GeoVIRGINIA 2025

Smithfield Center, Smithfield, Virginia, March 17-19, 2025

Geotechnical Consulting Group

Lessons Learnt from Tunnelling and Urban Infrastructure Construction

Dr Chris Menkiti BSc, MSc PhD ACGI

Senior Principal, Geotechnical Consulting Group



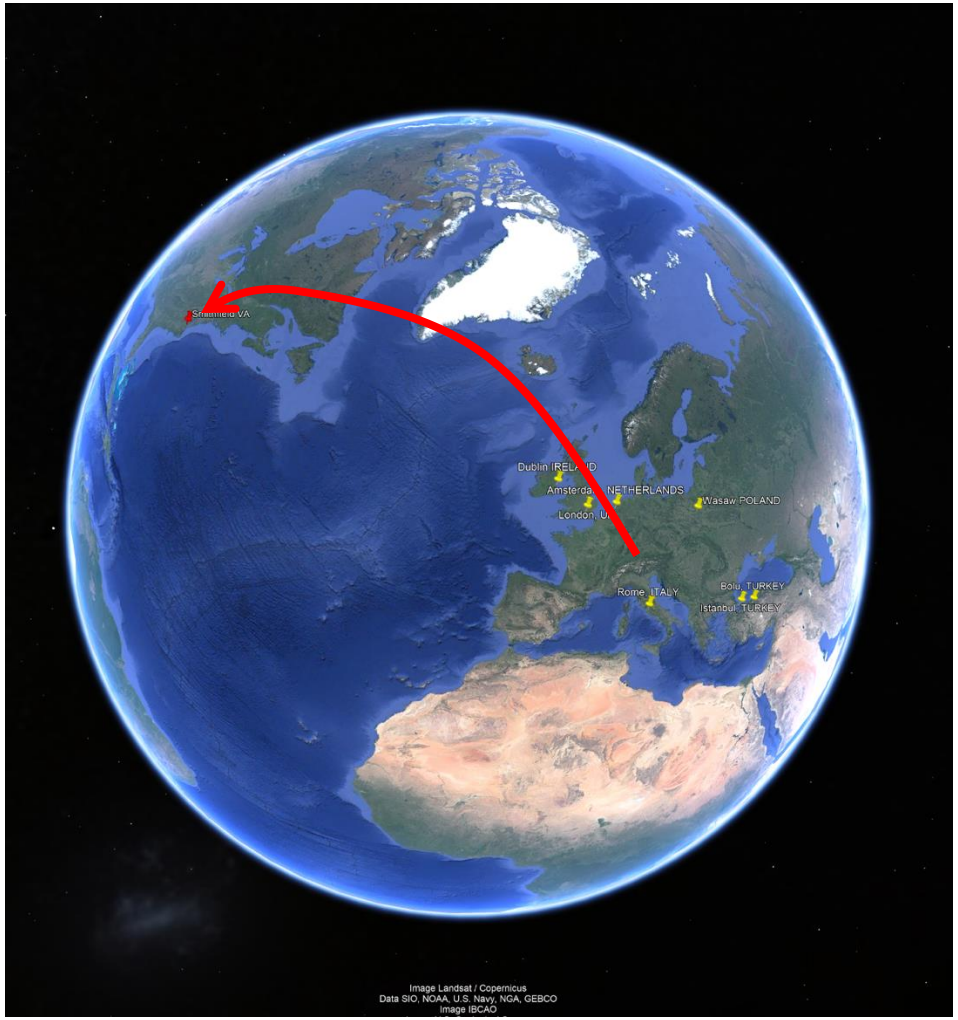
Geotechnical Consulting Group

Proven experts in a geotechnical world

Contents

1. Background
2. Jubilee Line Extension Project (JLEP), London **UK** - Big Ben & Westminster Station, Waterloo Station
3. Bologna High Speed Rail, **Italy**
4. Crossrail Project (The Elizabeth Line), London UK – Bond Street Station, **UK**
5. Forrestfield-Airport Link, Perth **Australia**
6. Warsaw Metro Line C, Warsaw **Poland** – C11 & C13 Stations
7. Conclusions and key lessons

Location of Case Studies







3. Case Studies from Tunnelling in the UK (JLEP & CRL)

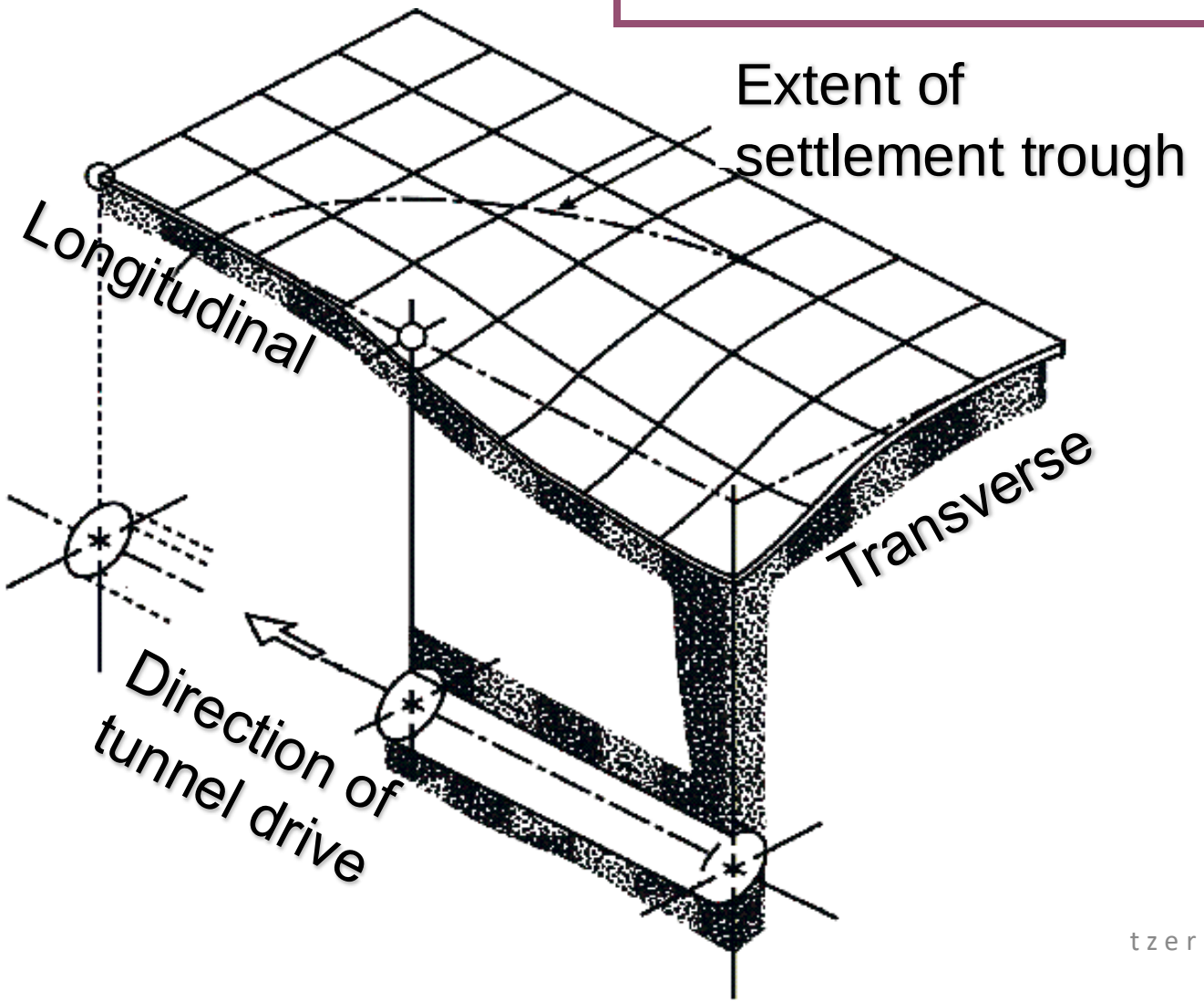
1. Background
2. Jubilee Line Extension Project (JLEP, xxx)
3. Crossrail Project (CRL, Elizabeth Line, Completed xxx)

Ground Movements due to Tunnelling

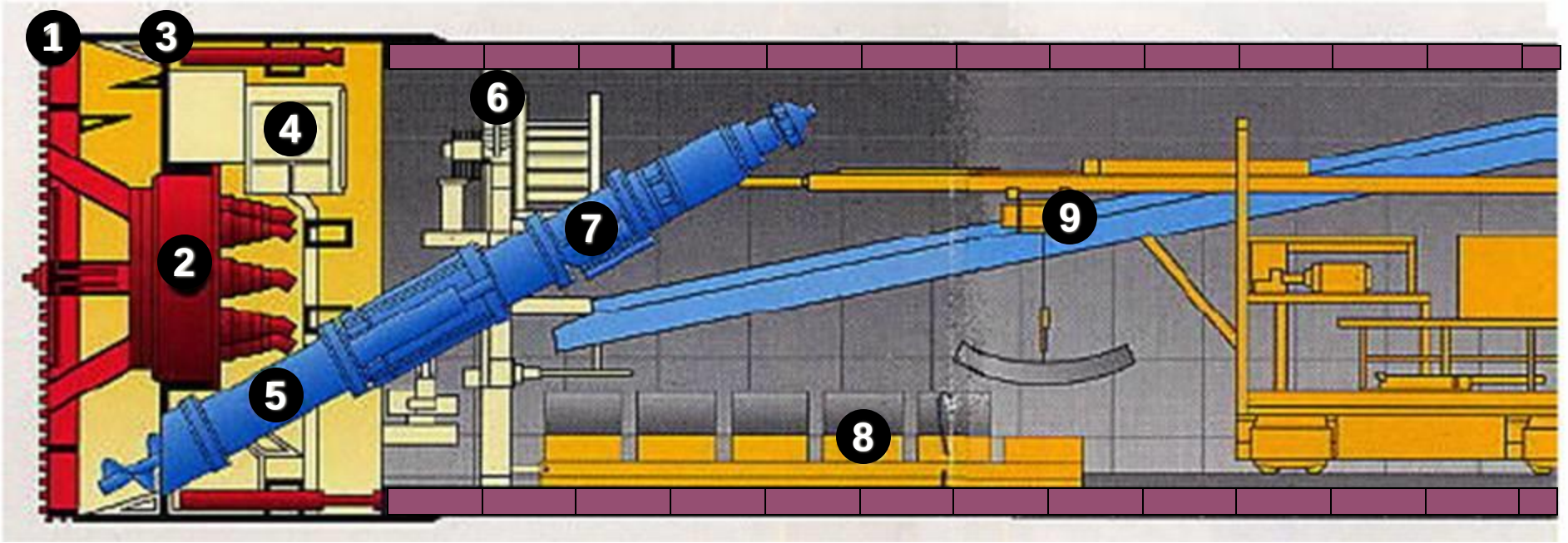
- Tunnel excavation causes potentially large ground movements
- Settlement and horizontal strains are generated at the ground surface, and in utilities and buildings
- Protective measures are needed for assets where predicted movements are above acceptable limits

Surface Settlement Trough

$$\text{Volume loss (\%)} = \frac{\text{Volume settlement trough}}{\text{Volume tunnel}}$$

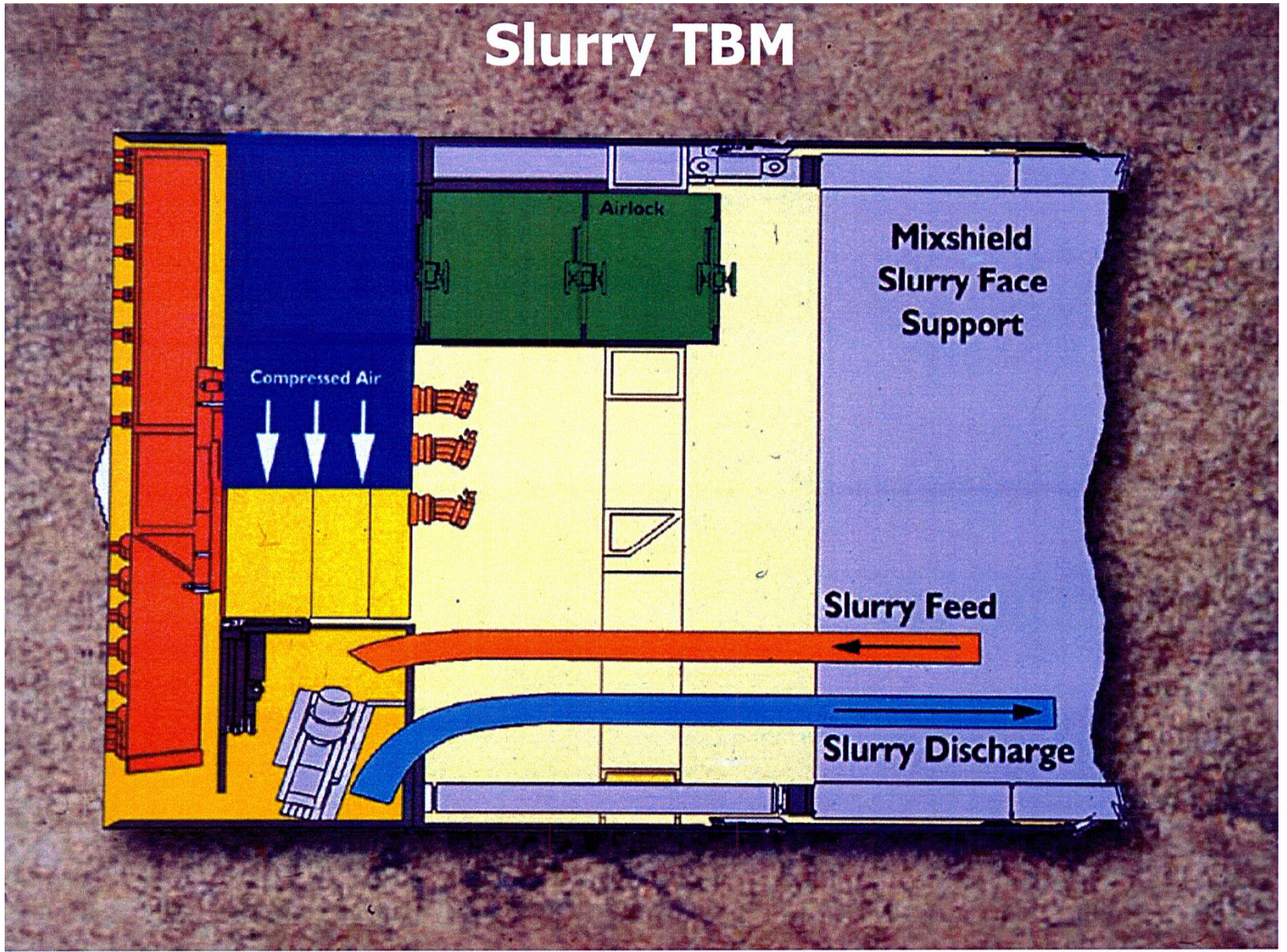


Tunnelling Methods – Closed Face Earth Pressure Balance (EPB) TBM

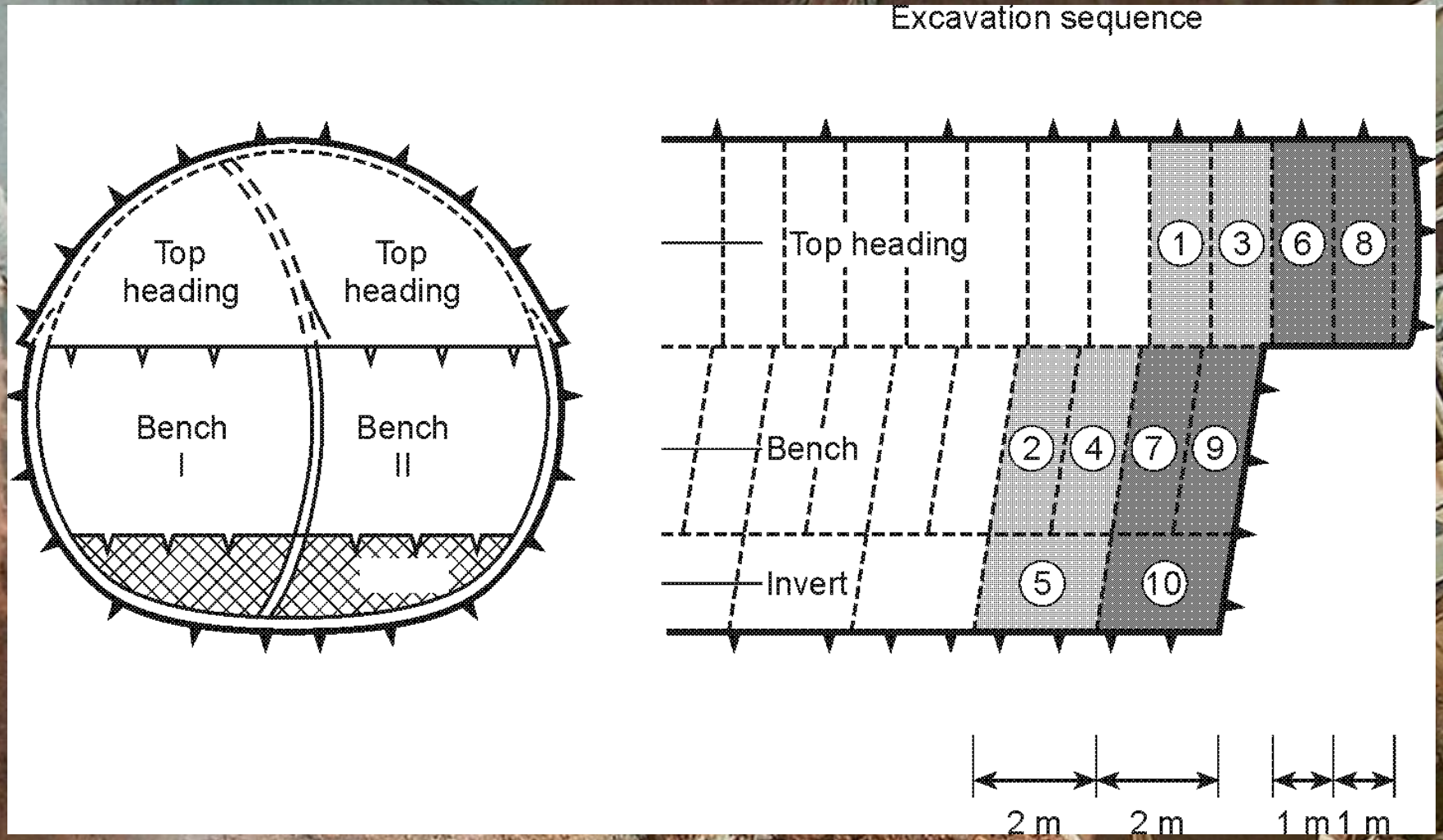


1 Cutter head
2 Drive motor
3 TBM skin
4 Air lock
5 Screw conveyor
6 Lining erector arm
7 Soil discharge
8 Lining segments
9 Belt conveyor

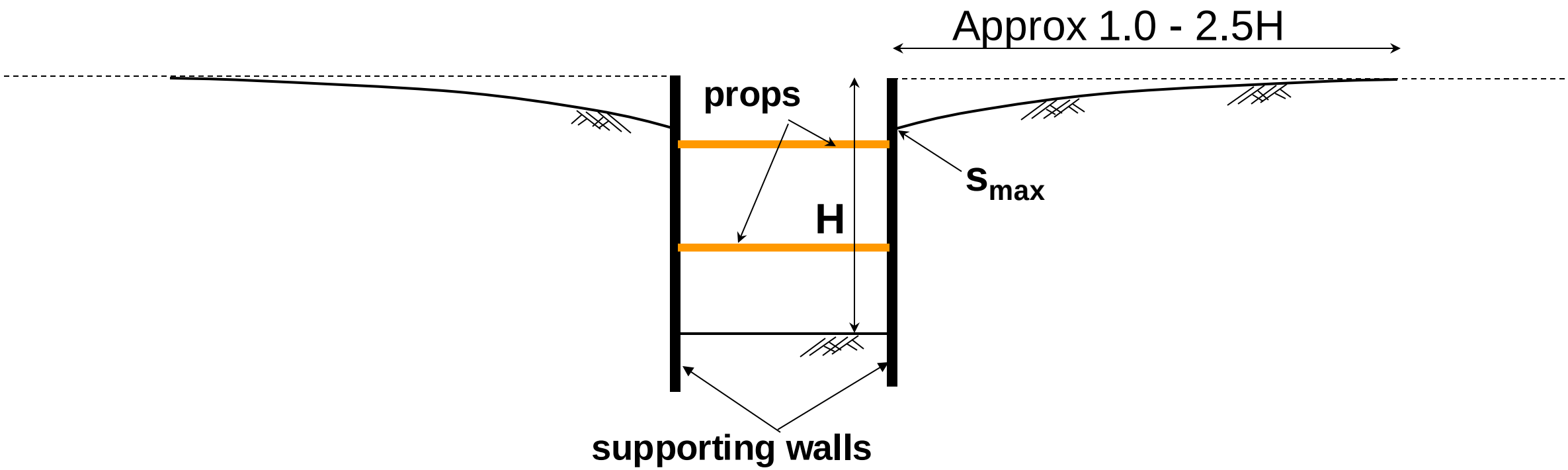
Tunnelling Methods – Slurry TBM



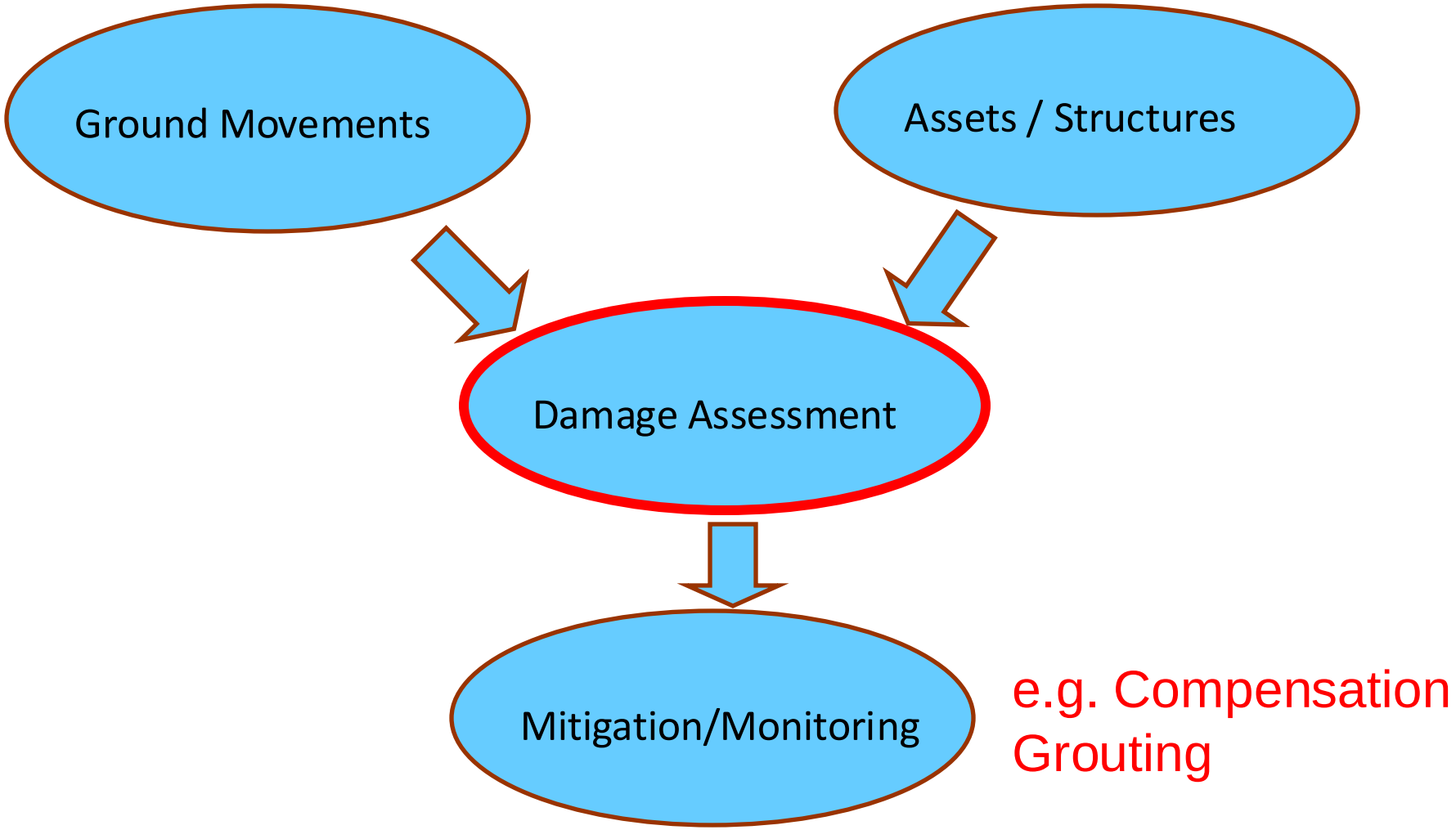
Tunnelling Methods – Sprayed Concrete Lining



