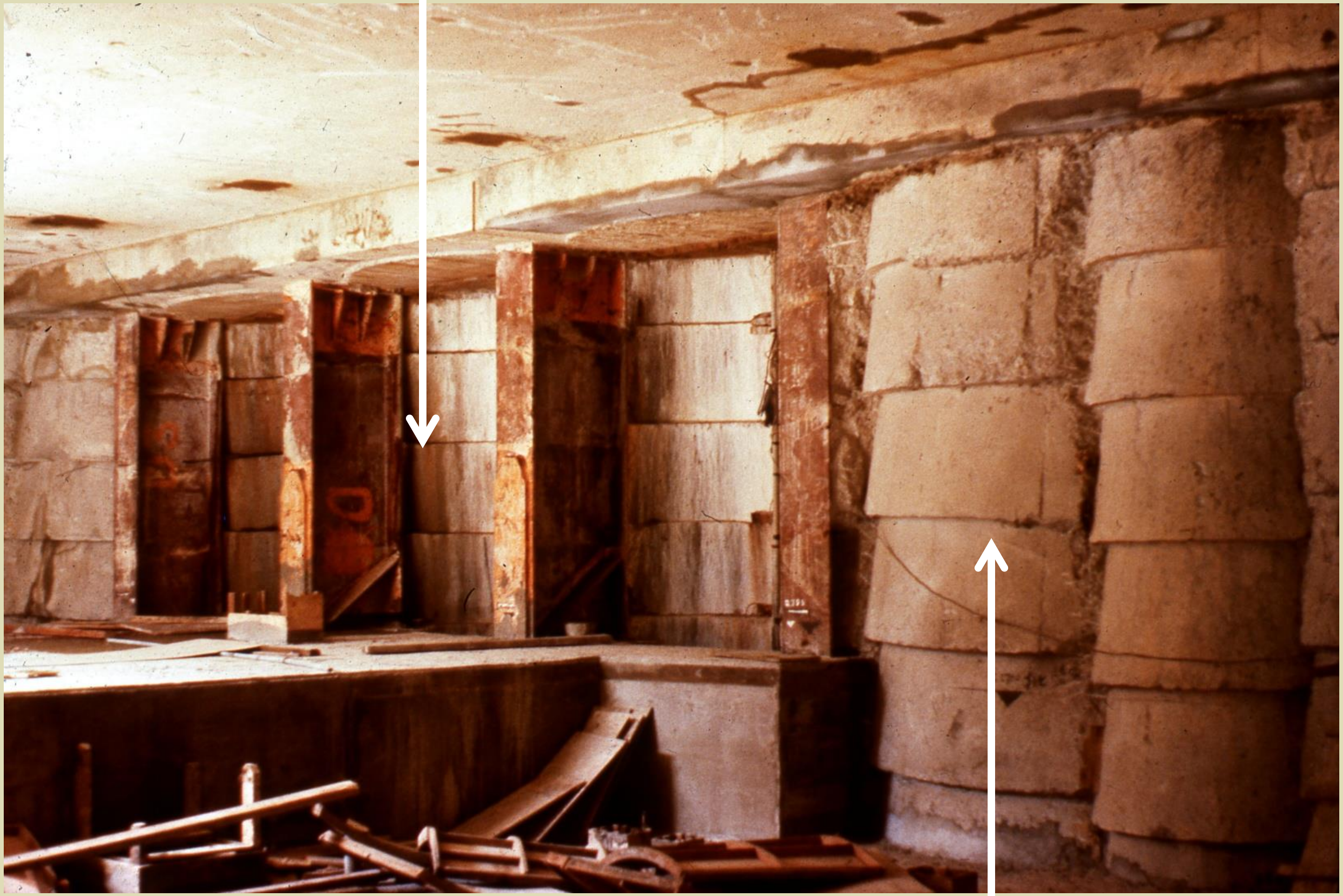
Adopted design

Steel Beams plunged into hand dug shafts

Plain concrete arches



Steel beams and concrete jack arches temporary walls



Contiguous hand excavated permanent concrete walls

