Challenges of going “High” at Kings Cross Station, London

March 2021

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RAMBOLL

King’s Cross Plots

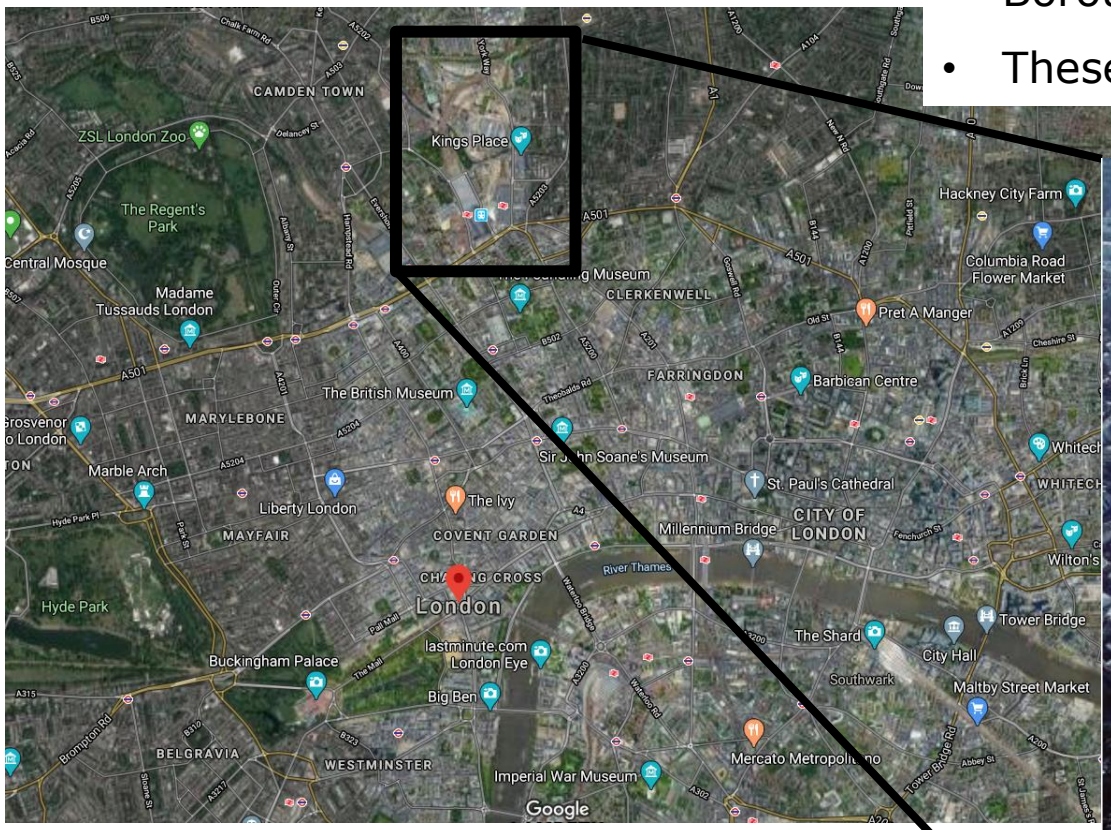
Contents

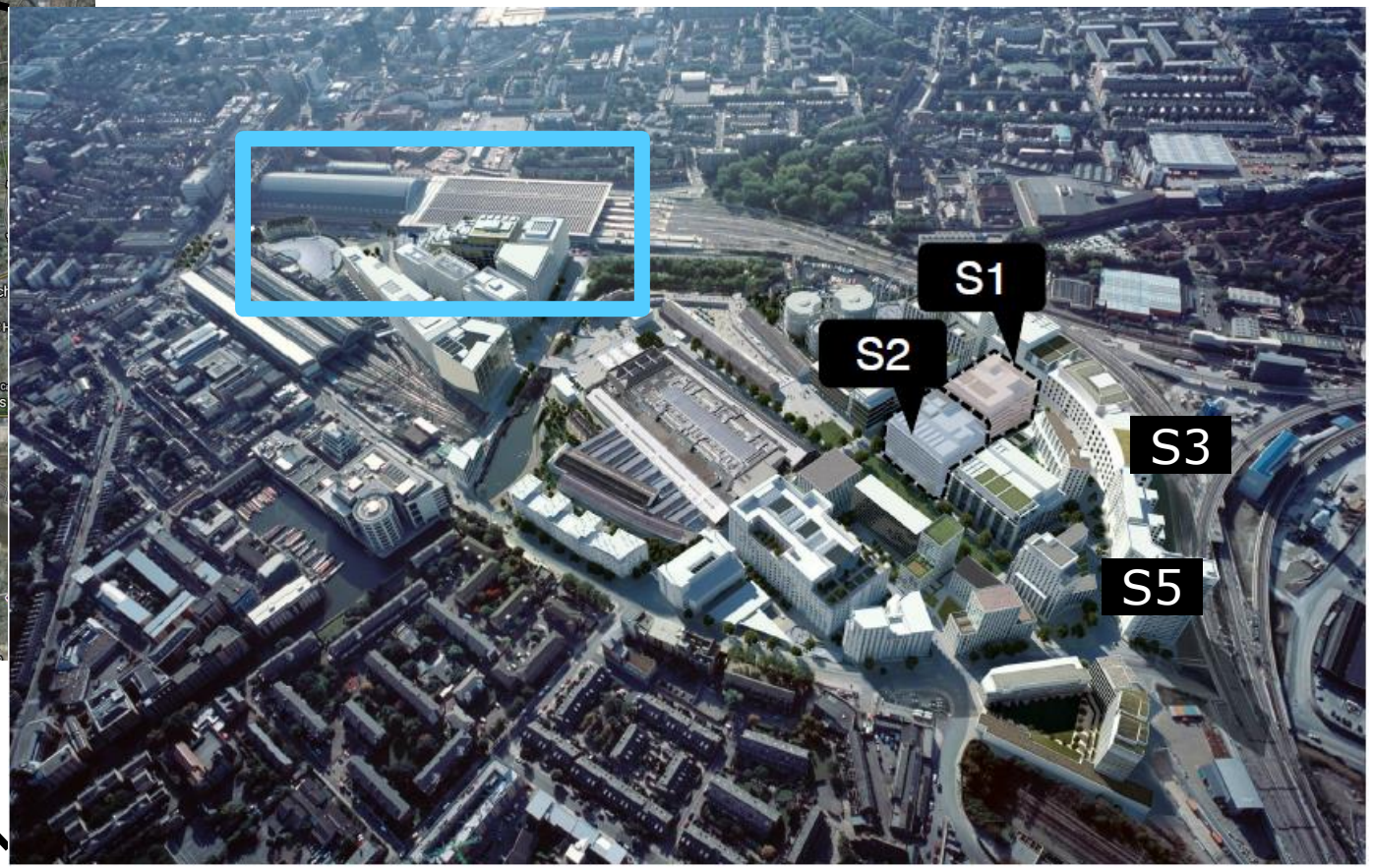
- Site Location
- Ground Conditions
- Thameslink Canal Tunnels – brief asset background
- The Structural Challenge at Kings Cross Plots
- Foundations:
  - Layout and piling restrictions
  - Numerical Analysis
  - Movement and Impact Assessments

King’s Cross Plots

SITE LOCATION

- All Plots in this area are within the King’s Cross Central Development area.
- The site is located on the North of Kings Cross Station in the London Borough of Camden - within Kings Cross Central Development.
- These projects shall provide commercial and residential office spaces.





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King's Cross Plots
GROUND CONDITIONS

- The Site Specified Ground Investigation for all the Plots identify a similar trend in terms of strata succession, namely:

  - Made Ground
  - London Clay
  - Lambeth Group
  - Thanet Sands

Geology	Horizon Levels (mOD)		
	Model: S1 Form B	Model: S5 Form B	Model: Global for S3 Form B
Made Ground	+26.5	+26.00	+27.50
London Clay	+23.45	+23.20	+22.50
Lambeth Group	-12.00	-12.00	-12.00
Thanet Sands	-32.00	N. A.	-32.00

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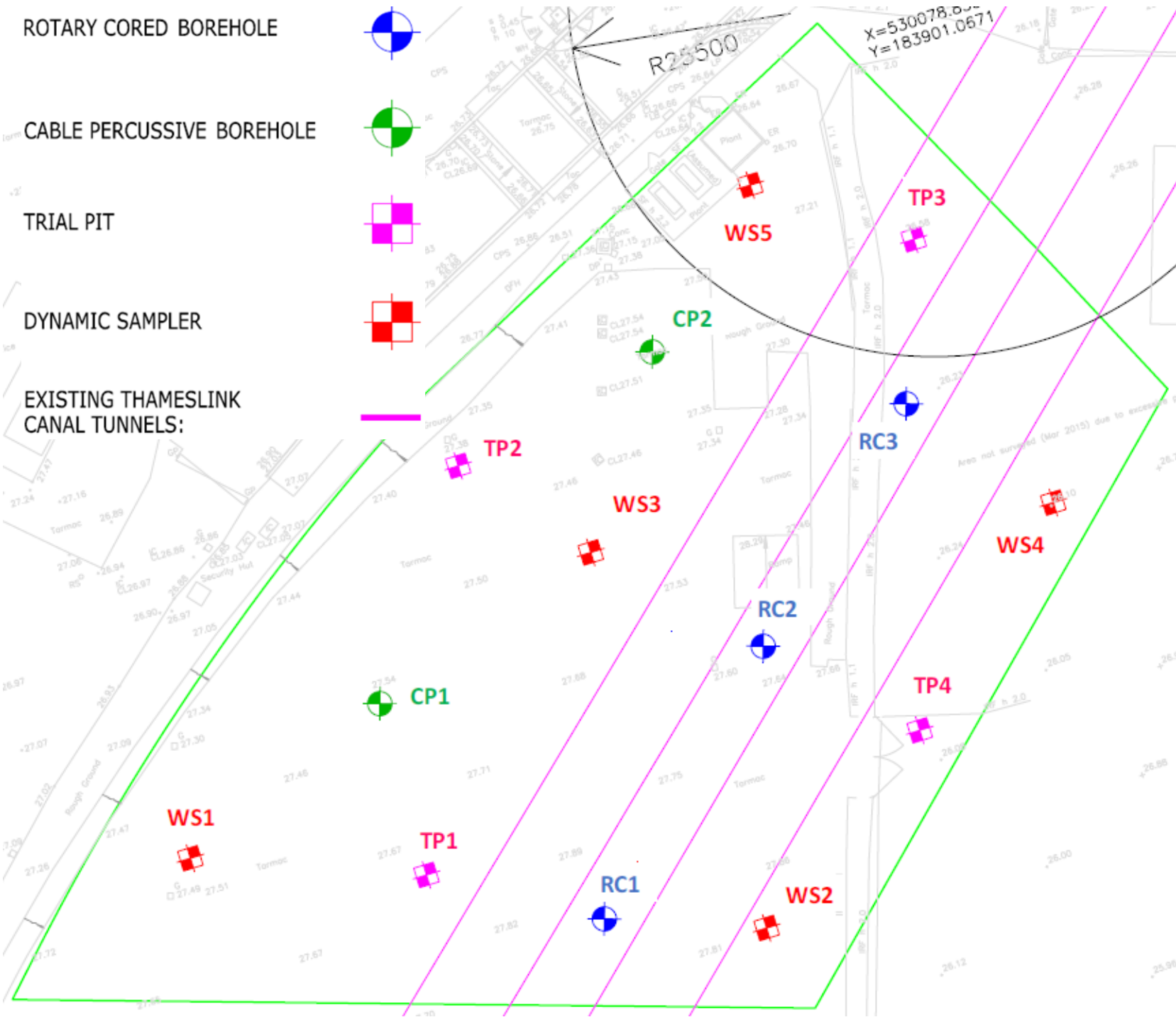
King’s Cross S3
GI Scope Example

- Rotary boreholes to retrieve high quality core samples between tunnels.
- Borehole locations to be independently checked.
- Advanced triaxial testing with measurements at small strains.
- Plus the additional information gathered already from adjacent plots



King’s Cross Plots

Thameslink Canal Tunnels

- Thameslink Canal twin bored tunn
- These tunnels have an internal dia
  linings are 300mm thick precast c
  fibres. The tunnels
- The tunnels are re
  eastwards.
- The tunnels have
  measured from th
  the structural inte