Boxes or Shafts (Stations, Portals, Launch Chambers, etc) also Cause Settlement

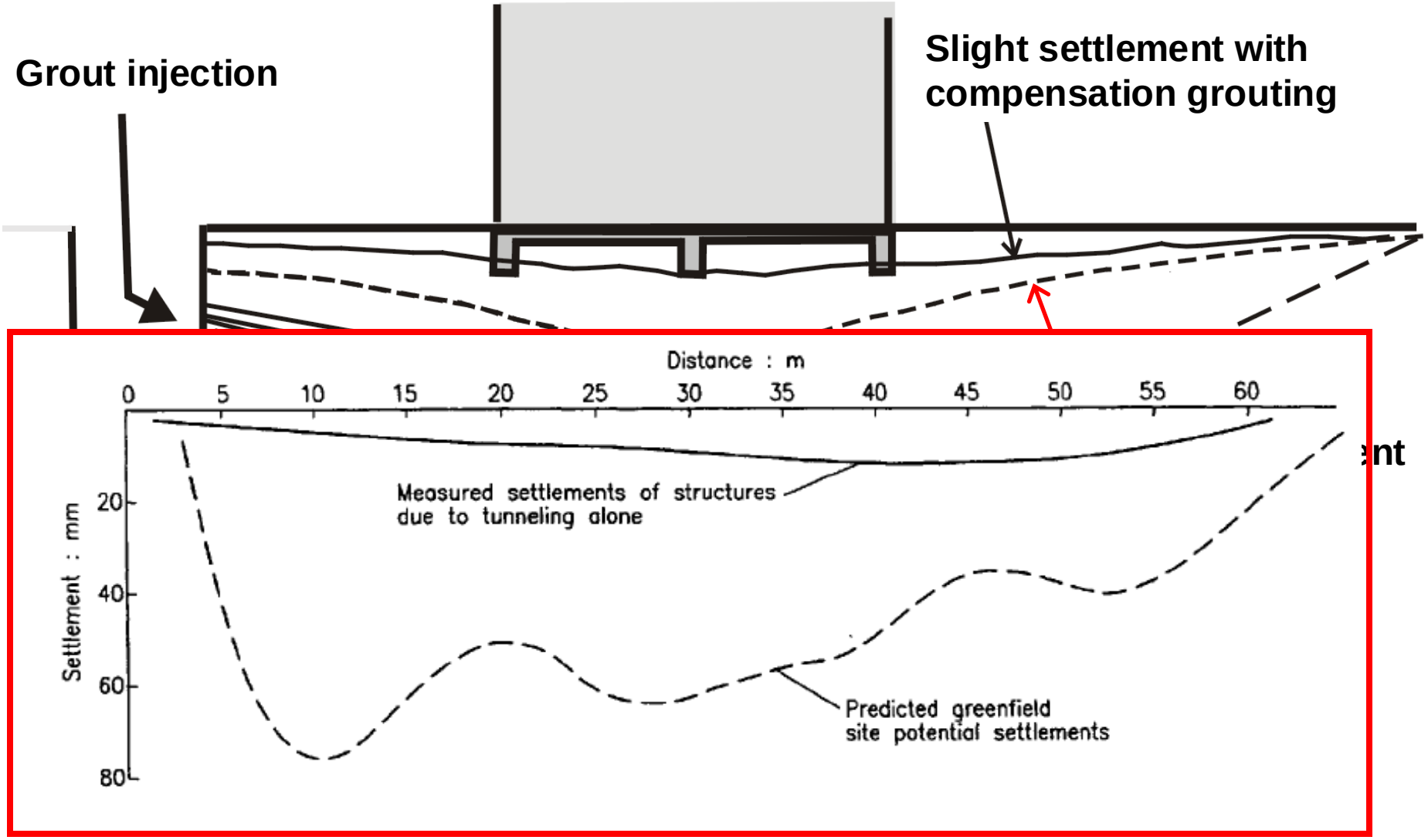


Damage Assessment Process

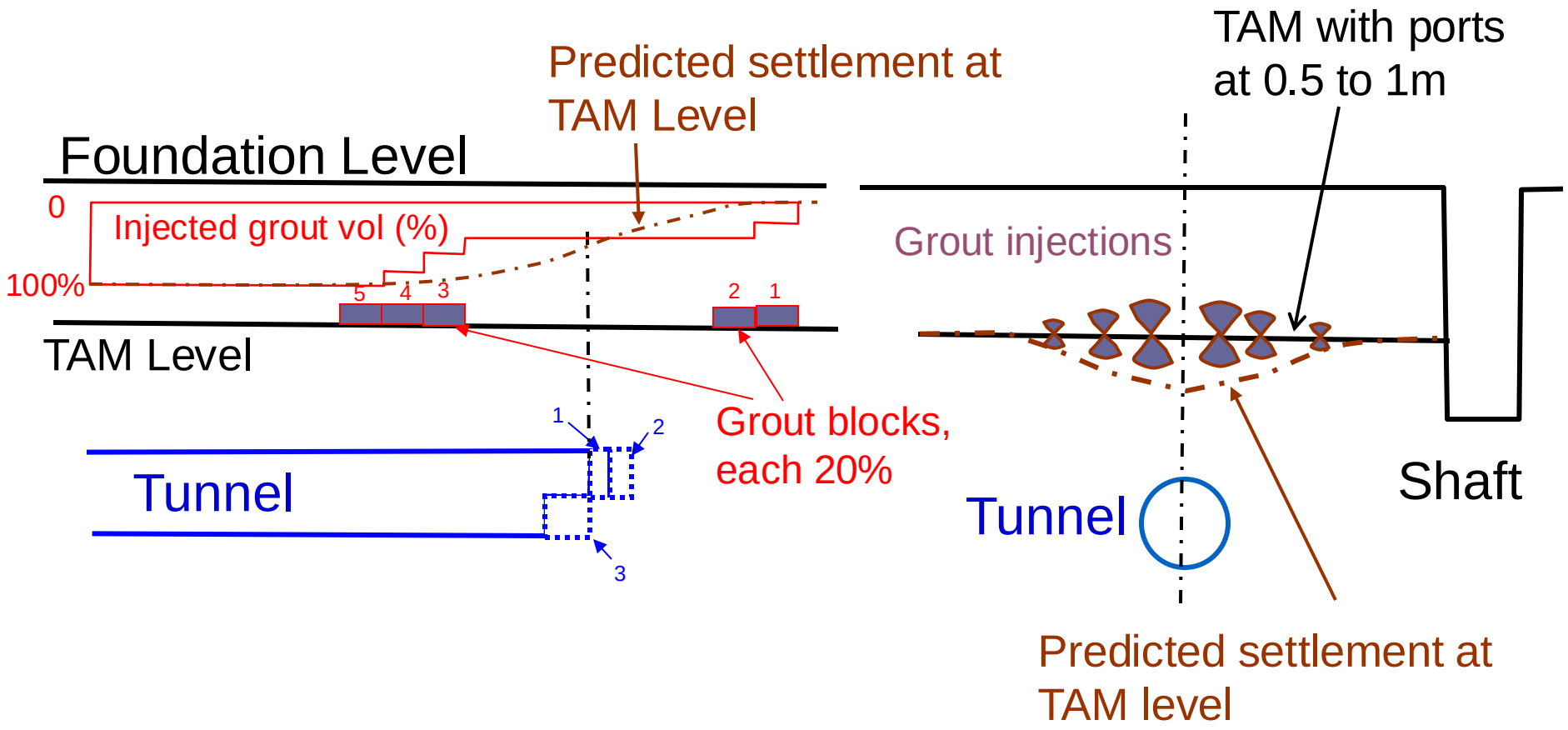


Principle of compensation grouting

Observational Method (Peck, 1969)

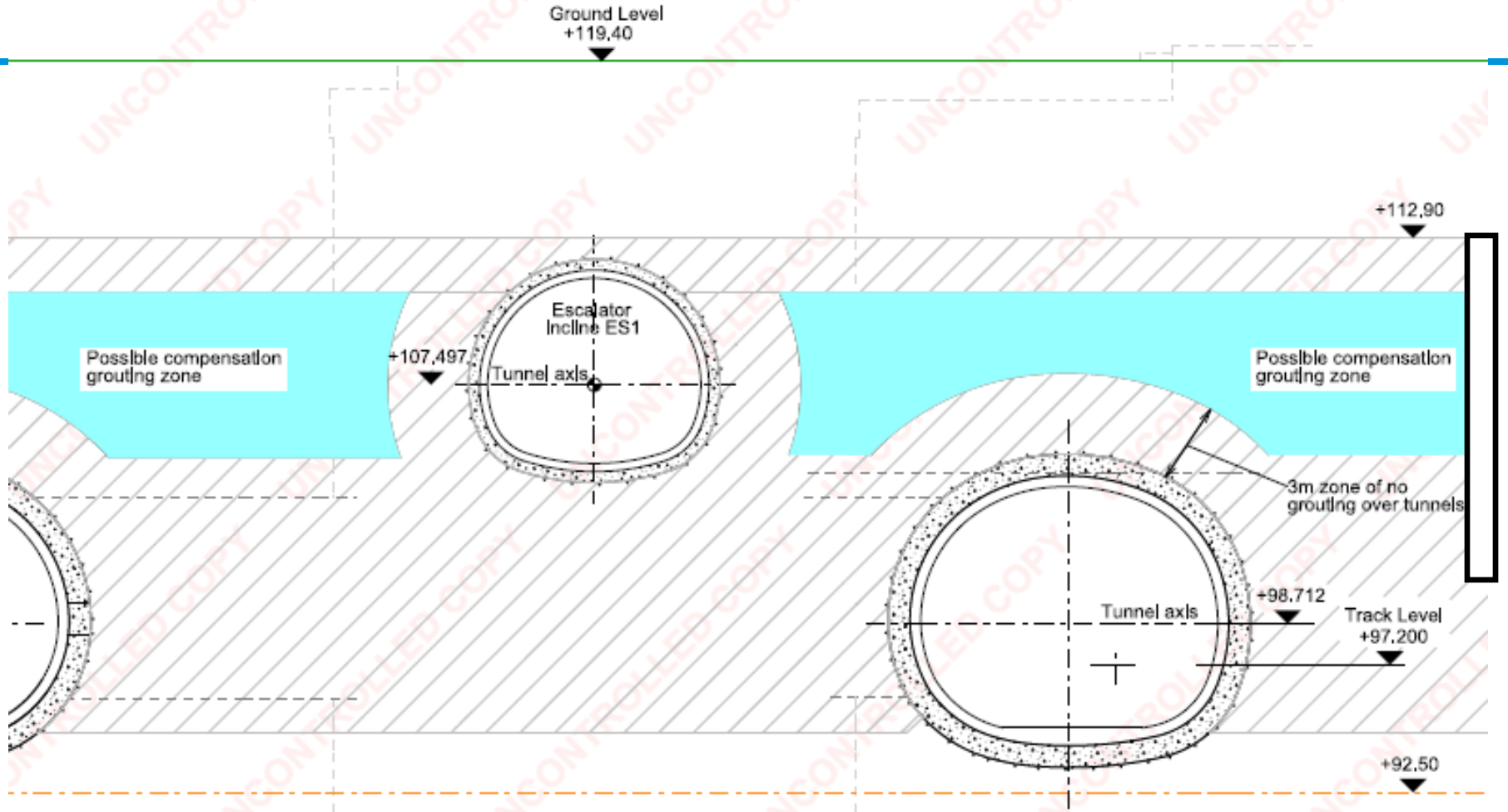


Application of Compensation Grouting - Theory

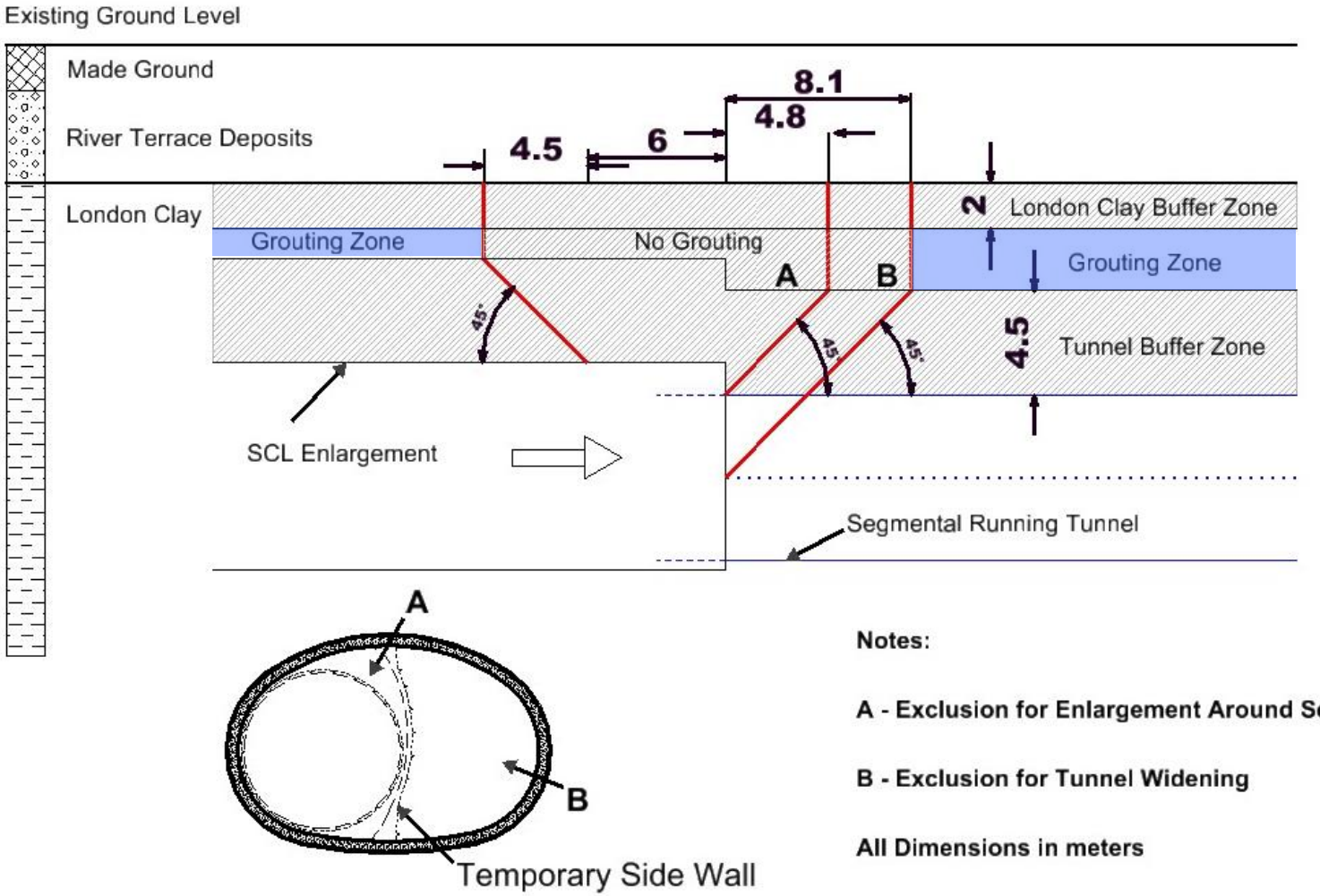


Some Issues to Consider

- Optimise TAM depth below assets - balance control vs responsiveness;
- Maximise cover to tunnels;
- Select target strata/ grouting horizons (ease of drilling, efficacy of grouting, water, obstructions etc);
- Design extent arrays - can be determined either by assets or tunnels generating the movements
- Identify locations to install TAMs – surface / shaft / tunnel
- Select maximum TAM spacing (e.g. end of arrays)
- Select port spacing and no of layers to give adequate redundancy
- Consider settlements due to shaft excavation and TAM installation (before CG system is active);


Ground Level
+119.40
+112.90
Possible compensation grouting zone
Escalator Incline ES1
+107.497
Tunnel axis
Possible compensation grouting zone
3m zone of no grouting over tunnels
Tunnel axis
+98.712
Track Level
+97.200
+92.50

GROUTING EXCLUSION INFRONT OF SCL



Notes:

A - Exclusion for Enlargement Around Segmental Tunnel

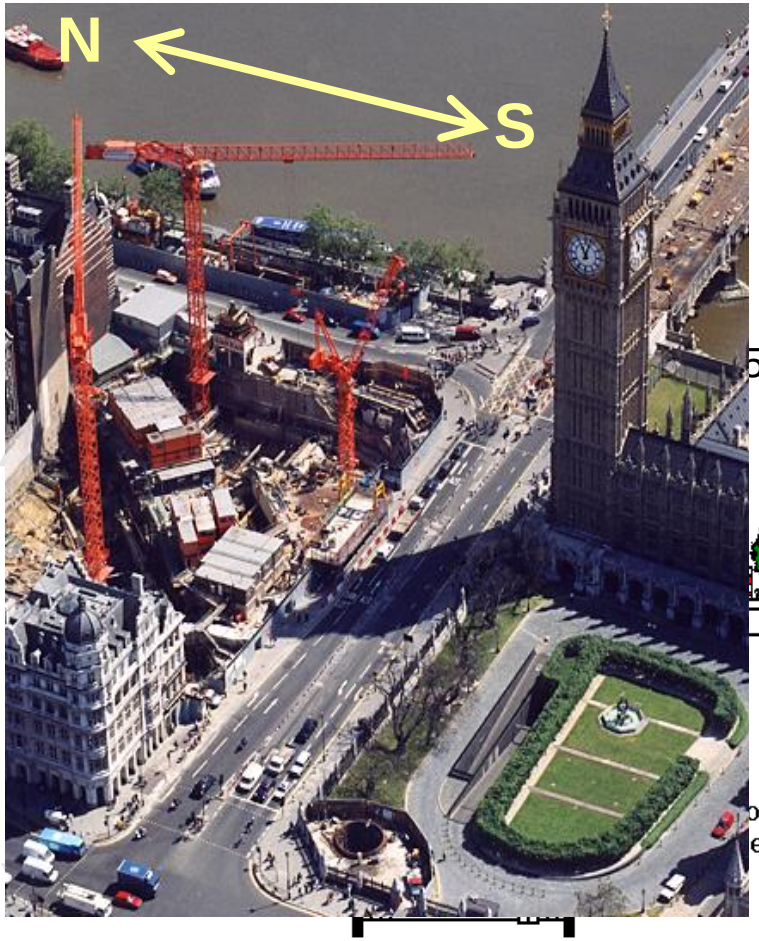
B - Exclusion for Tunnel Widening

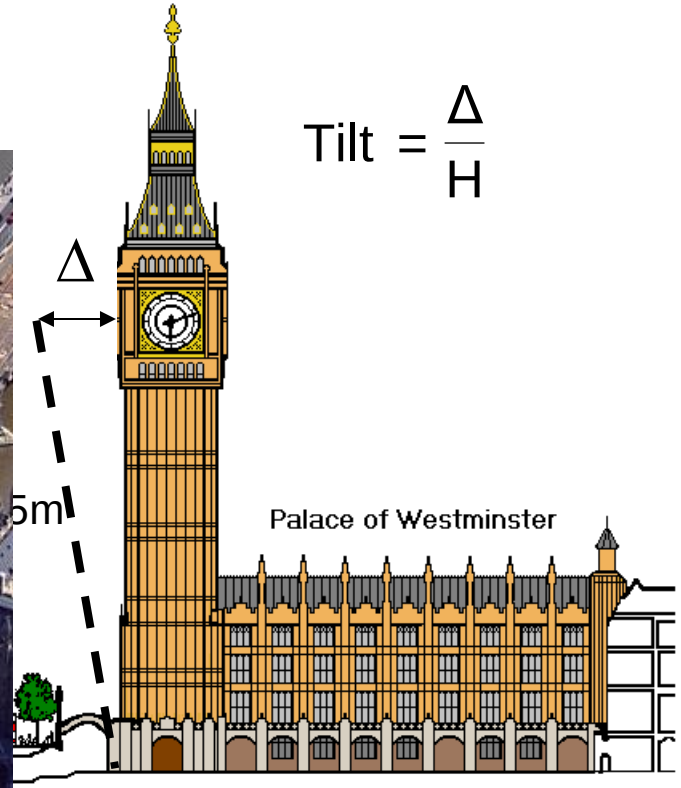
All Dimensions in meters

Case History #1 Jubilee Line Extension Project (JLEP), London

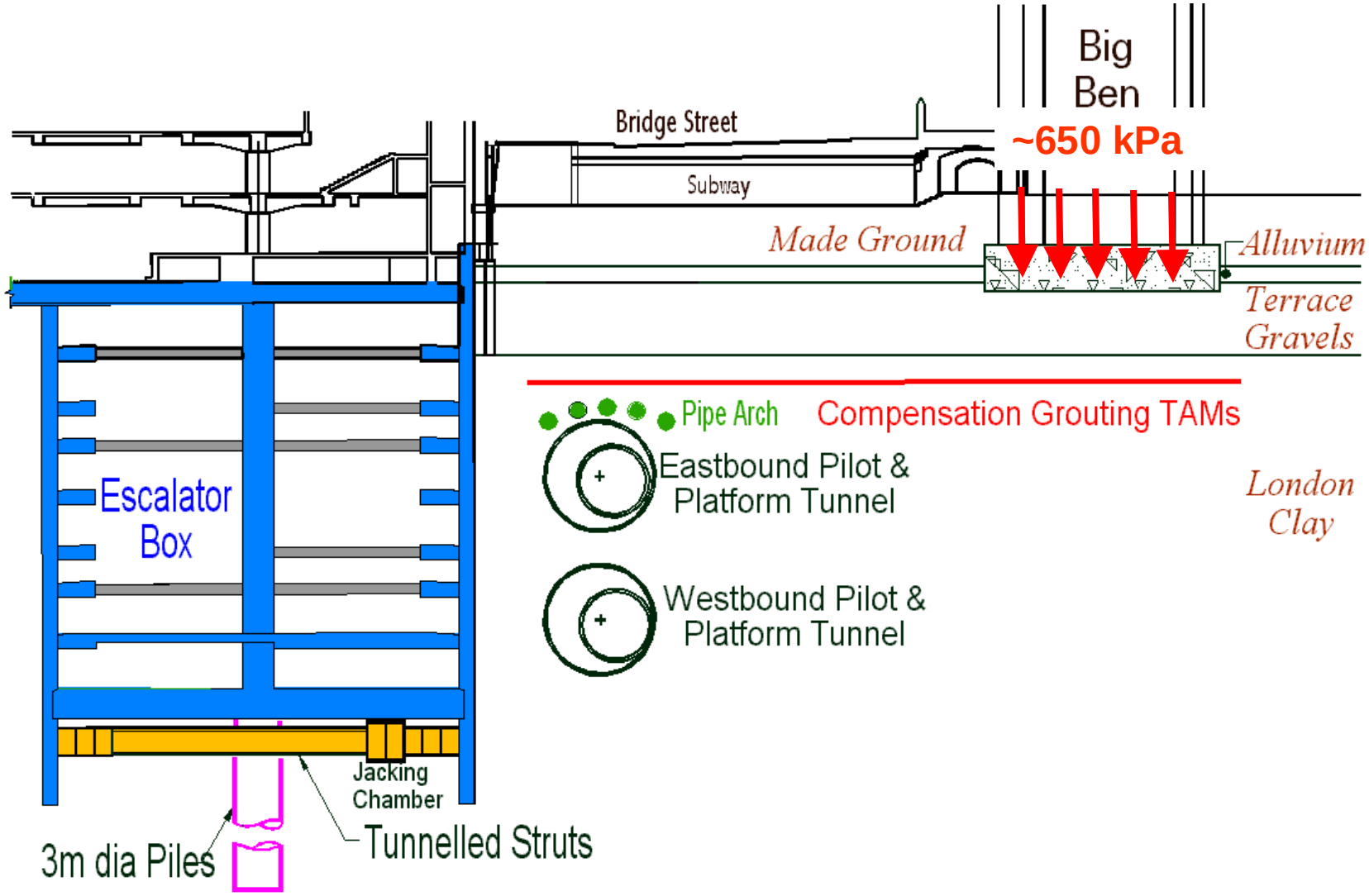
Big Ben & Westminster Station -1999

#5a. Case Histories –

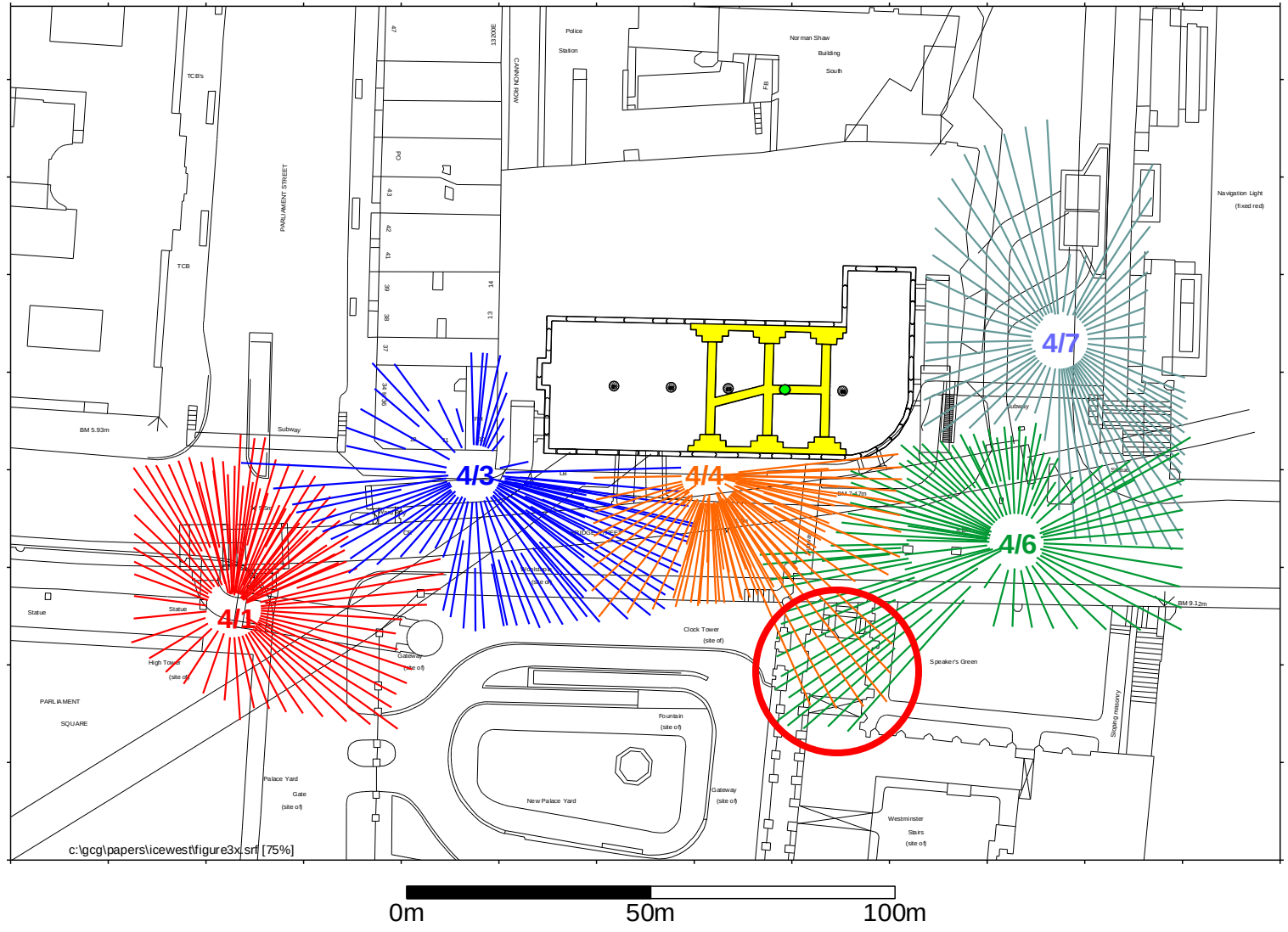




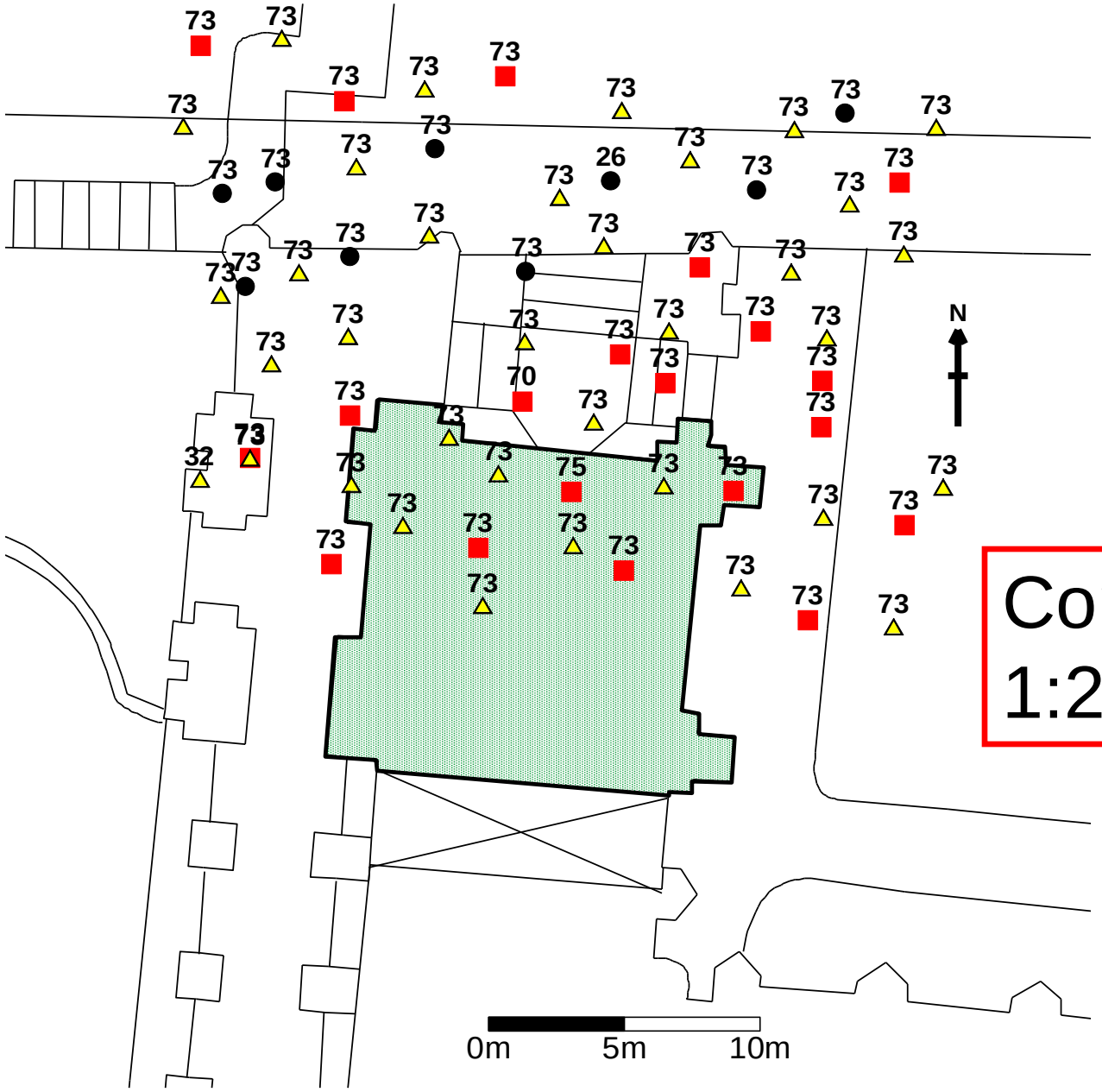
Cross section through Big Ben Clock Tower



Plan of compensation grouting arrays at JLE Westminster Station

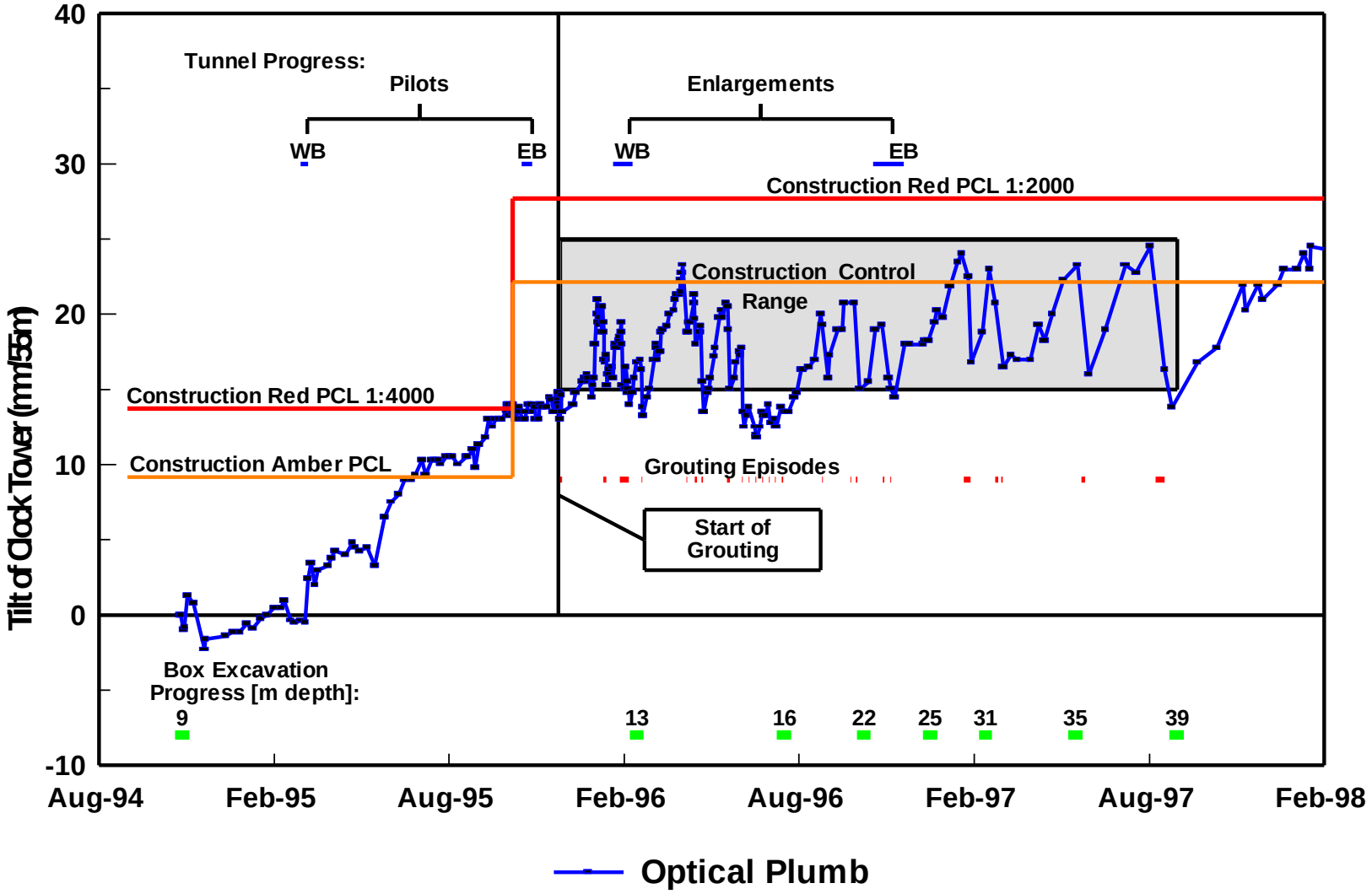


Big Ben - Grout Injection Locations
Episode 8



Control of tilt to 1:25,000

Control of Clock Tower Tilt using Compensation Grouting



Tunnel may give Big Ben that Pisa tilt

THE TOWER of Big Ben may be moved 2cm out of place by Tube tunnelling work close to the Palace of Westminster, according to engineers.

