SKANSKA

How to build a water tight segmental lining in Scandinavian conditions

Vanntette elementløsninger i TBM tunneler

Robert Sturk

Technical Advisor, Skanska Sverige AB,
Stora projekt


CTRL/High Speed 1
2001-2003

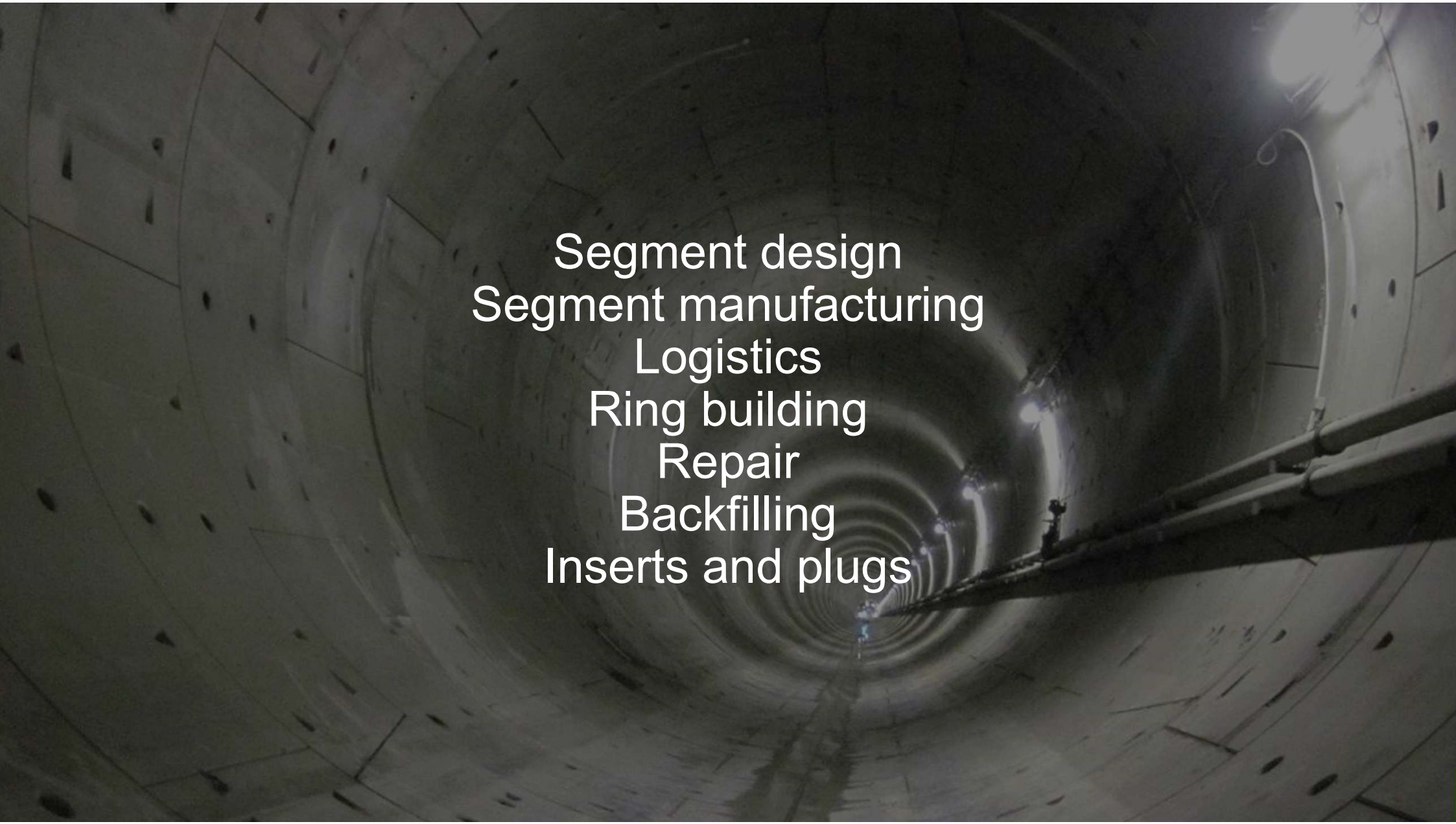

KONECRANES
KONECRANES
15t

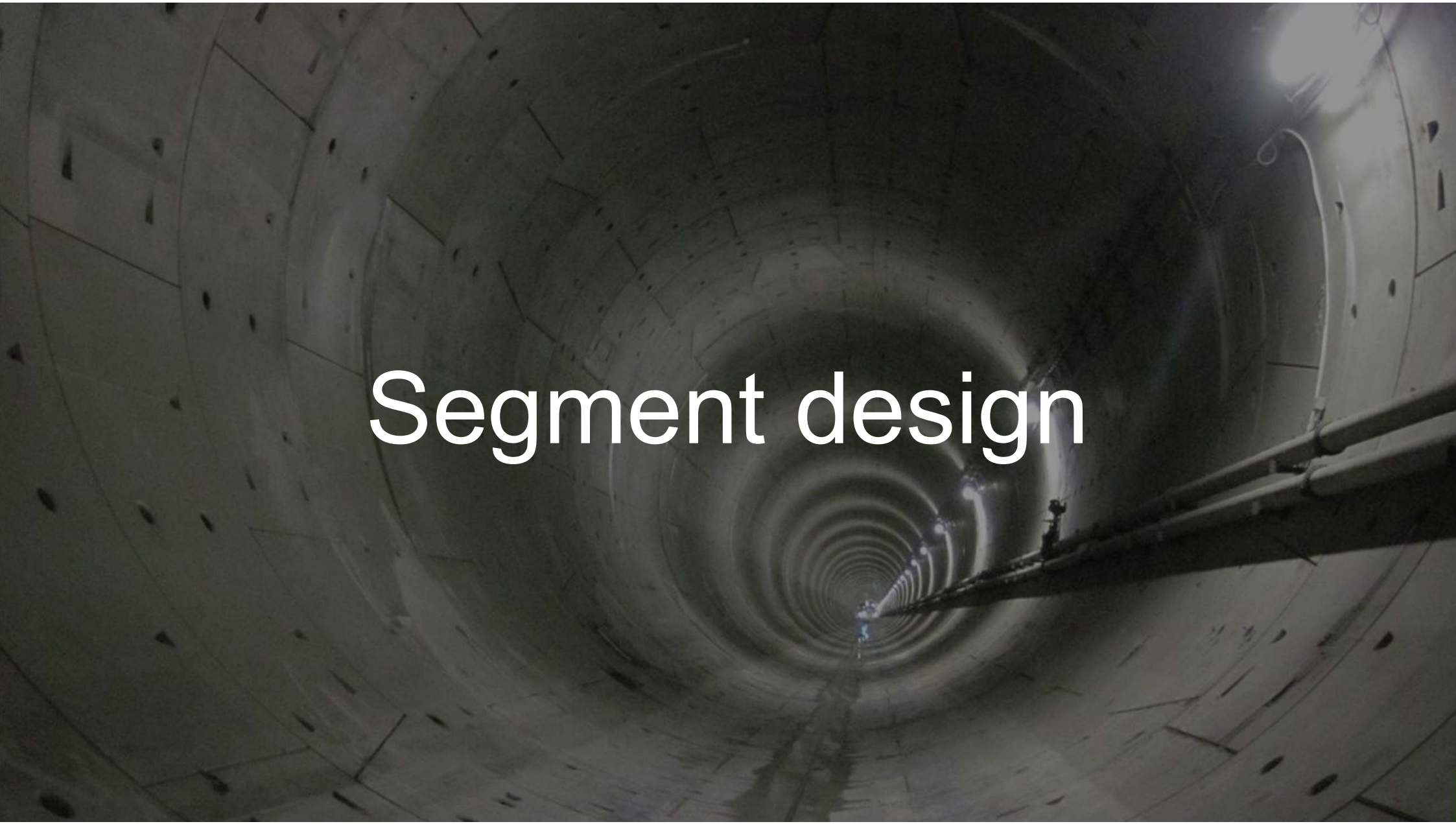

Hallandsås
2003-2013


Tight lining – the result of an interacting system with several parts
- Segments/Concrete
- EPDM gasket
- Inserts and plugs
- Backfilling
- (Rock/soil mass)