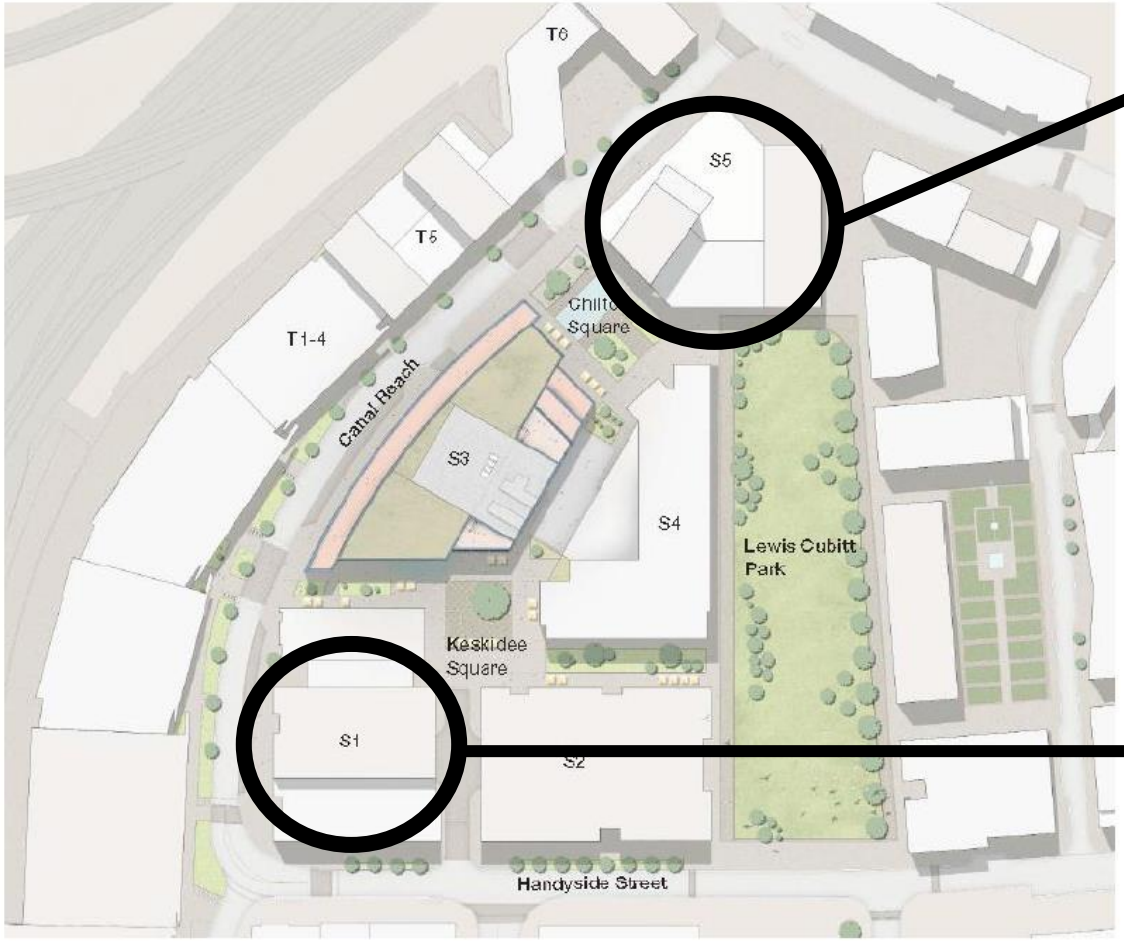
conal of soil

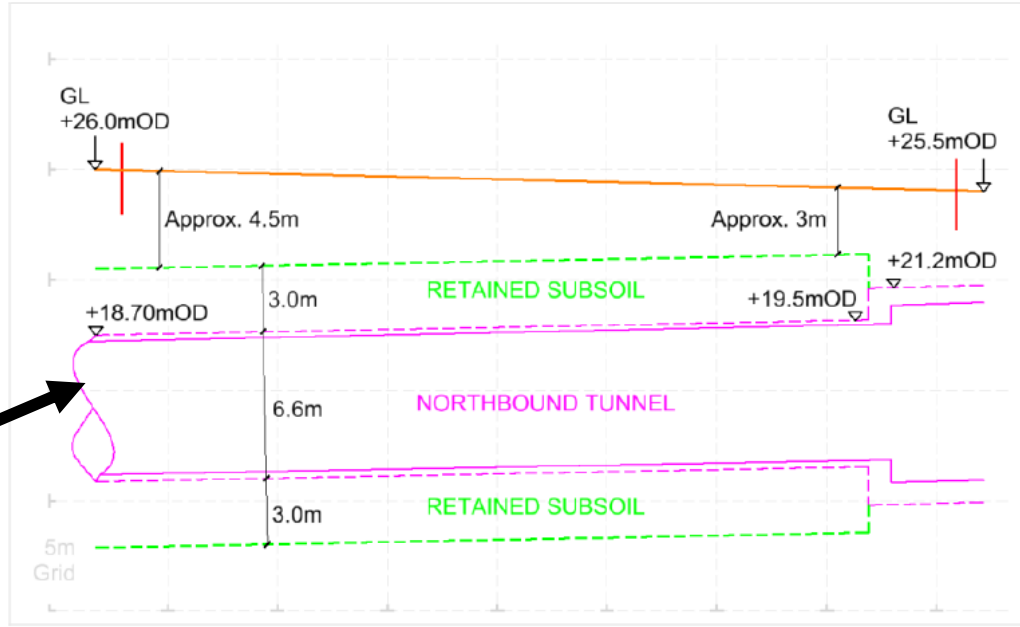
st evaluate

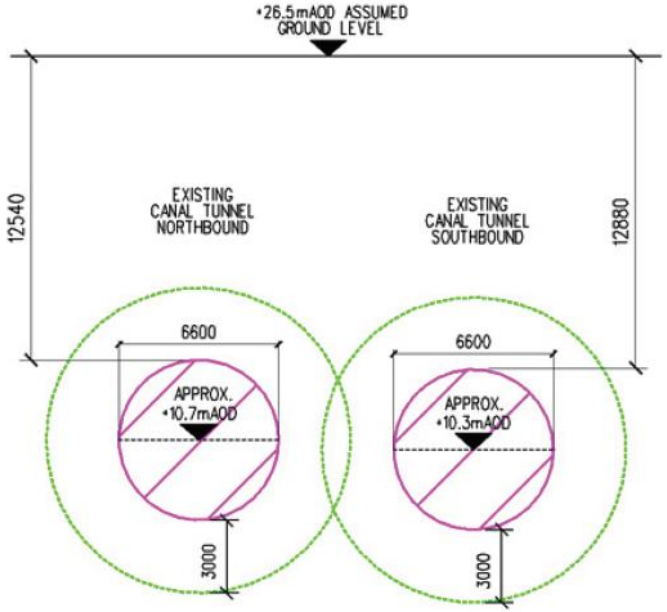
ilway line.

King's Cross Plots
Thameslink Canal Tunnels

- Cross Sections and elevation at different locations for the Thameslink Tunnels





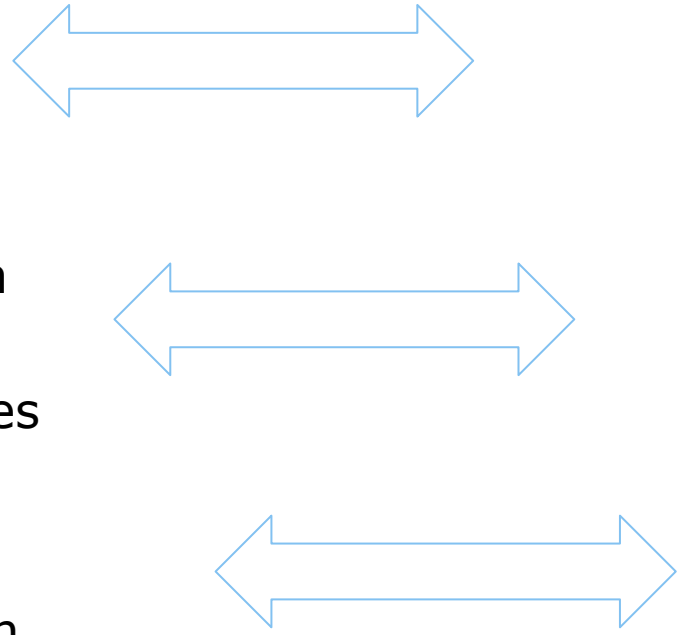


King’s Cross Plots
STRUCTURAL CHALLENGE

- Focused on meeting the demands of the site constraints and the aspirations of the clients brief.

CLIENTS BRIEF

- Flexible
- Robust and efficient cost plan
- Well-coordinated design solution
- An innovate design that enhances value
- A safety and sustainable solution



CONSTRAINTS

- Mitigate impact on NR tunnels by reducing ground floor transfer structure and excavations
- Mitigate impact on the tunnel by providing a lightweight design solution
- Mitigate any impact for underground utilities

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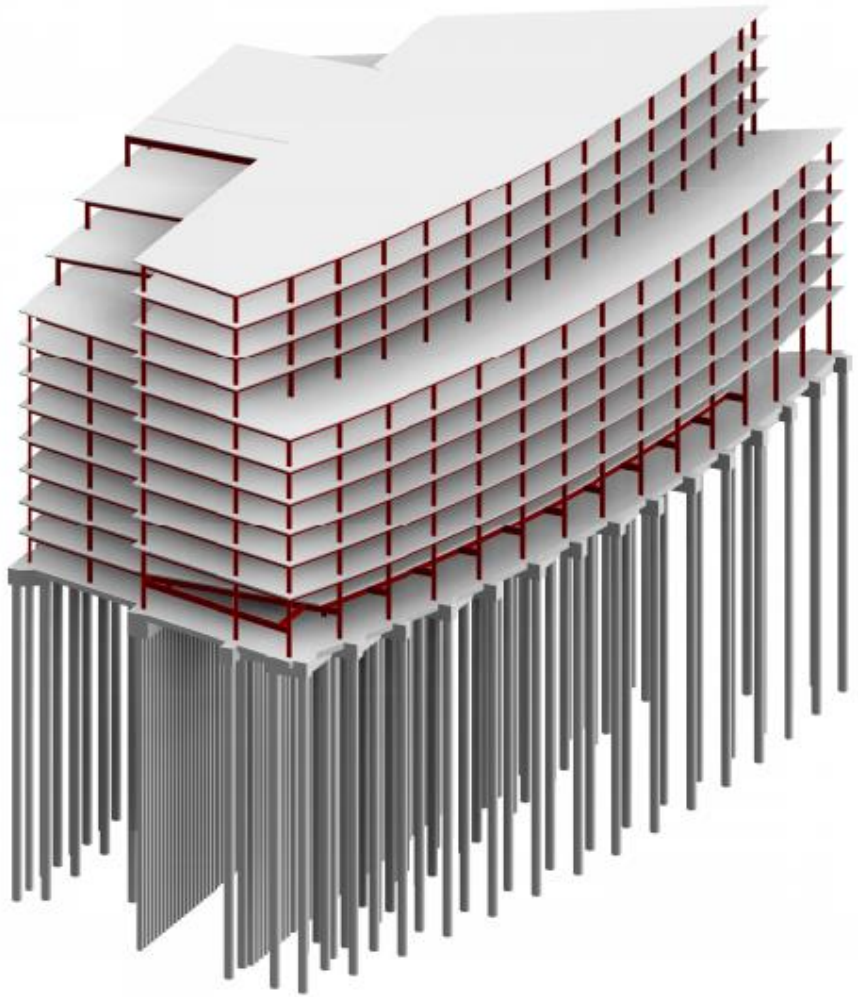
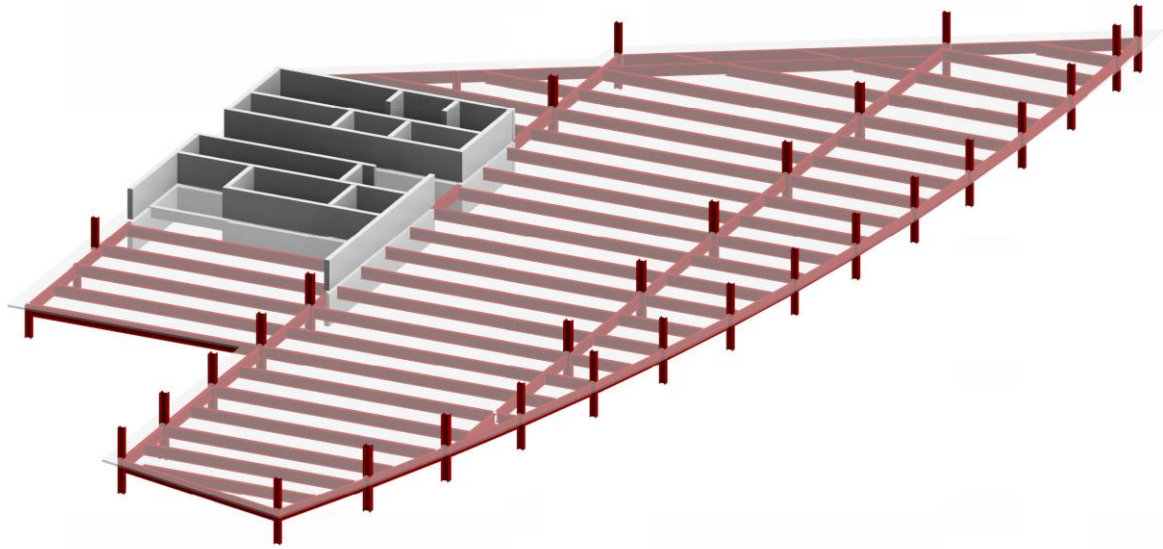
King’s Cross Plot S3

DEVELOPMENT PROPOSAL





- Lightweight composite steel frame
- Concrete core for stability
- Cellular beams to integrate structural and services zone

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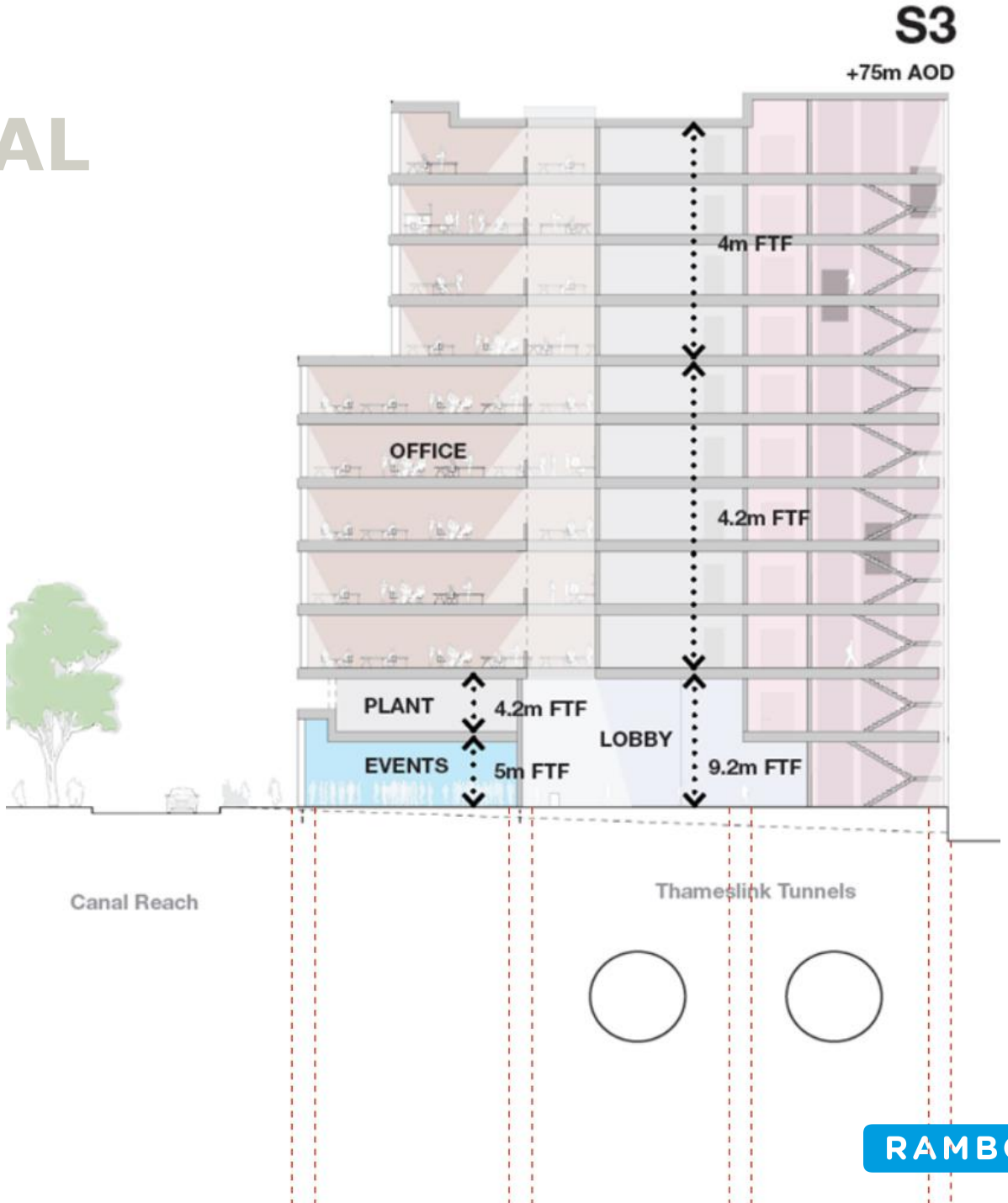
King’s Cross Plot S3
DEVELOPMENT PROPOSAL