They fear the possible stresses on the ground supporting the foundations of the Parliament building and the 136-year-old tower could result in damage. Their fears are revealed in leaked documents from the major engineering consultant firms of Ove Arup & Partners and Alan Baxter Associates who are helping to build the Jubilee Line Extension.

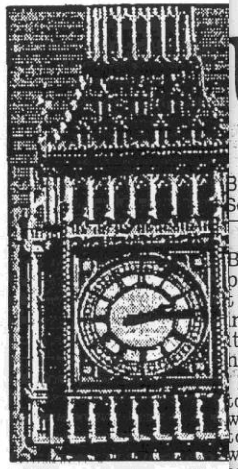
Two tunnels — each 23 feet wide — have been bored near the buildings. The tunnels are so close to the tower's foundations than an immense cage of steel tubes, filled with concrete, is being installed to shore up the ground.

The problem is no one can say for certain how much stress the ancient buildings and clock tower can take

by DICK MURRAY
Transport Correspondent

displacement (10-20mm?) leaving the Palace of Westminster behind. Perhaps we could discuss this at our next meeting".

Although there have been fears before about the Big Ben tower leaning these have always been firmly denied by LU. Also, the amount of lean has always been put in the region of 3mm-5mm which engineers say is an annual occurrence, possibly as a result of the effects of the tidal Thames and change in seasons.



Moving experience: Big may be put 2cm out of

Leaning tower of Big Ben is saved from an untimely fall

By **James Chapman**
Science Correspondent

BIG Ben had to be prevented from disastrously toppling into Parliament Square, it was revealed last night.

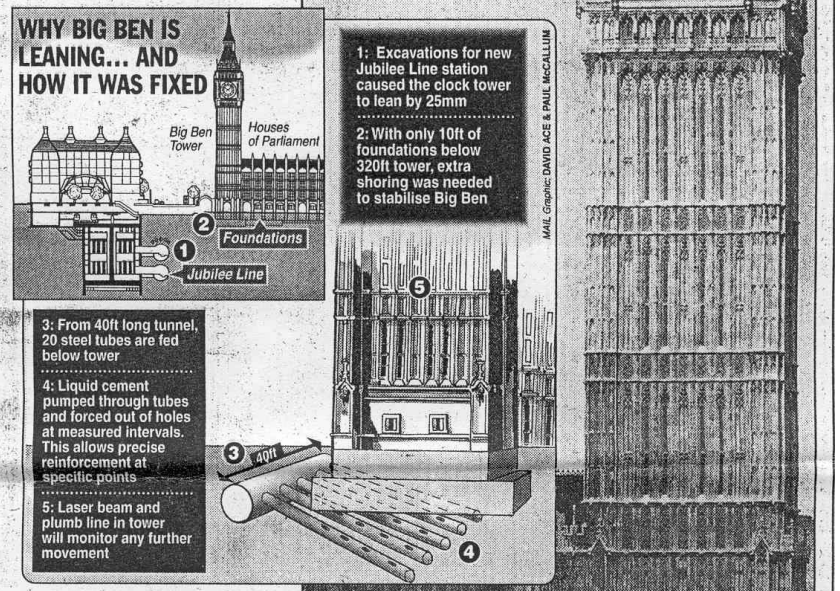
Engineers were called in to stop the collapse of the world's most famous clock tower when tunnelling work on a new Tube line caused it to lean alarmingly.

Thousands of tons of concrete were pumped underneath the structure – officially called St Stephen's Tower – after scientists warned that it was teetering so badly it could collapse.

The British engineer in charge of the project, Professor John Burland – who has worked on stabilising the Leaning Tower of Pisa – said Big Ben had been threatened

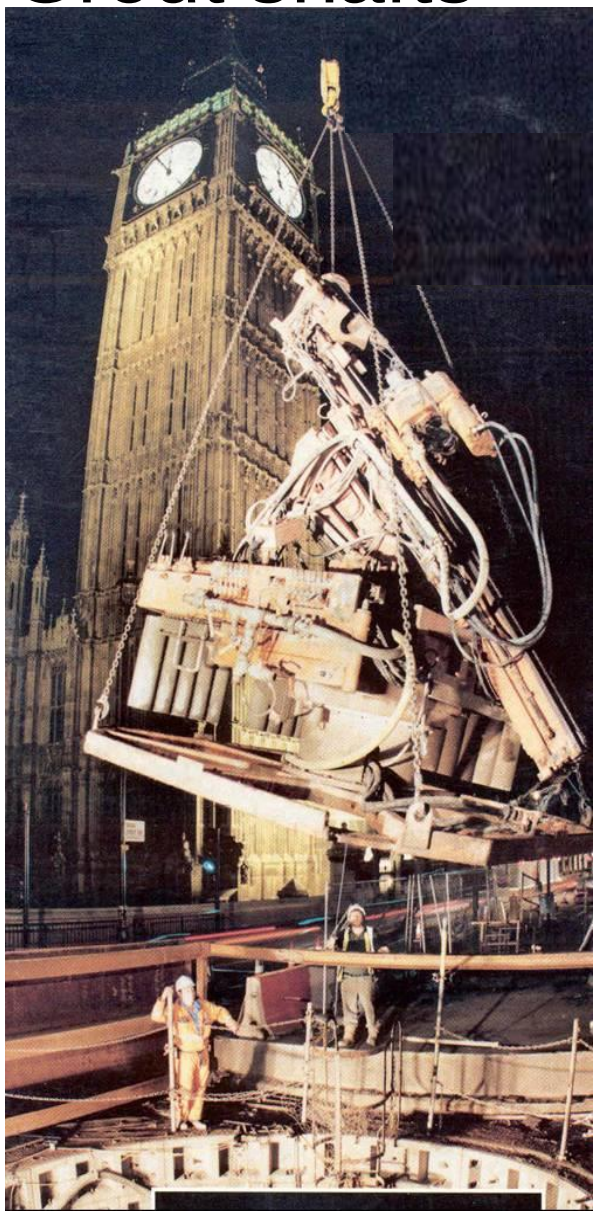
'It could have been grave'

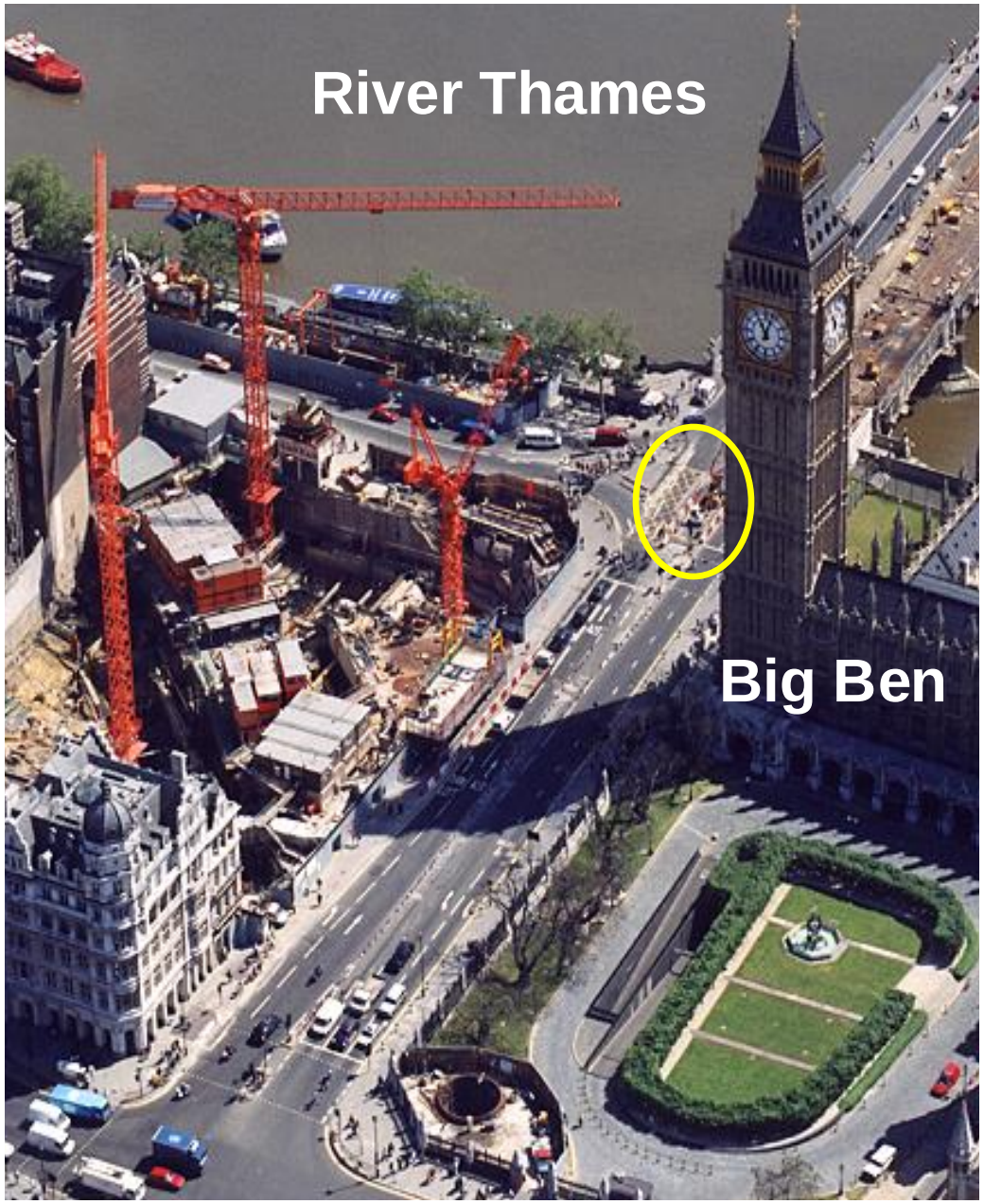
with 'serious damage' by subsidence caused by the excava-



ficiently for us to bring in protective measures. It started to move as soon as the westbound tunnel was bored.

Grout shafts





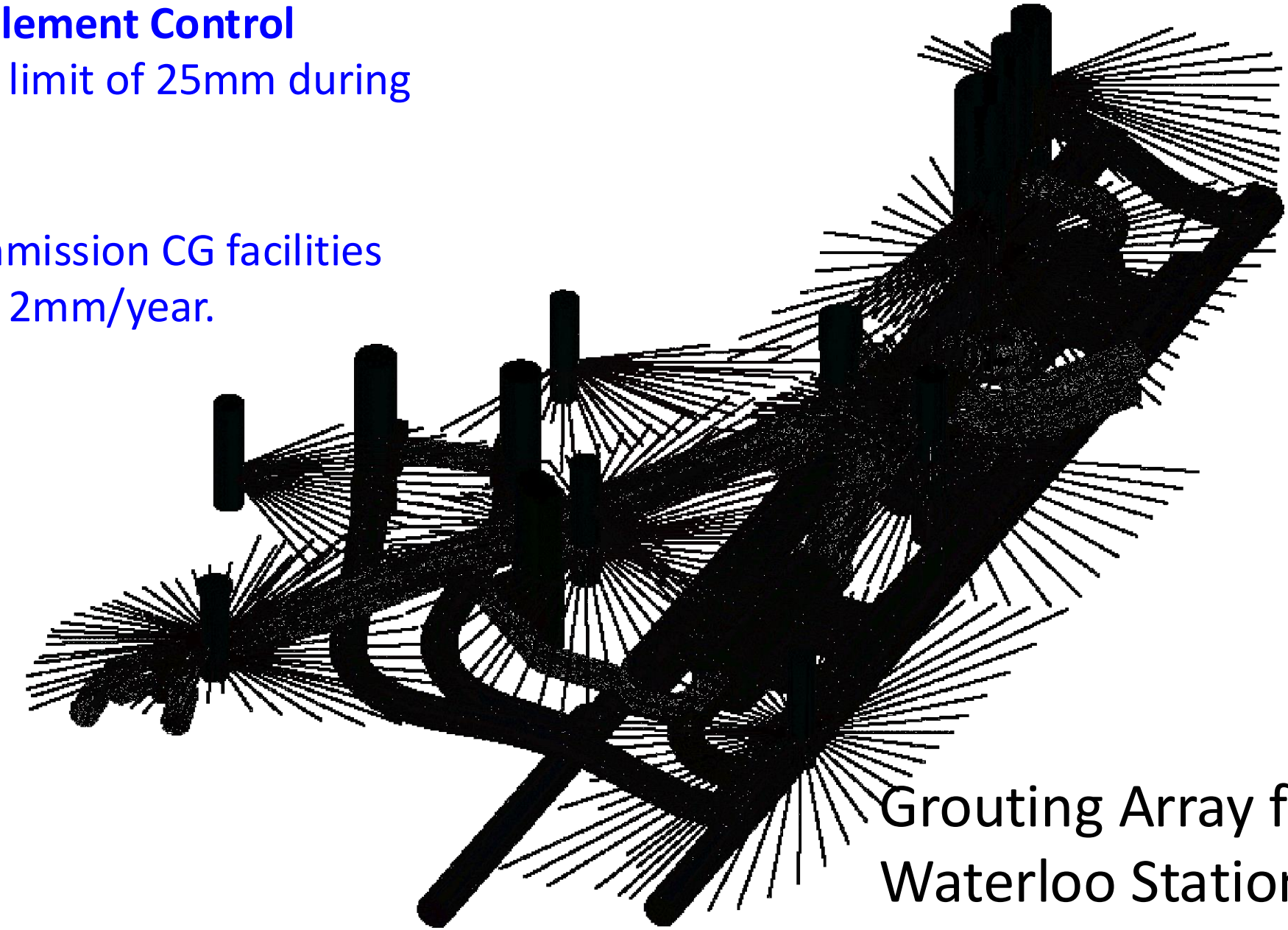
Case History #2 Jubilee Line Extension Project London

Waterloo Station -1999

Contract Limits for Settlement Control

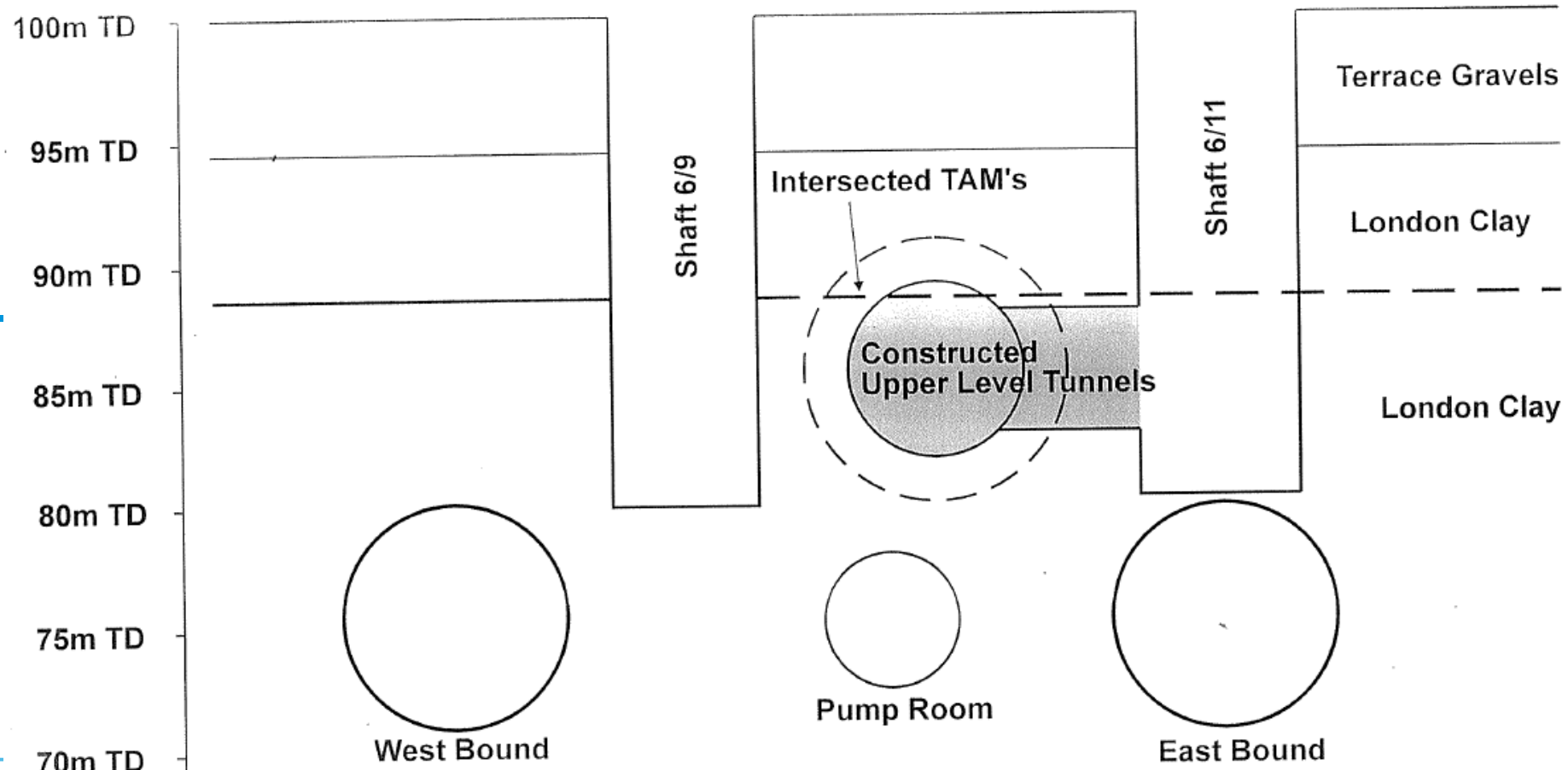
Settlements at contract limit of 25mm during construction.

After tunnelling, decommission CG facilities when movement rate < 2mm/year.



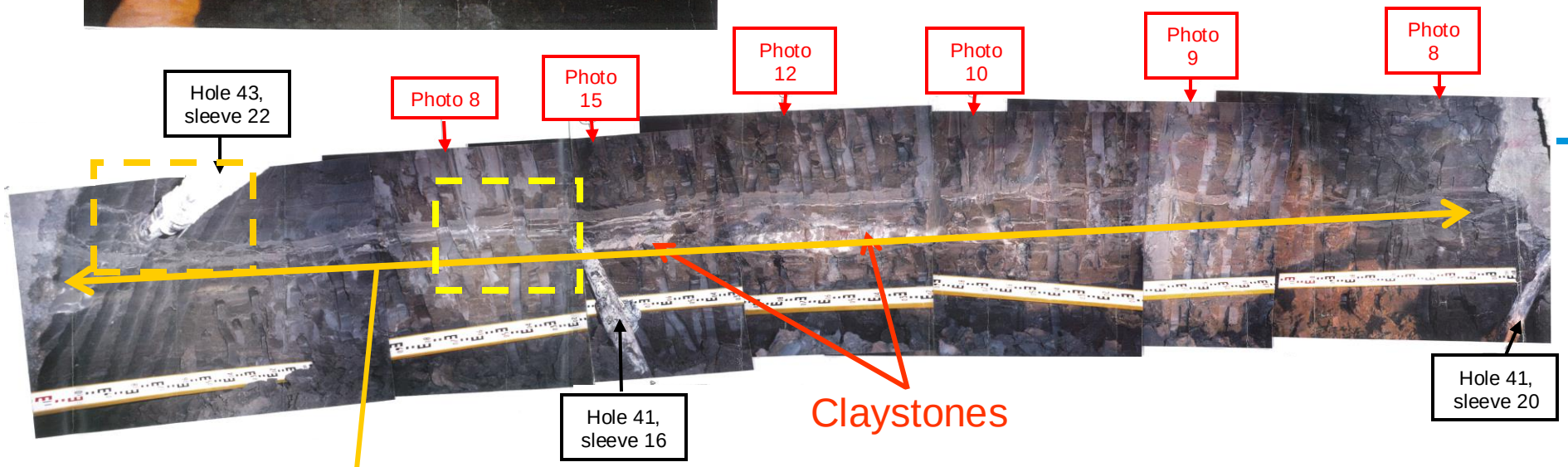
Grouting Array for Waterloo Station

Observation of Compensation Grout in the Stiff Clay (unpublished work, Menkiti et al, 2015)



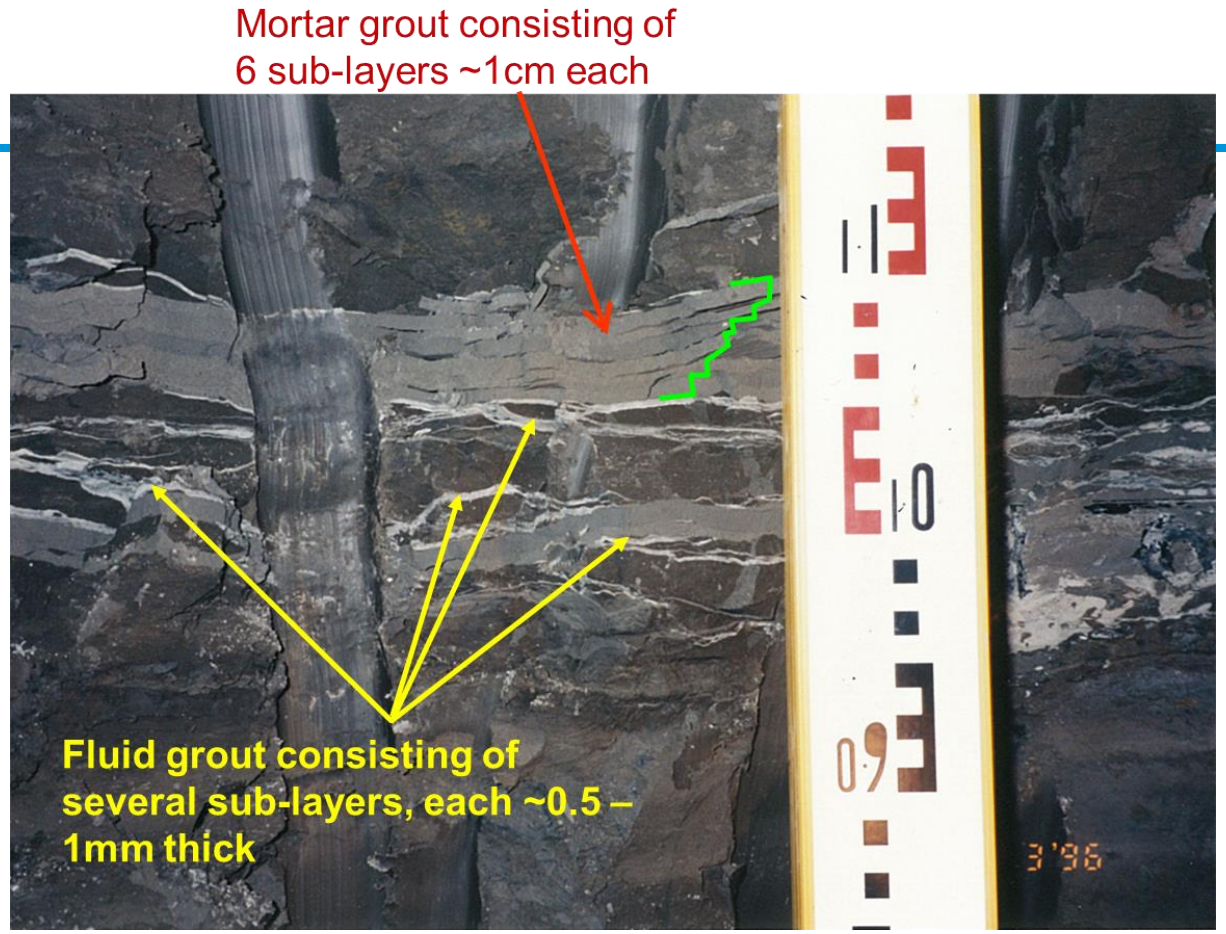


Top Heading



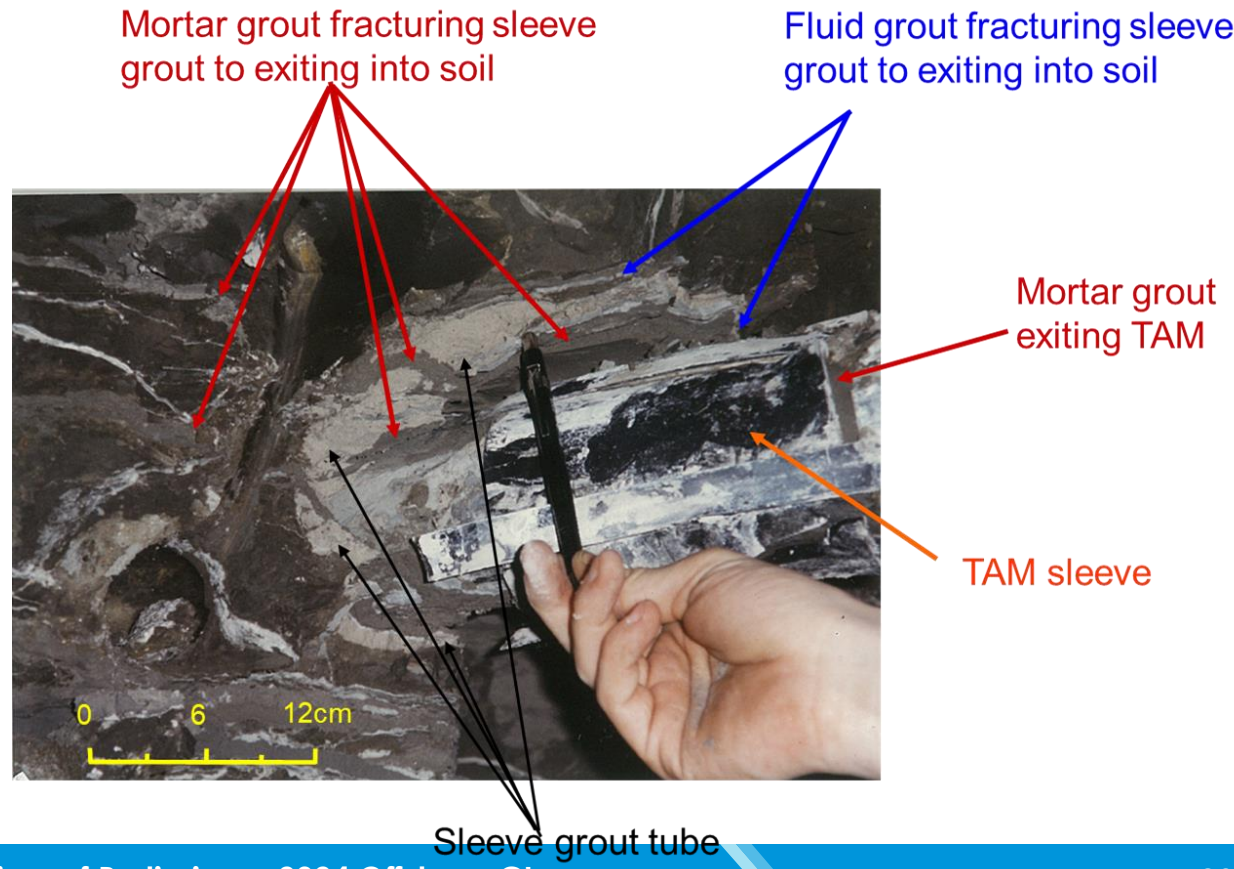
Grout from single injection seen to travel up to 5.5m from exit TAM