Quality and thoroughness in all activities – from manufacturing to installed ring

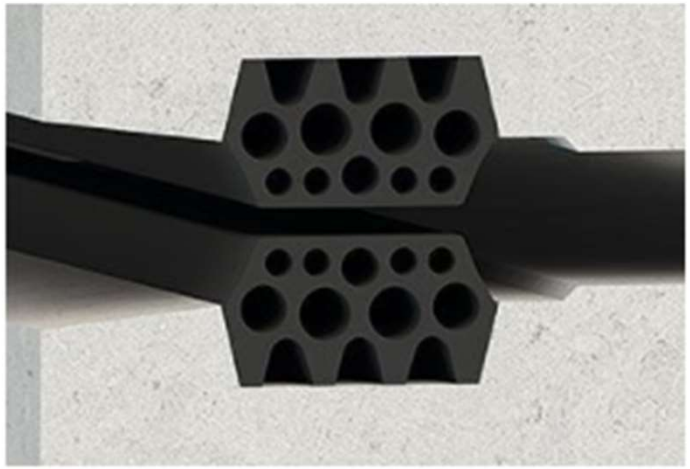
- All parts of the system interact and are dependent on each other
- Design, production and installation are also dependent on and influence each other
- Weakest link system

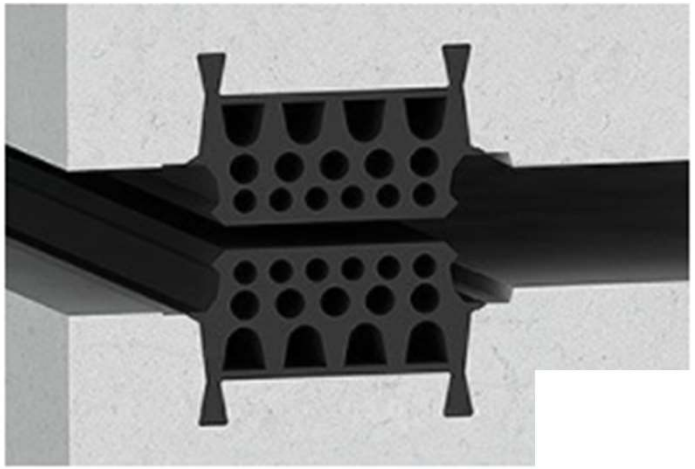

Segment design
Segment manufacturing
Logistics
Ring building
Repair
Backfilling
Inserts and plugs

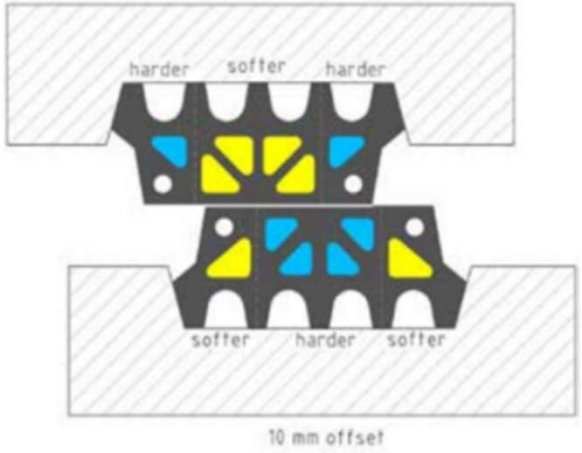

Segment design

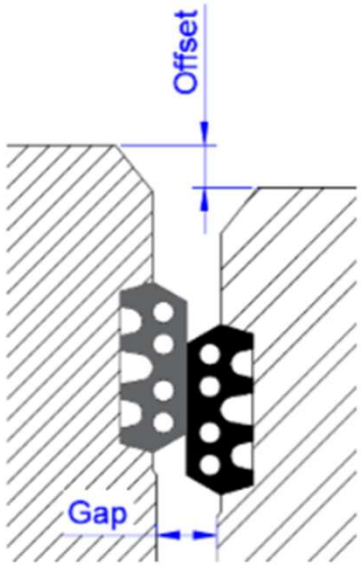
Design aspects – aiming at a tight lining

- Geological and hydrogeological conditions
  - Not only load bearing capacity
  - Water seepage along the tunnel
- Geometry and ring layout
- Reinforcement
  - Limit risk of cracking throughout the life of the segment (not least transport and installation)
- Inserts
  - Tightness, life length
- Buildability
  - The segment design/layout must facilitate accurate and effective production
  - Including backfilling
- Gaskets

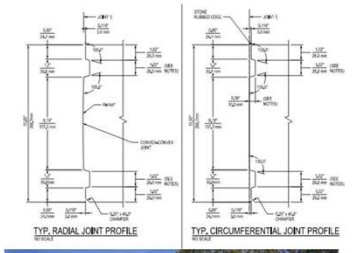





harder
softer
harder
softer
harder
softer
10 mm offset


Offset
Gap

Double gaskets



Example of double gasket system, but criteria was risk of gas as opposed to watertightness.