Design Stage:

- Currently developing the **RIBA Stage 2** design
- Grids and Core alignment fixed

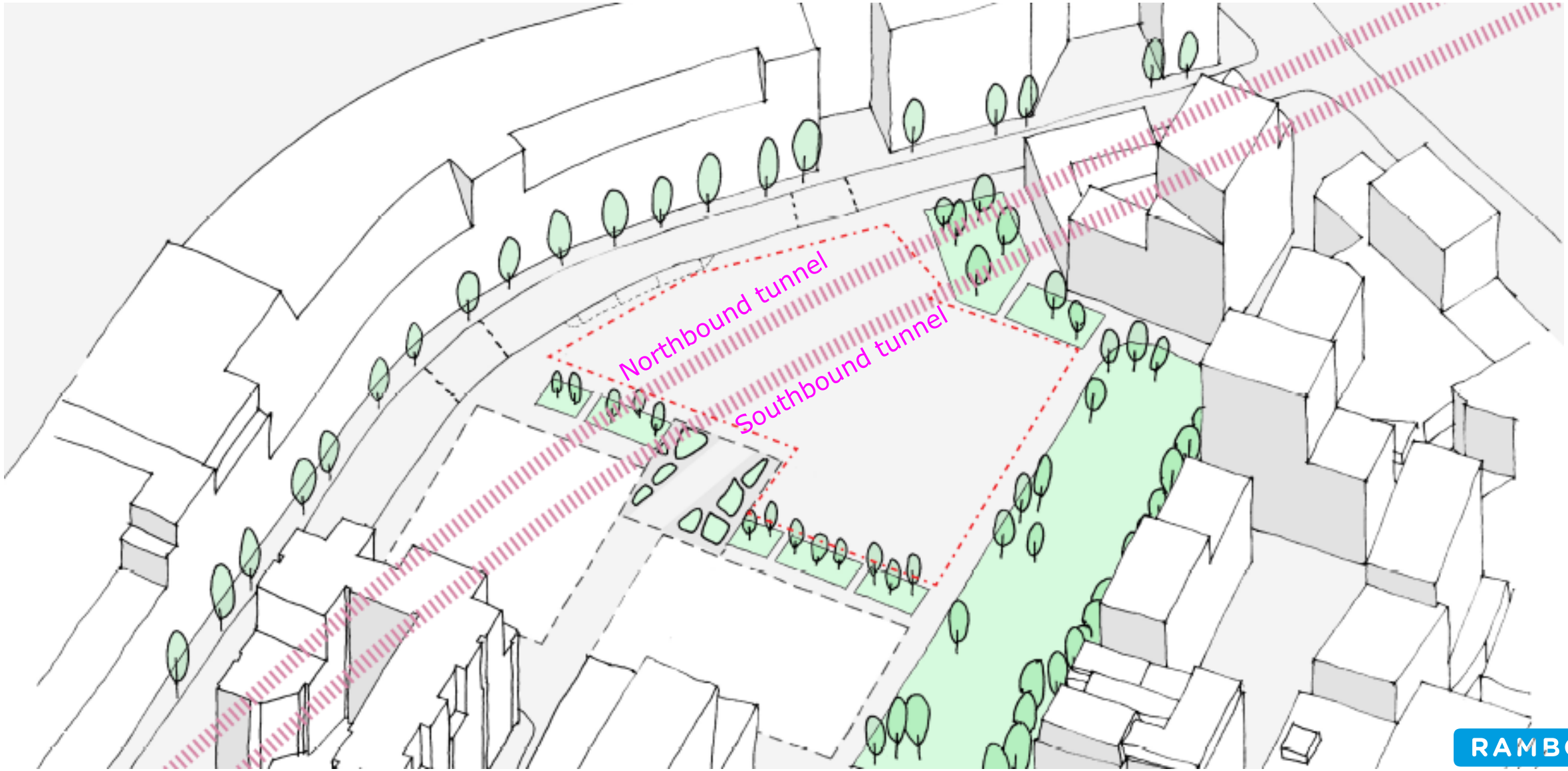
Key Features:

- Ground + 10 storeys
- Ground floor: Mixed
- Floors above: Office



King’s Cross Plot S3

DEVELOPMENT PROPOSAL

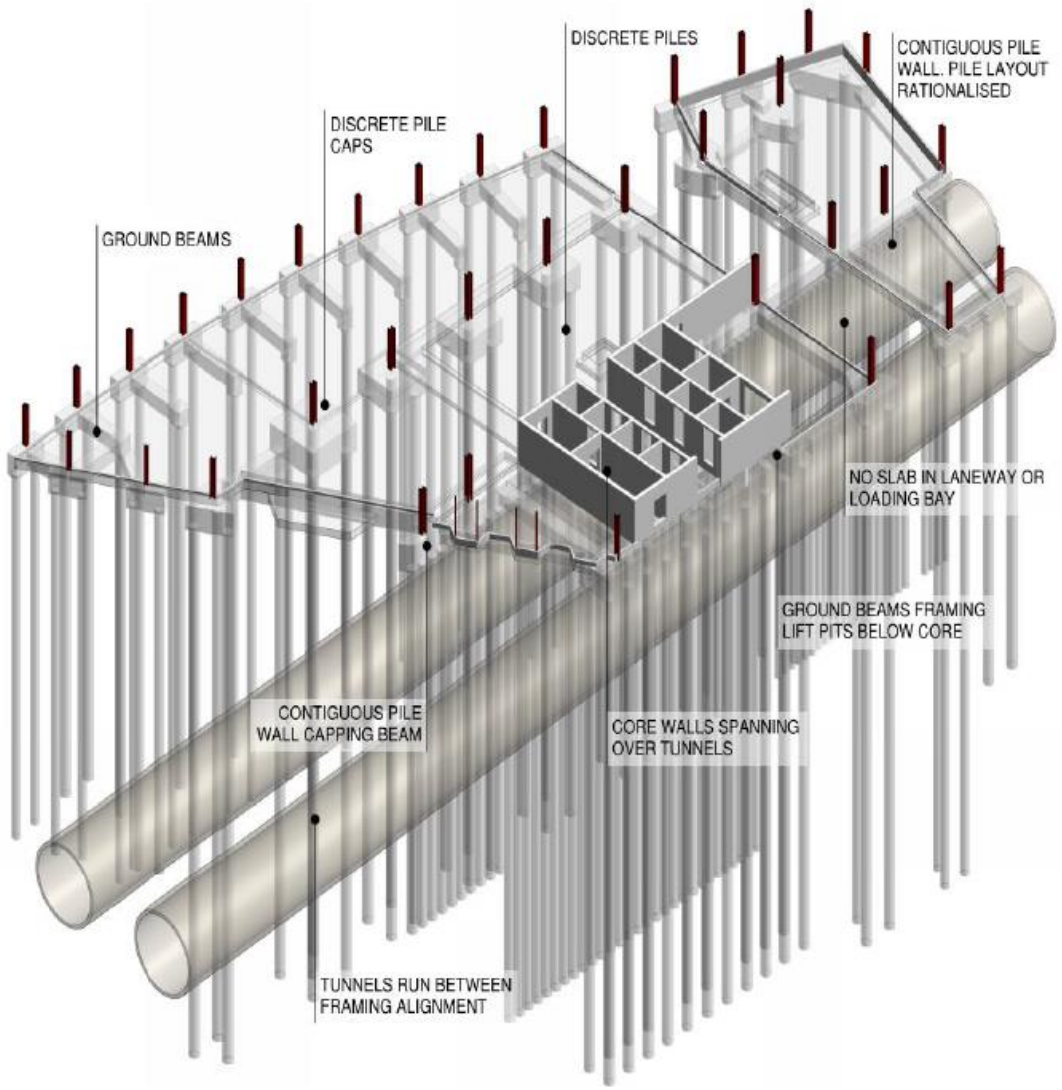


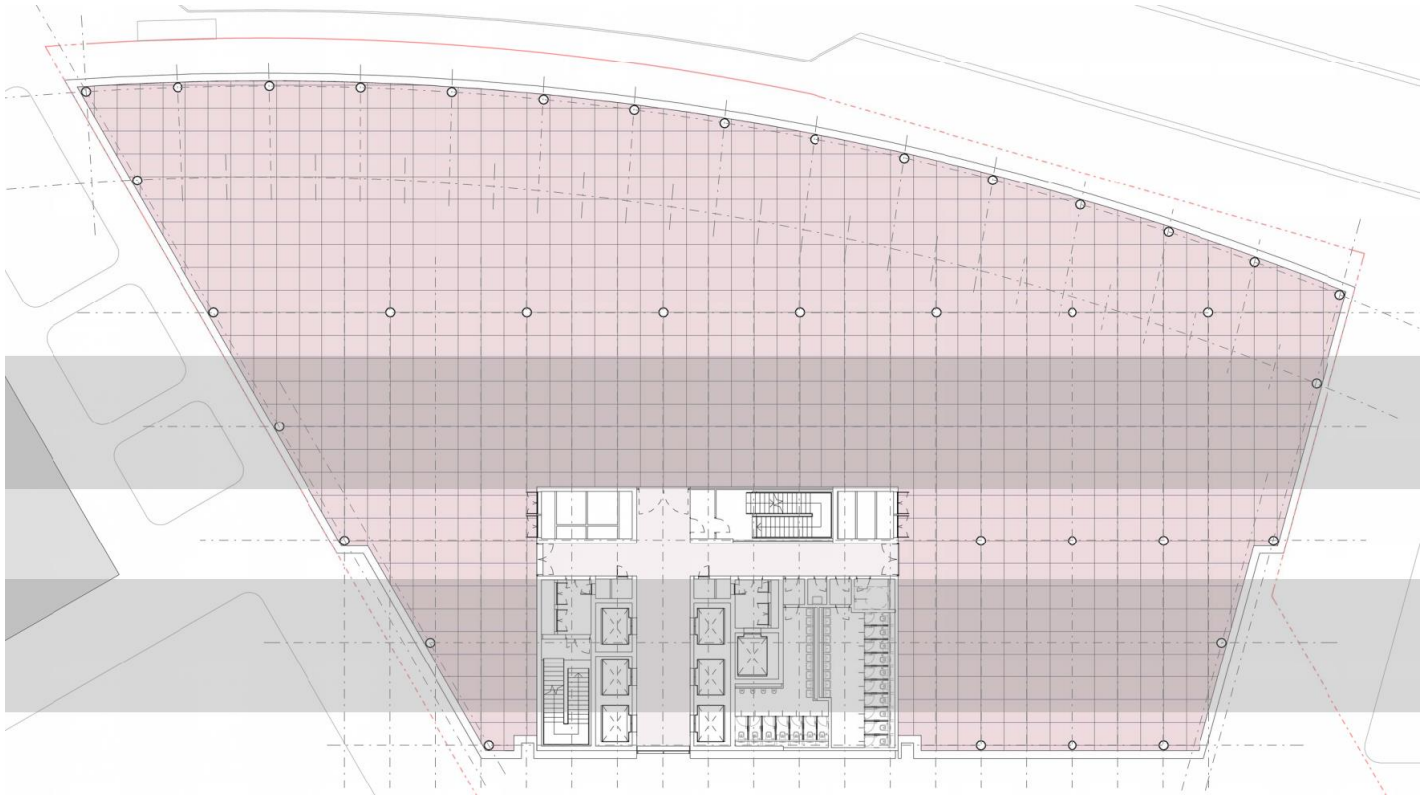
King’s Cross Plot S3

DEVELOPMENT PROPOSAL

King’s Cross Plot S3

FOUNDATION LAYOUT





- Grid/columns positioned away from tunnels
- Long span beams to avoid transfer
- Concrete core transfers over the tunnels and supported on grid