Grout Distribution In-situ



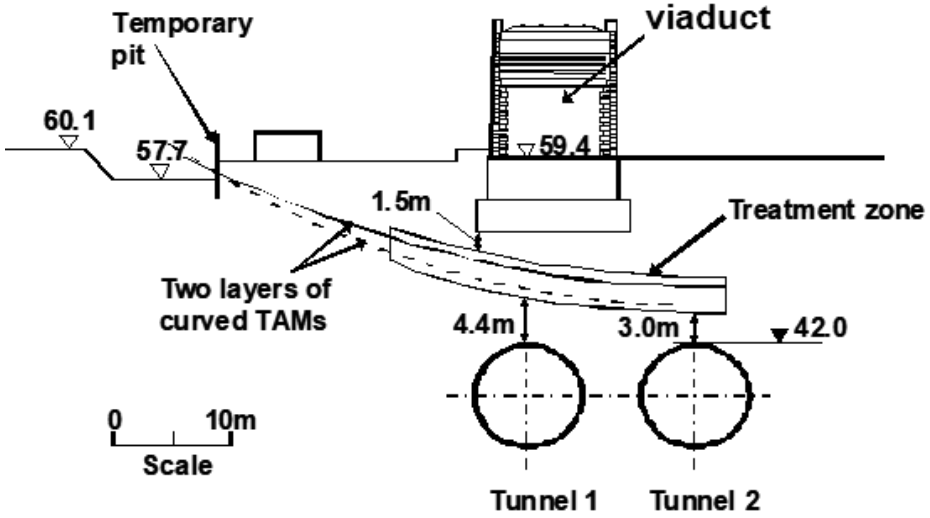
Grout Distribution In-situ

Exit Characteristics at A TAM



Case History #3 Bologna High Speed Rail Tunnels, Bologna, Italy - 1999

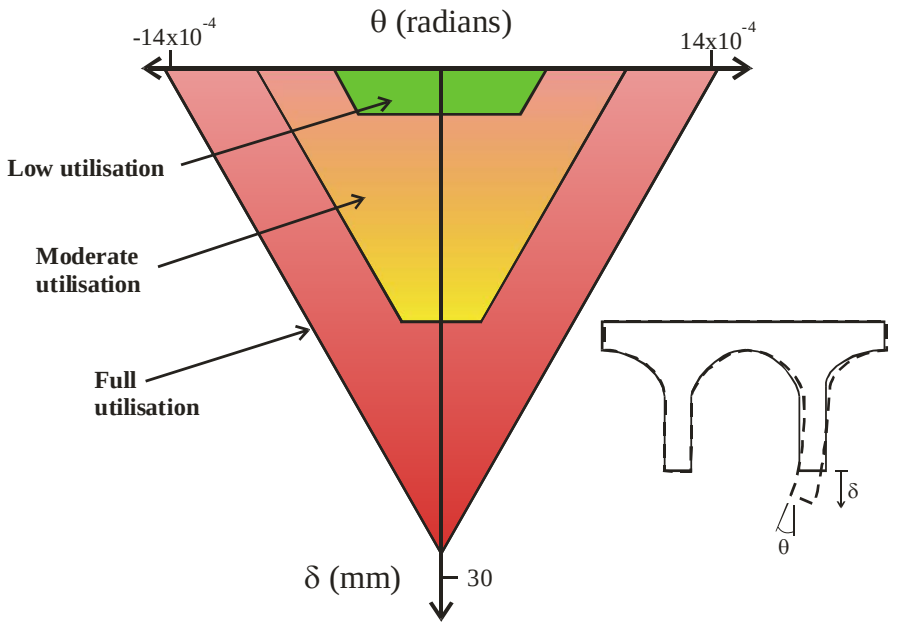
Bologna High Speed Rail Tunnels; Via Emilia Bridge (Pigorini et al 2009)



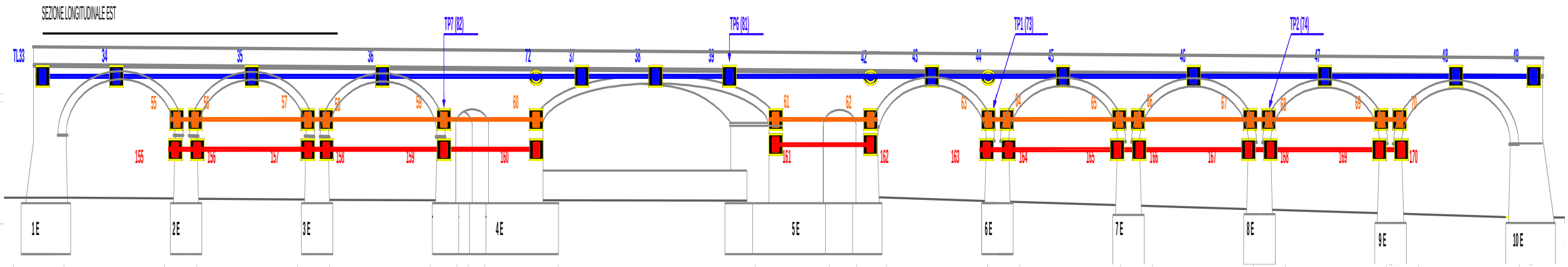


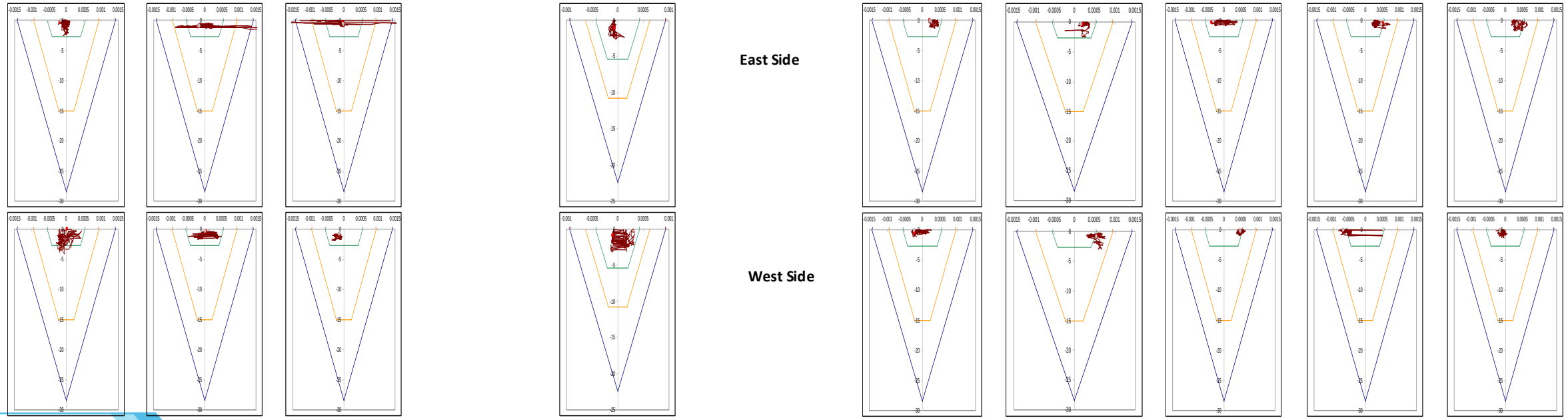
- Curved TAM
- Sands & Gravels





Bologna tunnels (Pigorini et al 2009)





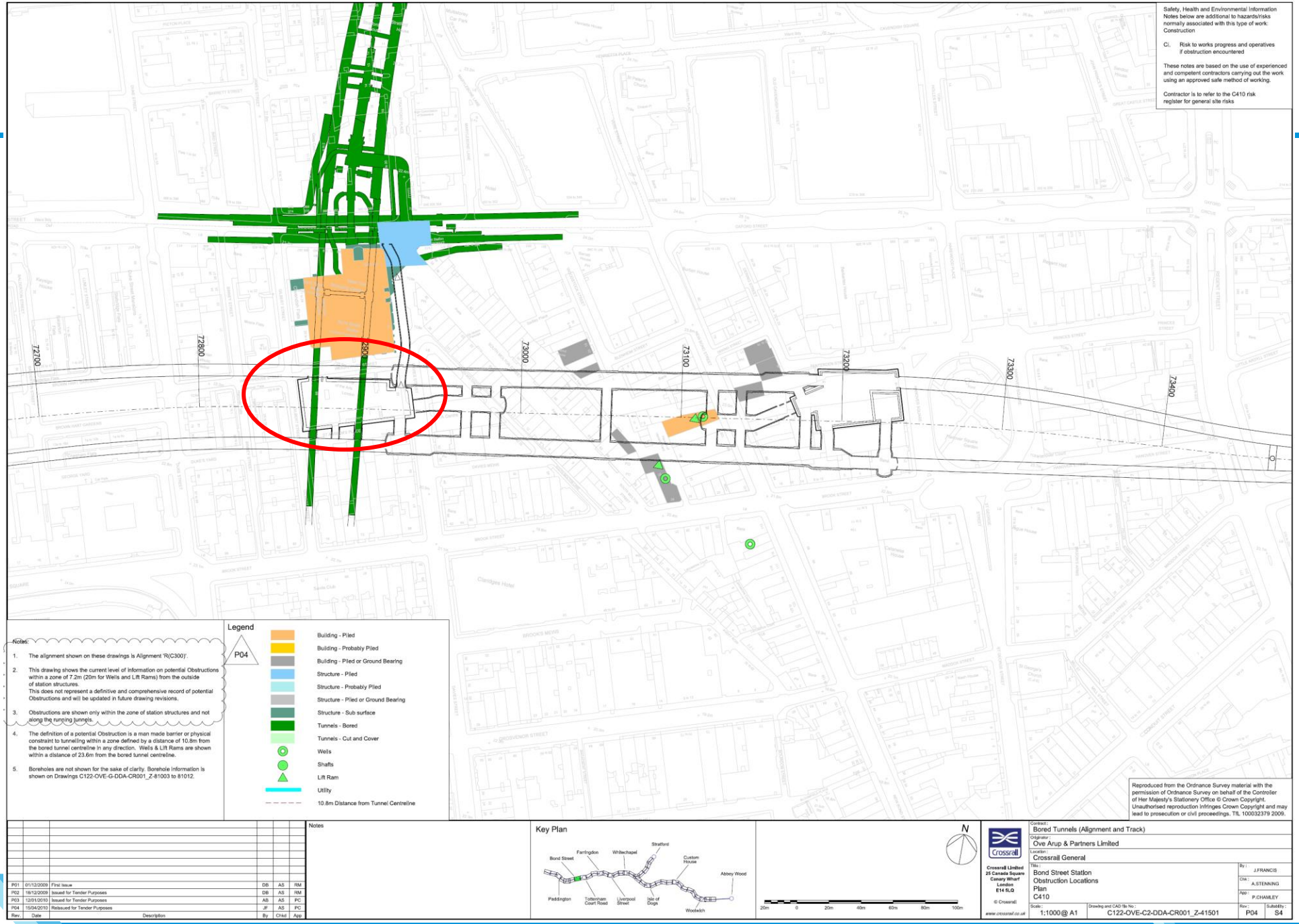
Some Recent Advances with Compensation Grouting

- Improved TBM VL control – CG now unlikely to be required TBM running tunnels; if used likely as a standby emergency response;
- Directional drilling (curved TAMs, TAMs up to 90m, avoid use of shafts)
- Improved quality – reduced redundancy in TAM layers from 3 to 2 and even 1 layer;
- Drilling from below GWL with blow-out preventer; use of polymer support in sands below water level.
- Advances in monitoring, data processing and presentation.
- Target differential settlement, not total settlements => total settlements can be quite high at the end of construction

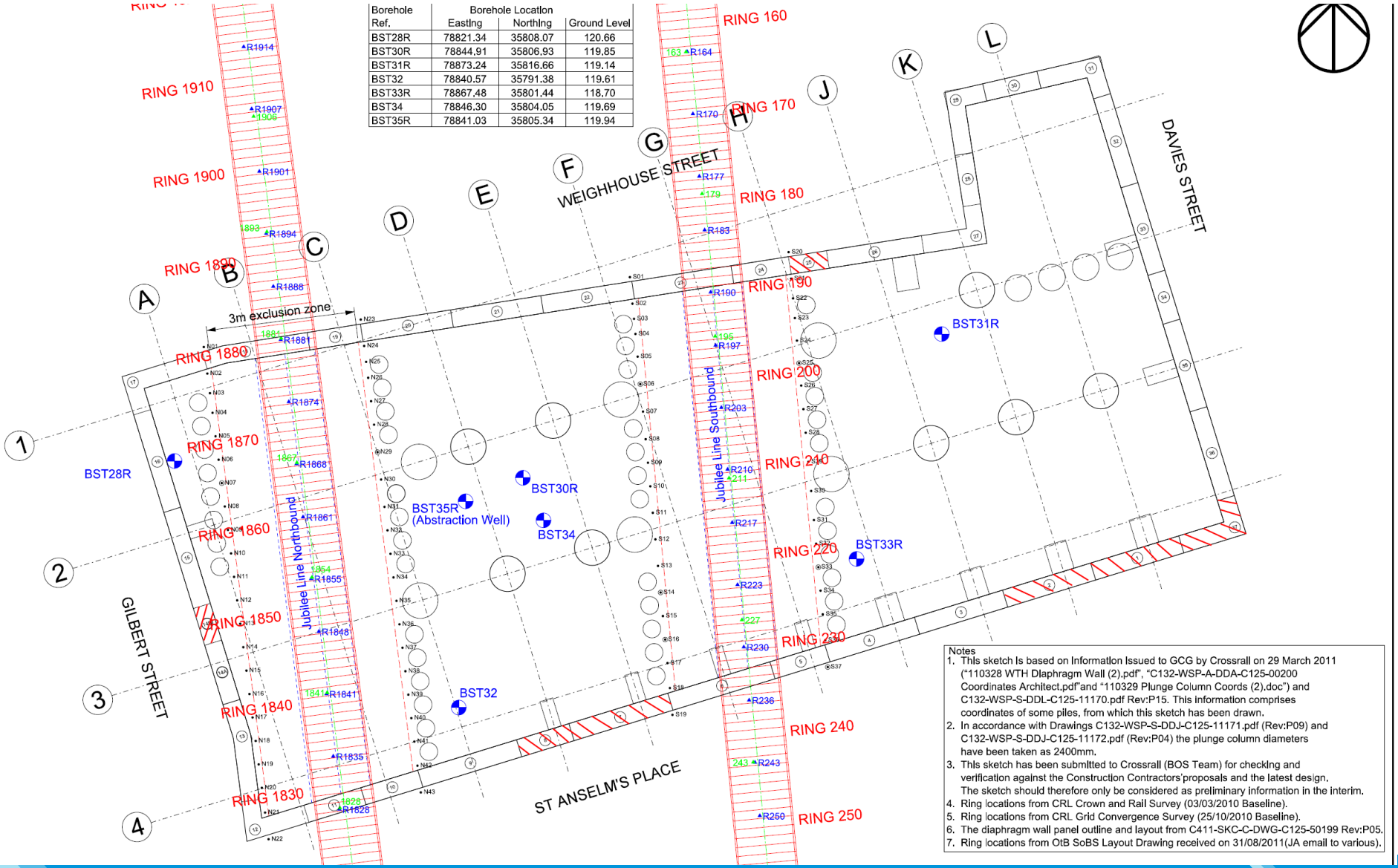
Caution – some important limitations

- CG does not work in soft or n/c clays and loose silts/ clayey sands! (See Soga et al 2004 & Shirlaw et al 2000.)
- Not viable where movements from shaft & TAM installation are unacceptable
- Not suitable for addressing horizontal movements.

Crossrail Bond Street Station Box

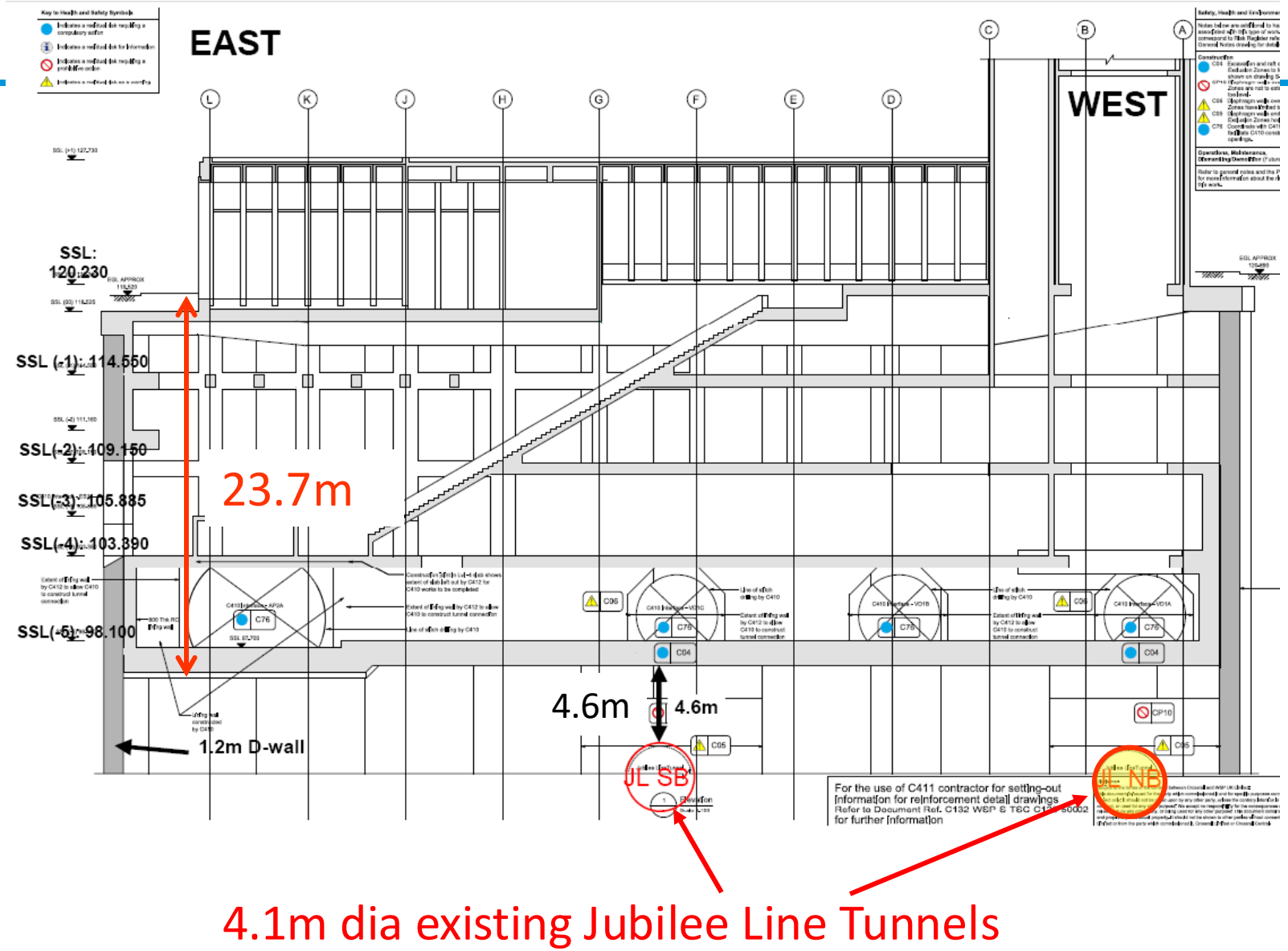

Safety, Health and Environmental Information
Notes below are additional to hazards/risks normally associated with this type of work:
Construction
CI. Risk to works progress and operatives if obstruction encountered
These notes are based on the use of experienced and competent contractors carrying out the work using an approved safe method of working.
Contractor is to refer to the C410 risk register for general site risks
72700
72800
72900
73000
73100
73200
73300
73400
Legend
P04
Building - Piled
Building - Probably Piled
Building - Piled or Ground Bearing
Structure - Piled
Structure - Probably Piled
Structure - Piled or Ground Bearing
Structure - Sub surface
Tunnels - Bored
Tunnels - Cut and Cover
Wells
Shafts
Lift Ram
Utility
10.8m Distance from Tunnel Centreline
Notes:
1. The alignment shown on these drawings is Alignment 'R(C300)'.
2. This drawing shows the current level of information on potential Obstructions within a zone of 7.2m (20m for Wells and Lift Rams) from the outside of station structures. This does not represent a definitive and comprehensive record of potential Obstructions and will be updated in future drawing revisions.
3. Obstructions are shown only within the zone of station structures and not along the running tunnels.
4. The definiton of a potential Obstruction is a man made barrier or physical constraint to tunnelling within a zone defined by a distance of 10.8m from the bored tunnel centreline in any direction. Wells & Lift Rams are shown within a distance of 23.6m from the bored tunnel centreline.
5. Boreholes are not shown for the sake of clarity. Borehole information is shown on Drawings C122-OVE-G-DDA-CR001_Z-81003 to 81012.
Reproduced from the Ordnance Survey material with the permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office © Crown Copyright. Unauthorised reproduction infringes Crown Copyright and may lead to prosecution or civil proceedings. TfL 100032379 2009.
P01 01/12/2009 First Issue DB AS RM
P02 18/12/2009 Issued for Tender Purposes DB AS RM
P03 12/01/2010 Issued for Tender Purposes AB AS PC
P04 15/04/2010 Reissued for Tender Purposes JF AS PC
Rev. Date Description By Chkd App
Notes
Key Plan
Bond Street
Farringdon
Whitechapel
Stratford
Custom House
Abbey Wood
Paddington
Tottenham Court Road
Liverpool Street
Isle of Dogs
Woolwich
N
20m 0 20m 40m 60m 80m 100m
Crossrail
Crossrail Limited
25 Canada Square
Canary Wharf
London
E14 5LQ
© Crossrail
www.crossrail.co.uk
Contract: Bored Tunnels (Alignment and Track)
Originator: Ove Arup & Partners Limited
Location: Crossrail General
Title: Bond Street Station Obstruction Locations Plan C410
By: J.FRANCIS
Chk: A.STENNING
App: P.CHAMLEY
Scale: 1:1000@ A1
Drawing and CAD file No.: C122-OVE-C2-DDA-CR001_Z-41501
Rev: P04
Suitability: S4

Close up view of WTH Box



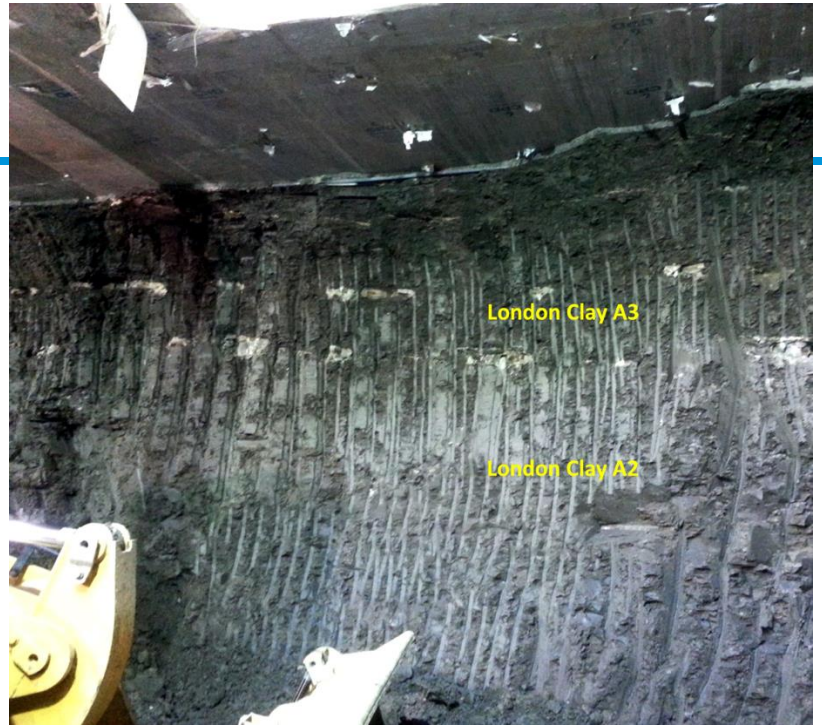
Borehole Ref.	Borehole Location Eastlng	Northlng	Ground Level
BST28R	78821.34	35808.07	120.66
BST30R	78844.91	35806.93	119.85
BST31R	78873.24	35816.66	119.14
BST32	78840.57	35791.38	119.61
BST33R	78867.48	35801.44	118.70
BST34	78846.30	35804.05	119.69
BST35R	78841.03	35805.34	119.94

Notes
1. This sketch is based on Information Issued to GCG by Crossrail on 29 March 2011 ("110328 WTH Diaphragm Wall (2).pdf", "C132-WSP-A-DDA-C125-00200 Coordinates Architect.pdf"and "110329 Plunge Column Coords (2).doc") and C132-WSP-S-DDL-C125-11170.pdf Rev:P15. This information comprises coordinates of some piles, from which this sketch has been drawn.
2. In accordance with Drawings C132-WSP-S-DDJ-C125-11171.pdf (Rev:P09) and C132-WSP-S-DDJ-C125-11172.pdf (Rev:P04) the plunge column diameters have been taken as 2400mm.
3. This sketch has been submitted to Crossrail (BOS Team) for checking and verification against the Construction Contractors'proposals and the latest design. The sketch should therefore only be considered as preliminary information in the interim.
4. Ring locations from CRL Crown and Rail Survey (03/03/2010 Baseline).
5. Ring locations from CRL Grid Convergence Survey (25/10/2010 Baseline).
6. The diaphragm wall panel outline and layout from C411-SKC-C-DWG-C125-50199 Rev:P05.
7. Ring locations from OtB SoBS Layout Drawing received on 31/08/2011(JA email to various).