Crenshaw-LAX Transit Corridor, US ARUP


Segment manufacturing


TMASTARNA
20 ton
TEKLA AB


LYFTMÄSTARNA


15 ton

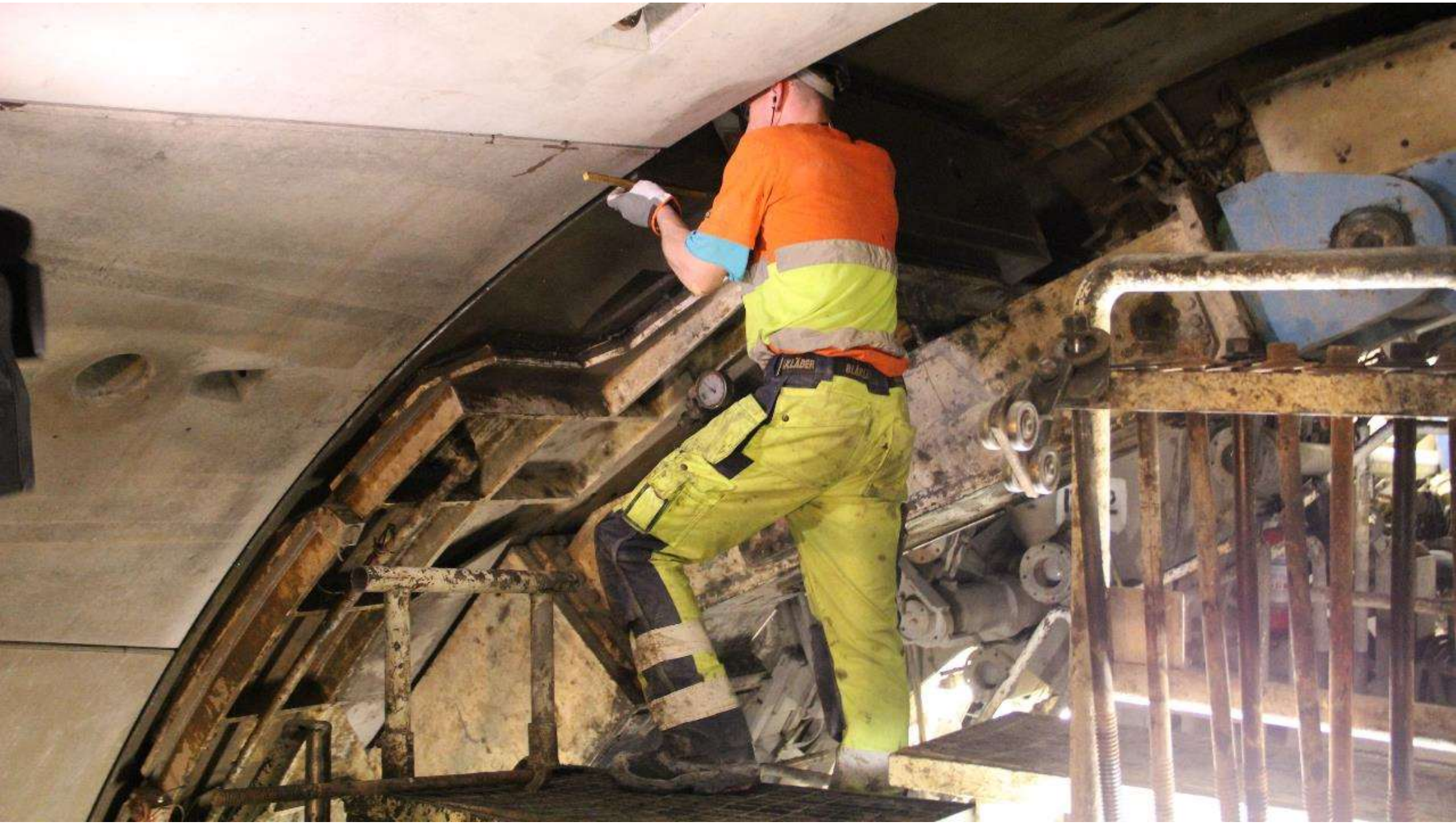

Logistics


05.09.07
05.09.19
05.08.17

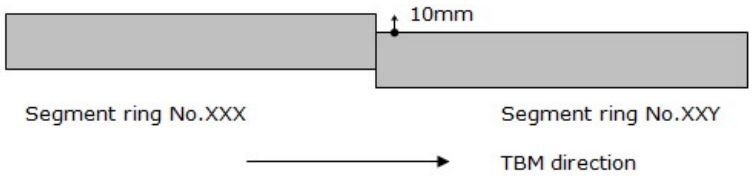

Ring building

Good ring building is fundamental

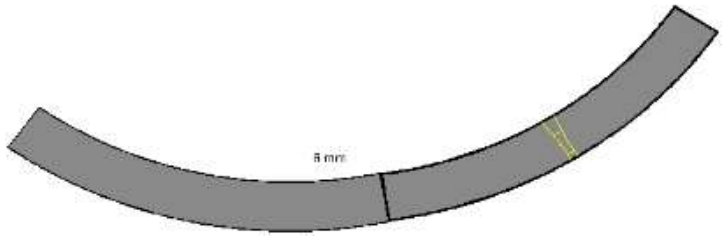
- Starts already during design
  - Guiding devices (e.g. dowels)
  - Markings
- Competence and precision
- Measurements
- TBM steering