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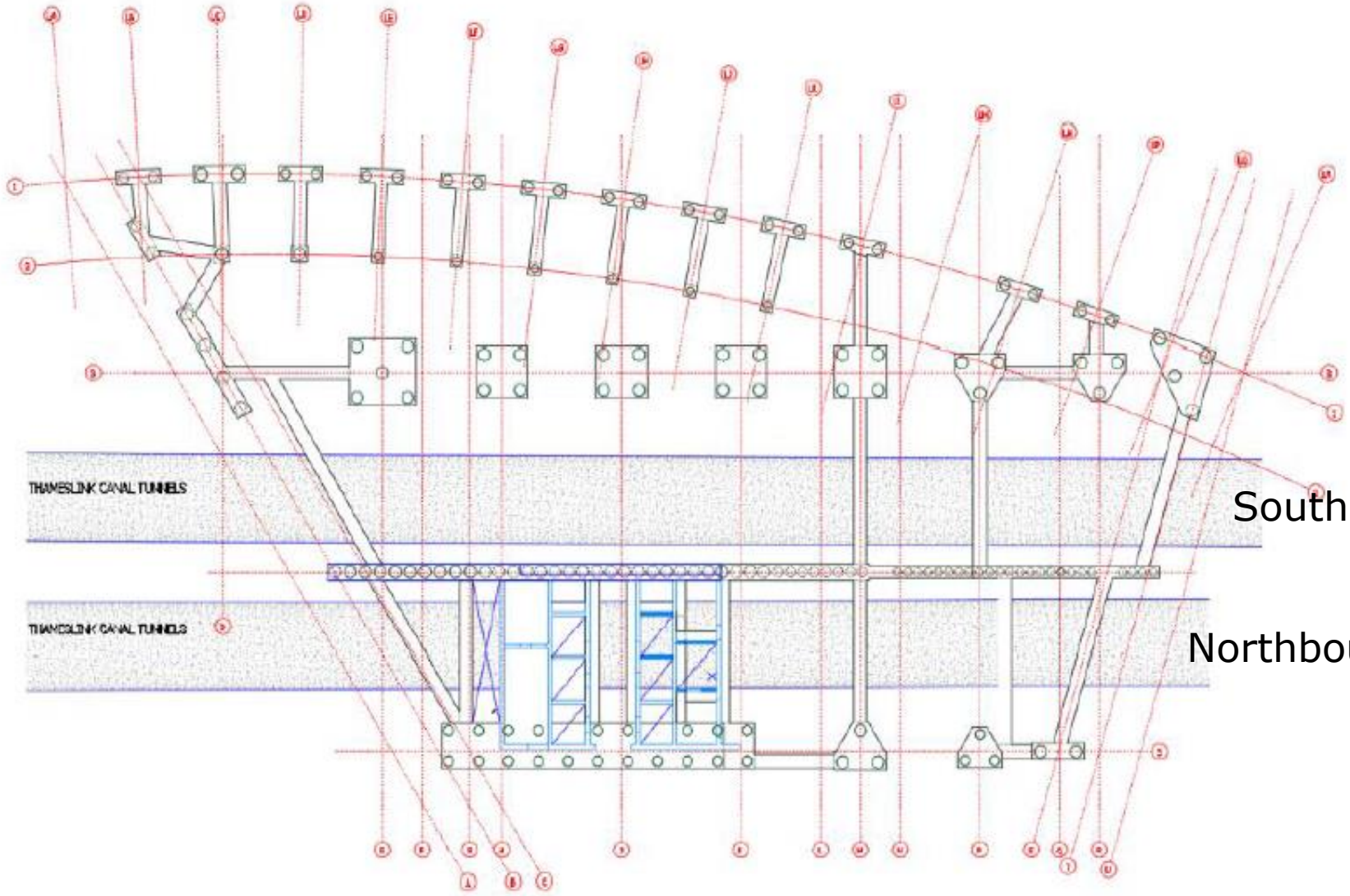
King’s Cross Plot S3

FOUNDATION LAYOUT



LEGEND:

- Contiguous Pile ø600mm, L=30m
- Contiguous Pile ø750mm, L=40m
- Contiguous Pile ø900mm, L=30m
- Contiguous Pile ø900mm, L=40m
- Discreet Pile ø900mm, L=30m
- Discreet Pile ø900mm, L=40m

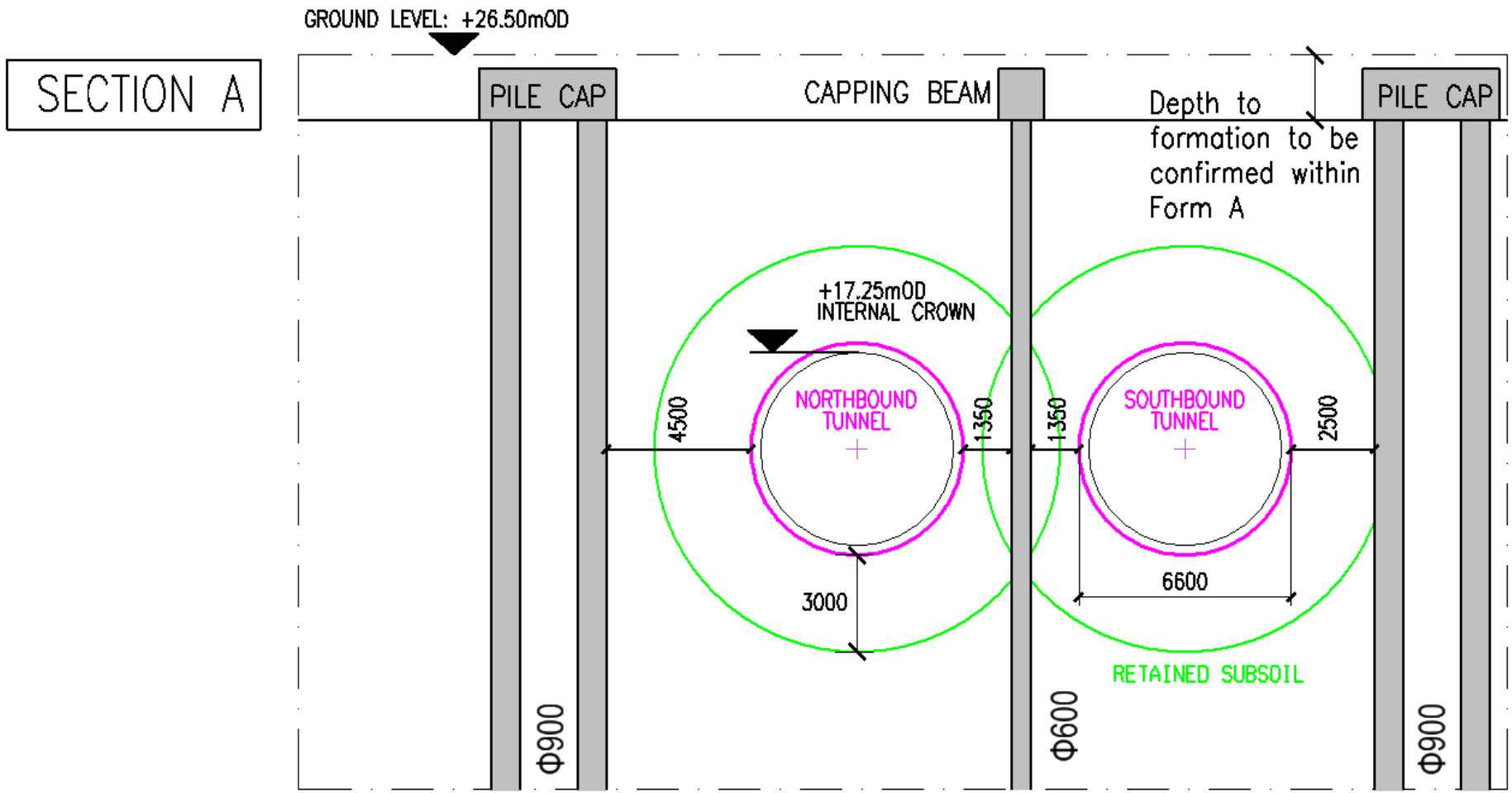
Southbound Tunnel

Northbound Tunnel

Figure 2-2: Pile Arrangement Adjacent to Tunnels

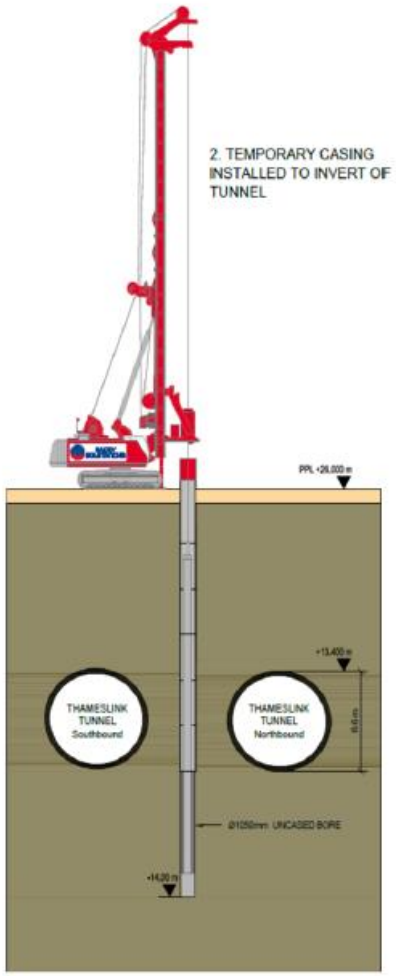
King’s Cross Plot S3

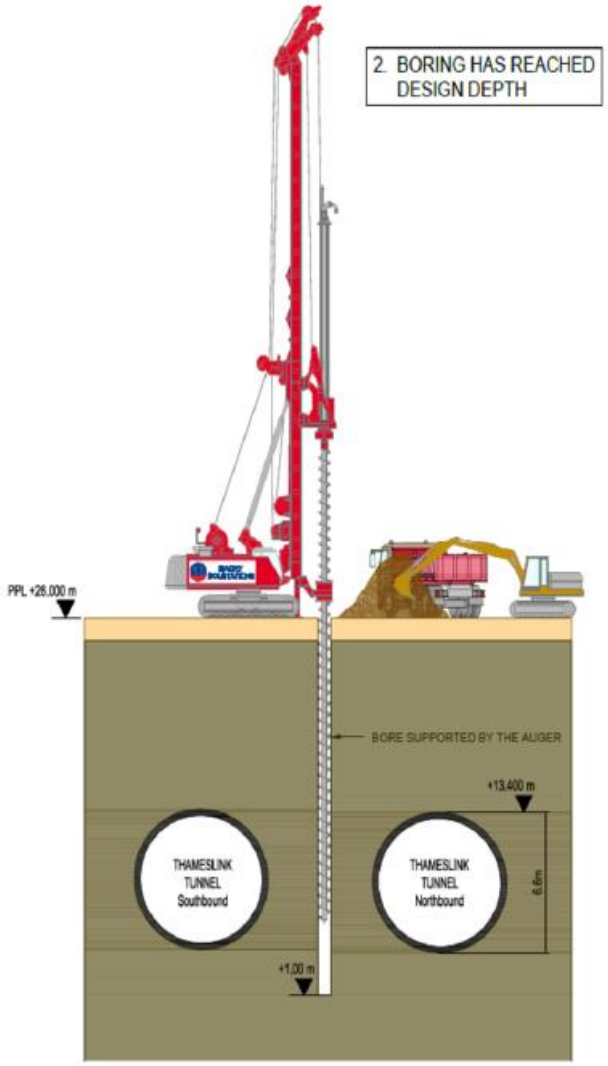
FOUNDATION LAYOUT



King’s Cross Plot S3

FOUNDATION LAYOUT – PILING TECHNIQUES

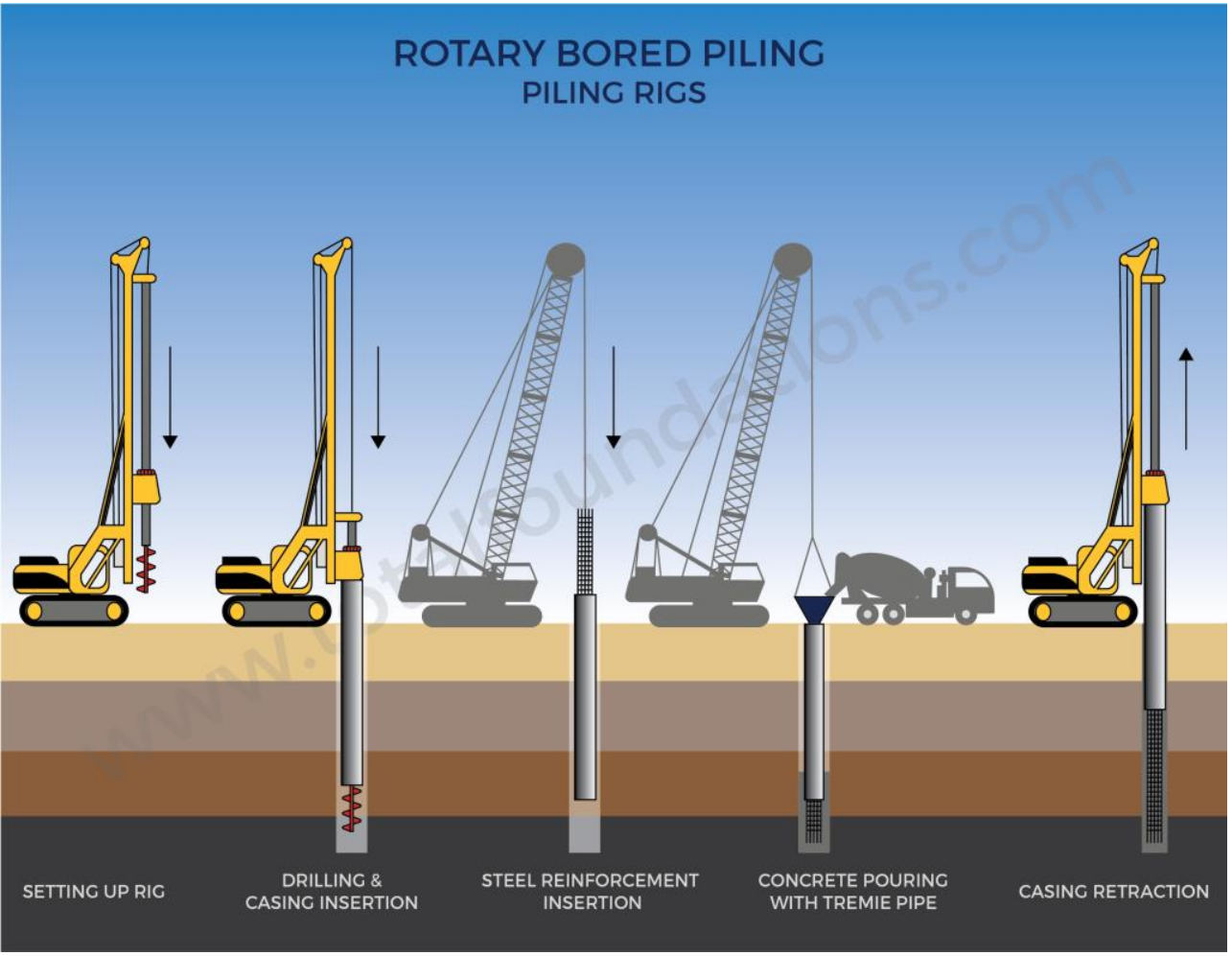




- **CFA (Continuous Flight Auger)** Technique
- Eliminates vibration and disturbance to adjacent structures
- Technique limited by length of auger rig.
- Suitable for medium dense sands and gravels to stiff clays
- Not recommended for very soft clays or loose sands.
- Casing can installed for a portion of length