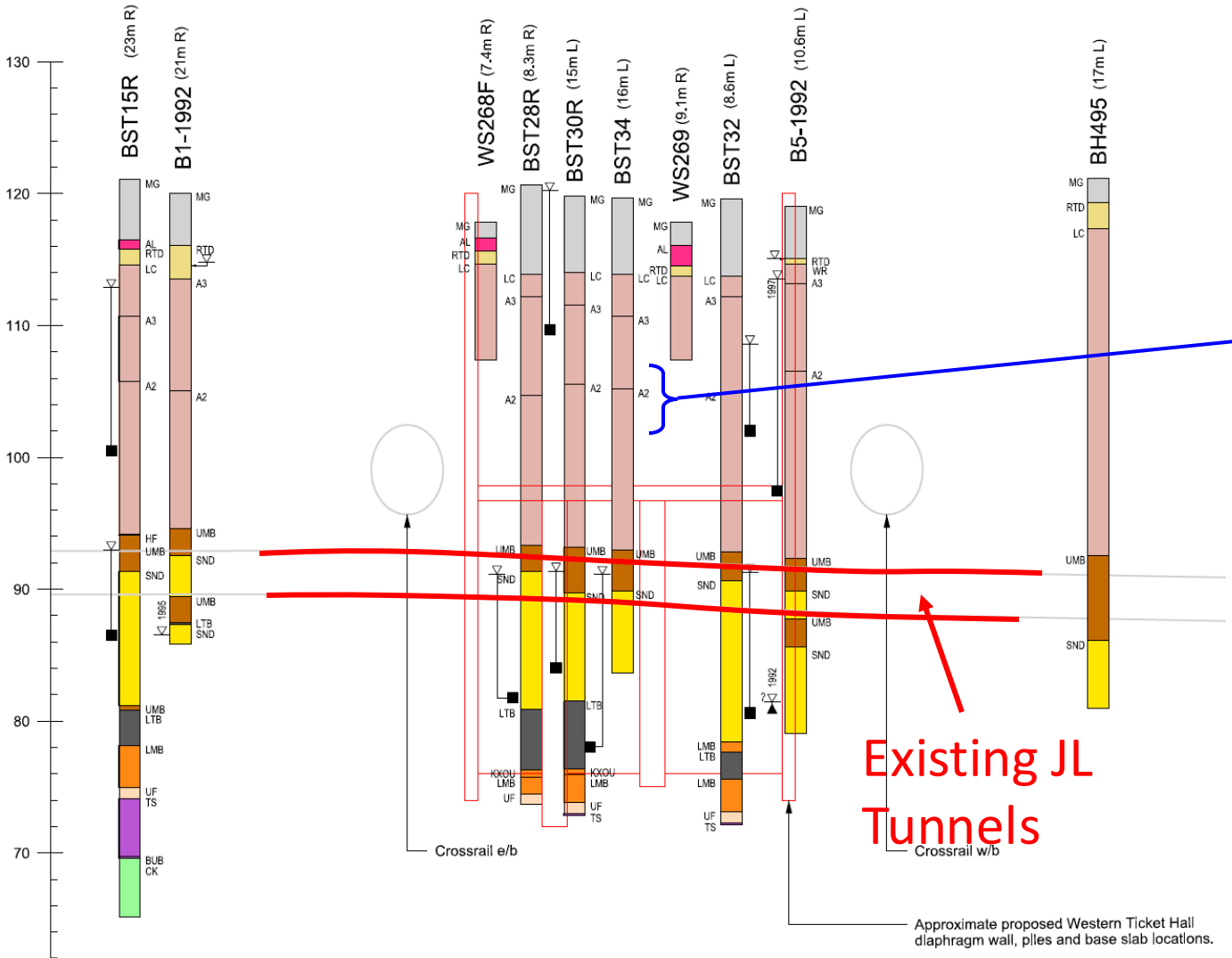


4.1m dia existing Jubilee Line Tunnels

Ground and Groundwater conditions



Excavation Face in London Clay at Bond Street Station (Central London)



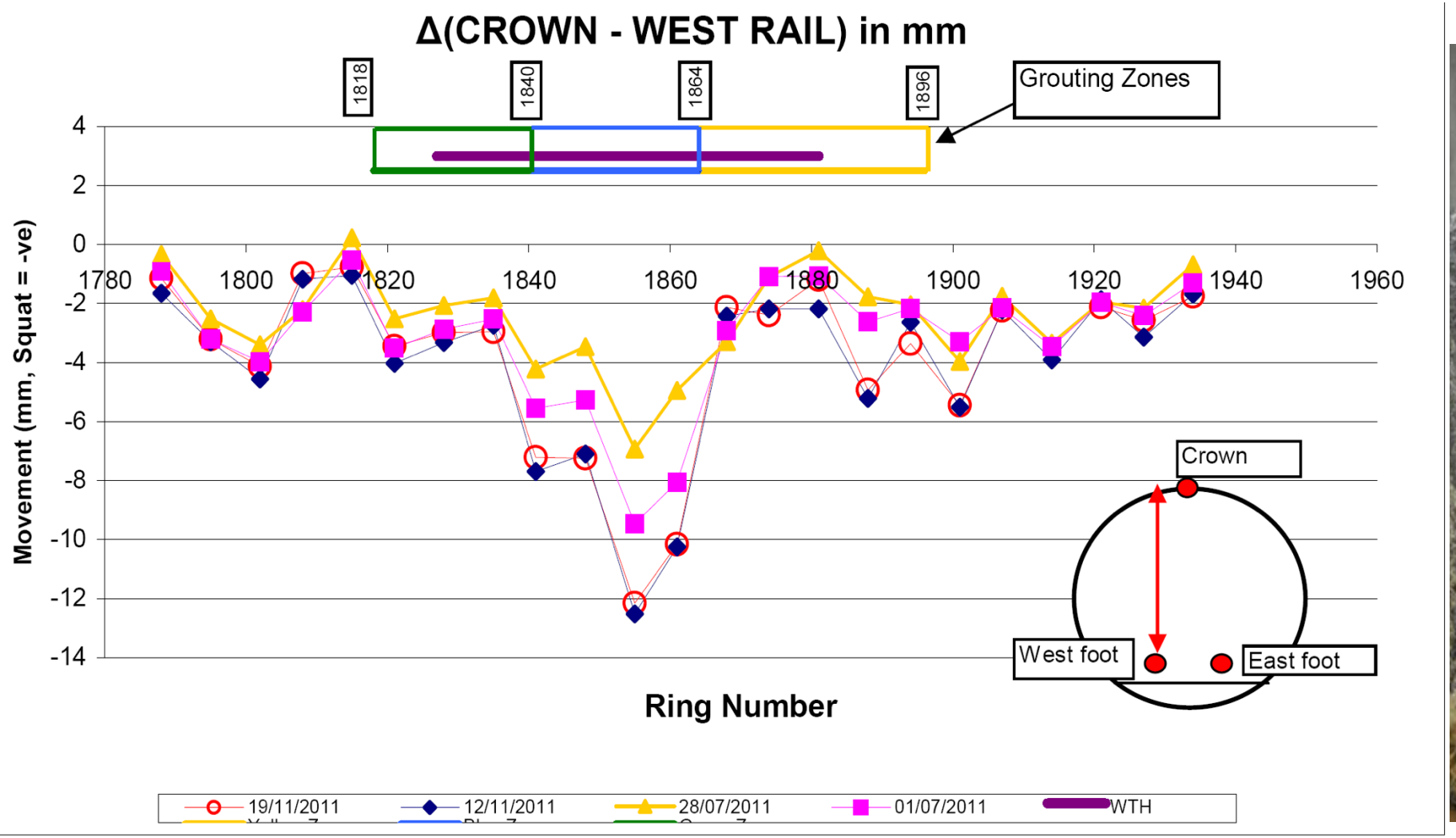
Photographs of London Clay A2



Photographs of London Clay A3ii



Sand and water ingress began during demolition of existing building at WTH location





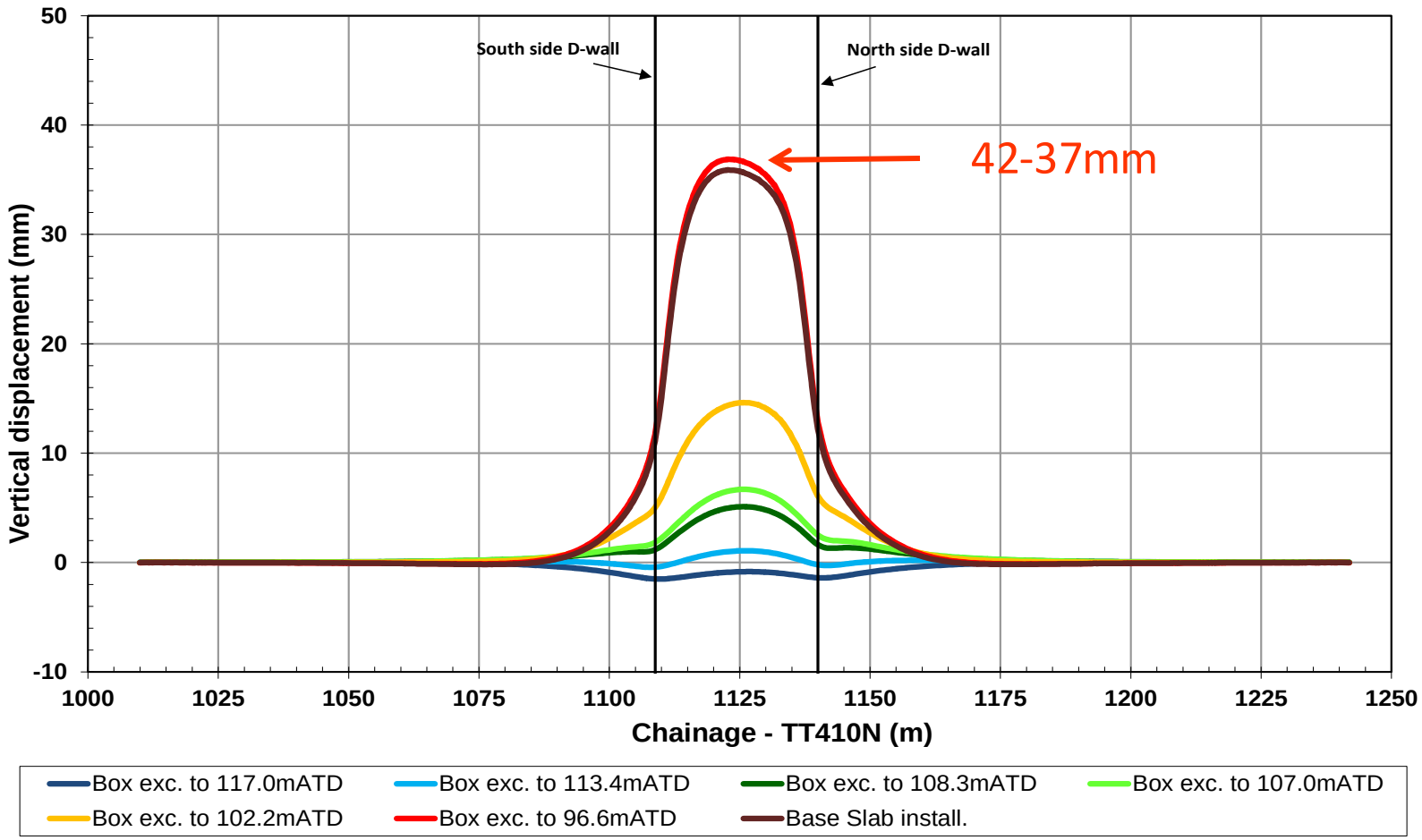
Grouting (voids up to 600mm deep)



Assessment of Existing JL Tunnel Lining

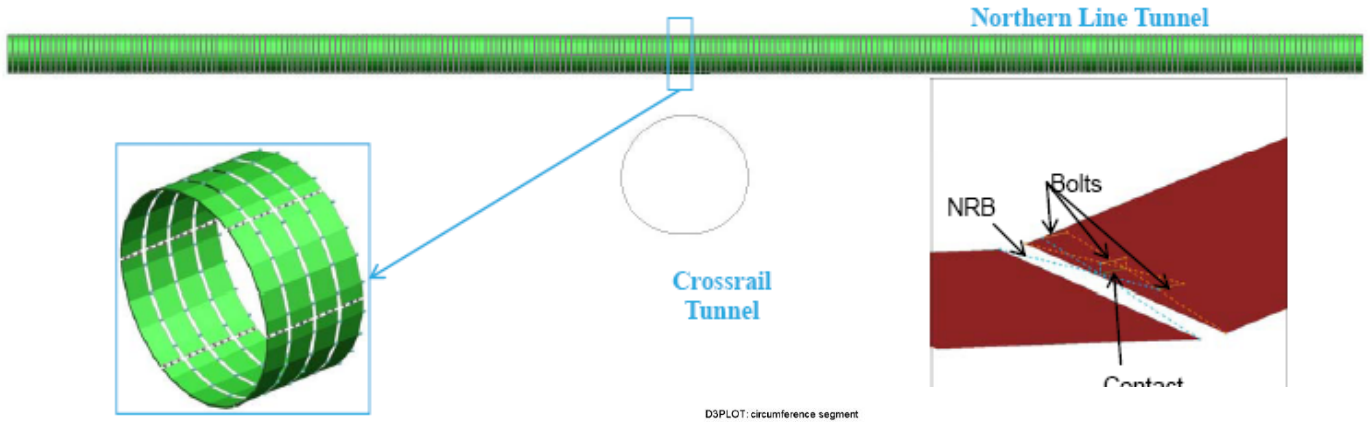
- 3D FE
- Small
- Effect
- Existi

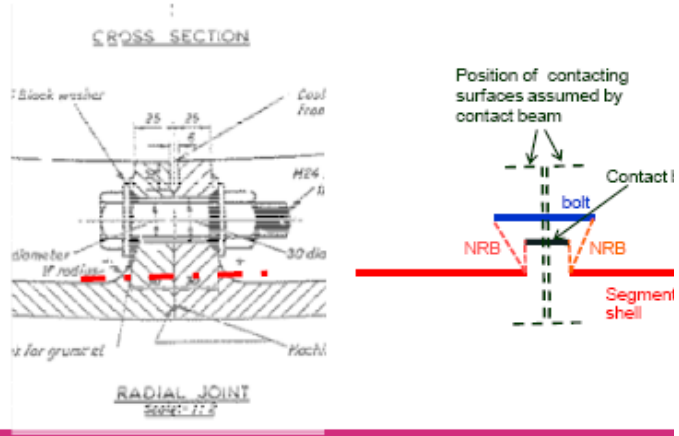
of soi

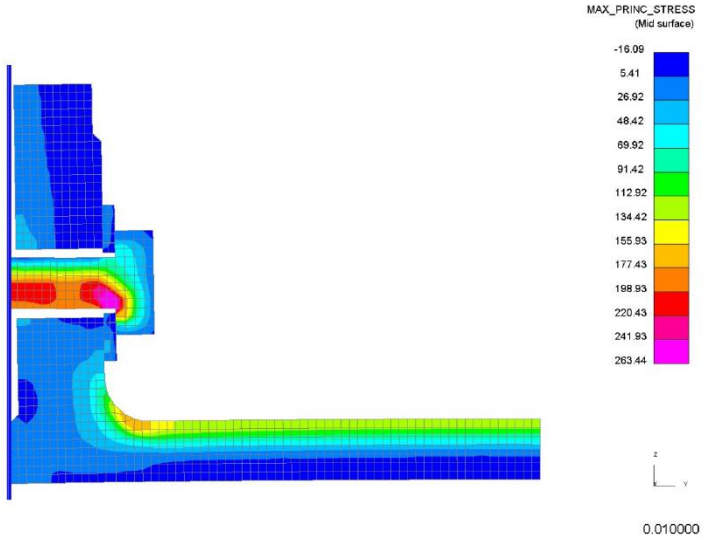


Proposed Mitigation Measures

FE Model – Tunnel details



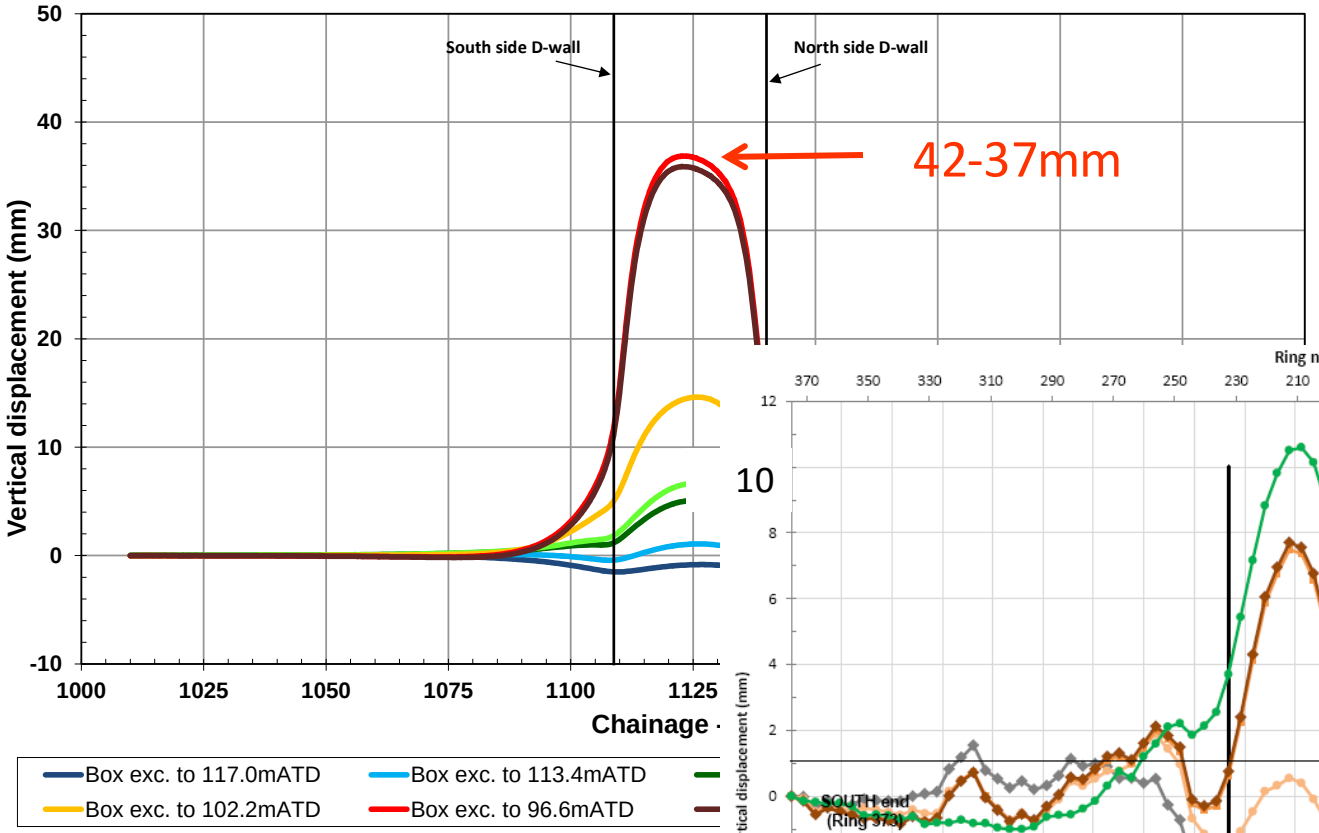


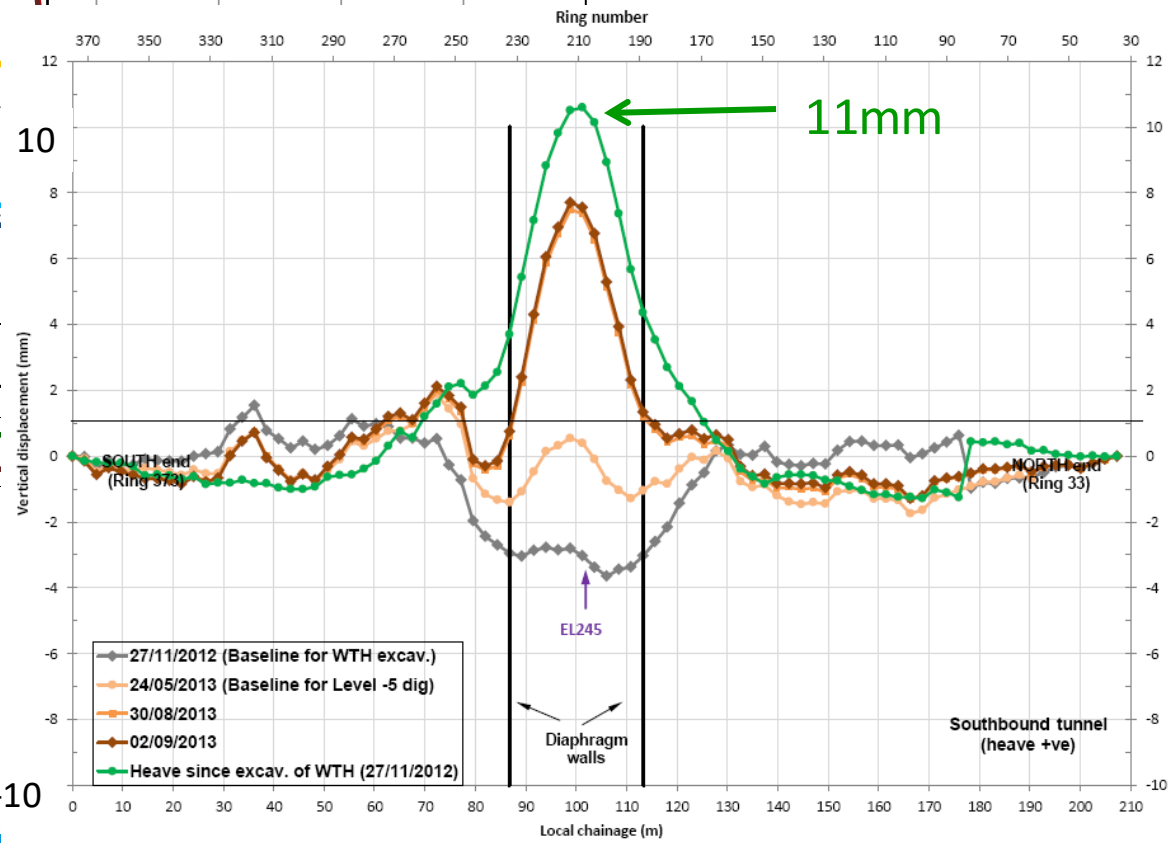


4 Figure F2.4 – Modelling the tunnel lin

Figure 2.4 Principal stresses through critical section of the model at end of Stage 2

Prediction N/B JL vs. Observations





Conclusions

- WTH completed without problems
- Mitigation measures worked – no gapping observed at loosened bolts
- Observed movements about 1/3 predicted, even with very sophisticated modelling
- Could we have completed without bolt loosening?

Tunnelling in Perth Australia (2018)

Forrestfield – Airport Link,

Tunnelling Beneath Perth Airport in sands and gravels with a high GW Table

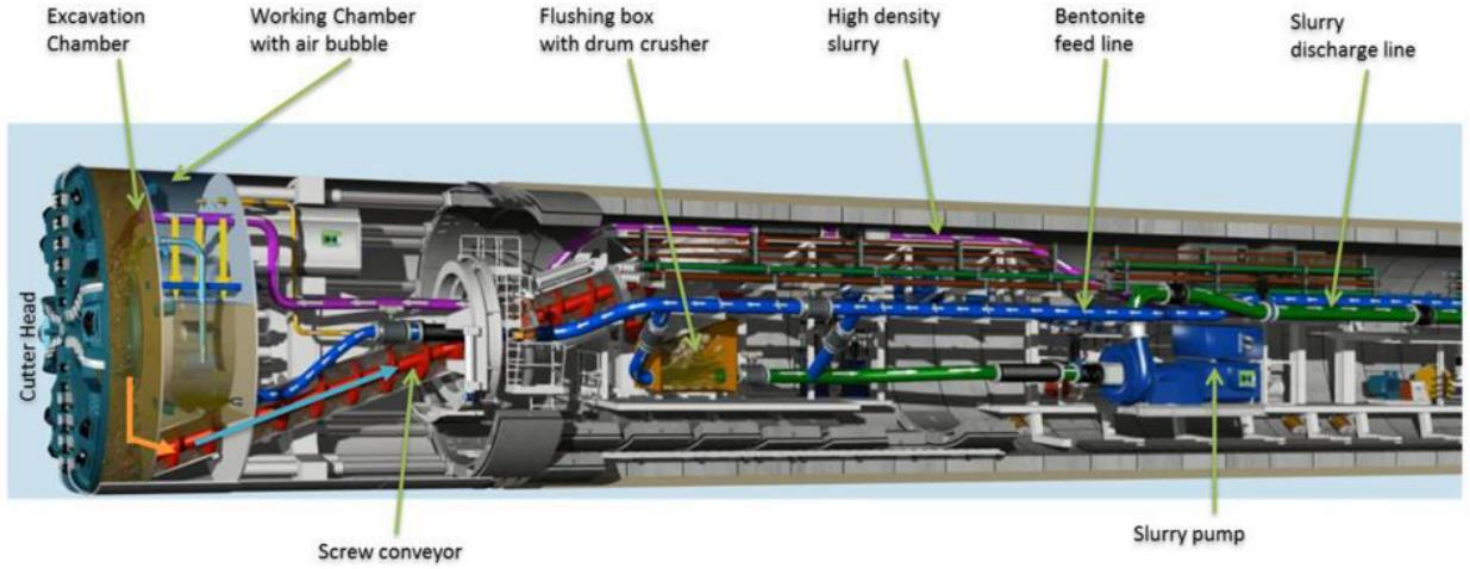
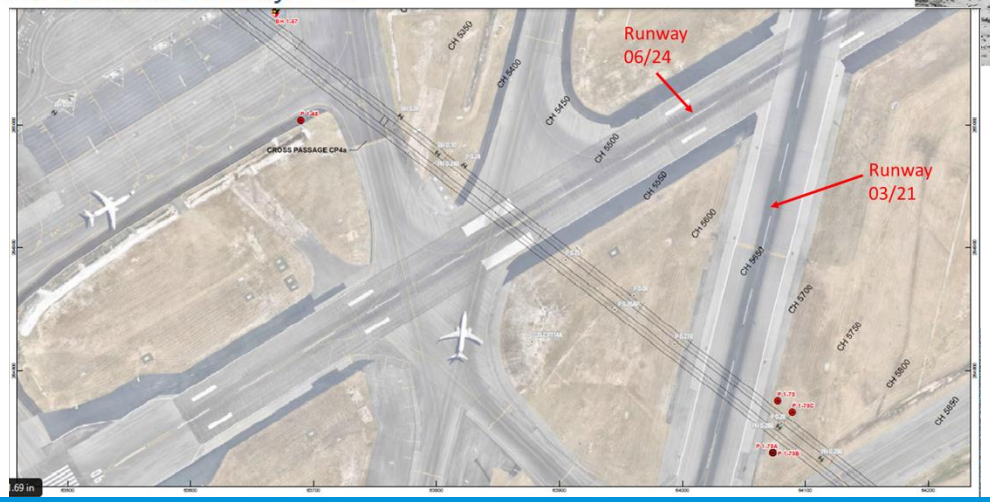