1975 Calculations for soil-structure interaction by hand

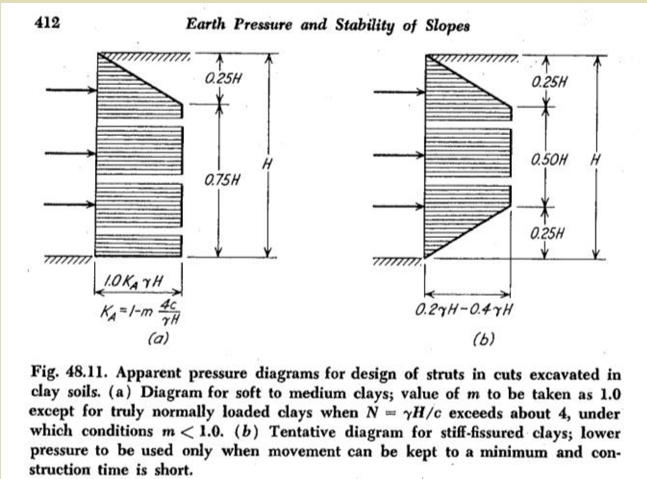
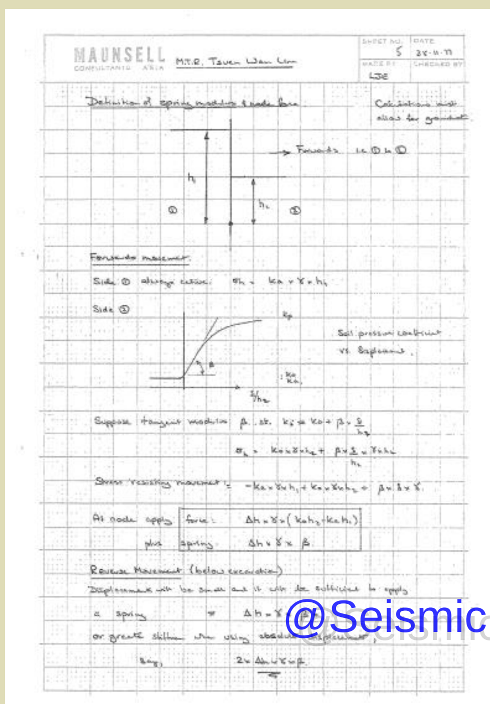
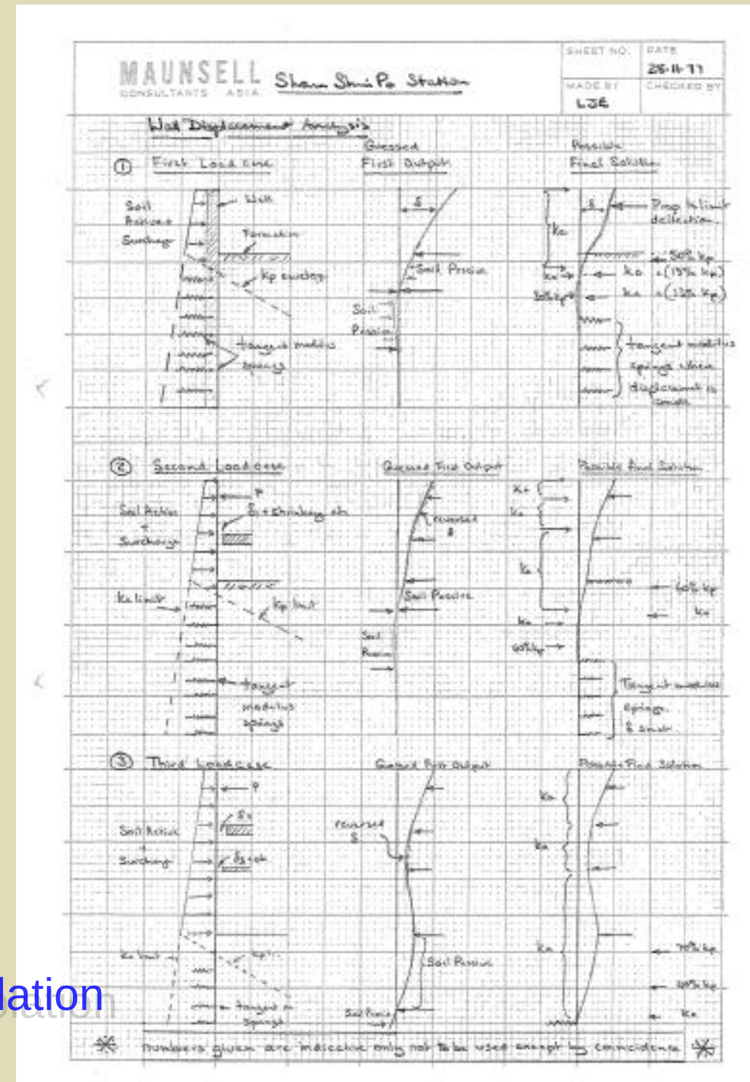
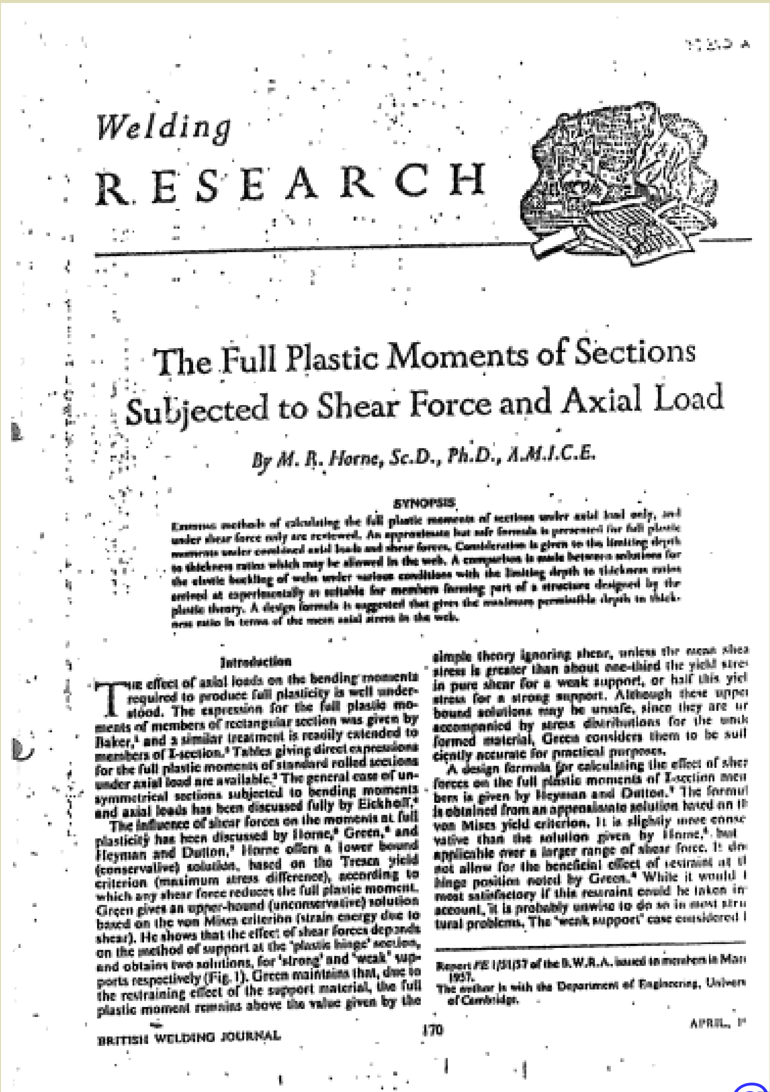