King’s Cross Plot S3

FOUNDATION LAYOUT – PILING TECHNIQUES



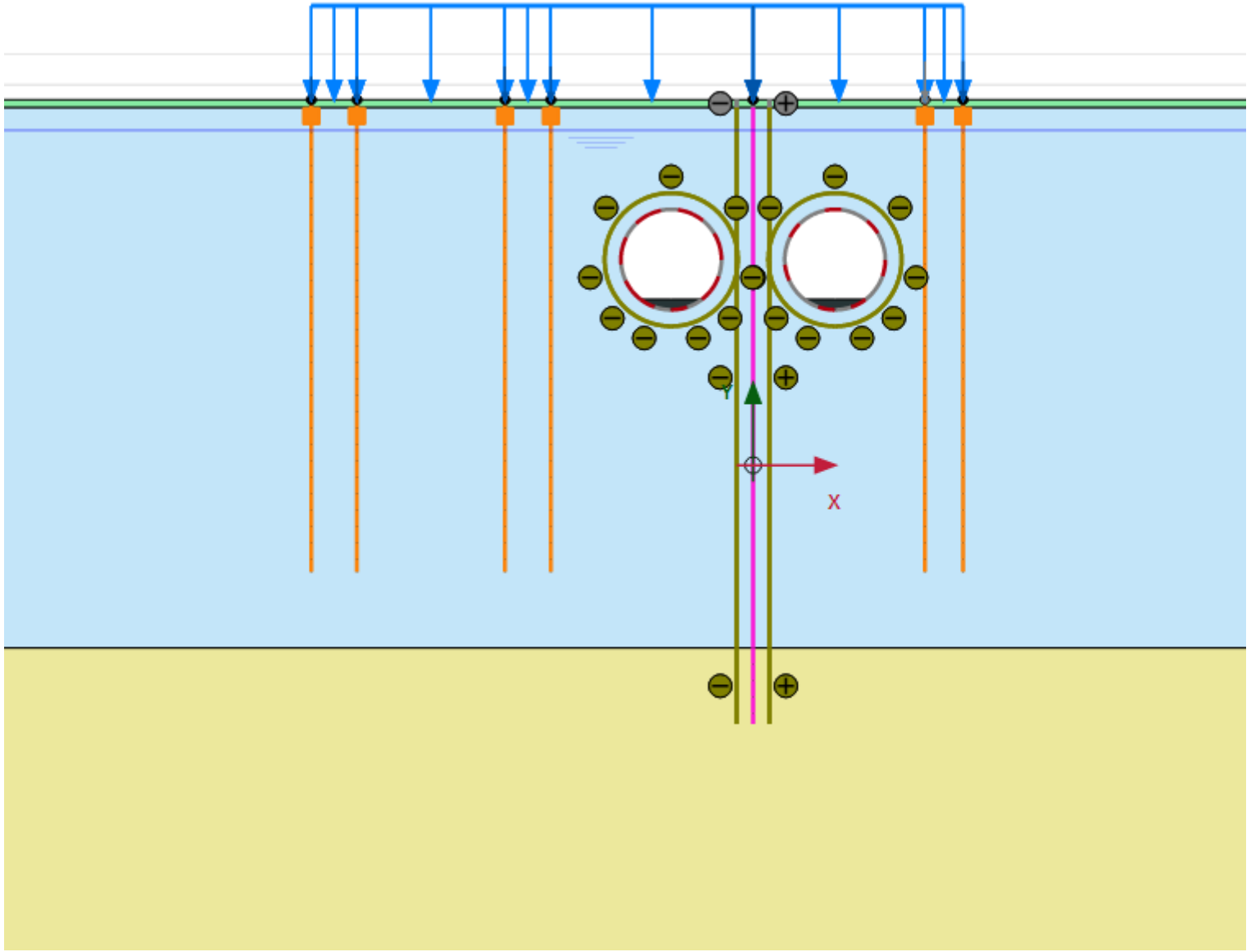
- **Rotary Bored Technique**
- Eliminates vibration and disturbance to adjacent structures
- Cases required, depending on soil properties
- Allows for longer piles (up to 65m)
- Allows for complex pile instrumentation and load cells
- Larger diameters

King’s Cross S3

FOUNDATION LAYOUT – NUMERICAL ANALYSIS

Plaxis 2D Studies

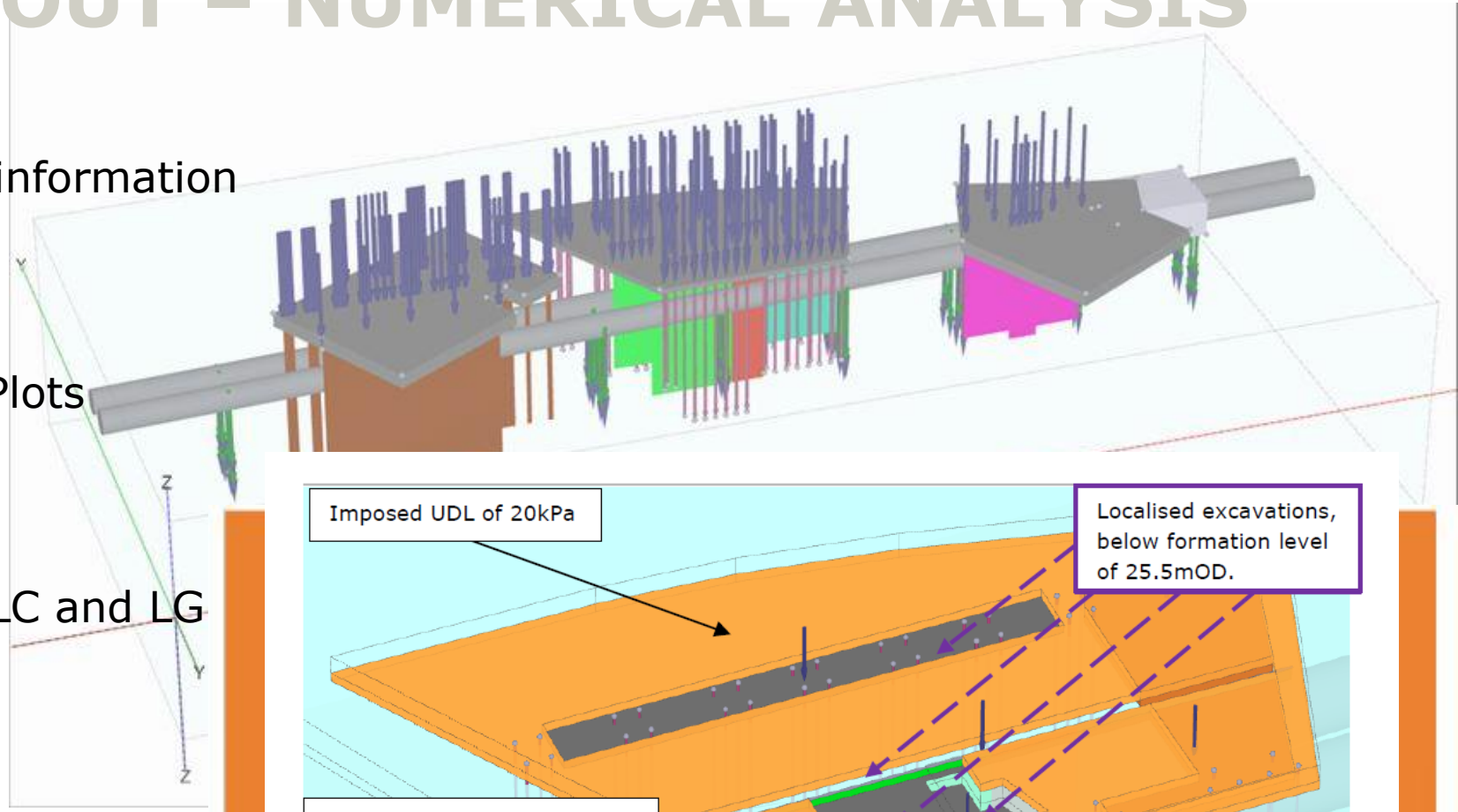
- HSSS Soil Model
- MC Soil Model
- Excavation depth
- Clay Permeability
- Tunnel Permeability
- Tunnel Reticulation



King's Cross S3 & S1 & S5

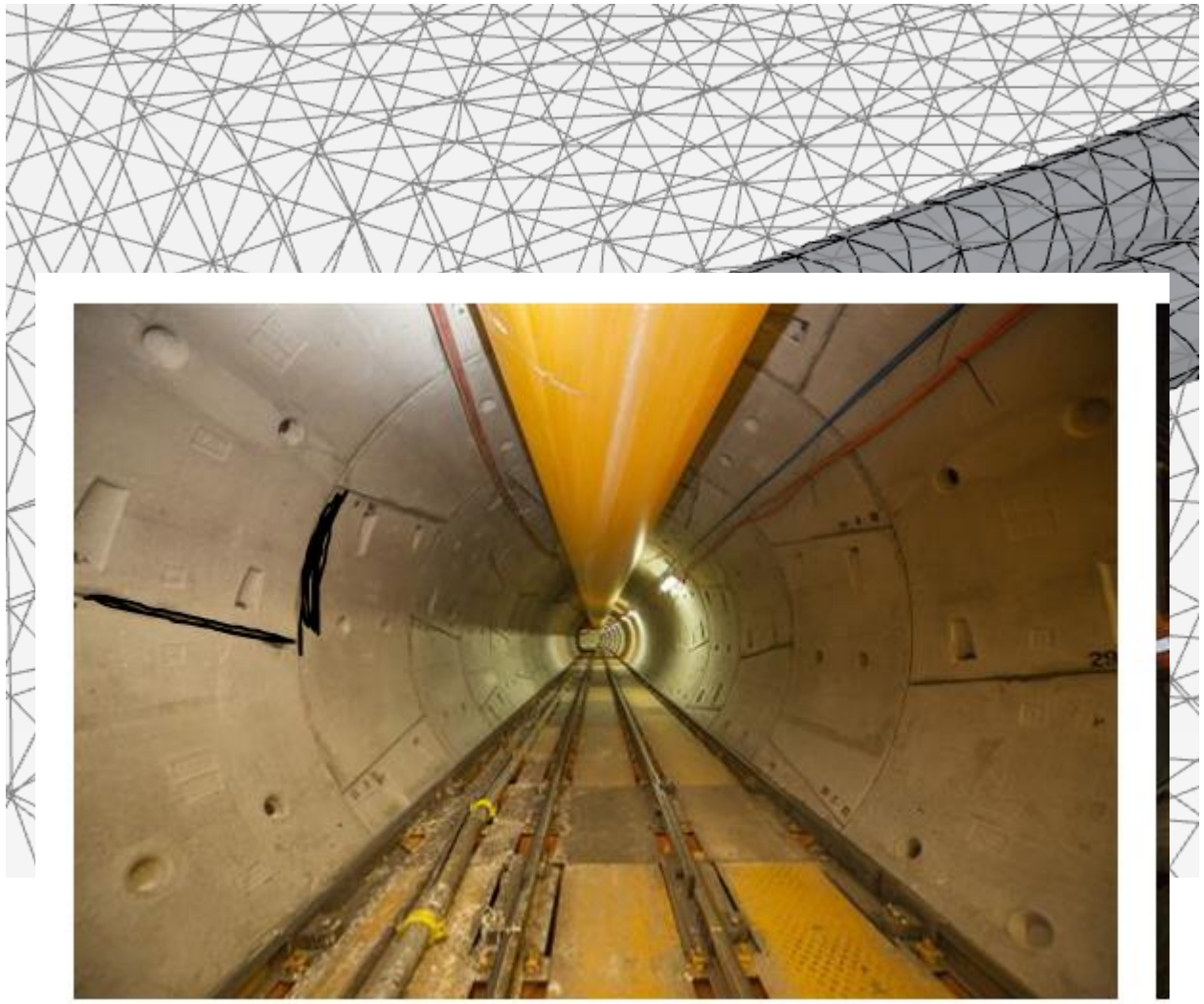
FOUNDATION LAYOUT – NUMERICAL ANALYSIS

- Ground Model based on S1 & S5 information
- 3D Plaxis baseline model with:
  - Stage construction for all Plots
  - Modelling of bored tunnels
  - HSSS Soil Parameters for LC and LG
- 2D Plaxis cross-section studies
- P-Disp & Cemset validation



King’s Cross S3

FOUNDATION LAYOUT – NUMERICAL ANALYSIS



Tunnel Elements

- Plates with lining thickness and stiffness properties as defined below.

Tunnel Reticulation

- The reticulation of the lining may affect its stiffness (upper and lower bounds)
- Bored Tunnels (lower-bound): 12GPa

Consolidation Phase

11 years

King's Cross S3

FOUNDATION LAYOUT – NUMERICAL ANALYSIS

Row of Contiguous Piles - Plates (PLAXIS3D):

Plate elements with positive and negative interfaces. Rint=0.67 (roughness) for London Clay modelling the correct interaction between soil and piles.