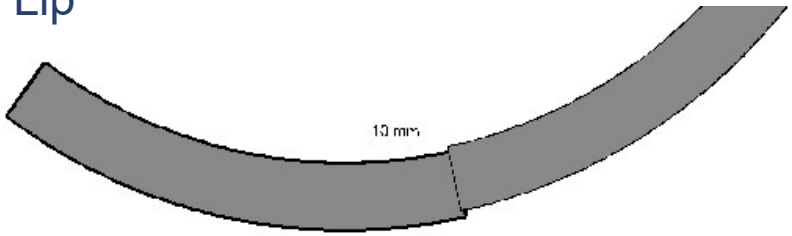
Step



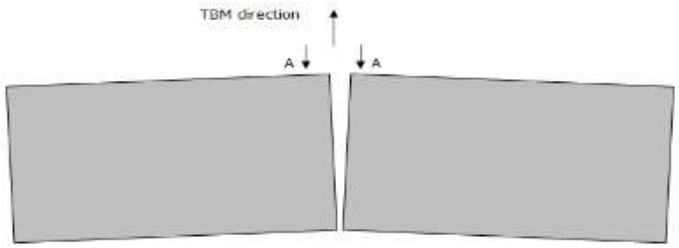
Yawning



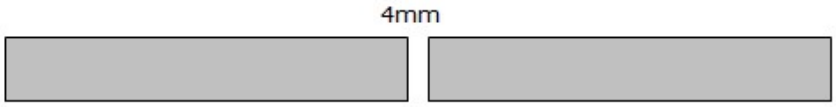
Lip



Birdsmouth

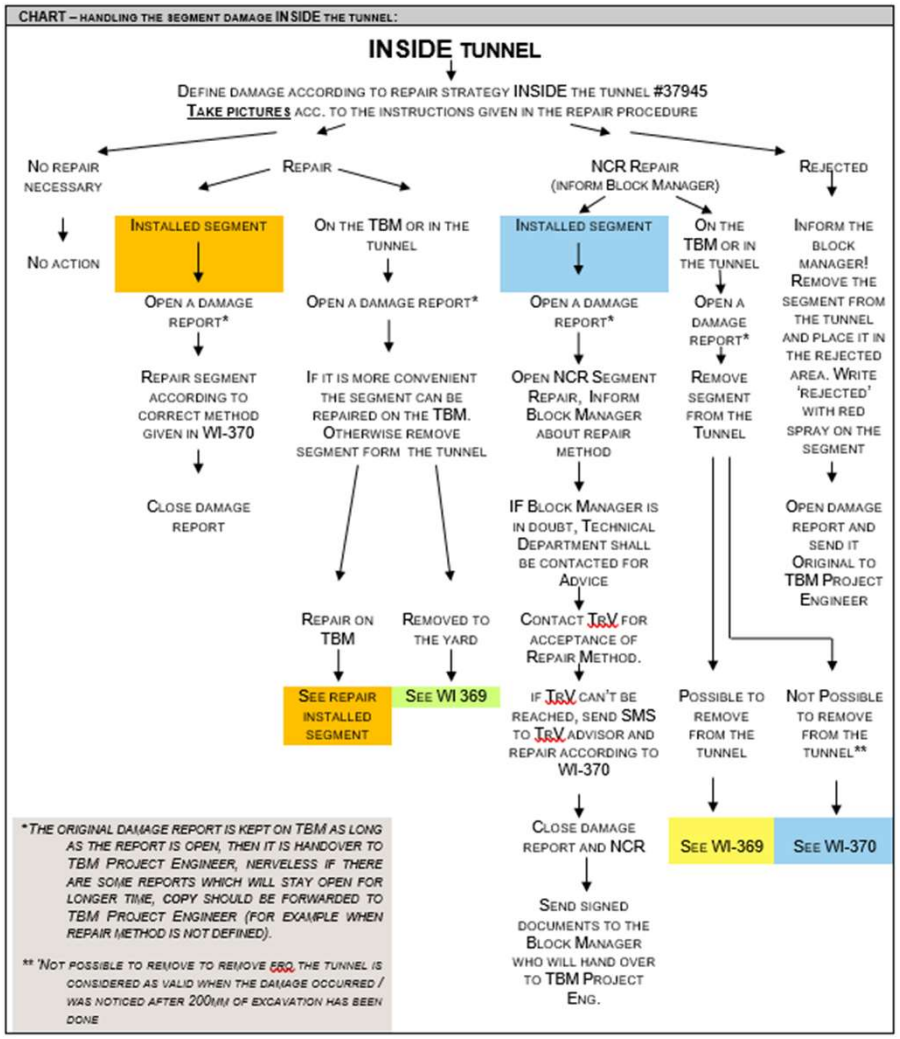


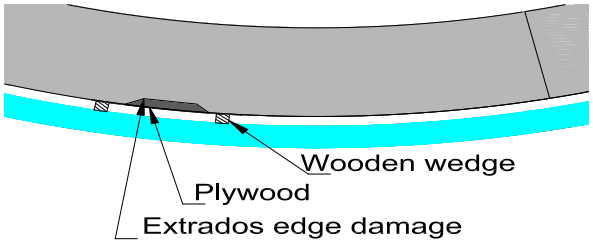
Gap

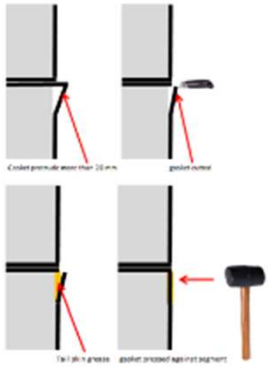


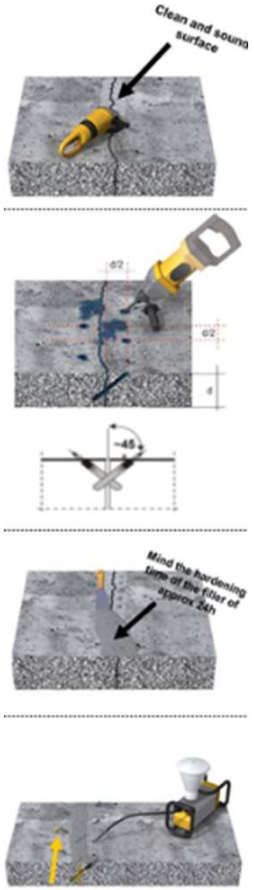

Repair

CHART – HANDLING THE SEGMENT DAMAGE INSIDE THE TUNNEL:







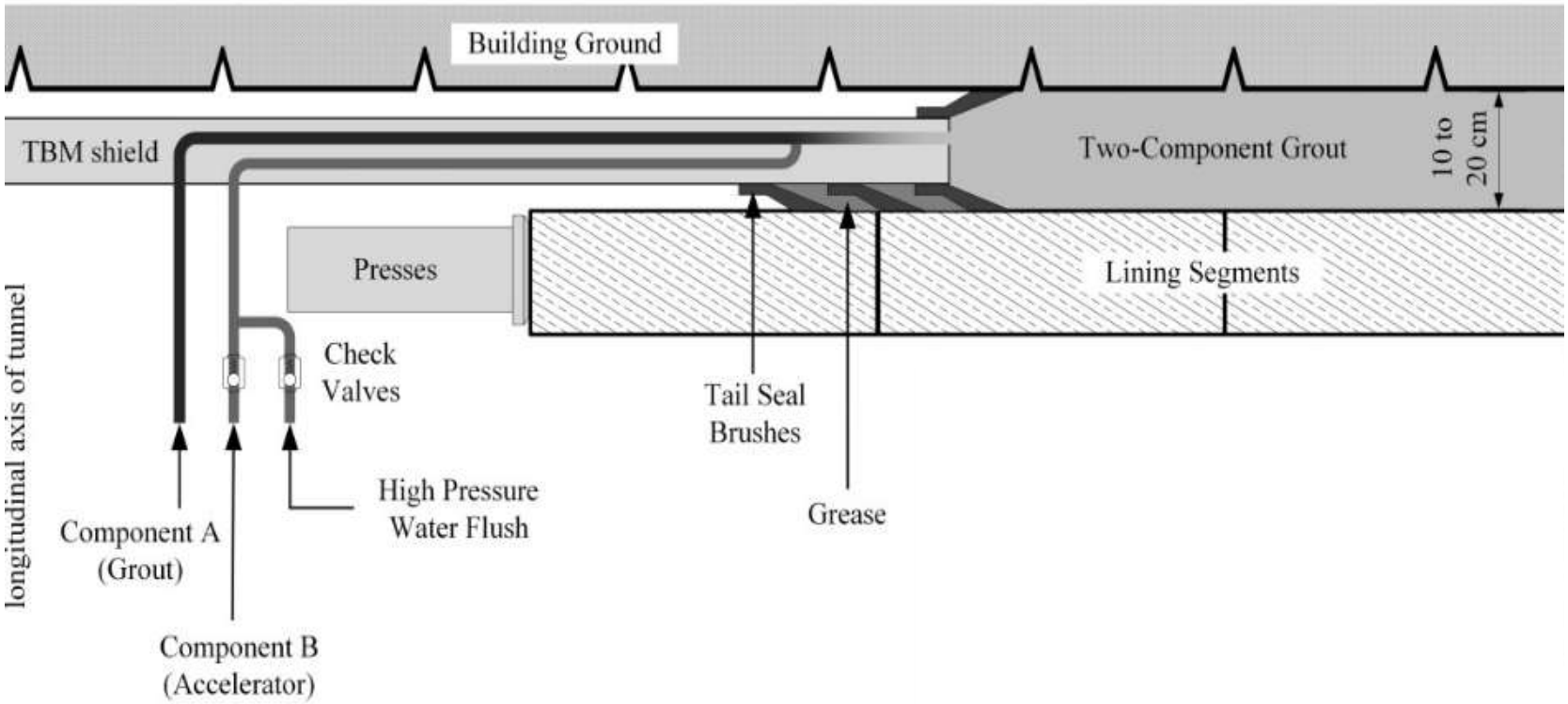



Backfilling

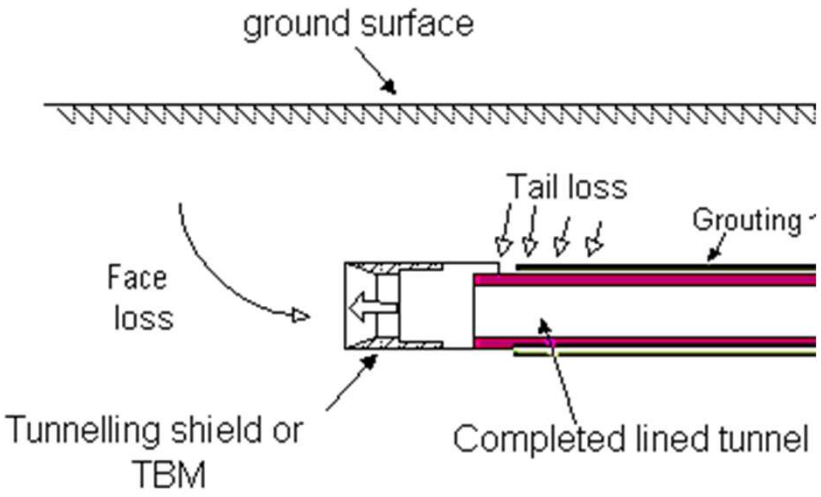
Why is the backfill important?