Fig. 48.11. Apparent pressure diagrams for design of struts in cuts excavated in clay soils. (a) Diagram for soft to medium clays; value of m to be taken as 1.0 except for truly normally loaded clays when $N = \gamma H/c$ exceeds about 4, under which conditions $m < 1.0$. (b) Tentative diagram for stiff-fissured clays; lower pressure to be used only when movement can be kept to a minimum and construction time is short.





1975 Plastic design for steel



Welding RESEARCH

The Full Plastic Moments of Sections Subjected to Shear Force and Axial Load

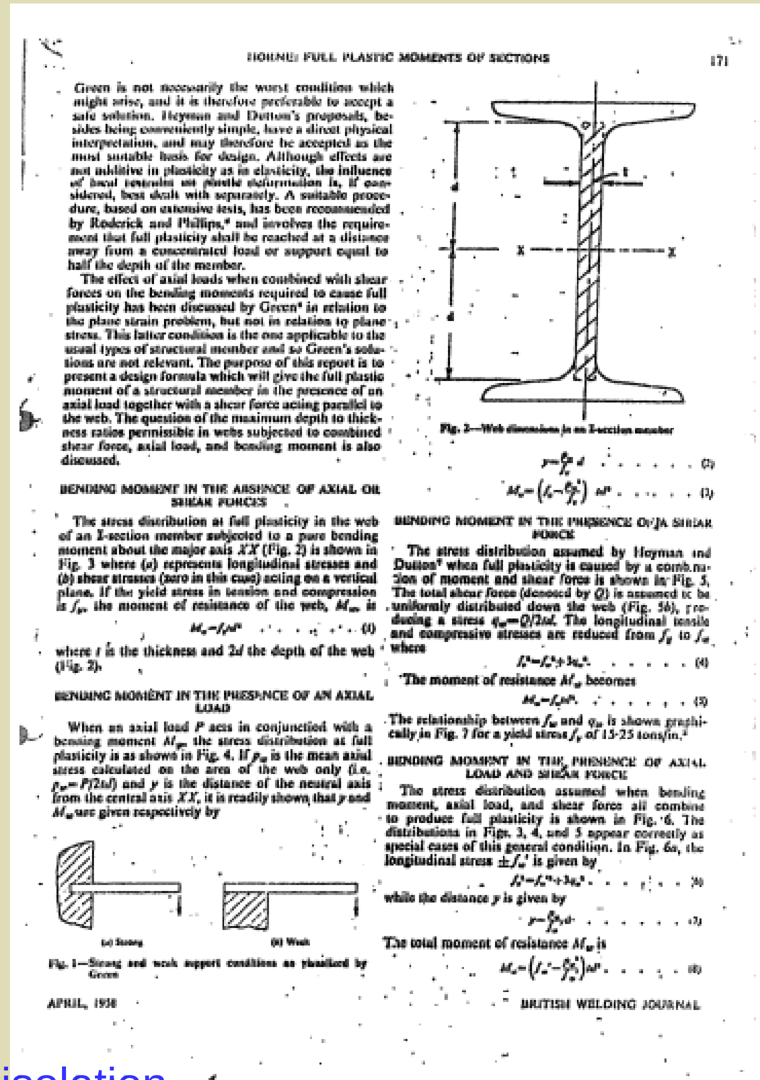
By M. R. Horne, Sc.D., Ph.D., A.M.I.C.E.