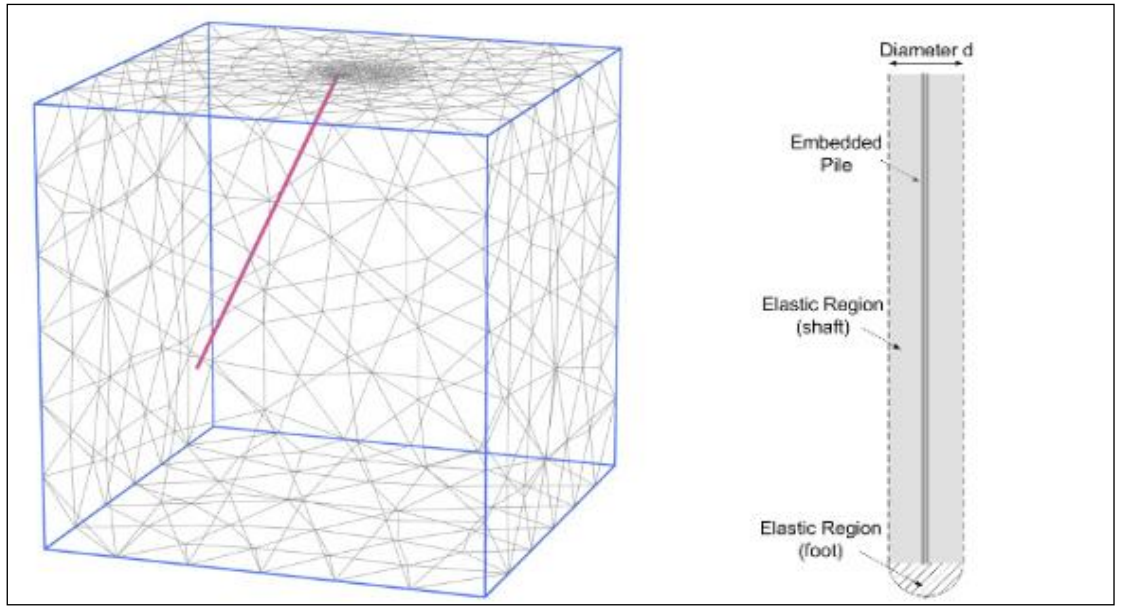
Plate properties depending on pile diameter and spacing.

Discreet Piles – Embedded Beams (PLAXIS3D):

Stiffness properties entered per pile assuming linear behaviour (E=35GPa).

Coupled via interface indirectly with mesh.

Properties based on calibration of single pile displacements – axial skin resistance and base resistance.



King’s Cross S3

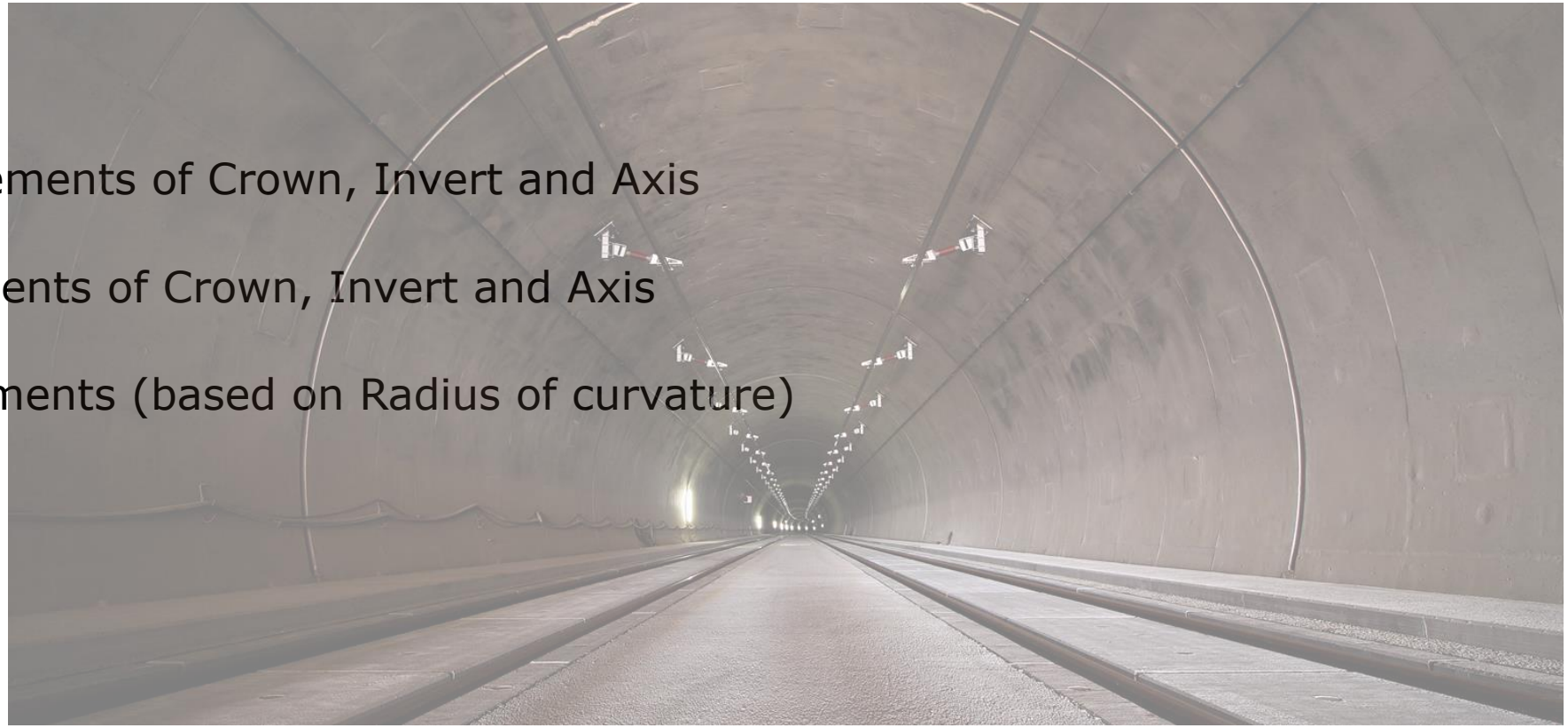
FOUNDATION LAYOUT – MOVEMENT & IMPACT ASSESSMENTS

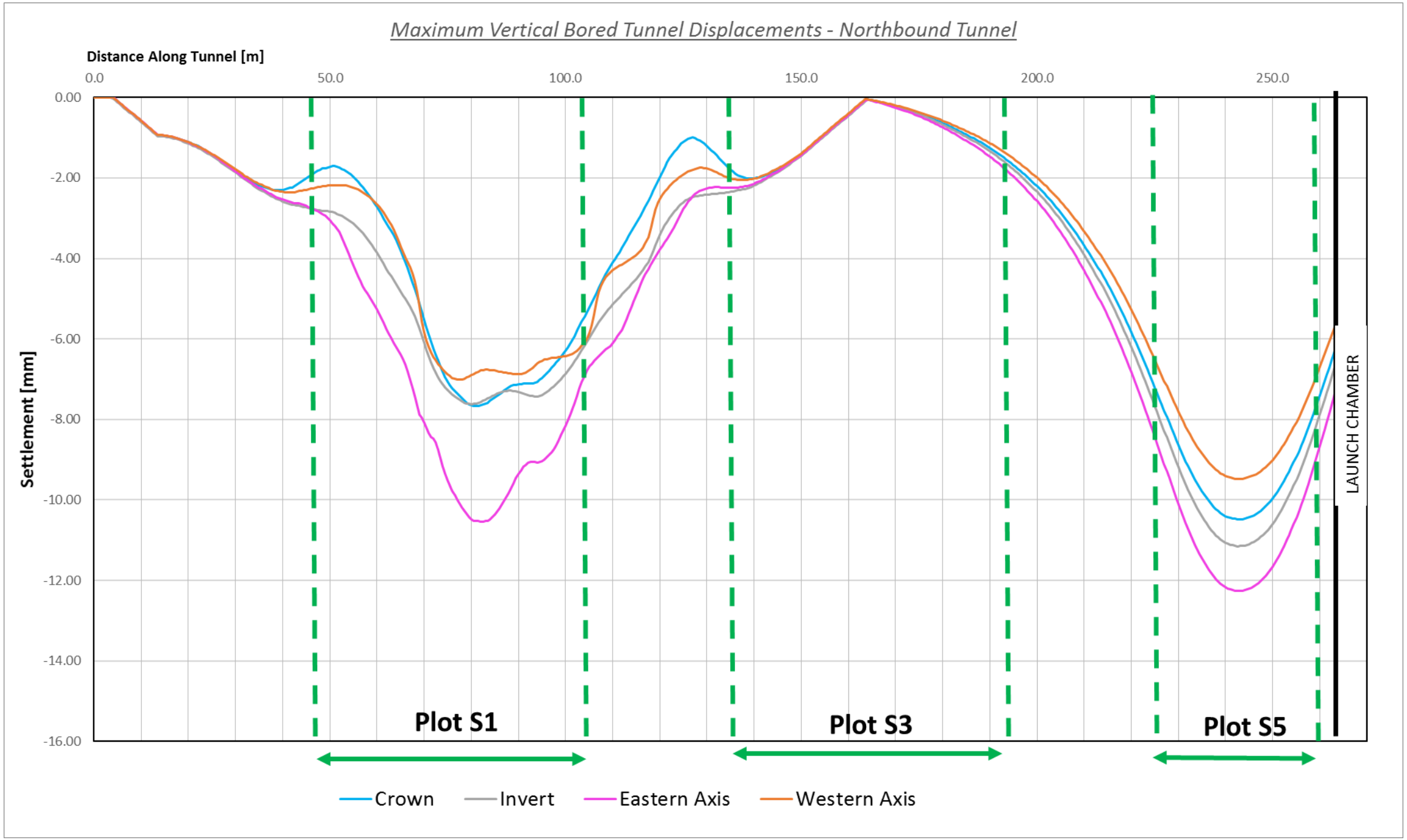
Most Relevant assessments are:

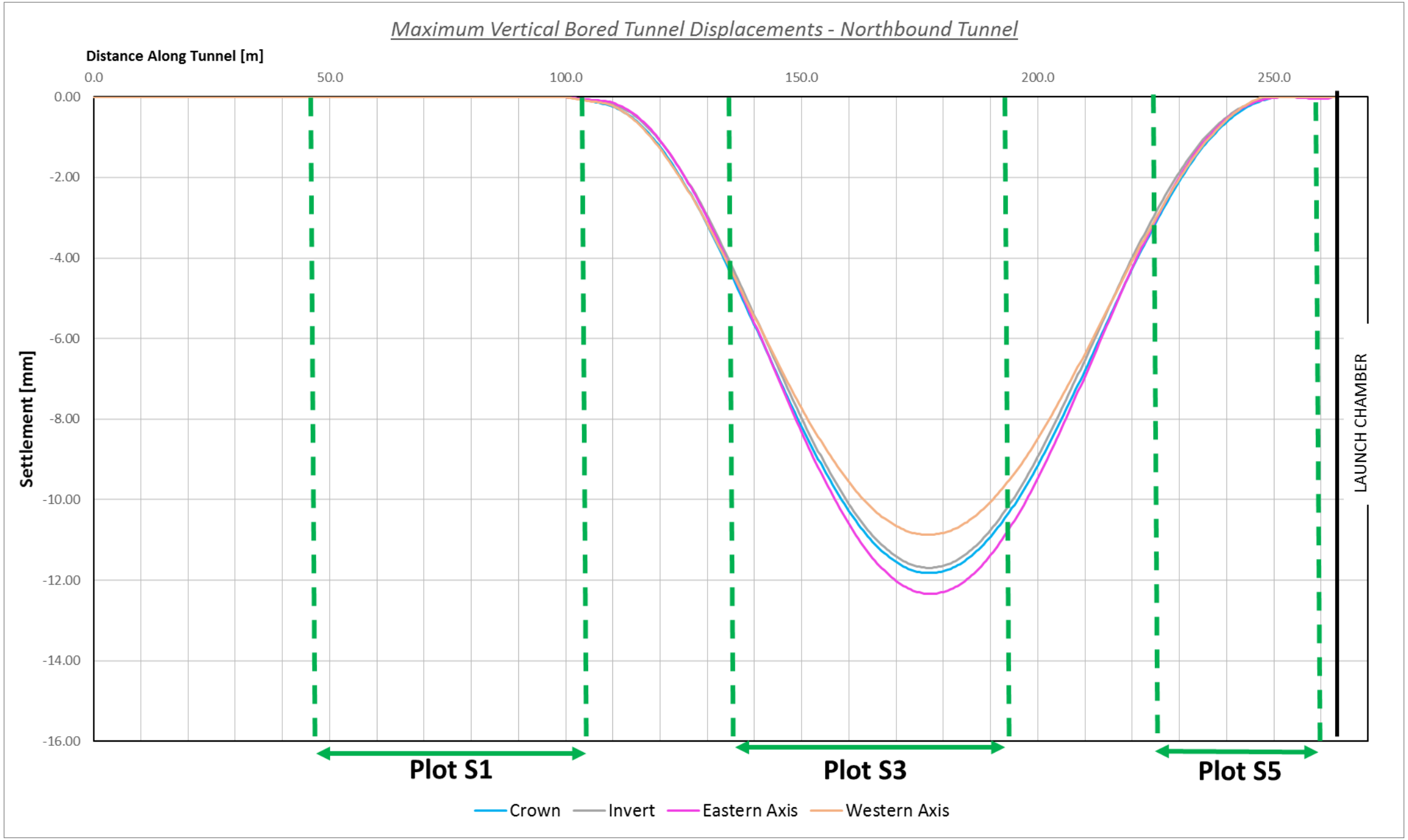
- Longitudinal Tunnel Movements of Crown, Invert and Axis