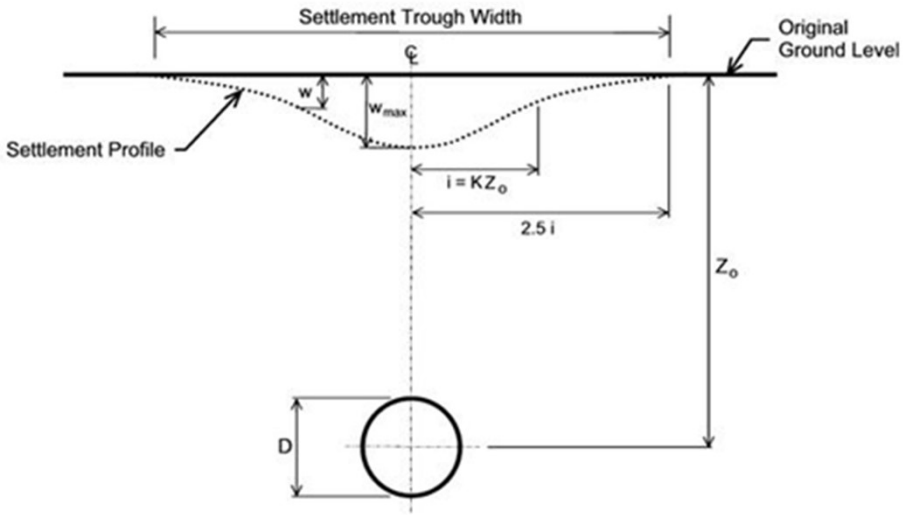
- Stable rings is a necessity
- Without a high quality backfill the rings will move and risk of leakage increases significantly
- The backfilling in itself is an extra barrier

- Different conditions require different backfilling solutions
  - Tightness
  - Surface settlements


Building Ground
TBM shield
Two-Component Grout
10 to 20 cm
Presses
Lining Segments
Check Valves
Tail Seal Brushes
High Pressure Water Flush
Grease
Component A (Grout)
Component B (Accelerator)
longitudinal axis of tunnel

High Speed 1 – Tunnelling under Central Line





Ground loss before the tunnel face	0.1%
Ground loss around the shield	0.1%
Ground loss at the tail skin	0.2%
Ground loss due to structural deformation of the linings	0%
Ground loss due to long term consolidation	0%


Chalfont & Latimer
Watford
Croxley
Chorleywood
Rickmansworth
Moor Park
Northwood
Northwood Hills
West Ruislip
Ruislip
Hillingdon
Ruislip Manor
Pinner
Ickenham
Eastcote
North Harrow
Ruislip Gardens
Rayners Lane
Harrow-on-the-Hill
West Harrow
South Ruislip
South Harrow
Northolt
Sudbury Hill
Sudbury Town
Alperton
Greenford
Perivale
Hanger Lane
Park Royal
North Ealing
Ealing Broadway
Watford Junction
Watford High Street
Bushey
Carpenders Park
Hatch End
Headstone Lane
Harrow & Wealdstone
Kenton
Northwick Park
South Kenton
North Wembley
Wembley Central
Stonebridge Park
Harlesden
Willesden Junction
Kensal Green
Queen's Park
Kilburn Park
Maida Vale
Warwick Avenue
Royal Oak
Westbourne Park
Ladbroke Grove
Latimer Road
Shepherd's Bush
East Acton
White City
North Acton
Wood Lane
West Acton
Acton Central
Stanmore
Canons Park
Queensbury
Kingsbury
Preston Road
Wembley Park
Neasden
Dollis Hill
Willesden Green
Kilburn
Kensal Rise
Brondesbury Park
Brondesbury
Kilburn High Road
South Hampstead
Edgware
Burnt Oak
Colindale
Hendon Central
Brent Cross
Golders Green
Hampstead
Finchley Road & Frognal
West Hampstead
Finchley Road
Swiss Cottage
St. John's Wood
Belsize Park
Chalk Farm
Camden Town
Mornington Crescent
Gospel Oak
Hampstead Heath
Kentish Town West
Kentish Town
Camden Road
Caledonian Road
Caledonian Road & Barnsbury
Holloway Road
Arsenal
Upper Holloway
Tufnell Park
Crouch Hill
Archway
Highgate
East Finchley
Finchley Central
Woodside Park
West Finchley
Totteridge & Whetstone
High Barnet
Mill Hill East
Paddington
Edgware Road
Marylebone
Baker Street
Great Portland Street
Euston
King's Cross St. Pancras
Angel
Old Street
Farringdon
Barbican
Liverpool Street
Moorgate
Chancery Lane
St. Paul's
Bank
Holborn
Covent Garden
Leicester Square
Green Park
Warren Street
Euston Square
Russell Square
Regent's Park
Oxford Circus
Bayswater
Notting Hill Gate
Lancaster Gate
Queensway
Bond Street
Marble Arch
Holland Park
Goodge Street
Tottenham Court Road
High Street Kensington
Aldgate
Aldgate East
Whitechapel
Shadwell
Westferry
Shoreditch High Street
Dalston Junction
Dalston Kingsland
Canonbury
Highbury & Islington
Finsbury Park
Manor House
Turnpike Lane
Arnos Grove
Southgate
Bounds Green
Wood Green
Oakwood
Cockfosters
Harringay Green Lanes
Seven Sisters
Tottenham Hale
South Tottenham
Blackhorse Road
Walthamstow Central
Walthamstow Queen's Road
Leyton
Leyton Midland Road
Leytonstone
Leytonstone High Road
Wanstead
Redbridge
Gants Hill
Newbury Park
Barkingside
Fairlop
Hainault
Chigwell
Roding Valley
Grange Hill
Woodford
South Woodford
Snaresbrook
Buckhurst Hill
Loughton
Debden
Theydon Bois
Epping
Hackney Central
Hackney Wick
Homerton
Haggerston
Hoxton
Bethnal Green
Mile End
Bow Road
Bow Church
Devons Road
Langdon Park
All Saints
Blackwall
Stepney Green
West Ham
Bromley-by-Bow
Pudding Mill Lane
Stratford
Stratford International
Stratford High Street
Abbey Road
Star Lane
Canning Town
Royal Victoria
Woodgrange Park
Upton Park
East Ham
Plaistow
Barking
Upney
Becontree
Dagenham East
Dagenham Heathway
Wanstead Park
Leyton
Upminster Bridge
Hornchurch