SYNOPSIS

Introduction

The effect of axial loads on the bending moments required to produce full plasticity is well understood.

BRITISH WELDING JOURNAL 170 APRIL, 19



HORNE: FULL PLASTIC MOMENTS OF SECTIONS 171

BENDING MOMENT IN THE ABSENCE OF AXIAL OR SHEAR FORCES

BENDING MOMENT IN THE PRESENCE OF AN AXIAL LOAD

BENDING MOMENT IN THE PRESENCE OF A SHEAR FORCE

BENDING MOMENT IN THE PRESENCE OF AXIAL LOAD AND SHEAR FORCE

Fig. 1—Strong and weak support conditions as visualized by Green

Fig. 2—Web dimensions in an I-section member

APRIL, 1958 BRITISH WELDING JOURNAL

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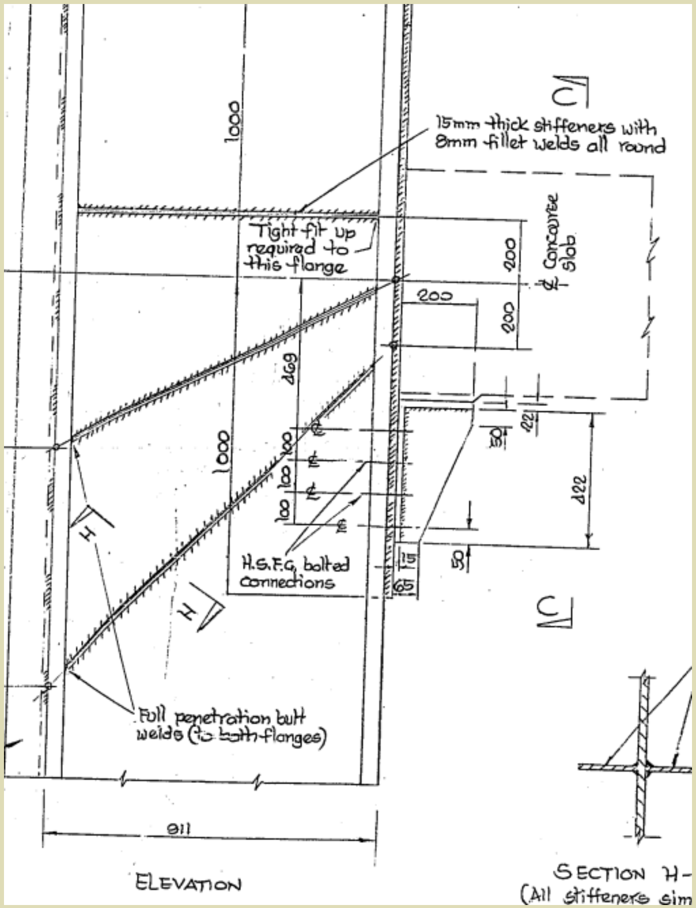
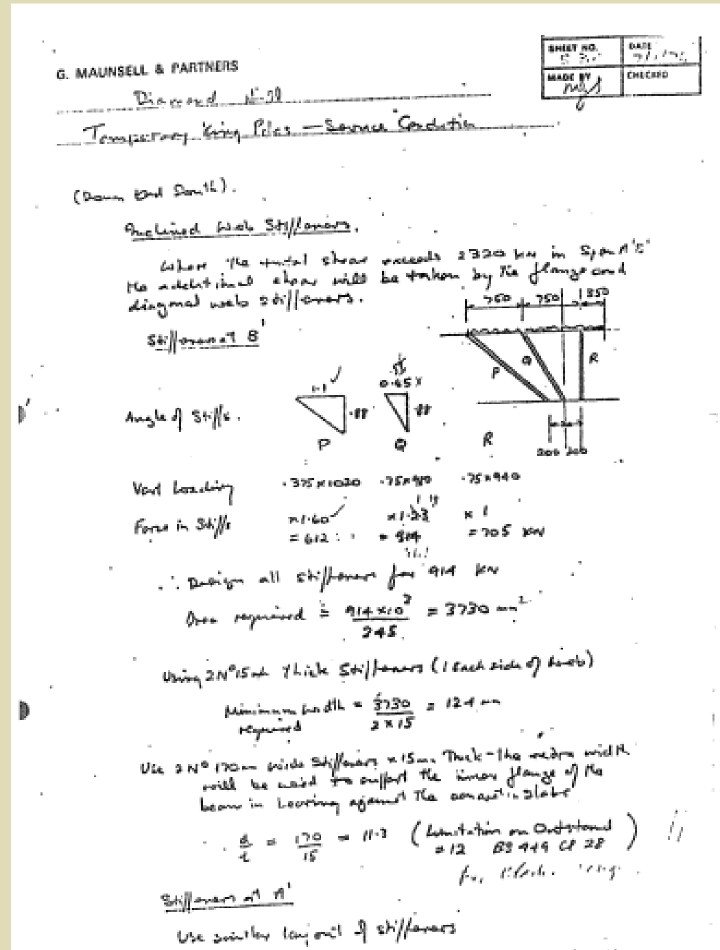
Steel detailing: Bending plus Shear




G. MAUNSELL & PARTNERS

SHEET NO. | DATE
MADE BY | CHECKED

Temporary King Piles — Service Condition

Inclined Web Stiffeners.