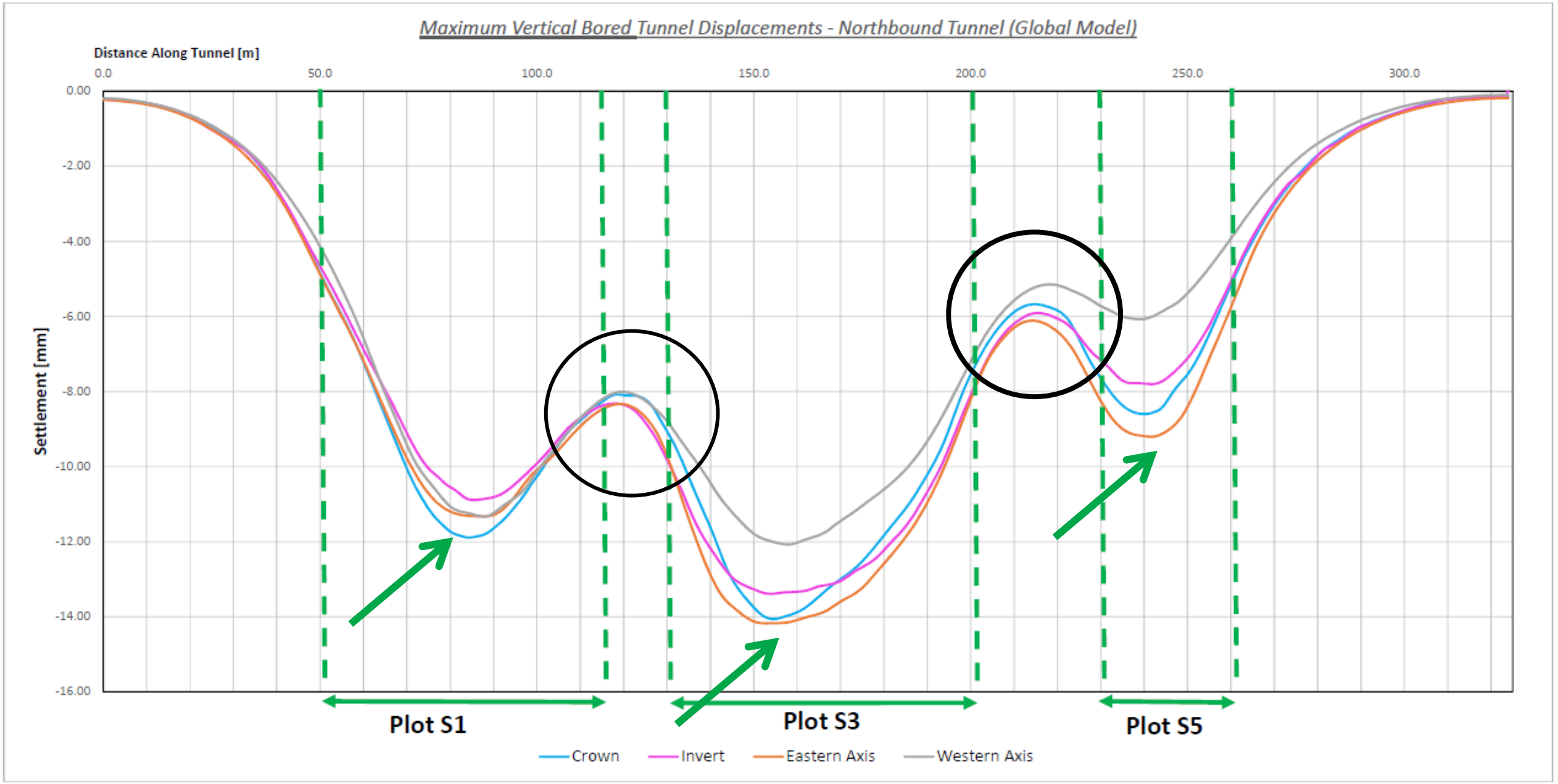
- Horizontal Tunnel Movements of Crown, Invert and Axis

- Assets Structural Assessments (based on Radius of curvature)




Maximum Vertical Bored Tunnel Displacements - Northbound Tunnel
Distance Along Tunnel [m]
0.0
50.0
100.0
150.0
200.0
250.0
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
-16.00
Settlement [mm]
LAUNCH CHAMBER
Plot S1
Plot S3
Plot S5
Crown
Invert
Eastern Axis
Western Axis


Maximum Vertical Bored Tunnel Displacements - Northbound Tunnel
Distance Along Tunnel [m]
0.0
50.0
100.0
150.0
200.0
250.0
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
-16.00
Settlement [mm]
LAUNCH CHAMBER
Plot S1
Plot S3
Plot S5
Crown
Invert
Eastern Axis
Western Axis


Maximum Vertical Bored Tunnel Displacements - Northbound Tunnel (Global Model)
Distance Along Tunnel [m]
0.0
50.0
100.0
150.0
200.0
250.0
300.0
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
-16.00
Settlement [mm]
Plot S1
Plot S3
Plot S5
Crown
Invert
Eastern Axis
Western Axis

King’s Cross Plots
TQ Rail Movements

- Allowable rail movements assume that the installation tolerances have been fully used.
- Allowable rail movements comprise the maintenance tolerances minus the installation tolerances.

Parameter	Value [mm]
Absolute vertical alignment	+0,-15
Absolute horizontal alignment	±19
Cross-level variation (Cant)	±5
Rate of change of vertical alignment (over 10m offsets)	6
Rate of change of horizontal alignment (over 10m offsets)	4
Twist (over 4m offsets)	4

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King's Cross Plots
Tunnel Assessments

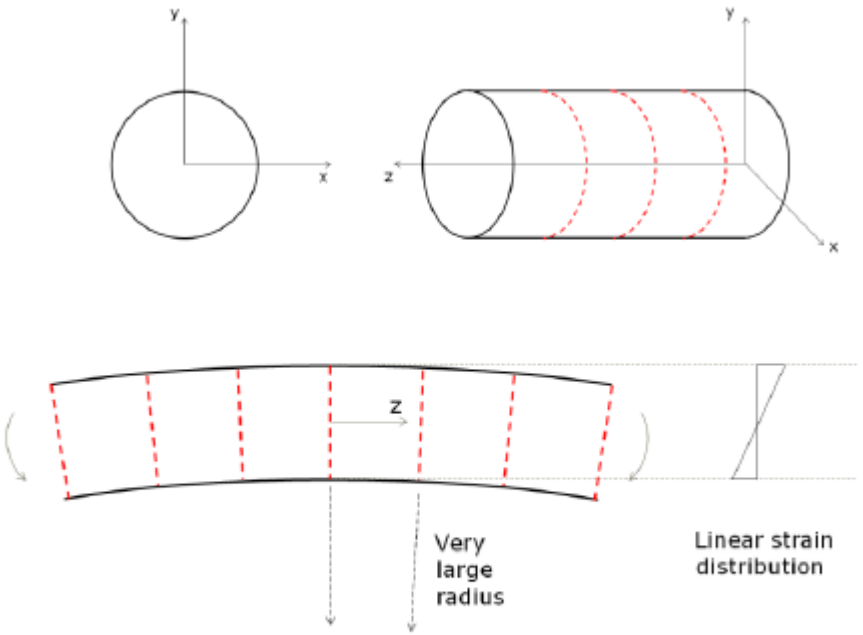


Figure 9-1: Curvature of the Tunnel along its Length

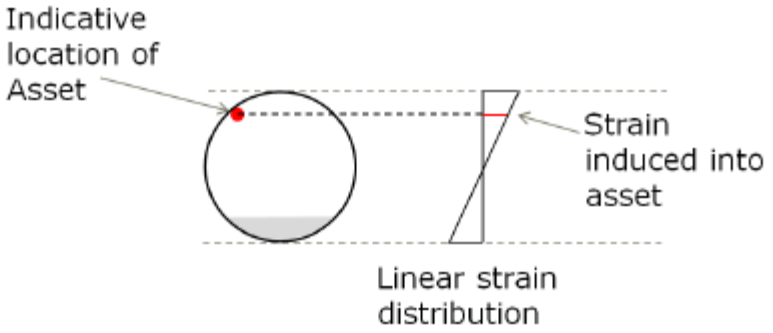


Figure 9-2: Determination of Strain in the Assets Rigidly Attached to the Lining

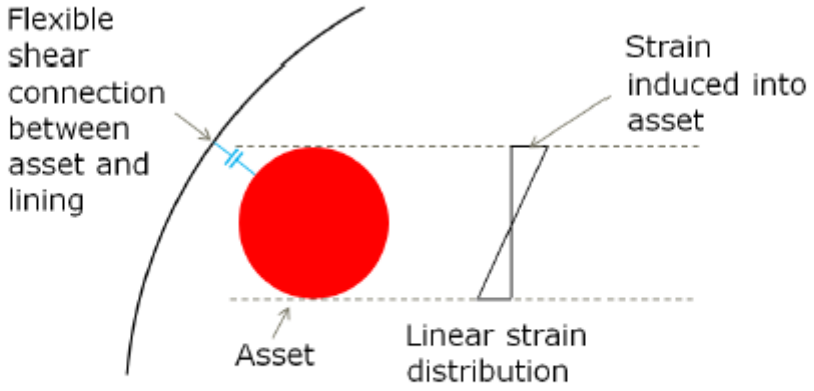


Figure 9-3: Determination of Strain in Assets Bending Independently to the Tunnel

King’s Cross Plots

Structural assessments of fit-out elements (1/2)

KINGS CROSS CENTRAL - PLOT S3

FORM B - STRUCTURAL ASSESSMENT OF FIT-OUT ASSETS

TRACK SLAB (SHEET 1)

PLOT S3 ONLY CASE

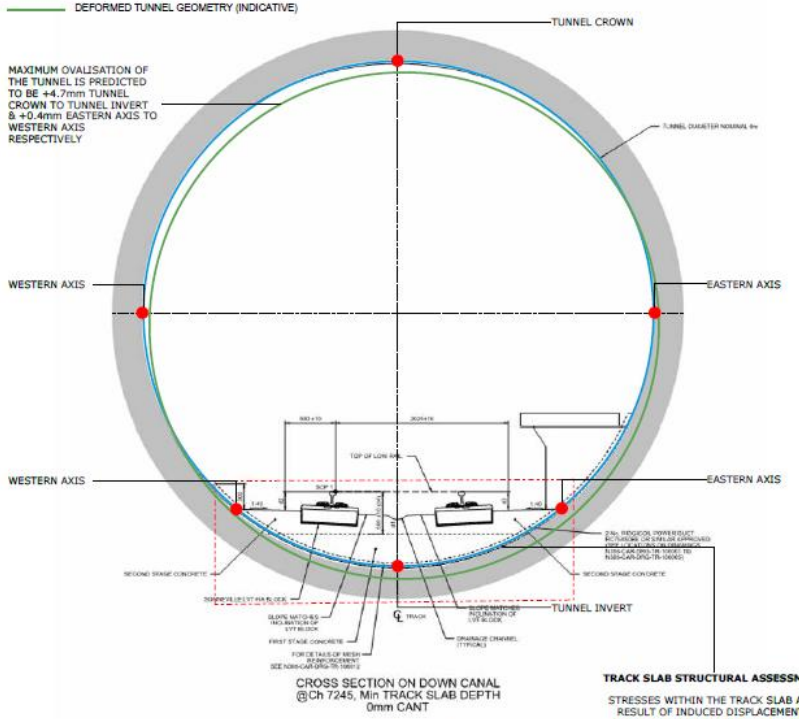
RAMBOLL

Project Title	Kings Cross S3
Project N°	1620005613
Sketch N°	1620005613_S_SK090
Title	See Title
Scale	NTS

Eng:	Rev:	Date:	Checked:
RC	P01	08/11/19	ME

AS BUILT TUNNEL GEOMETRY

DEFORMED TUNNEL GEOMETRY (INDICATIVE)



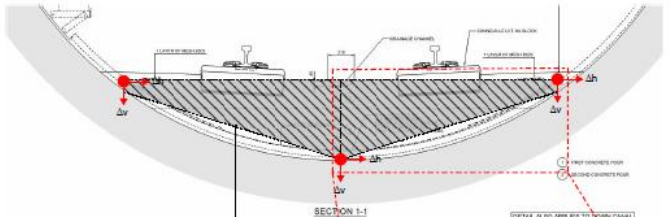
CROSS SECTION ON DOWN CANAL @Ch 7245, Min TRACK SLAB DEPTH 0mm CANT

SECTION A-A

TYPICAL TUNNEL CROSS SECTION WITH TRACK SLAB

TRACK SLAB STRUCTURAL ASSESSMENT

STRESSES WITHIN THE TRACK SLAB AS A RESULT OF INDUCED DISPLACEMENTS VERTICALLY AND HORIZONTALLY HAVE BEEN CONSIDERED. WHERE STRESSES EXCEED THE TENSILE CAPACITY OF THE CONCRETE CRACK, RESULTING CRACK WIDTH HAVE BEEN CALCULATED. IT HAS BEEN CONSERVATIVELY ASSUMED THE TENSILE STRAIN IS DISSIPATED AT A SINGLE CRACK LOCATION.