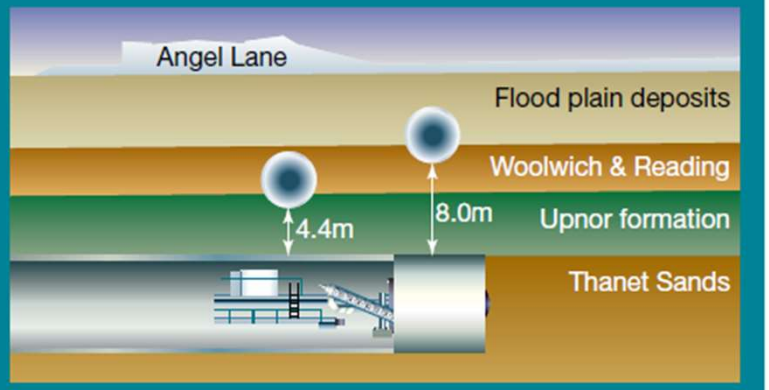
Under the Central Line

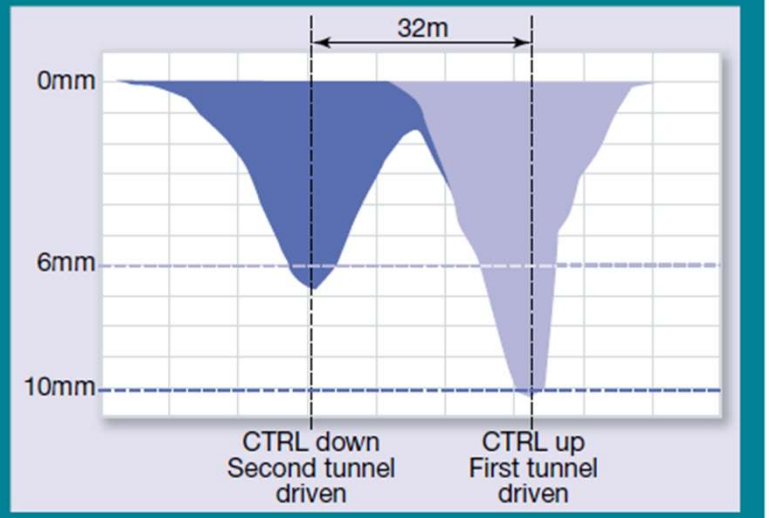
The CTRL tunnels pass only 4m beneath London Underground Ltd's (LUL) Central Line. The tunnels were built in the 1930s to a very high standard using tapered cast iron with machined joint faces and no packing in any joints. The tunnels were likely to be very stiff and rigid in both cross and long section. The effect of any settlement due to tunnelling was therefore likely to be very serious once the very limited flexural capacity was exceeded. CSB predicted ground loss would be less than 0.5% based on EPB experience and by taking into account the settlement minimisation measures designed into the machines. This was accepted by LUL and the designers and analysts employed by CSB, RLE, LUL and their infraco iBCV. It was also recognised that with only 30m of the drive before crossing under the Central Line it was necessary to mitigate the tunnels for a possible upper bound settlement far greater than 0.5%. The analysts were pushed into calculations that were far more rigorous than anything they had ever done but eventually they were able to demonstrate that by removing the circle bolts and thereby introducing longitudinal discontinuities at roughly 4m centres the tunnel would no longer be in danger of breaking its back. Removing the 70 year old bolts was a major exercise as some were encased in the concrete of the trackbed.

CMCS supplied the instrumentation to monitor the tunnels longitudinally with electrolevels, across the circle joints with displacement transducers and demec studs and in cross section using electrolevels and convergence arrays. The crown and the rails were monitored using precise levelling.

A full emergency plan and cascade of reactions to monitoring was established and a hot line set up between the monitoring review team and the line controller. The tunnels passed beneath the Central Line with approximately 10mm as the maximum settlement equating to approximately 0.3% ground loss.

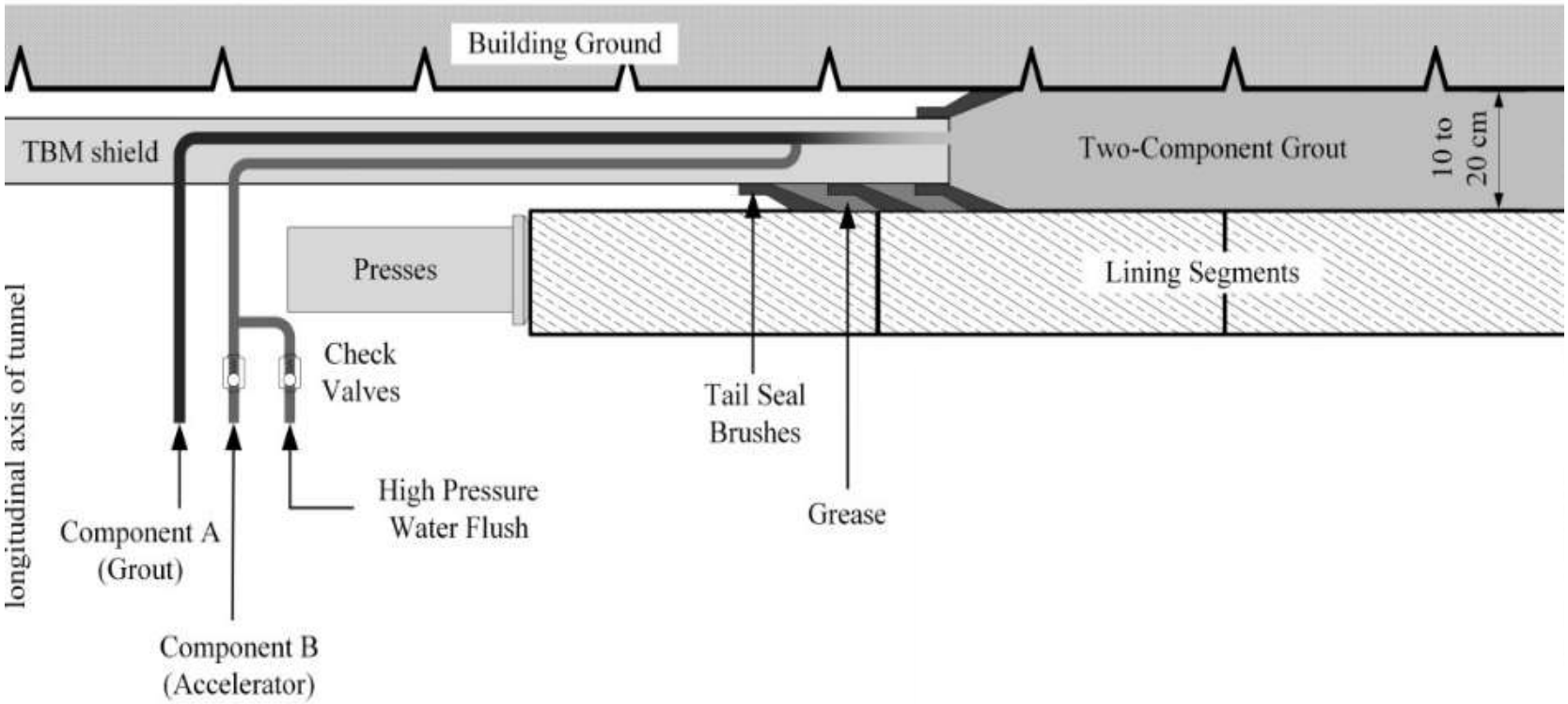
The displacement transducers and demec measurements registered no movement.





Top: Longitudinal section showing the proximity of the C240 drives under London Underground's Central Line

Above: Graph showing the settlement figures achieved during the underpass of the 70 year old Central Line Tunnels


Building Ground
TBM shield
Two-Component Grout
10 to 20 cm
Presses
Lining Segments
Check Valves
Tail Seal Brushes
High Pressure Water Flush
Grease
Component A (Grout)
Component B (Accelerator)
longitudinal axis of tunnel

Wash-out

- Only minor water flow will cause wash-out of a conventional two-component mortar backfill