When the total shear exceeds 2320 kN in Span 'C' the additional shear will be taken by the flange and diagonal web stiffeners.

750 | 750 | 1350

P Q R

Angle of Stiffs. P Q R

Vert loading ·375 x 1020 ·75 x 910 ·75 x 940

Force in Stiffs x 1·60 x 1·33 x 1

= 612 = 914 = 705 kN

∴ Design all stiffeners for 914 kN

Area required = $\frac{914 \times 10^3}{245}$ = 3730 mm^2

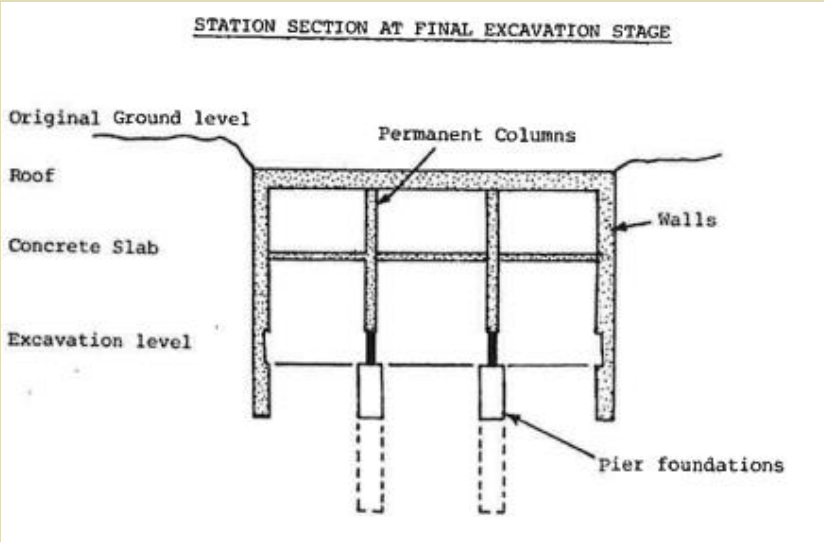
Using 2 N° 15 mm thick Stiffeners (1 each side of web)

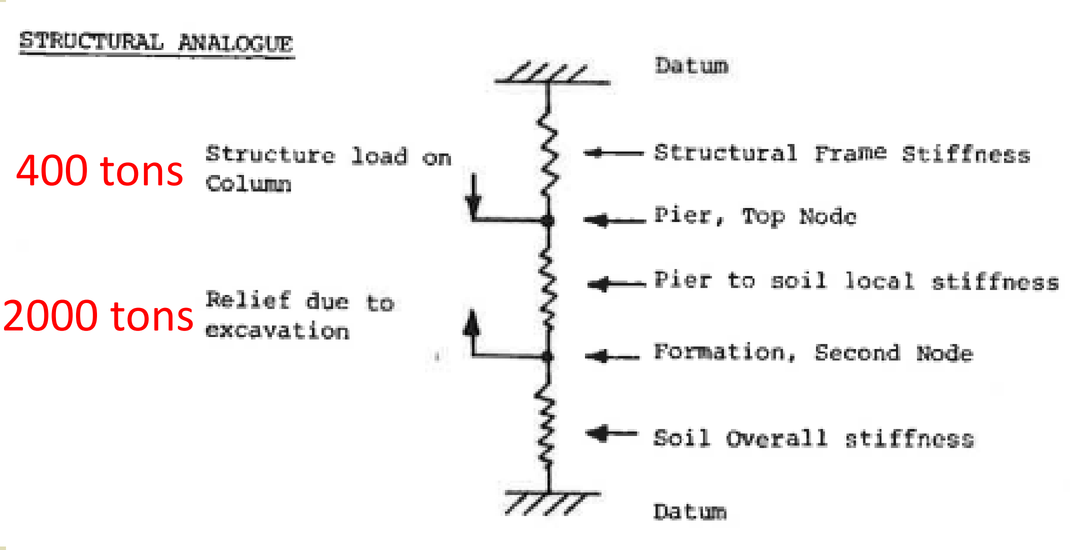
Minimum width required = $\frac{3730}{2 \times 15}$ = 124 mm

Use 2 N° 170 mm wide Stiffeners x 15 mm Thick – the extra width will be used to support the inner flange of the beam in bearing against the concrete slab.