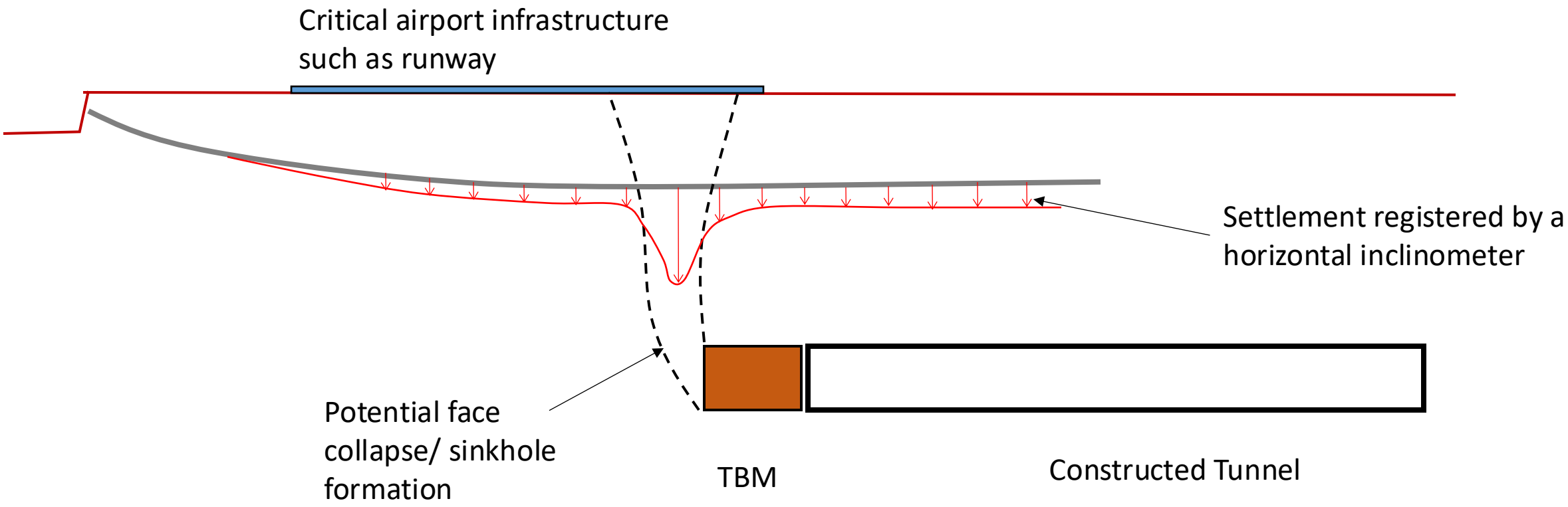
Figure 2 - The Variable Density TBM



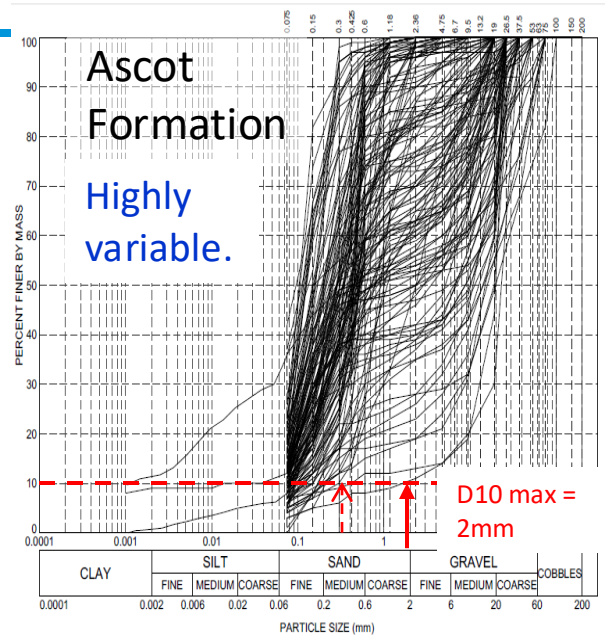




Risk of sinkhole formation under critical infrastructure

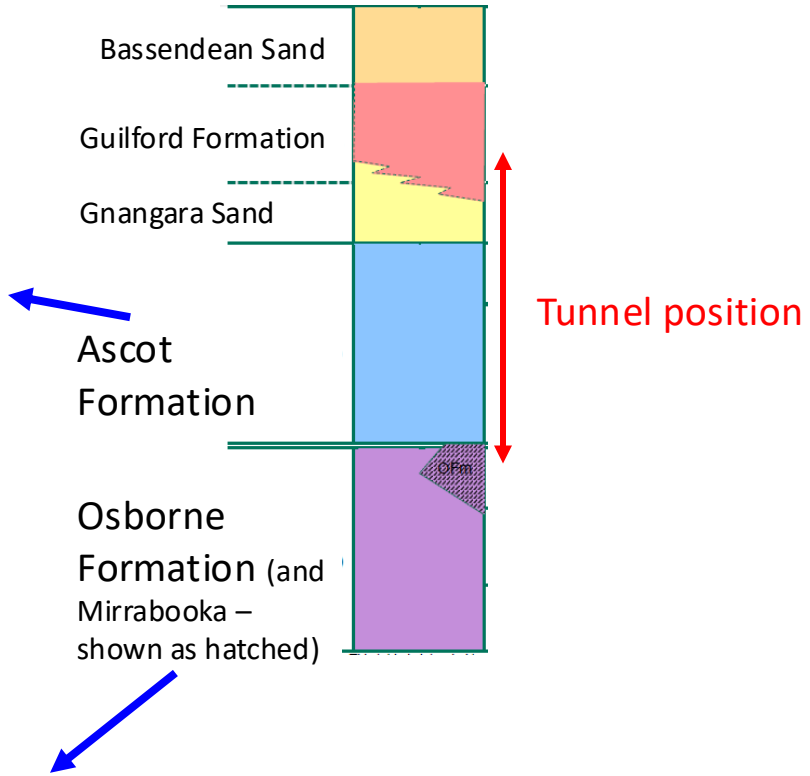


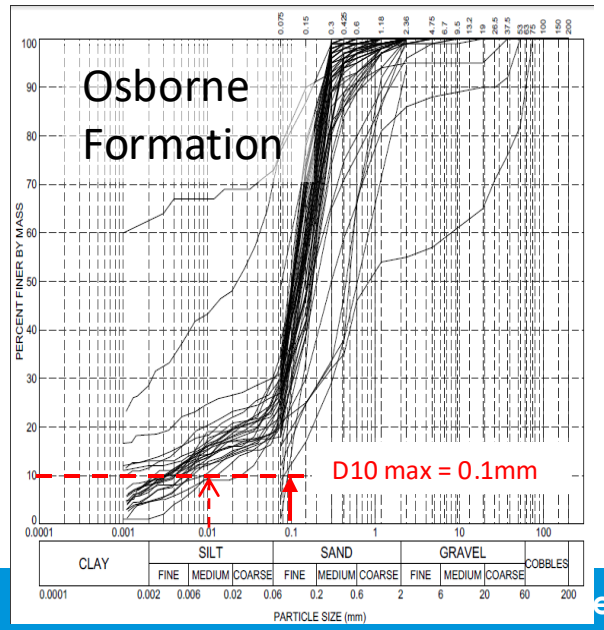
Geotechnical data of Ascot and Osborne Formations



Ascot Formation - low to intermediate plasticity clay

- **medium to low risk of clogging**
- **Highly variable cementation and particle size**

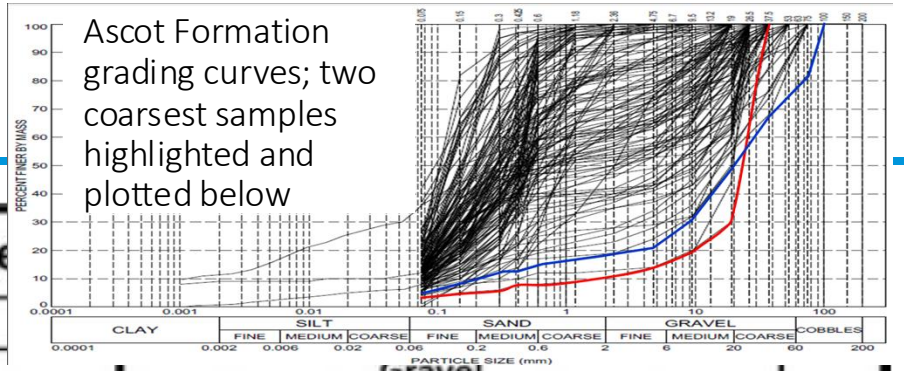




Osborne Formation – High and Intermediate plasticity clays present

- **High clogging risk**

Ascot Formation grading curves; two coarsest samples highlighted and plotted below



EPB / MIX – Shield Range

Sieve Size

Clay | Silt: Fine, Medium, Coarse | Sand: Fine, Medium, Coarse | Gravel: Fine, Medium, Coarse

EPM

Slurry Mode

HDSM

% Passing

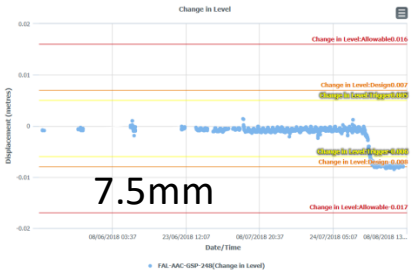
100 90 80 70 60 50 40 30 20 10 0

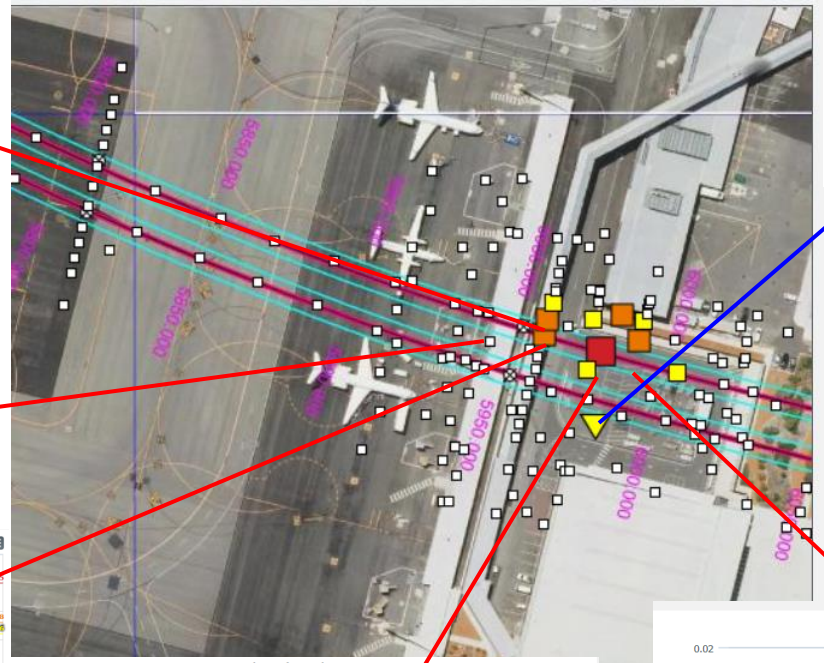
0,001 0,002 0,006 0,02 0,06 0,2 0,6 2,0 6,0 20,0 60,0

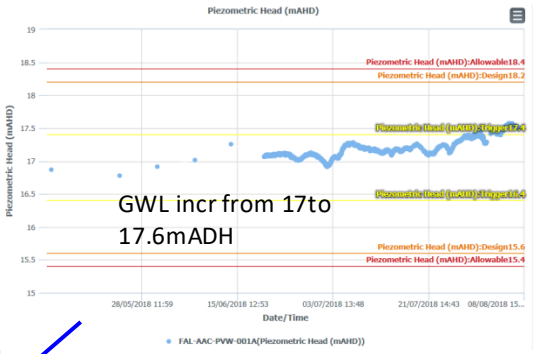
Size (mm)

Extension of the range for slurry machine using High Density Slurry and High Viscosity Slurry

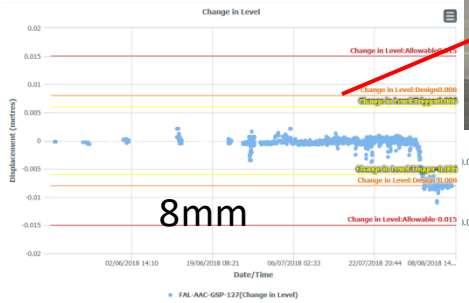
Airside Approach

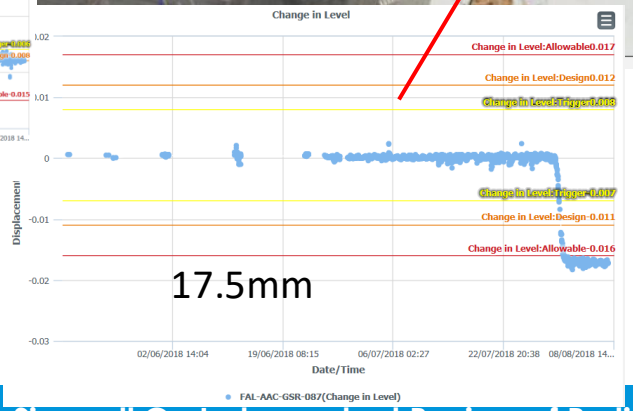


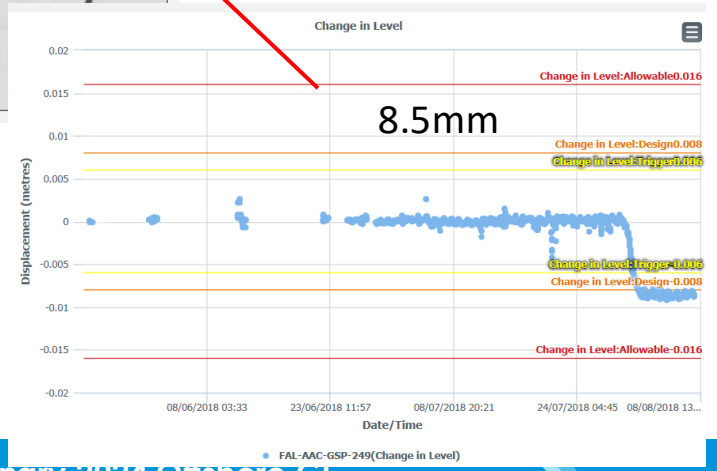




GWL incr from 17to 17.6mADH







Airside

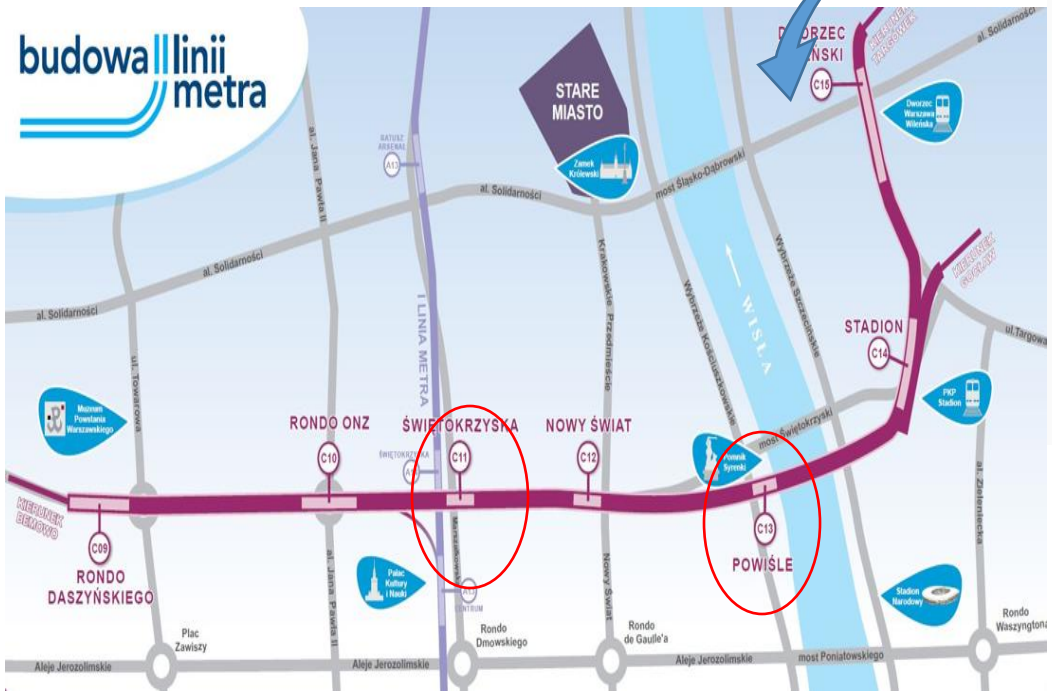


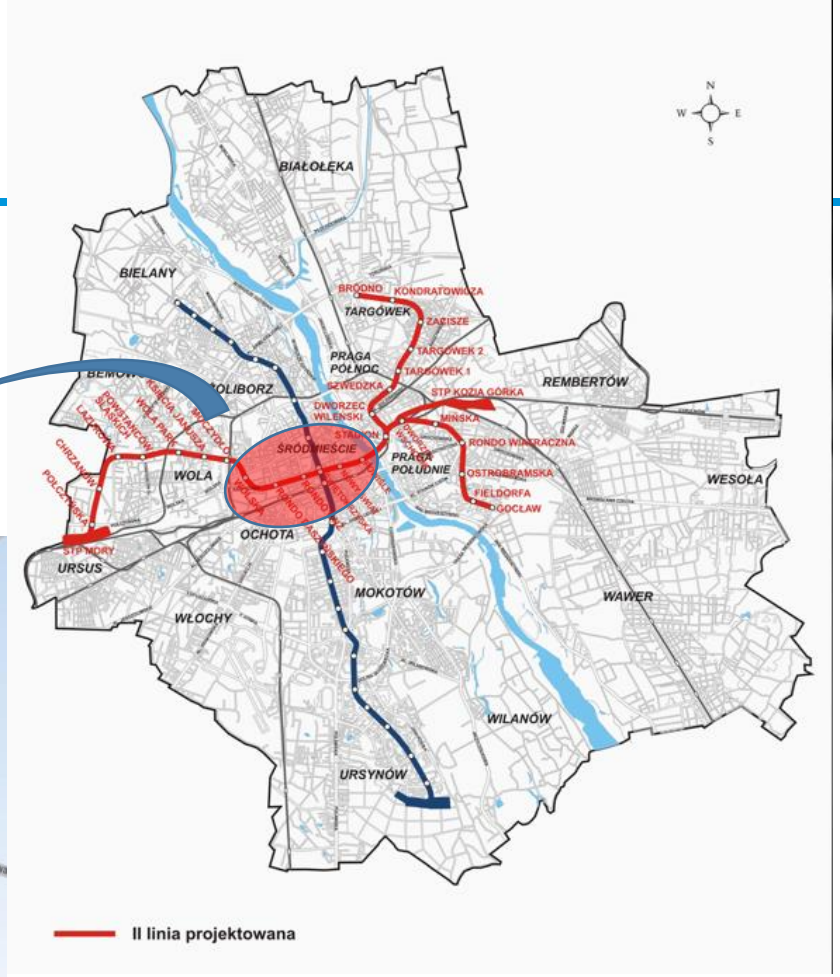
Settlements well controlled (<5mm)

3(3) Warsaw Metro Line 2, Station C11, Poland

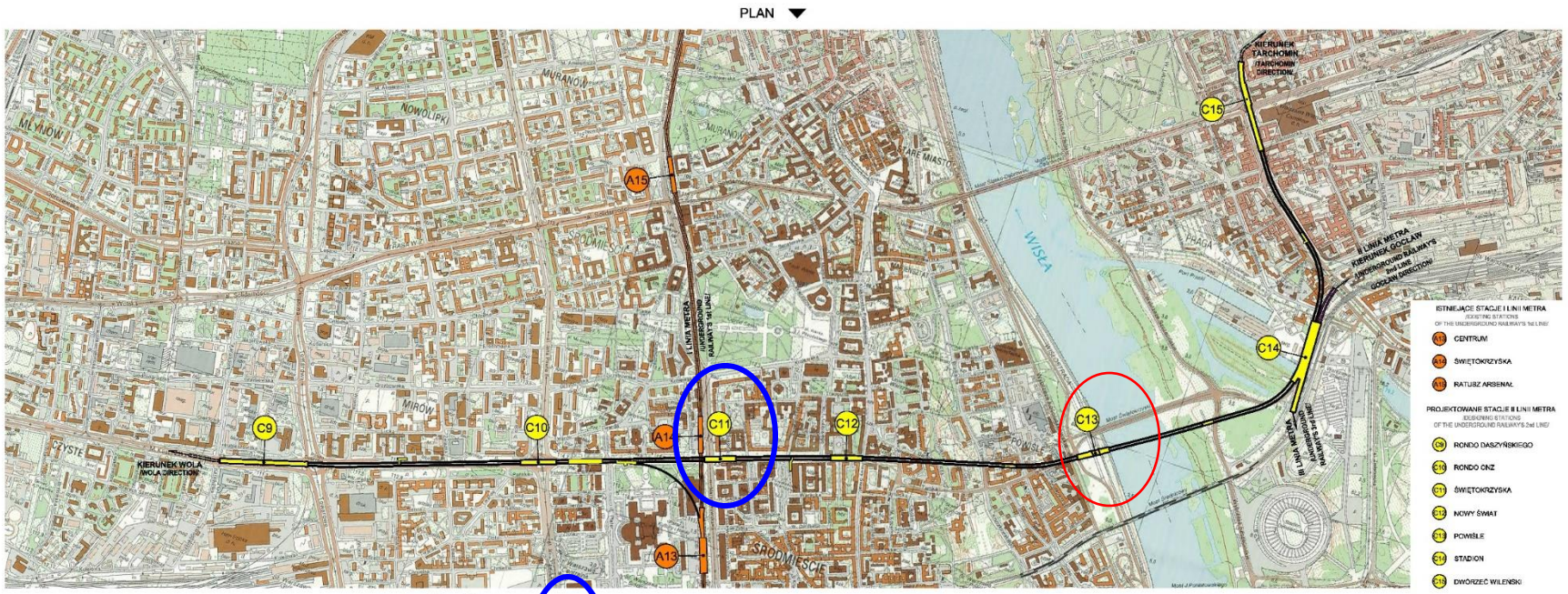


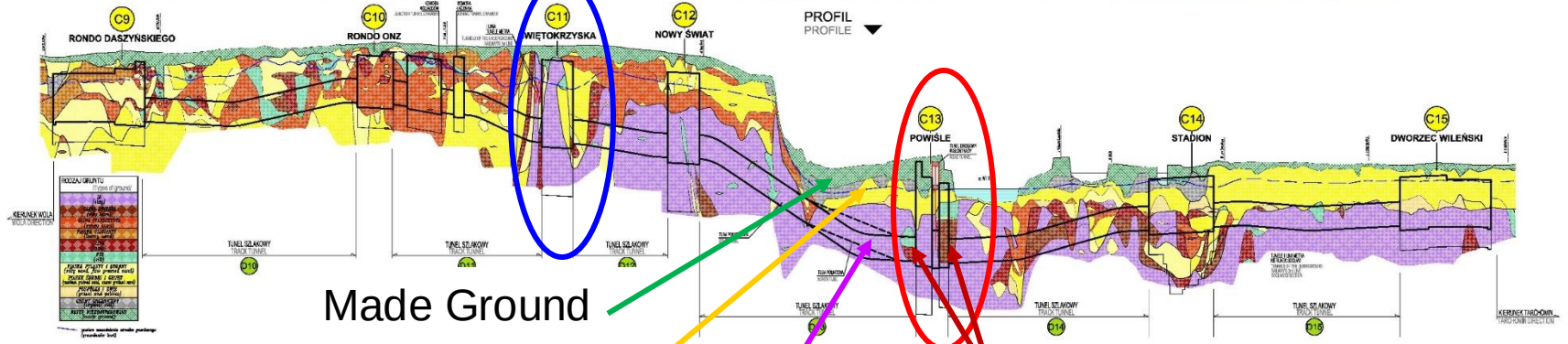
- Euro 960M
- 10km of tunnels
- 7 Stations + 6 Vent Shafts
- 600m of tunnels under River Vistula.
- Connections to existing Line 1
- Contractor Astaldi, Gulermak BDim JV
- GCG Specialist Adviser brought in to assist with solution to problems


budowa II linii metra
STARE MIASTO
STADION
RONDO ONZ
ŚWIĘTOKRZYSKA
NOWY ŚWIAT
POWIŚLE
RONDO DASZYŃSKIEGO
I LINIA METRA
WISŁA
Plac Zawiszy
Rondo Dmowskiego
Rondo de Gaulle'a
Aleje Jerozolimskie
most Poniatowskiego
al. Solidarności


BIAŁOŁĘKA
BIELANY
TARGÓWEK
PRAGA PÓŁNOC
REMBERTÓW
KOLIBORZ
ŚRÓDMIEŚCIE
PRAGA POŁUDNIE
WOLA
WESOŁA
OCHOTA
URSUS
MOKOTÓW
WAWER
WŁOCHY
WILANÓW
URSYNÓW
II linia projektowana

Case Study #2 Tunnel collapse and recovery – mixed ground site





Made Ground

Quaternary Sands

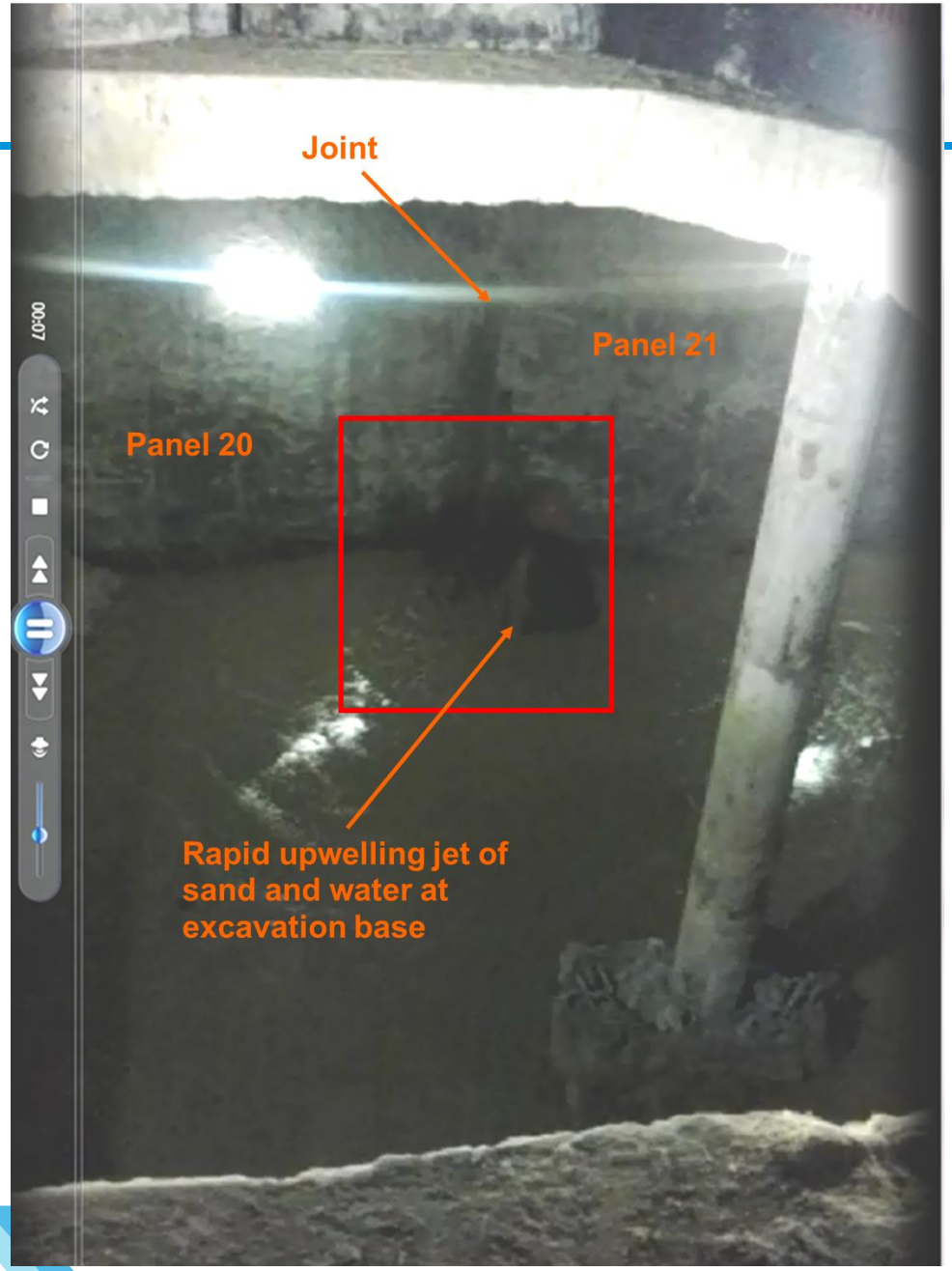
Stiff to hard Pliocene Clay

Pockets of silt and fine sand in the Pliocene Clay

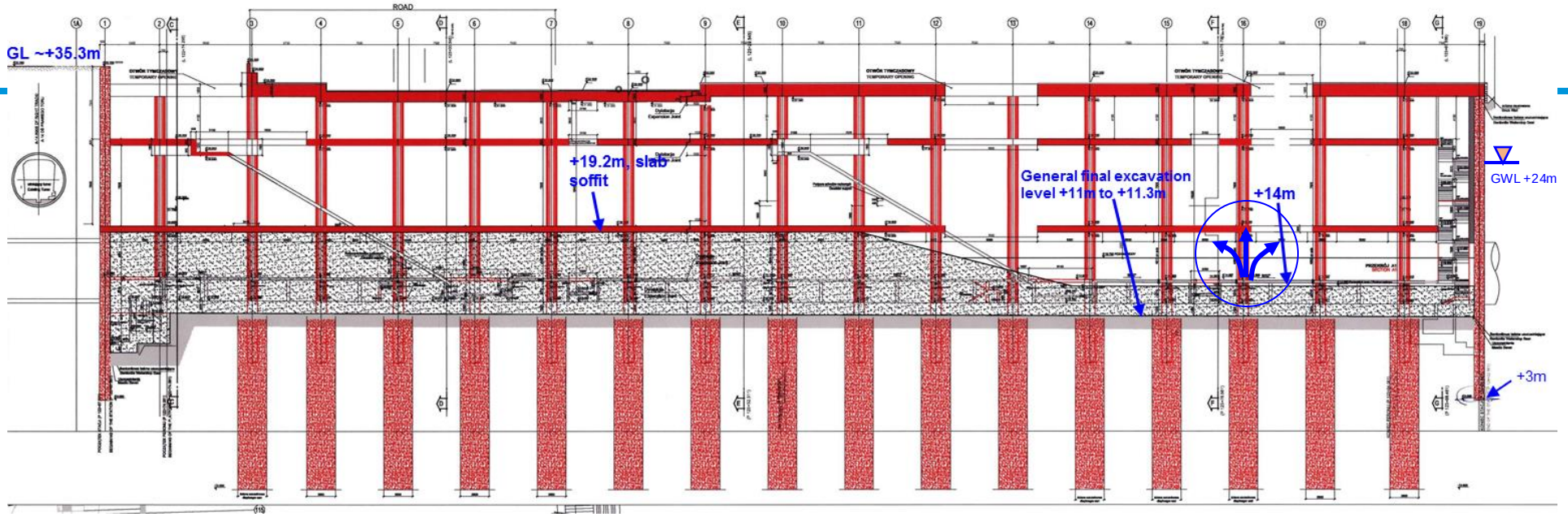
56

Case history #1: boiling and piping in a sand site

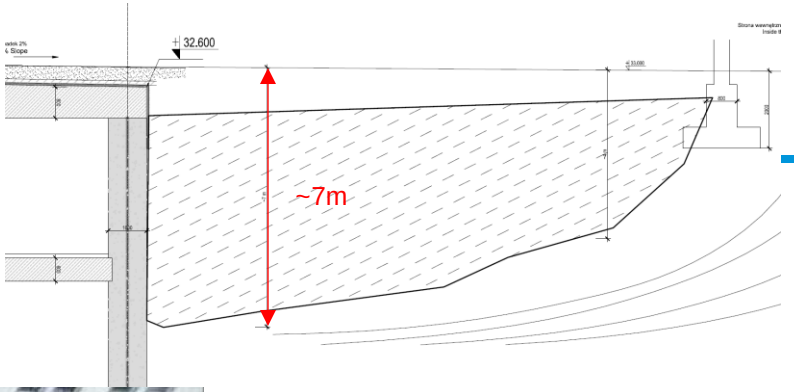
- Construction of Metro Line 2 in Warsaw in 2012
- Station C11 comprised a D-wall box to 24m final depth, with D-walls to 32m depth.
- In Oct when excavation was down to 21m depth, event occurred.
- Boiling, ingress of ~600m3 of sand and water into the excavation, large sink hole