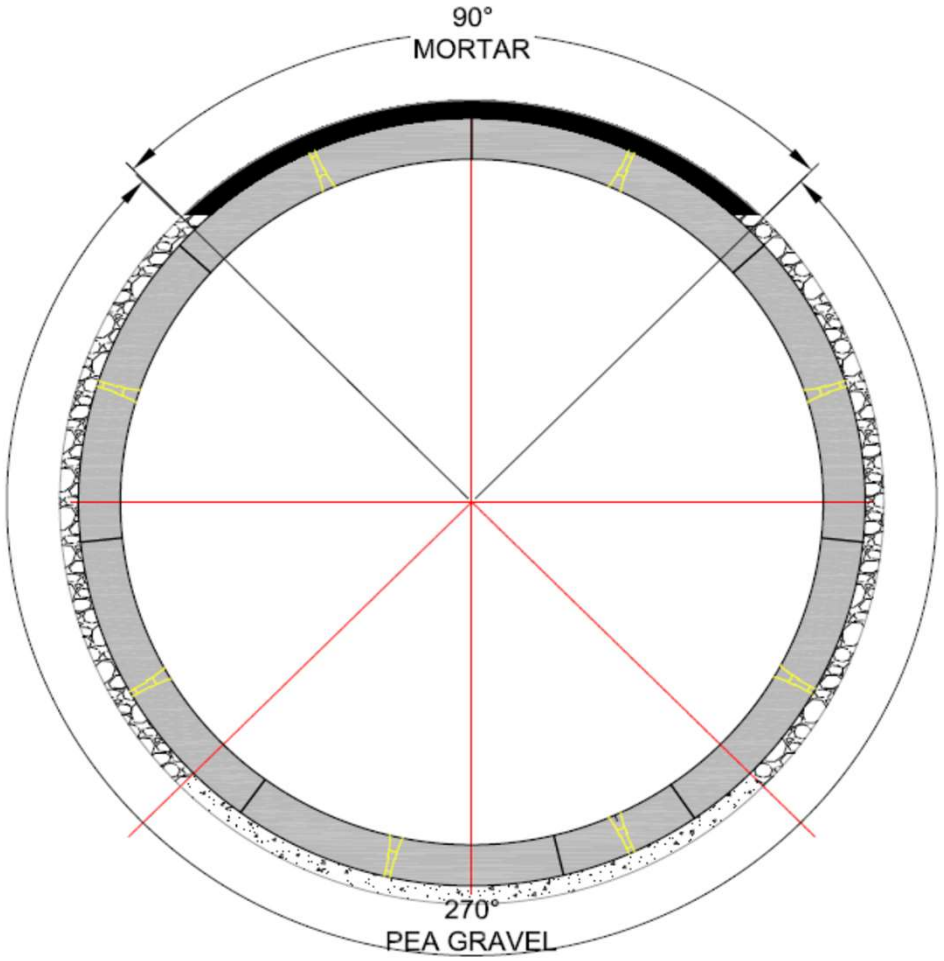
Uplift

- Monitoring revealed that the lining was uplifted (all the way up to the roof)
- Practically no backfill left in some sections
- The lining was damaged

The solution

- Pea gravel (ensgradert grus) in combination with mortar

- In difficult situations it is necessary to regularly build tight barriers


90°
MORTAR
270°
PEA GRAVEL

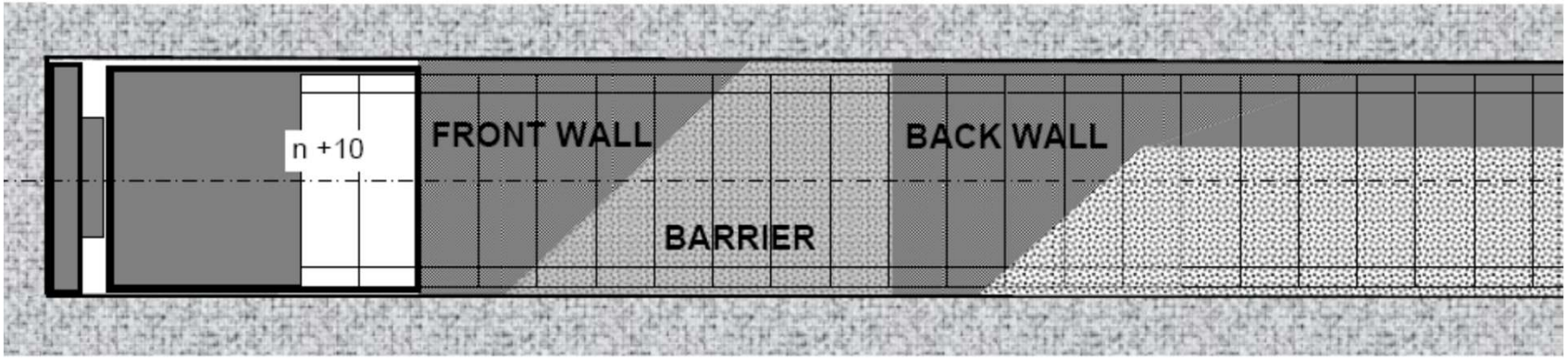

2012/07/20


As Johannes said this is an
Iterative process!

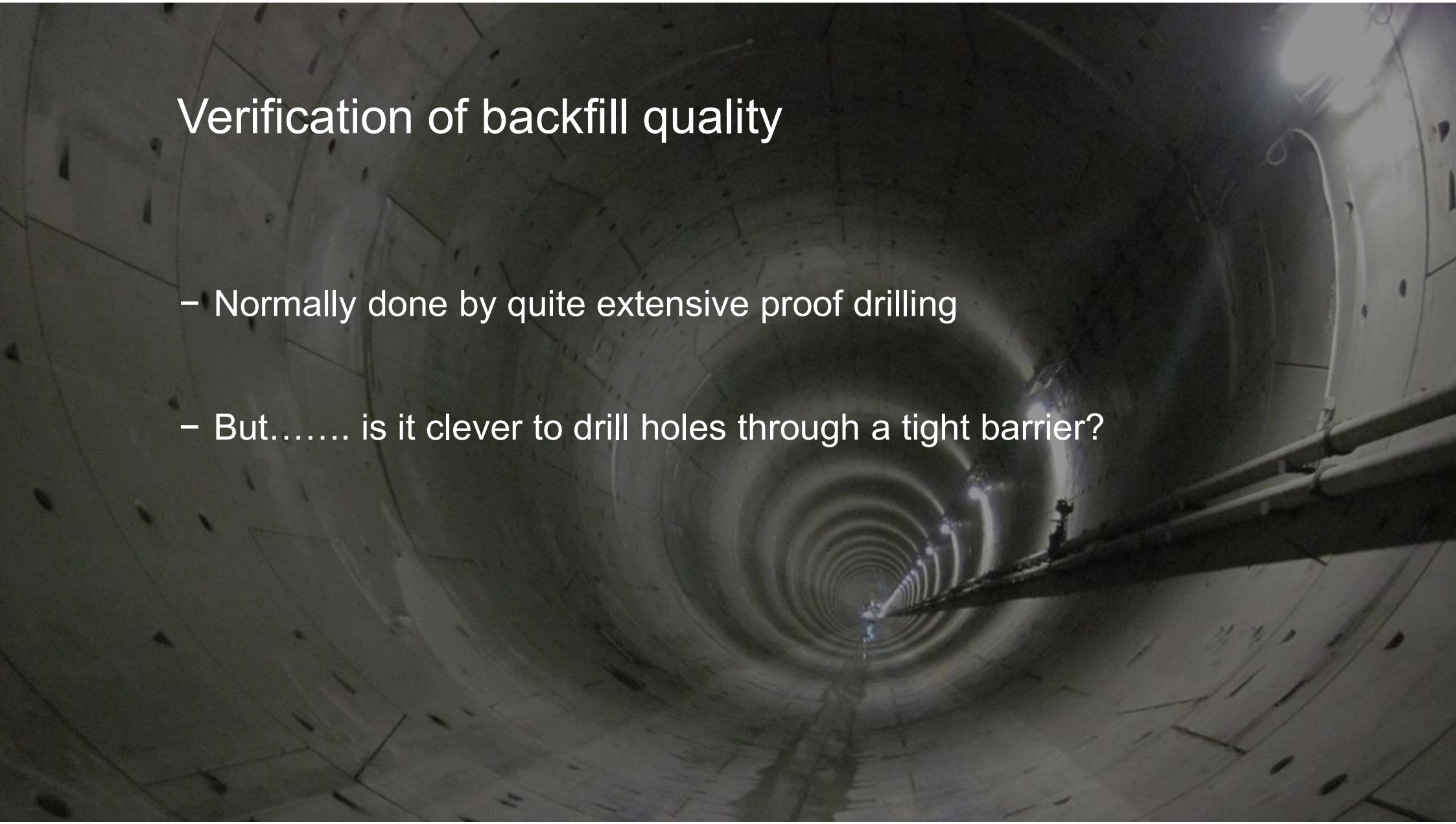
Barriers at Hallandsås

Mortar & grouted pea gravel in closed mode (can also be done in open mode)