$\frac{b}{t} = \frac{170}{15} = 11 \cdot 3$ (Limitation on Outstand = 12 BS 449 Cl 28)

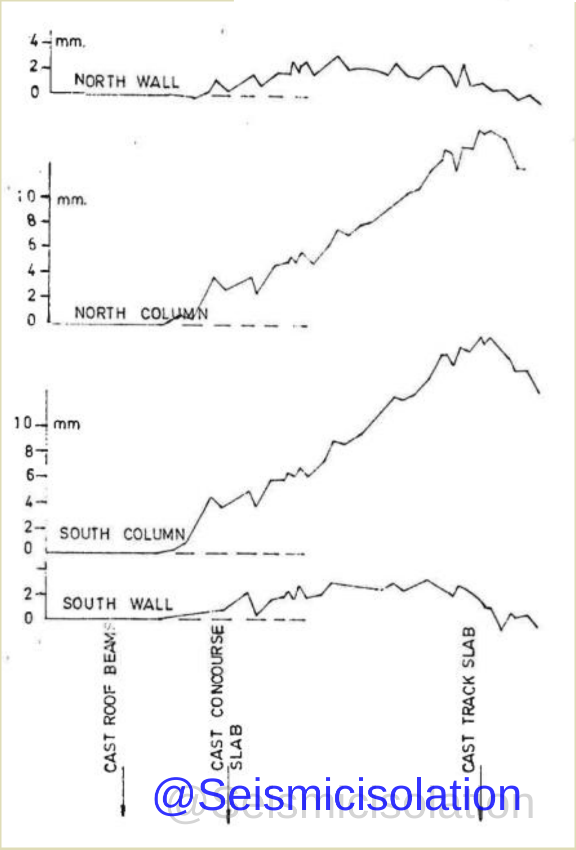
Use similar layout of stiffeners





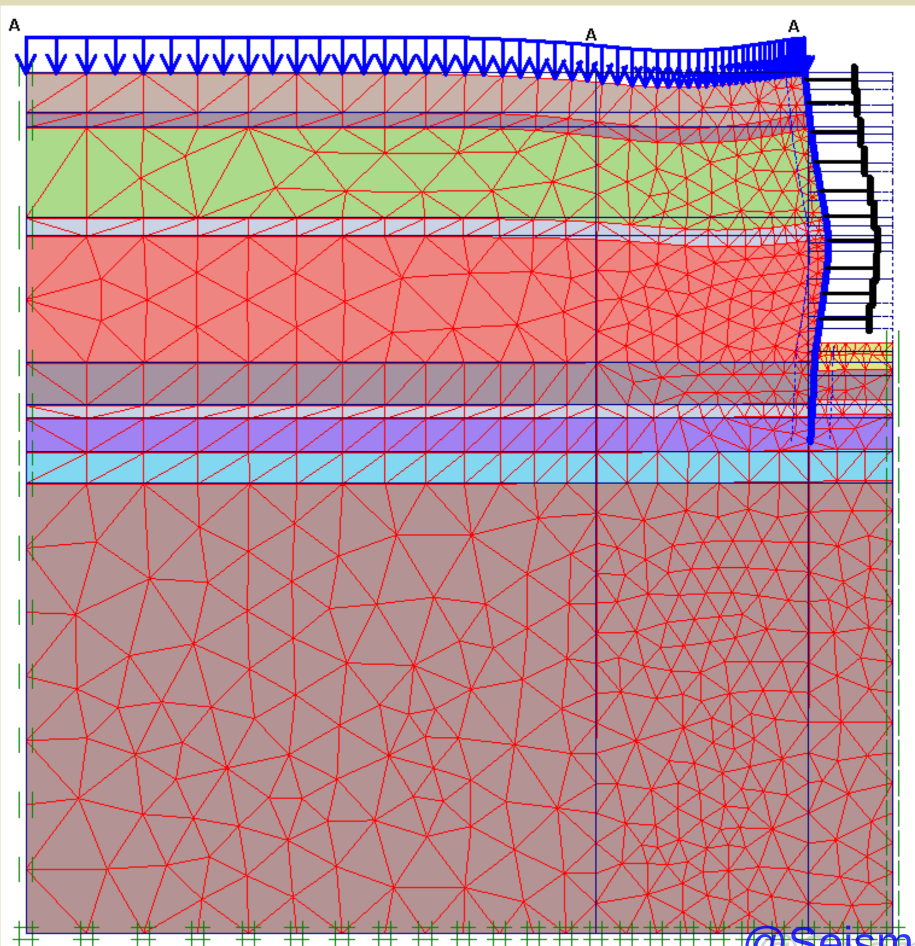
Vertical soil/structure interaction

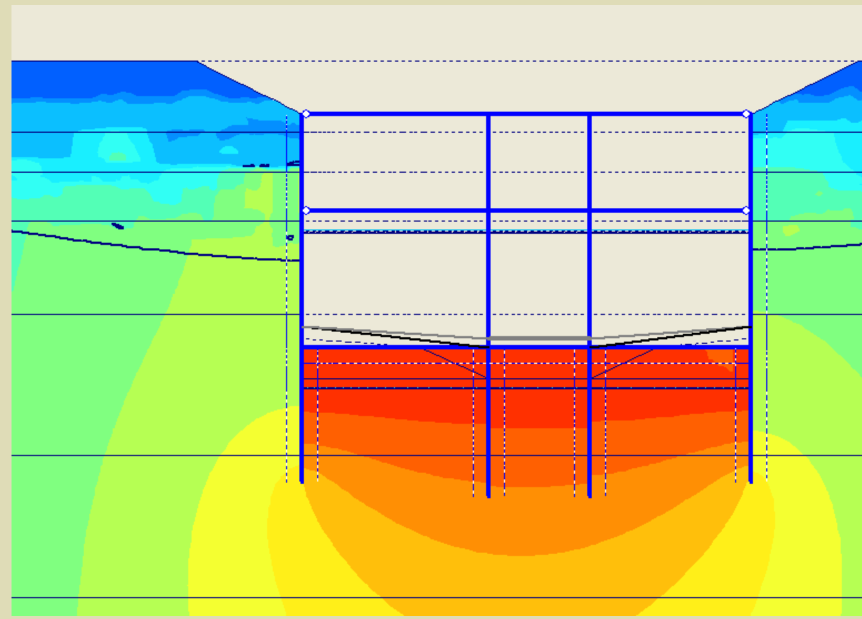
Inadequate pier foundations?