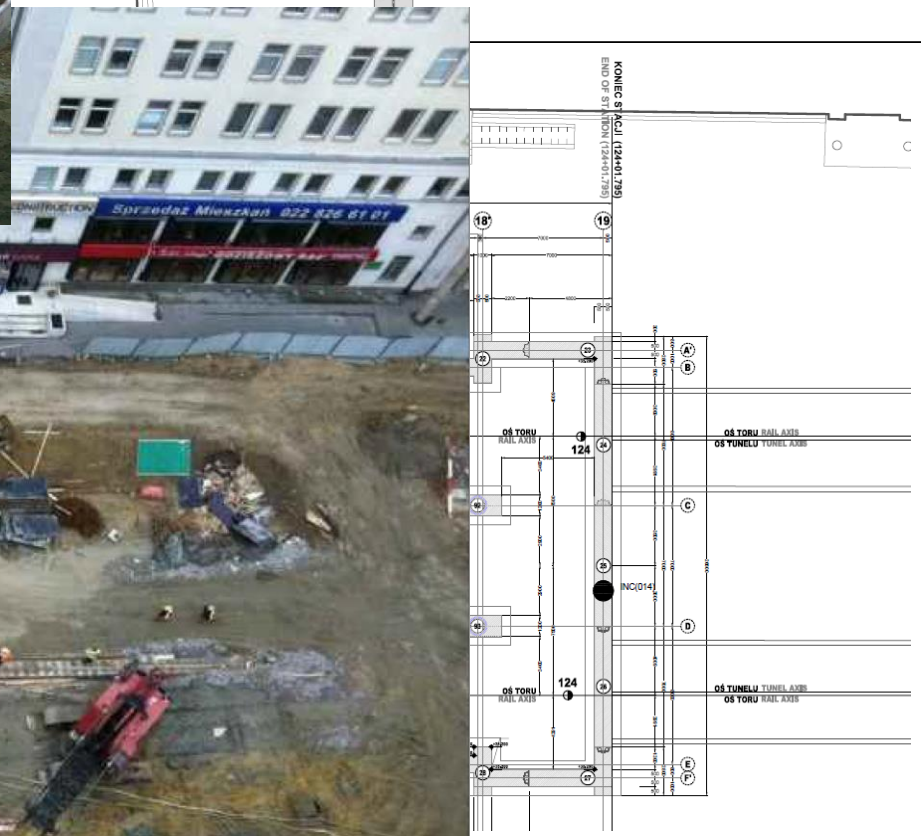

Joint
Panel 21
Panel 20
Rapid upwelling jet of sand and water at excavation base

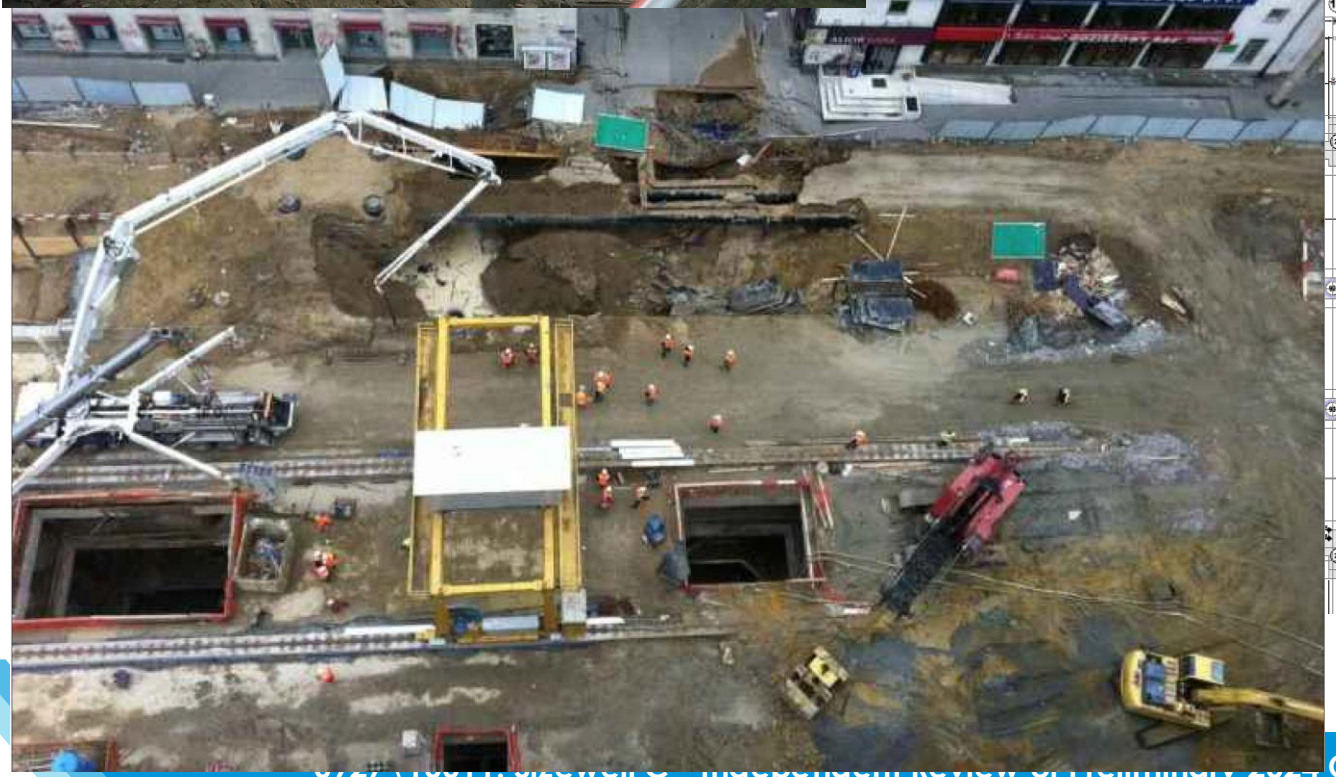

Joint
Jet


ROAD
GL ~+35.3m
+19.2m, slab soffit
General final excavation level +11m to +11.3m
+14m
GWL +24m
+3m



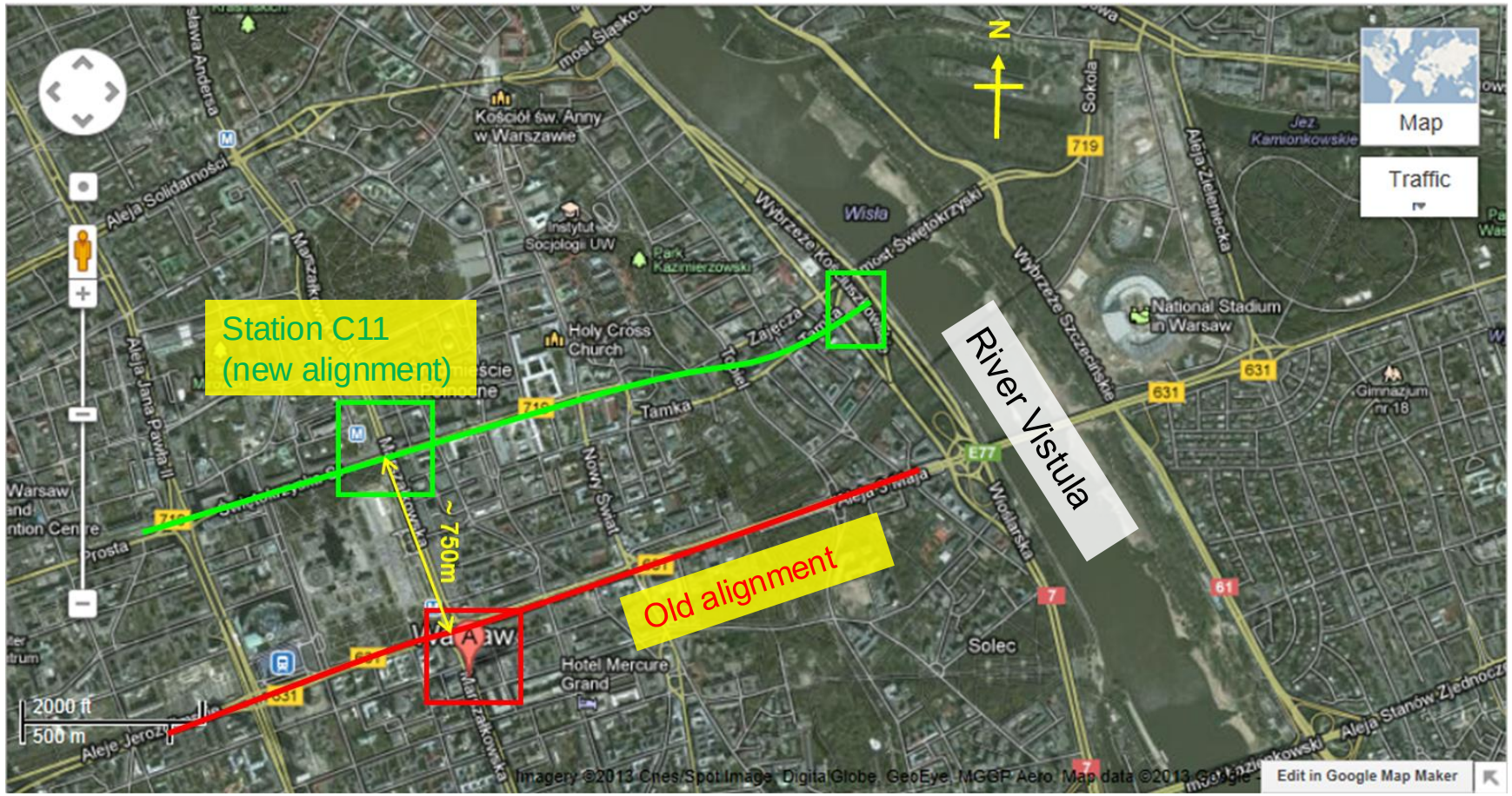






Geotechnical Consulting Group

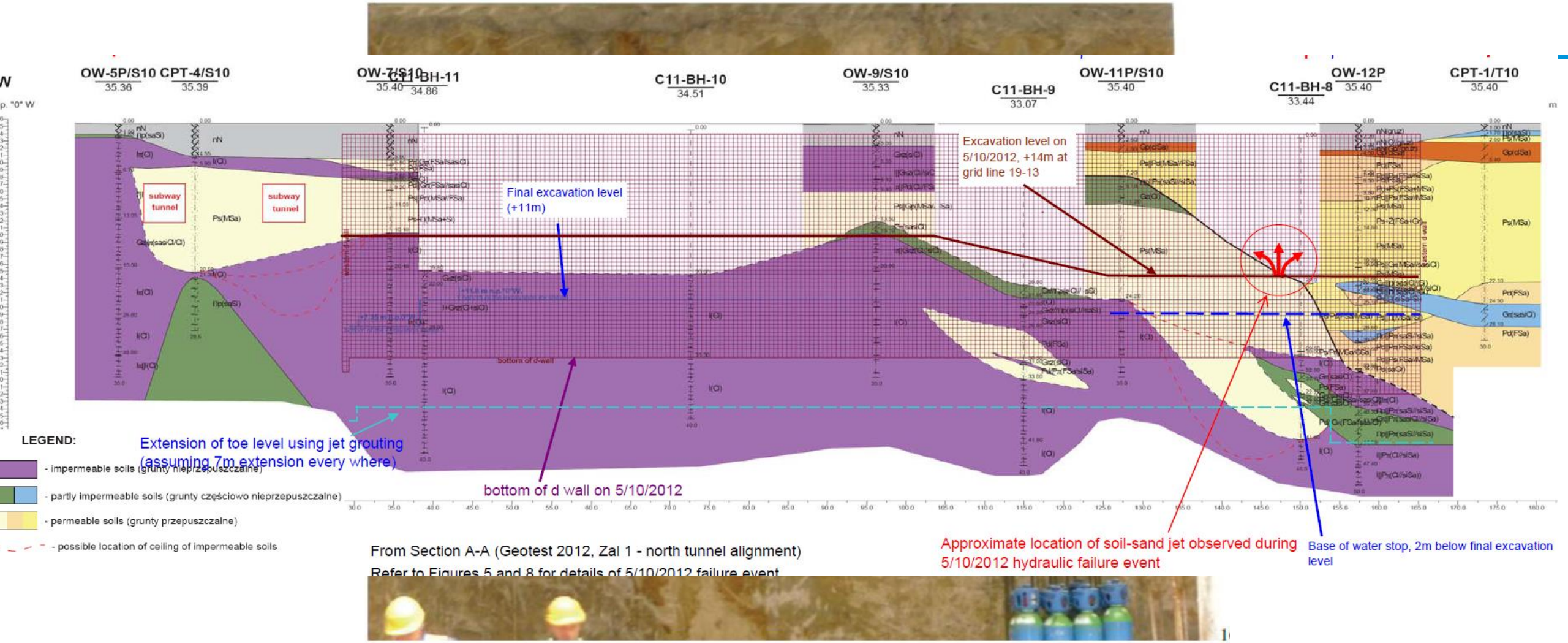
Location


Station C11
(new alignment)
River Vistula
Old alignment
~ 750m
Map
Traffic
Wisła
Holy Cross Church
National Stadium in Warsaw
Hotel Mercure Grand
Solec
Tamka
Zajęcza
Nowy Świat
Aleja Solidarności
Aleja Jana Pawła II
Wybrzeże Kościuszkowskie
Wybrzeże Szczecińskie
Most Świętokrzyski
Aleja Stanów Zjednoczonych
2000 ft
500 m
Imagery ©2013 Cnes/Spot Image, DigitalGlobe, GeoEye, MGGP Aero, Map data ©2013 Google
Edit in Google Map Maker

Ground and groundwater conditions, C11

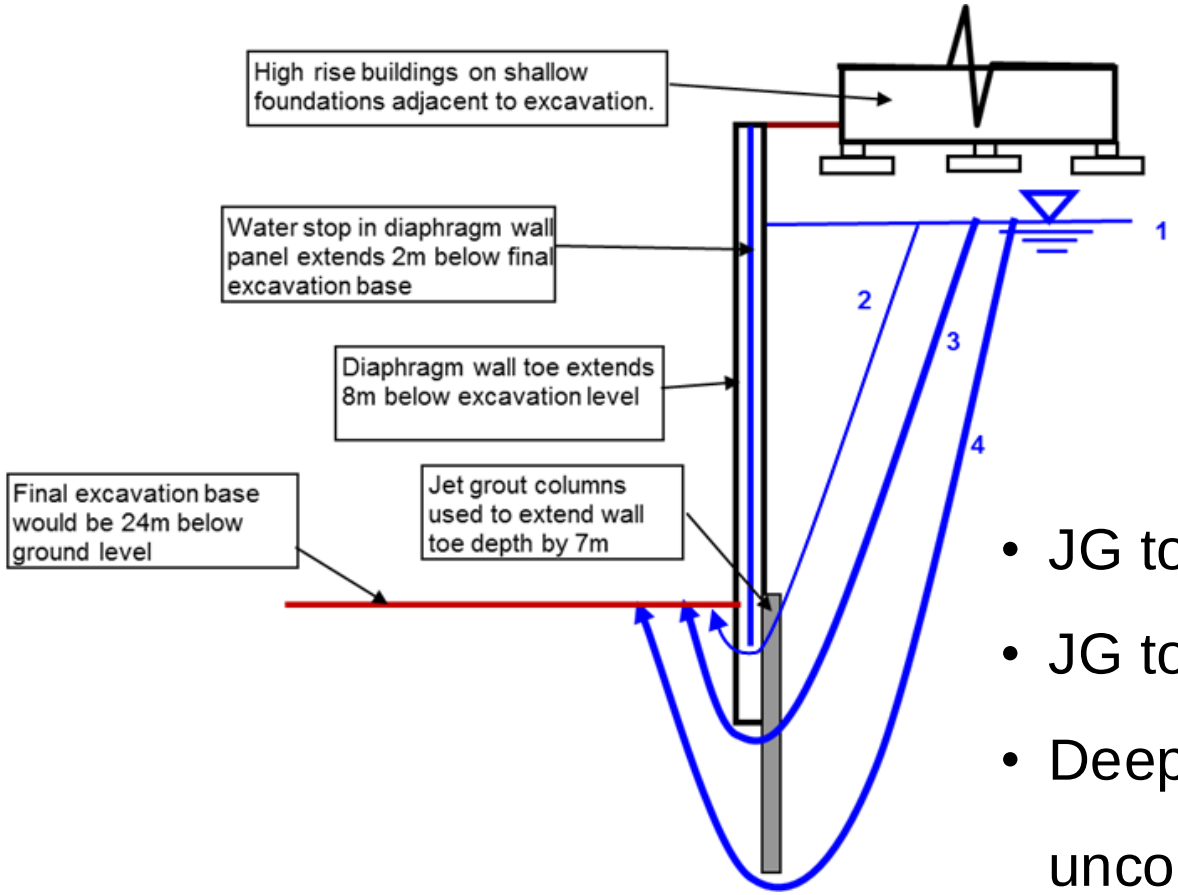
Geology

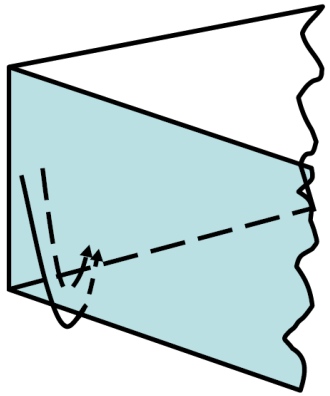
- Very complex, laterally very variable, highly glaciotectonised.
- Made ground over Pliocene Clay – stiff, highly plastic clay with pockets of water bearing sand (semi-confined aquifer)
- On eastern side, 30m thick water bearing Quaternary sands and gravels below 7m MG above Pliocene deposits;
- Station located at edge of an anticline in the Pliocene Clay



Sequence of strata indicated by colouration on an internal cavity wall – brown colouration are sand bodies inclined at >45 degs and penetrating to depth

Solution implemented

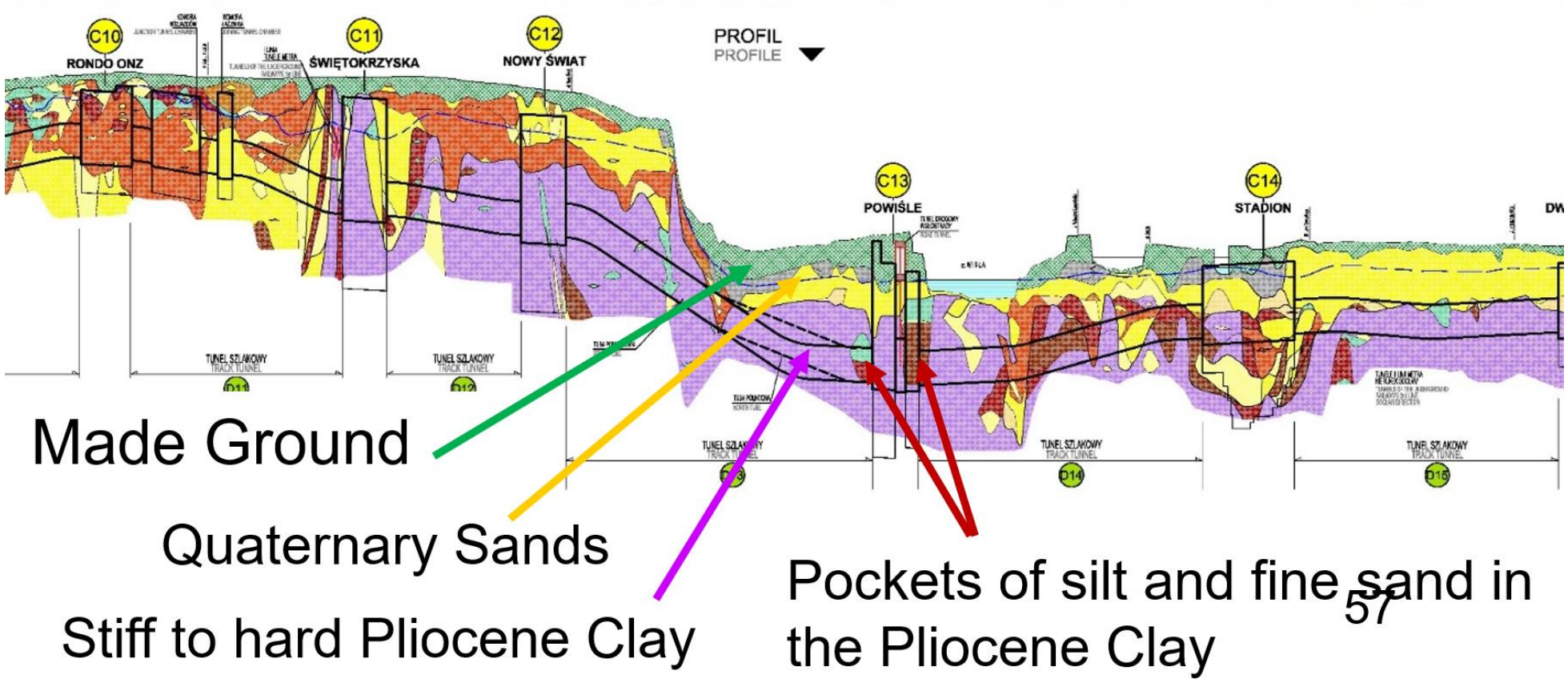




- JG to seal D-wall joints, augmented by TAM grouting
- JG to extend toe of D-wall by 7m
- Deep wells to depressurize semi-confined and unconfined water-bearing zones, augmented by and vacuum wells in silty zones

3(3) Warsaw Metro Line 2, Station C13, Poland

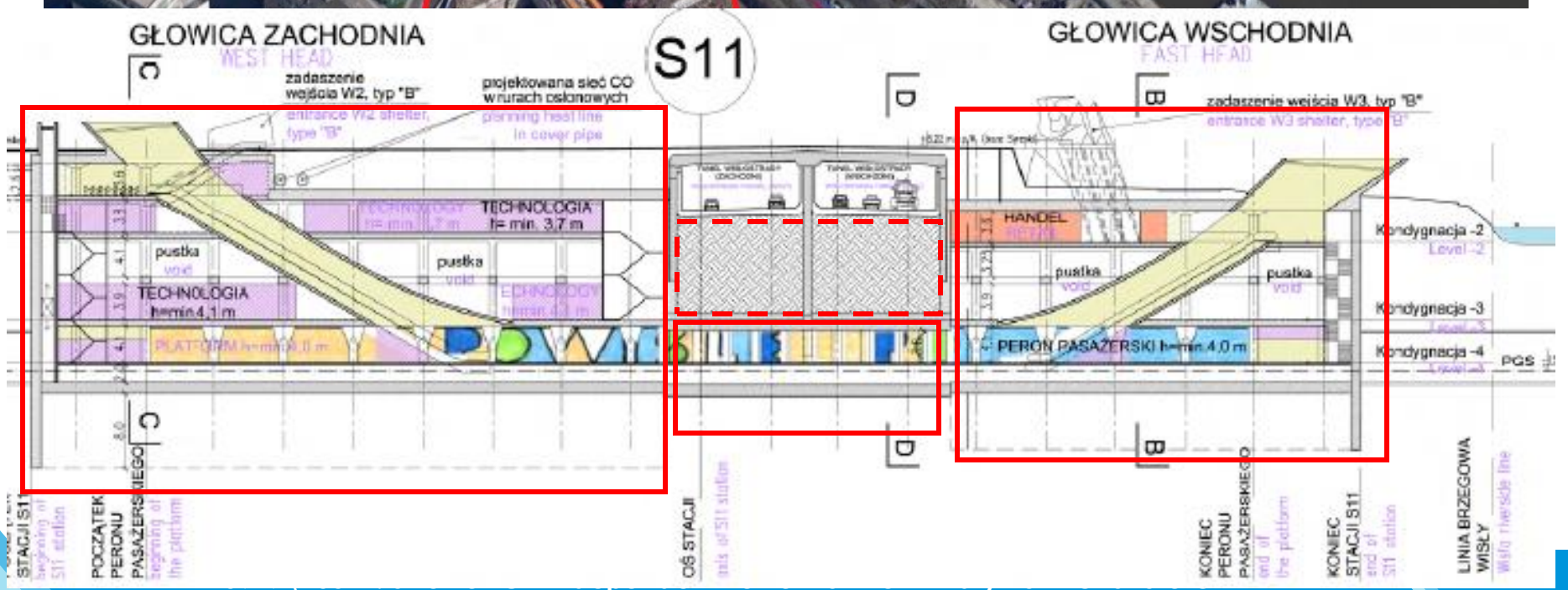
Case Study #2 Tunnel collapse and recovery – mixed ground site