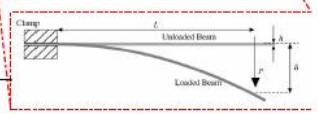


SECTION B-B

TRACK SLAB CROSS SECTION

TRACK SLAB IDEALISED AS A TAPERING BEAM WITH TUNNEL DISPLACEMENTS PREDICTED AT WESTERN AXIS, EASTERN AXIS & TUNNEL INVERT

TRACK SLAB ASSUMED TO BE PINNED AT EASTERN AXIS AND WESTERN AXIS. INDUCED VERTICAL DISPLACEMENT AT TUNNEL INVERT APPLIED TO TAPERED BEAM. SIMPLY SUPPORTED BEAM ANALYSISED AS A FIXED CANTILEVER WITH POINT LOAD



VERTICAL DISPLACEMENT EQUIVALENT POINT LOAD

$$\delta_v = -\frac{P}{3Eu}\ln\left(\frac{L^3 u}{I_o}+1\right)$$

HORIZONTAL DISPLACEMENT EQUIVALENT POINT LOAD

$$\delta_h = -\frac{P}{3k}\ln\left(\frac{kL}{A_o}+1\right)$$

ASSUMPTIONS

1. SLAB IS FULLY BONDED TO TUNNEL LINING WITH SHEAR KEYING ALLOW FOR NO-SLIP
2. NO ADDITIONAL LOADING HAS BEEN ASSUMED (SRINKAGE, CREEP, THERMAL)
3. CONCRETE ASSUMED C30/37 AS PER NETWORK RAIL DRAWING "N306-CAR-DRG-TR-106012"
5. INDUCED VERTICAL DEFLECTIONS CAUSING COMPRESSIVE STRAIN IN THE TOP OF THE TRACK SLAB ARE ASSUMED TO BE BENIFICIAL AND NOT CONSIDERED.
6. LOADING IS TREATED AS ACCIDENTAL LOADING AS PER "EC0 6.4.3.3; Eq 6.11b"

GENERAL NOTES

1. SKETCHES ARE SCHEMATIC ONLY AND NOT TO SCALE;
2. SKETCHES SHOULD BE READ IN CONJUNCTION WITH ALL RELEVENT ENGINEERS AND ARCHITECTURAL DOCUMENTATION;
3. ALL DIMENSIONS ARE MILLIMETRES U.N.O
4. ALL LEVELS ARE IN METRES ABOVE ORDINANCE DATUM U.N.O
5. SKETCHES ARE PRELIMINARY ONLY AND ARE TO BE DEVELOPED DURING DESIGN DEVELOPMENT

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King’s Cross Plots

Structural assessments of fit-out elements (2/2)

KINGS CROSS CENTRAL - PLOT S3

FORM B - STRUCTURAL ASSESSMENT OF FIT-OUT ASSETS

TRACK SLAB (SHEET 3)

PLOT S3 ONLY CASE

RAMBOLL

Project Title	Kings Cross S3		
Project N°	1620005613		
Sketch N°	1620005613_S_SK092		
Title	See Title		
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Eng:	Rev:	Date:	Checked:
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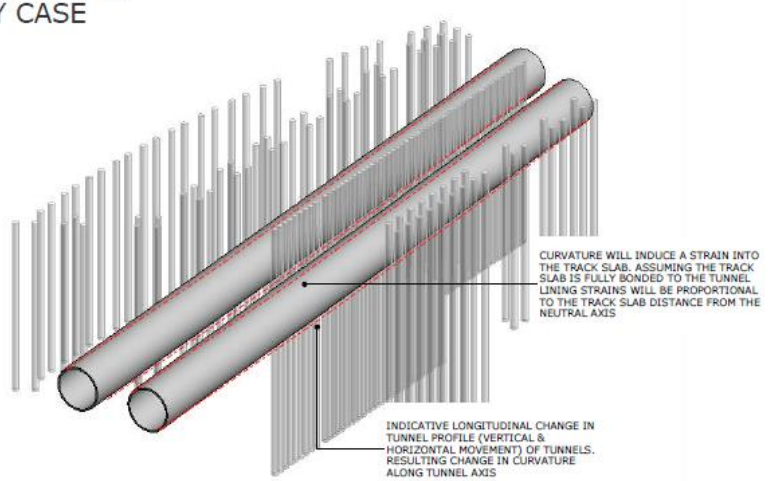


3D VIEW

THAMESLINK CANAL TUNNELS AND CONTIG PILES

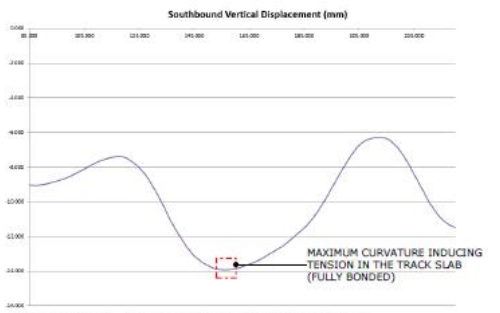
SOUTHBOUND MOBILISED TRACK SLAB		
Min Radius of Curvature	16.05	km
Max strain	1.81E-04	
Min strain	-1.74E-04	
Max stress	3.11	MPa
Min stress	-2.99	MPa
hc,eff	150	mm
ρp,eff	0.34%	%
Sr,max	925	mm
Crack Size	0.167634	mm

NORTHBOUND MOBILISED TRACK SLAB		
Min Radius of Curvature	17.81132	km
Max strain	1.63E-04	
Min strain	-5.43E-05	
Max stress	2.79	MPa
Min stress	-0.93	MPa
hc,eff	150	mm
ρp,eff	0.34%	%
Sr,max	925	mm
Crack Size	0.150606	mm

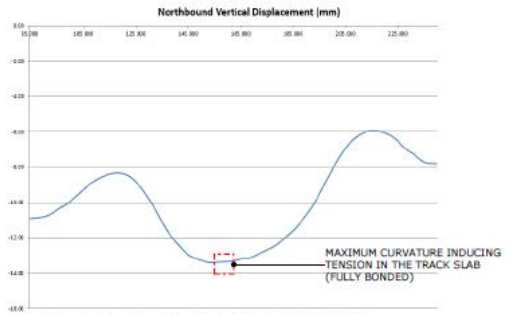
TRACK SLAB STRUCTURAL ASSESSMENT

STRESSES WITHIN THE TRACK SLAB AS A RESULT OF INDUCED CURVATURES HAVE BEEN CONSIDERED. THE CURVATURE DUE TO HORIZONTAL MOVEMENT IS NEGLIGIBLE AND HAS NOT BEEN CONSIDERED. WHERE STRESSES EXCEED THE TENSILE CAPACITY OF THE CONCRETE RESULTING CRACK WIDTH HAVE BEEN CALCULATED.

1. MAX CRACK WIDTH AND MAX CRACK SPACING (Wk, Sr,max) HAS BEEN CALCULATED IN ACCORDANCE WITH EC2 c.7.3.4
2. MEAN STRAIN WITHIN THE CONCRETE BETWEEN SECTIONS HAS BEEN NEGLECTED FOR CALCULATION PURPOSES
3. COVER HAS BEEN ASSUMED TO BE 60mm AS STATED WITHIN NETWORK RAIL DRAWING "N306-CAR-DRG-TR-106012"
4. LOADING IN TREATED AS ACCIDENTAL LOADING AS PER "EC0 6.4.3.3; Eq 6.11b"



DISPLACEMENT (mm) Vs DISTANCE ALONG TUNNEL AXIS (m)



DISPLACEMENT (mm) Vs DISTANCE ALONG TUNNEL AXIS (m)

Table NA.4 — Recommended values of w_{max}

Exposure	Reinforced members and prestressed members without bonded tendons (quasi-permanent load combination) mm	Prestressed members with bonded tendons (frequent load combination) mm
X0, XC1	0,3[a]	0,2
XC2, XC3, XC4	0,3	0,2[b]
XD1, XD2, XD3, XS1, XS2, XS3		0,2 and decompression[c]

[a] For X0, XC1 exposure classes, crack width has no influence on durability and this limit is set to produce acceptable appearance. In the absence of specific requirements for appearance this limit may be relaxed.
[b] For these exposure classes, in addition, decompression should be checked under the quasi-permanent combination of loads.
[c] $w_{max} = 0,2$ mm applies to parts of the member that do not have to be checked for decompression.

NA TO EC2 - GUIDANCE ON RECOMMENDED CRACK WIDTH

CONCLUSION

INDUCED CURVATURE WITHIN THE SOUTHBOUND TUNNEL MAY RESULT IN MAXIMUM TENSILE STRESSES OF 3.11MPa. THESE MAY INDUCED MAXIMUM CRACK WIDTH OF 0.17mm AT A MAXIMUM CRACK SPACING OF c 0.9m. THIS IS WITHIN RECOMMENDED VALUES AS GIVEN WITHN EC2 OF 0.3mm. REFER TO UK NA TO EC2 TABLE NA.4

INDUCED CURVATURE WITHIN THE NORTHBOUND TUNNEL MAY RESULT IN MAXIMUM TENSILE STRESSES OF 2.79MPa. THESE MAY INDUCED MAXIMUM CRACK WIDTH OF 0.15mm AT A MAXIMUM CRACK SPACING OF c 0.9m. THIS MEETS THE RECOMMENDED VALUES AS GIVEN WITHN EC2 OF 0.3mm. REFER TO UK NA TO EC2 TABLE NA.4

GENERAL NOTES

1. SKETCHES ARE SCHEMATIC ONLY AND NOT TO SCALE;
2. SKETCHES SHOULD BE READ IN CONJUNCTION WITH ALL RELEVENT ENGINEERS AND ARCHITECTURAL DOCUMENTATION;
3. ALL DIMENSIONS ARE MILLIMETRES U.N.O
4. ALL LEVELS ARE IN METRES ABOVE ORDINANCE DATUM U.N.O
5. SKETCHES ARE PRELIMINARY ONLY AND ARE TO BE DEVELOPED DURING DESIGN DEVELOPMENT

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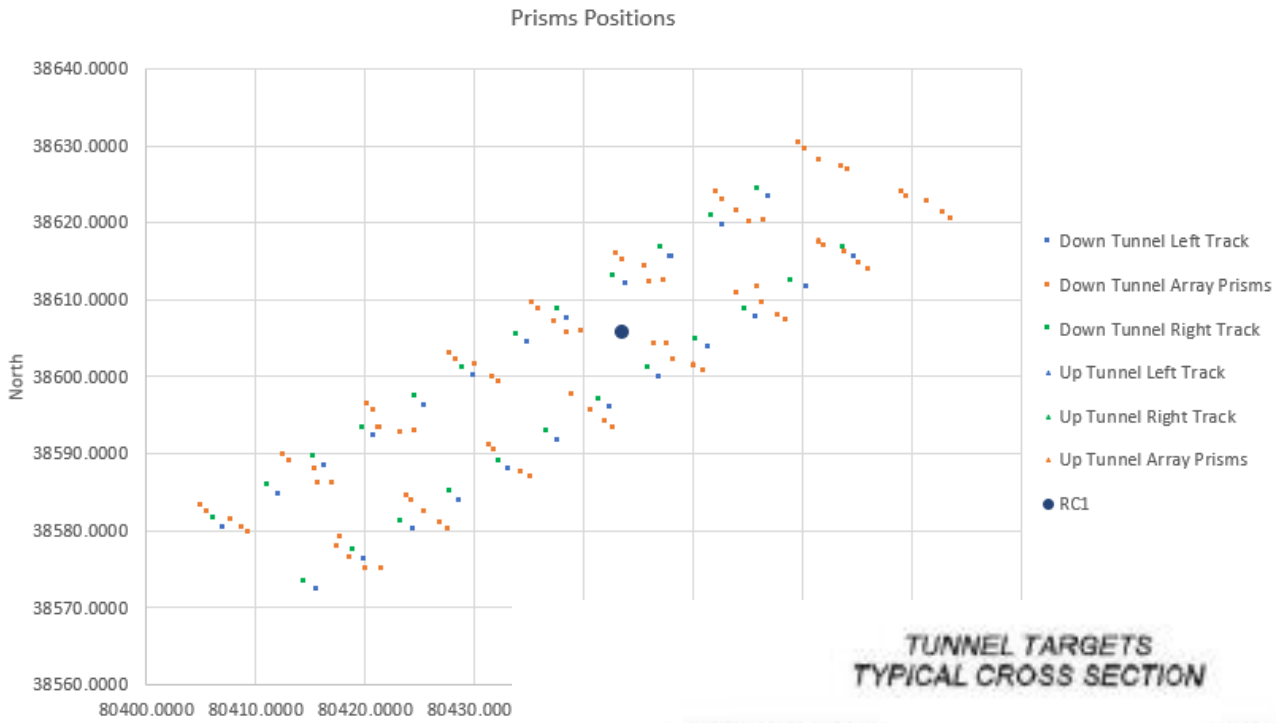
King's Cross Plots Monitoring

- **Monitoring Instrumentation:**
  - Automated monitoring system operational below the tunnels
  - Instrumentation used to monitor tunnels during ongoing construction works
  - Primary system are a series of prism 5 points array attached to segmental linings at 10m intervals and pair of prisms attached to the rails at 6m intervals



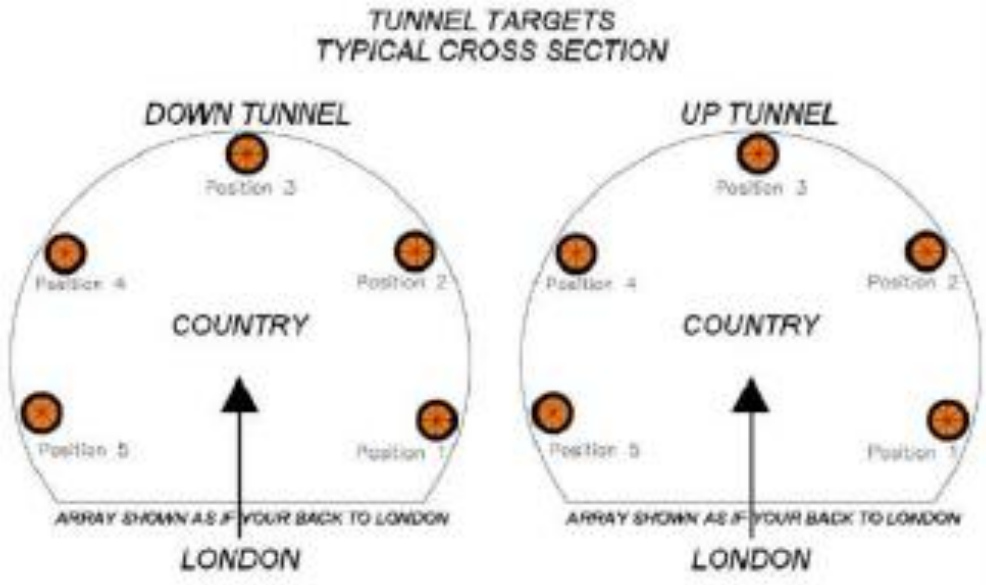


Figure 2.1: Prism Naming Convention

King’s Cross Plots
Summary

- **Numerical Analysis allowed to:**
  - Assess magnitudes of ground movements;

King’s Cross Plots

View of Proposed Development – PLOT S3

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