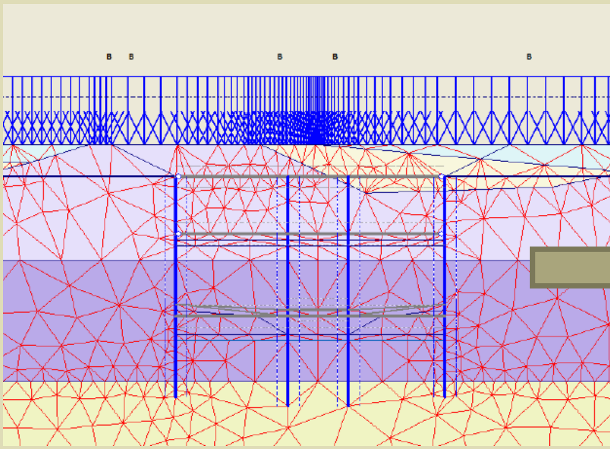
20 mm Heave

Re-evaluation:
PLAXIS analysis of original construction

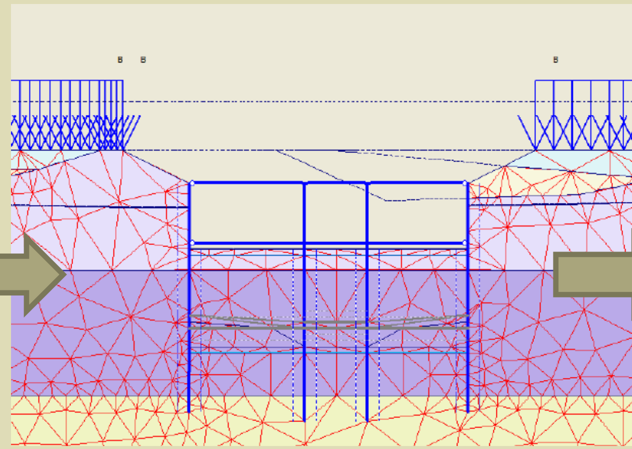




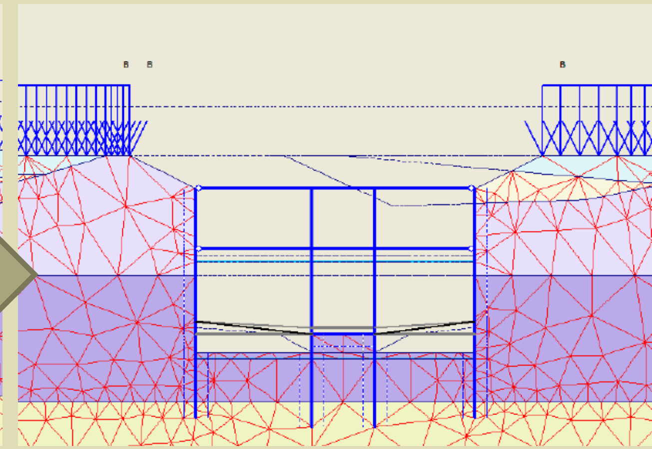
New analysis of original construction to estimate locked-in deformation after construction