57

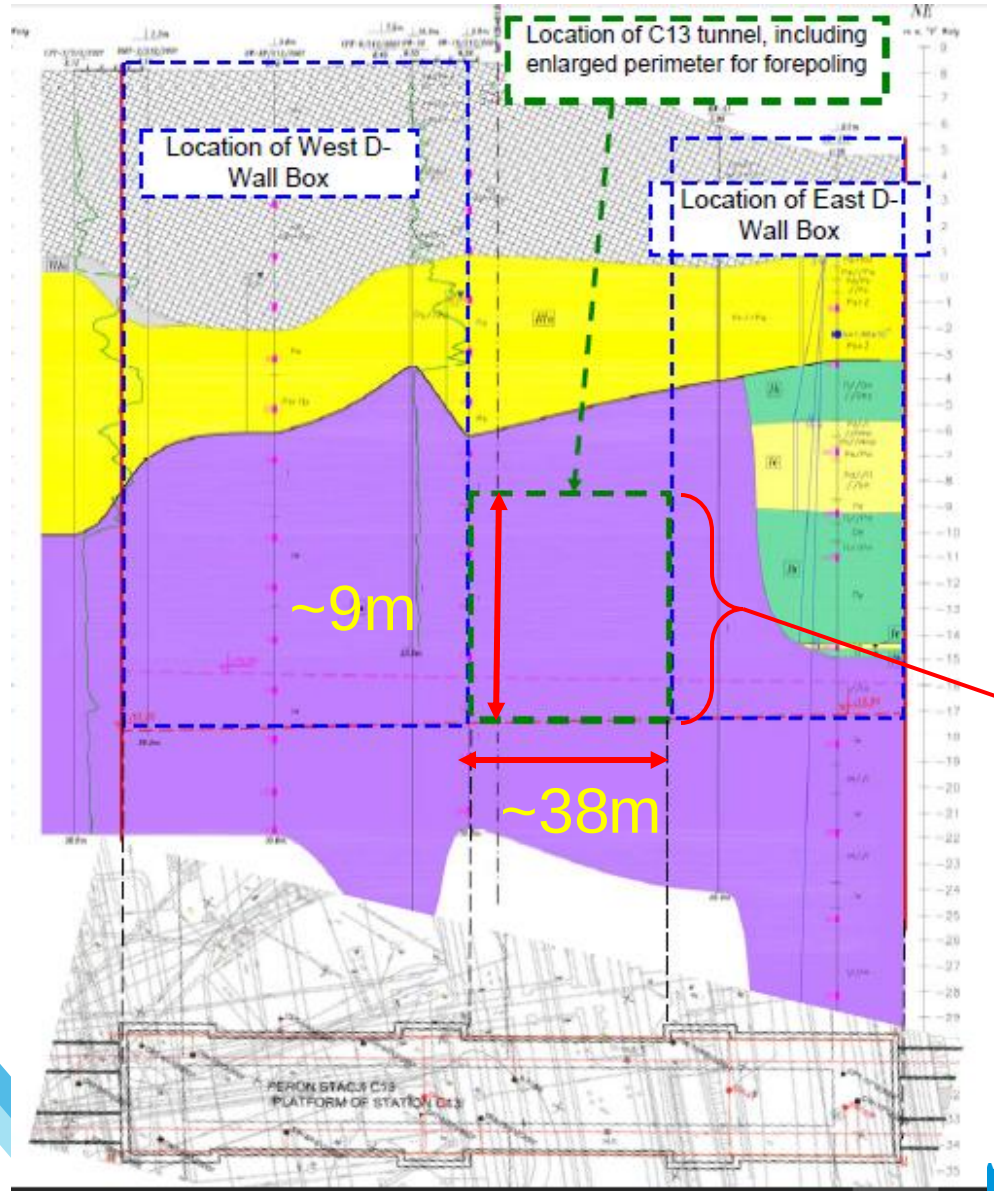


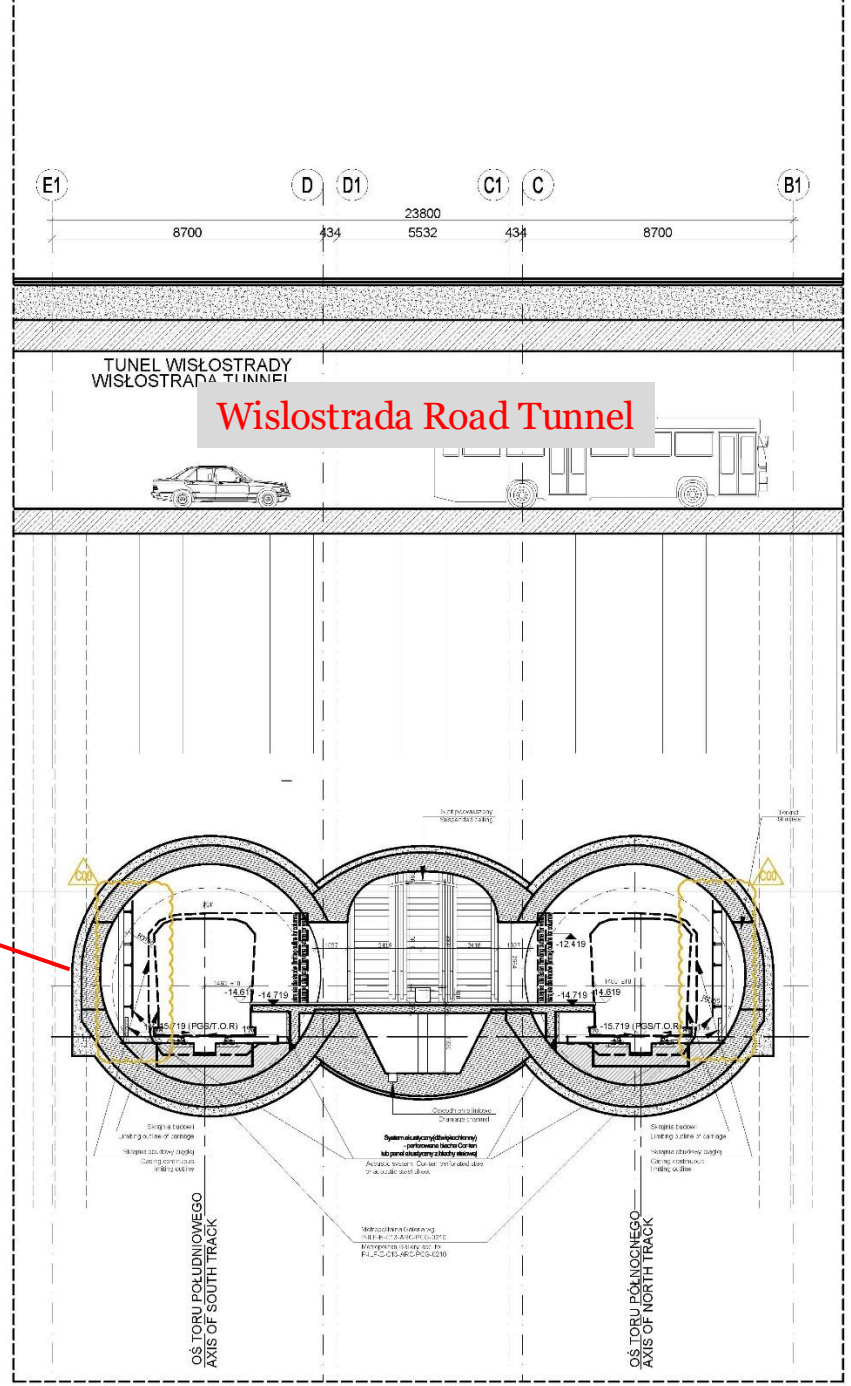




Geotechnical Consulting Group

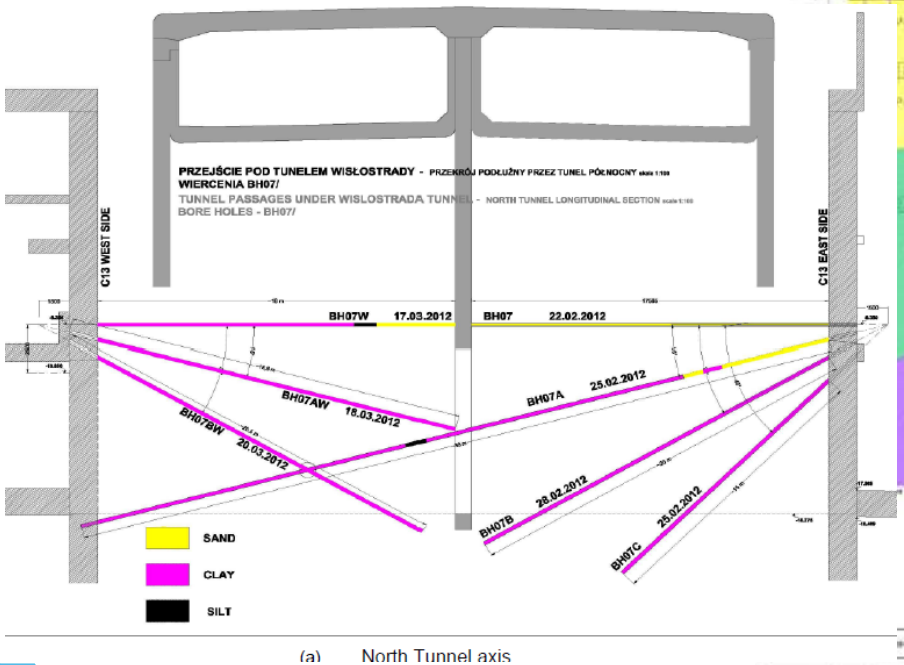
Initial design: in clay



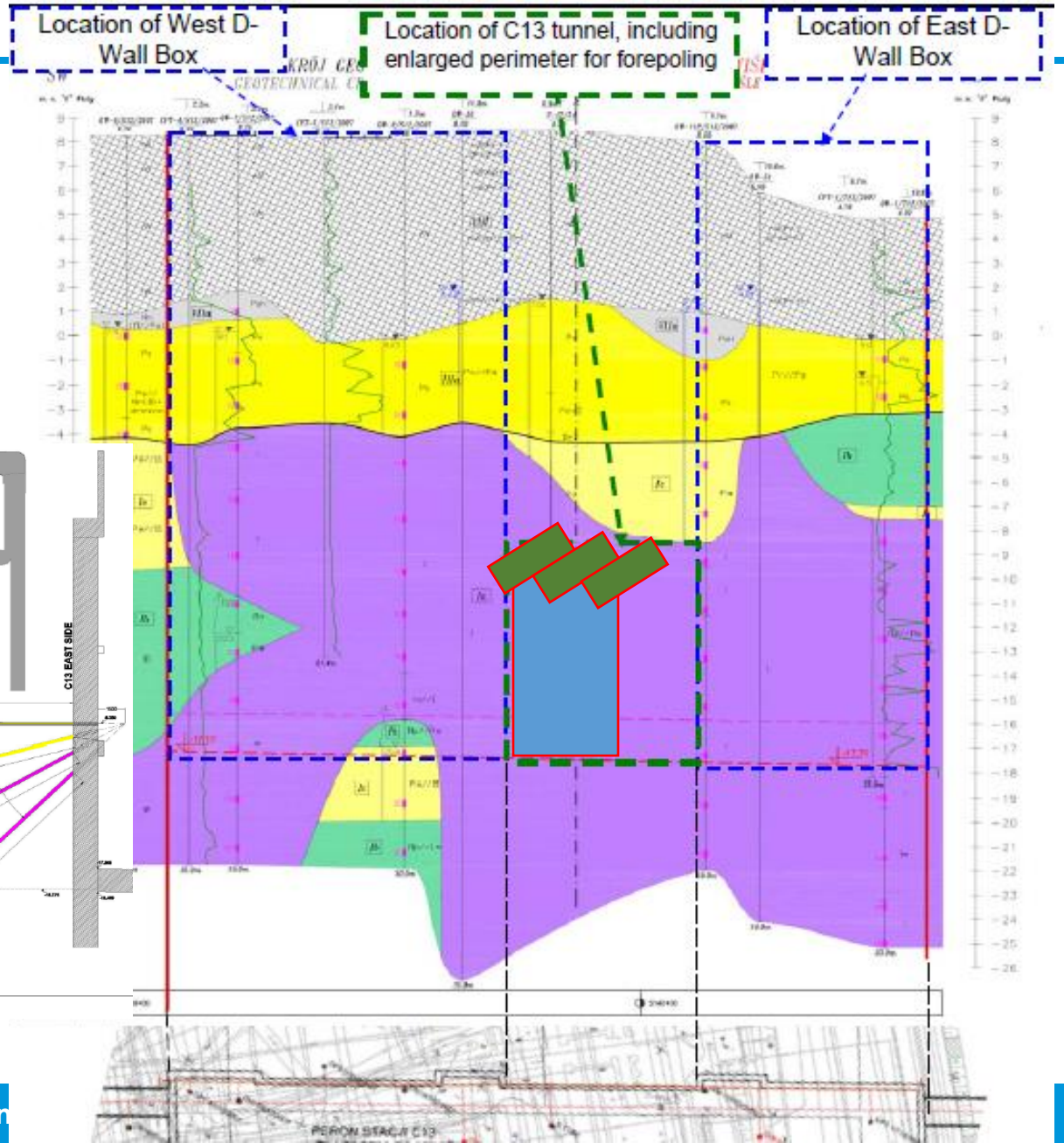


Geotechnical Consulting Group

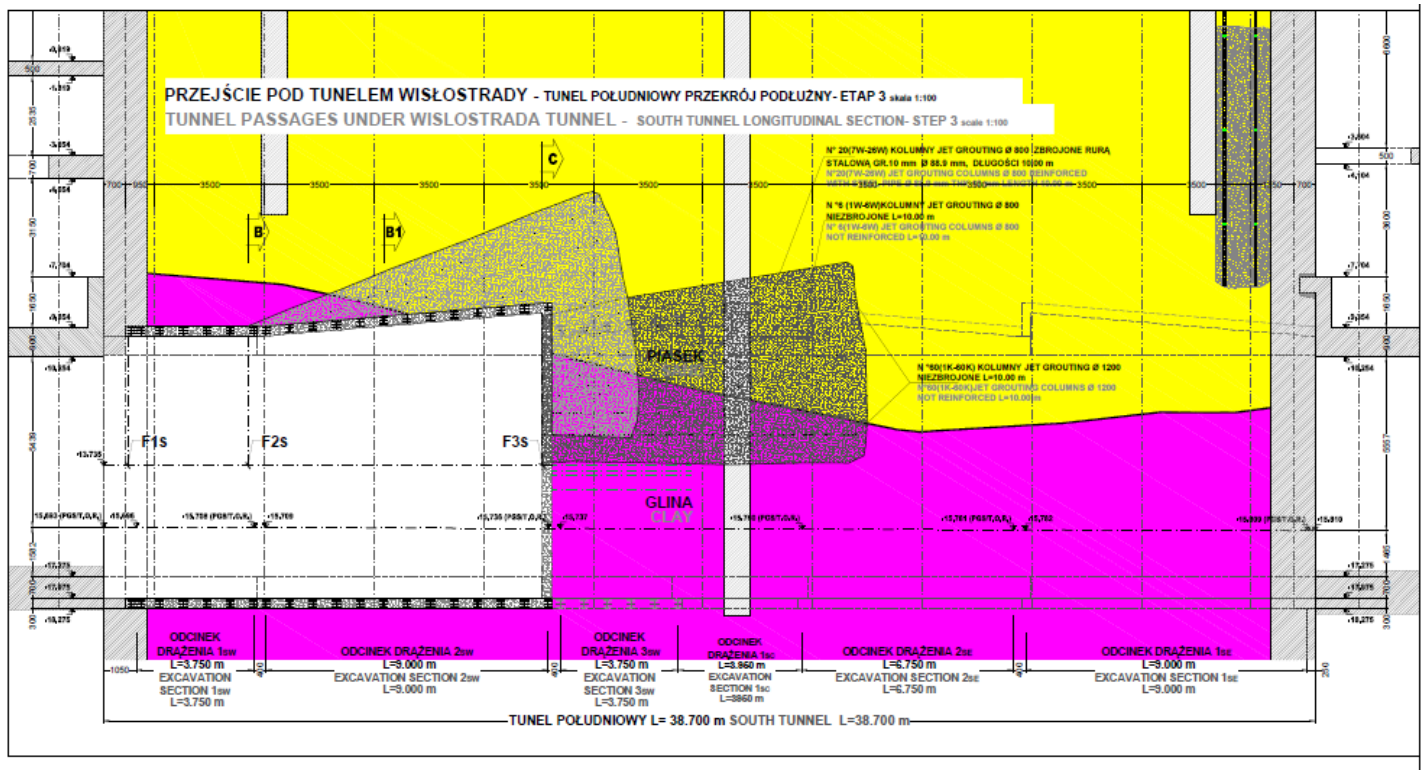
Updated design after probing start from west with beefed-up design



(a) North Tunnel axis



Collapse event 14 Aug 2012 N/S



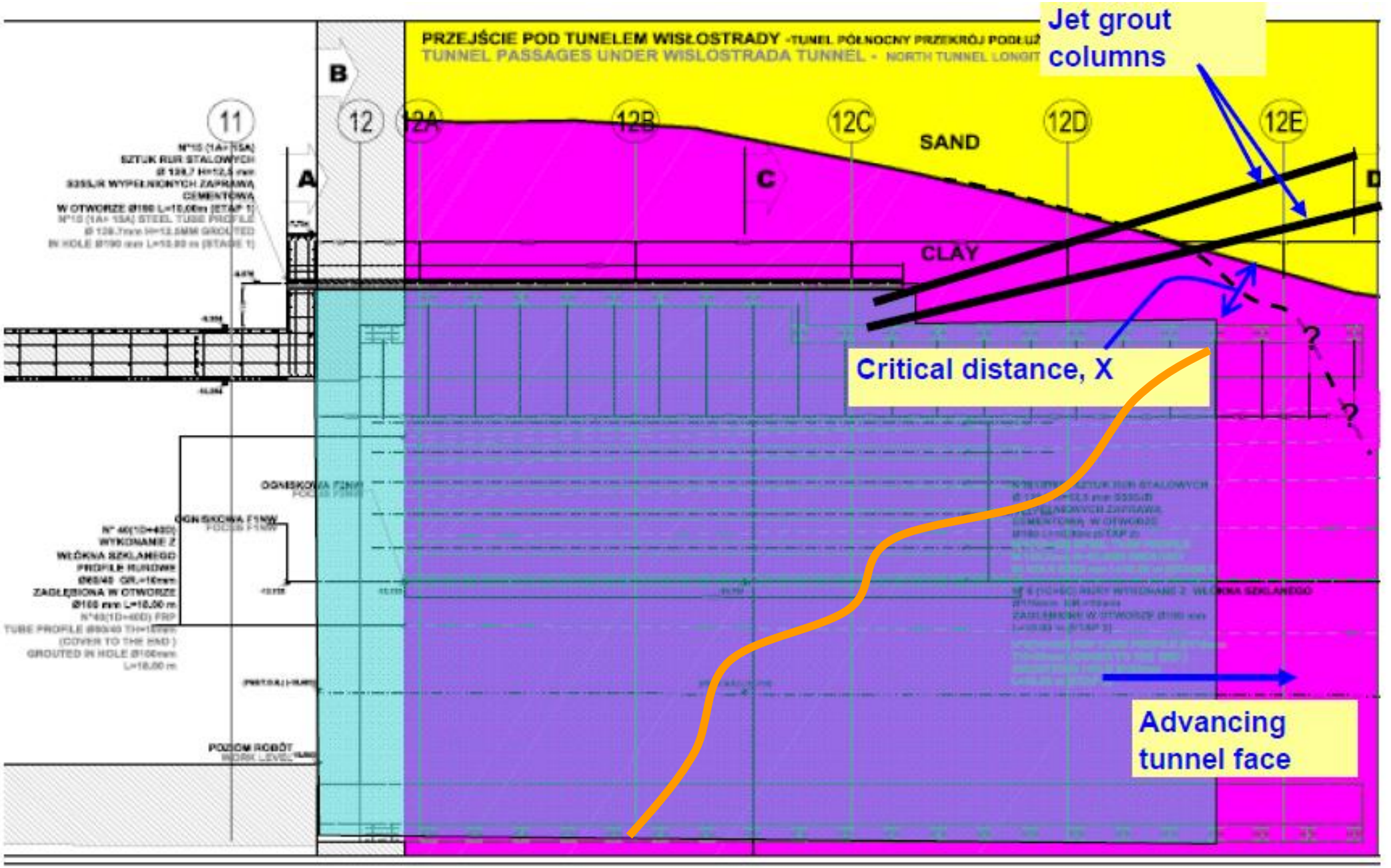




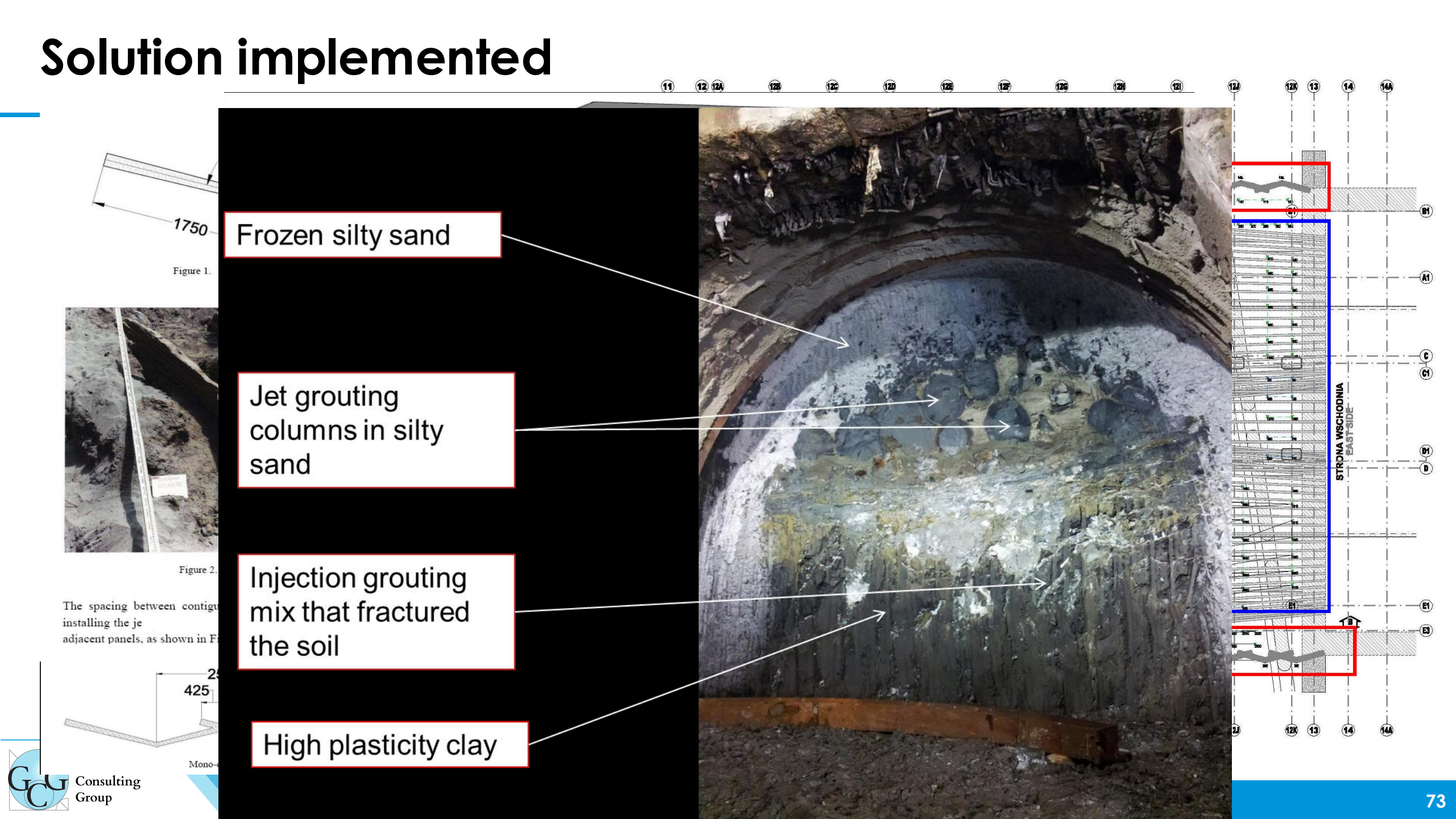
Ingress of sand and water partly fills stub tunnel 14/8/2012 01:35



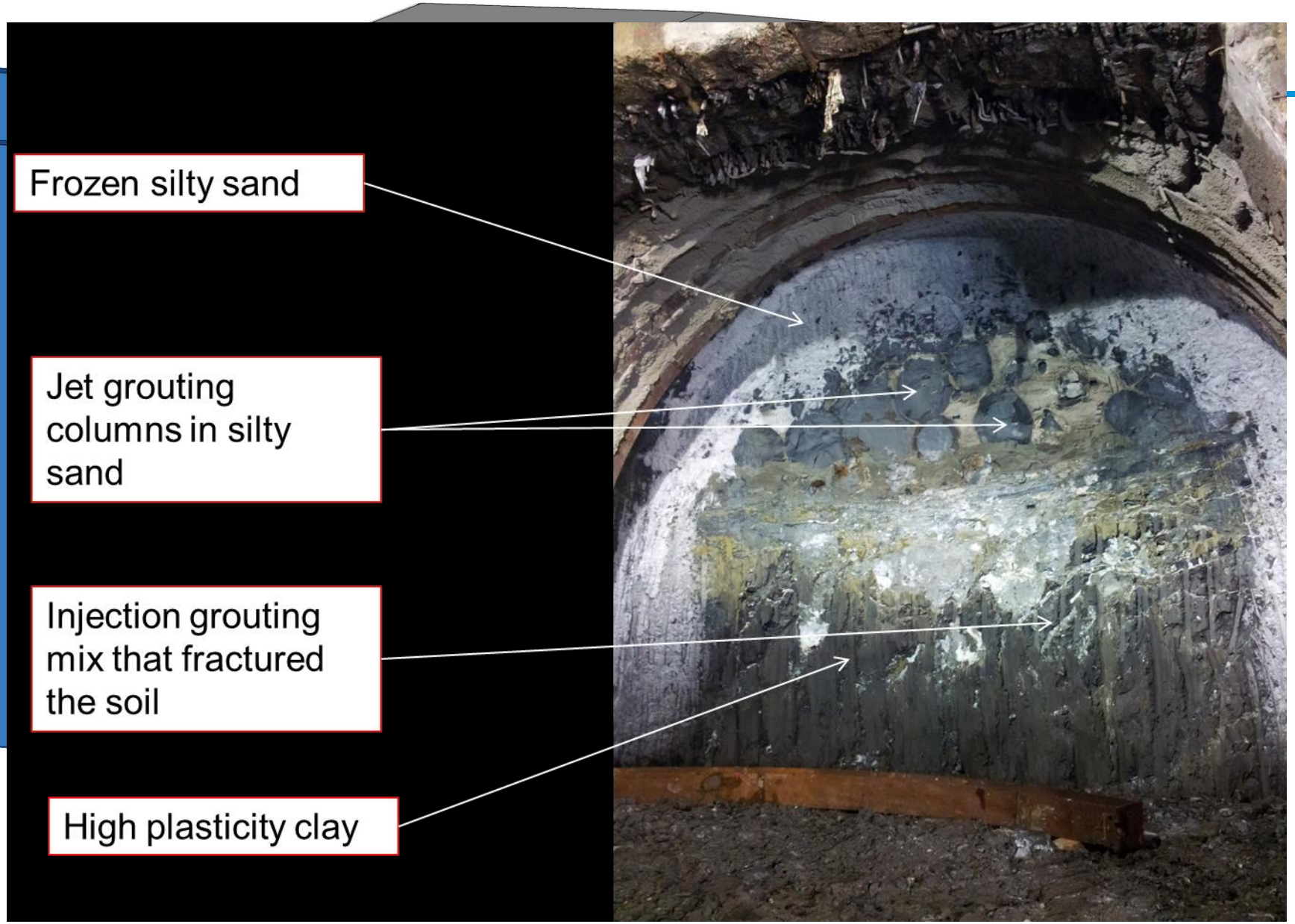



PRZEJŚCIE POD TUNELEM WISŁOSTRADY
TUNNEL PASSAGES UNDER WISŁOSTRADA TUNNEL
Jet grout columns
SAND
CLAY
Critical distance, X
Advancing tunnel face
11
12
12A
12B
12C
12D
12E
A
B
C
D

Solution implemented



Consulting Group


Frozen silty sand
Jet grouting columns in silty sand
Injection grouting mix that fractured the soil
High plasticity clay

Conclusions & Lessons Learned

- Serious ground risk missed because GI in area below Wislostrada Road Tunnel was not permitted (traffic disruption, key Client Requirement);
- This area proved critical.
- Remedial measures involved diversion of Wislostrada, extensive GI within its footprint, and construction using; Ground Freezing, Jet Grouting, Permeation Grouting and dewatering.

Lessons Learned – Observational Method

1. How was agreement to use the Observational Method reached and how were the concerns (if there were any) overcome? – driven D&B Contract (v punitive lane charges), contractor's ambitious requirements to avoid it, OM approach suggested & pushed by GCG, and detailed RA
2. What (if any) requirements (e.g., robustness, repeatability and reliability) were placed on the use of instrumentation and monitoring? – high repeatability & reliability, dedicated site monitoring team for duration, educated on importance of their contribution.
3. How were the trigger values chosen? – geological triggers that could promote dissipation of suction. Key monitoring parameter was horizontal displacement. PWP measured but is NOT reliable as a trigger (increase or decrease in pwp is dangerous).
4. What contingencies were adopted? – fully nail slope, support berm, use of flash-set s/c

Conclusions & Key Lessons

Overall Conclusions -Successful Management of Ground Risk

- Follow careful and exhaustive process of risk identification, elimination, minimisation, mitigation, communication/ transfer and management.
- Clear benefits from high quality GI and interpretative re
- Update and disseminate ground and groundwater moc
- Challenge key restriction – are they necessary? Carefu



- Problems usually from unrecognised risks or unwillingn s.
- Experience, rigour and good imagination necessary to interpretation essential.
- Good well-designed monitoring - to pick up problems e solutions;
- Contingency planning (including communication & edu
- The observational method (Peck, 1969) can offer a helpful way out of difficult situations

Geotechnical Consulting Group

Proven experts in a geotechnical world

150 Brompton Road, London SW3 1HX

T: 020 7581 8348 E: admin@gcg.co.uk

For more info, visit

Web: gcg.co.uk

LinkedIn: Geotechnical Consulting Group

References

1. To be added