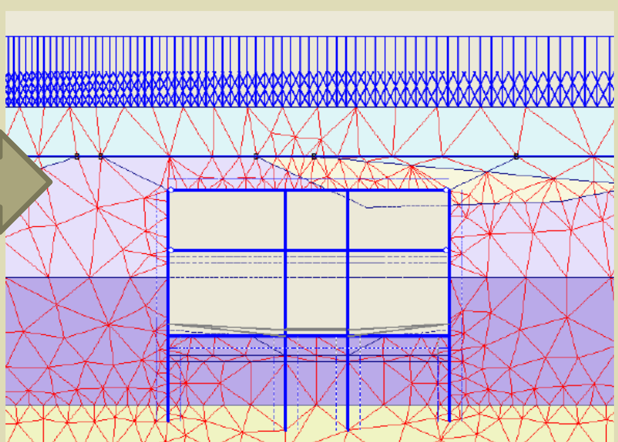
(1) Road level at about +8.5mPD



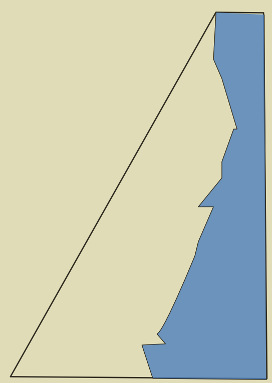
(2) Start Excavation, cast roof and concourse slabs



(3) Excavate to Track Slab cast Base Slab



(4) Backfill to current ground level



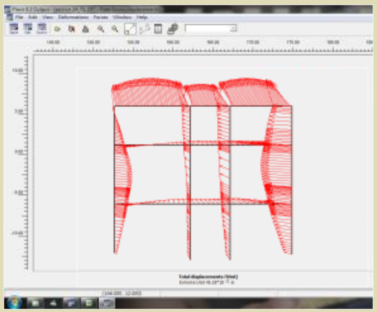
<u>Computed lateral pressure at end of construction < Ko</u>

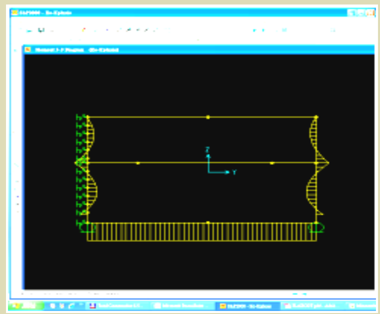
Design code requires Ko in the long term.

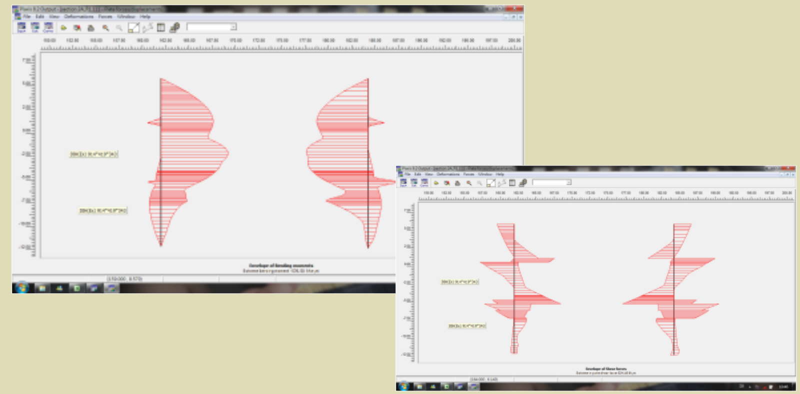
Concrete shrinks, walls move inwards and soil pressure increases.

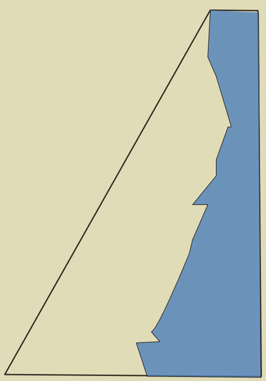
PLAXIS does not permit <u>negative stiffness</u> for soil

Permanent Case Structural Analysis - Present Superimposition of K_{PLAXIS} and $K_{O\text{-}PLAXIS}$

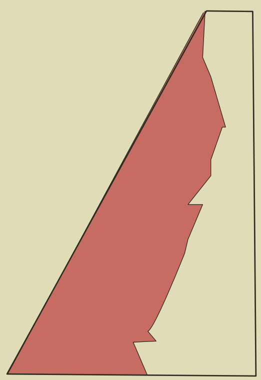




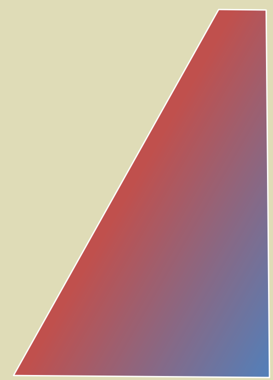




K_{PLAXIS} +



$K_{O\text{-}PLAXIS}$ =



K_O

PLAXIS derived “Locked-in Stresses” due to Construction

SAP2000 to evaluate the Transition Stresses from transient active stage to permanent static stage ($K_{o\text{-}Plaxis}$)

Loads are combined for checking long term case

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	Combined Stress	
	BS5950:1990	HK COP2005 Steel Code
Moment and Axial Force Utilization Factor	0.91 (Max)	

Analysis and Condition Survey confirmed
serviceability as permanent walls

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Thank you