STEP 10 De-pressurization + flushing circuits + opening muck ring + removing valves + cleaning
Checking effectiveness of the barrier + Resuming excavation

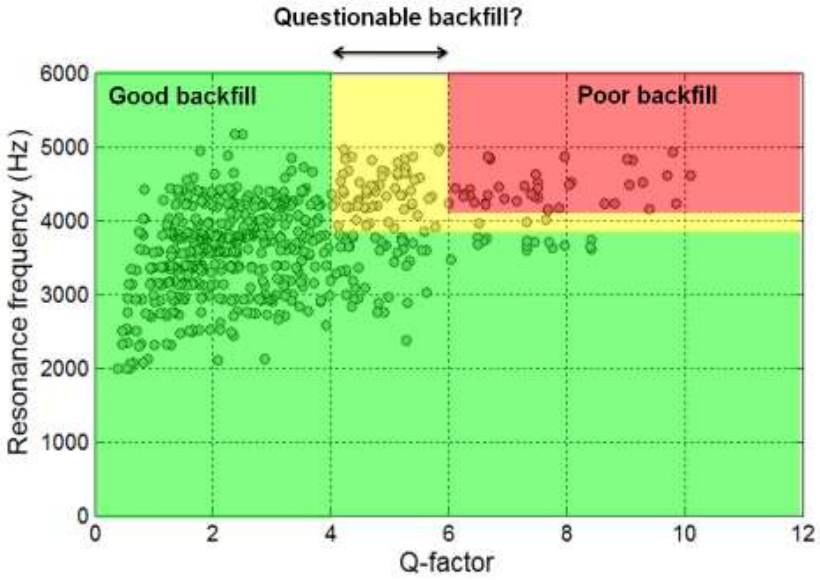


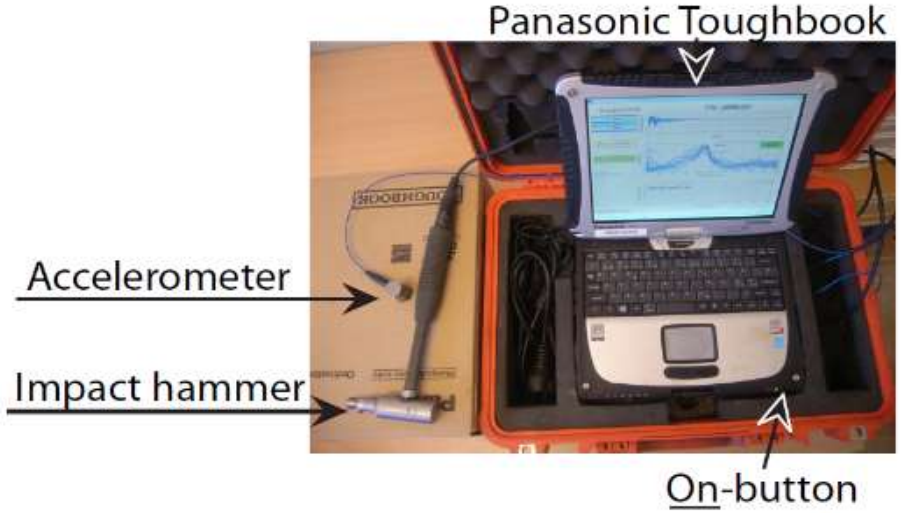
Verification of backfill quality



- Normally done by quite extensive proof drilling
- But……. is it clever to drill holes through a tight barrier?

Non Destructive Testing



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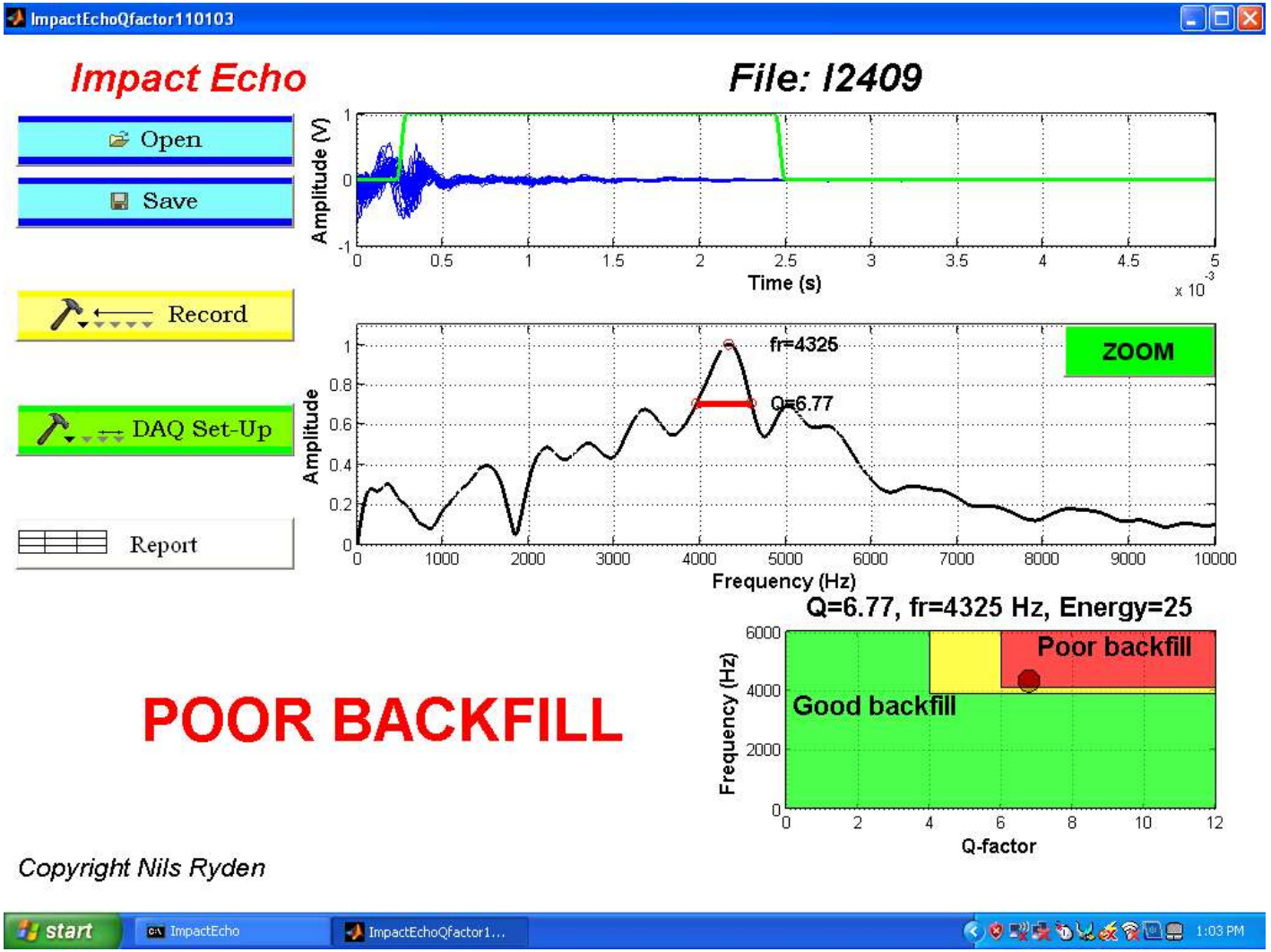
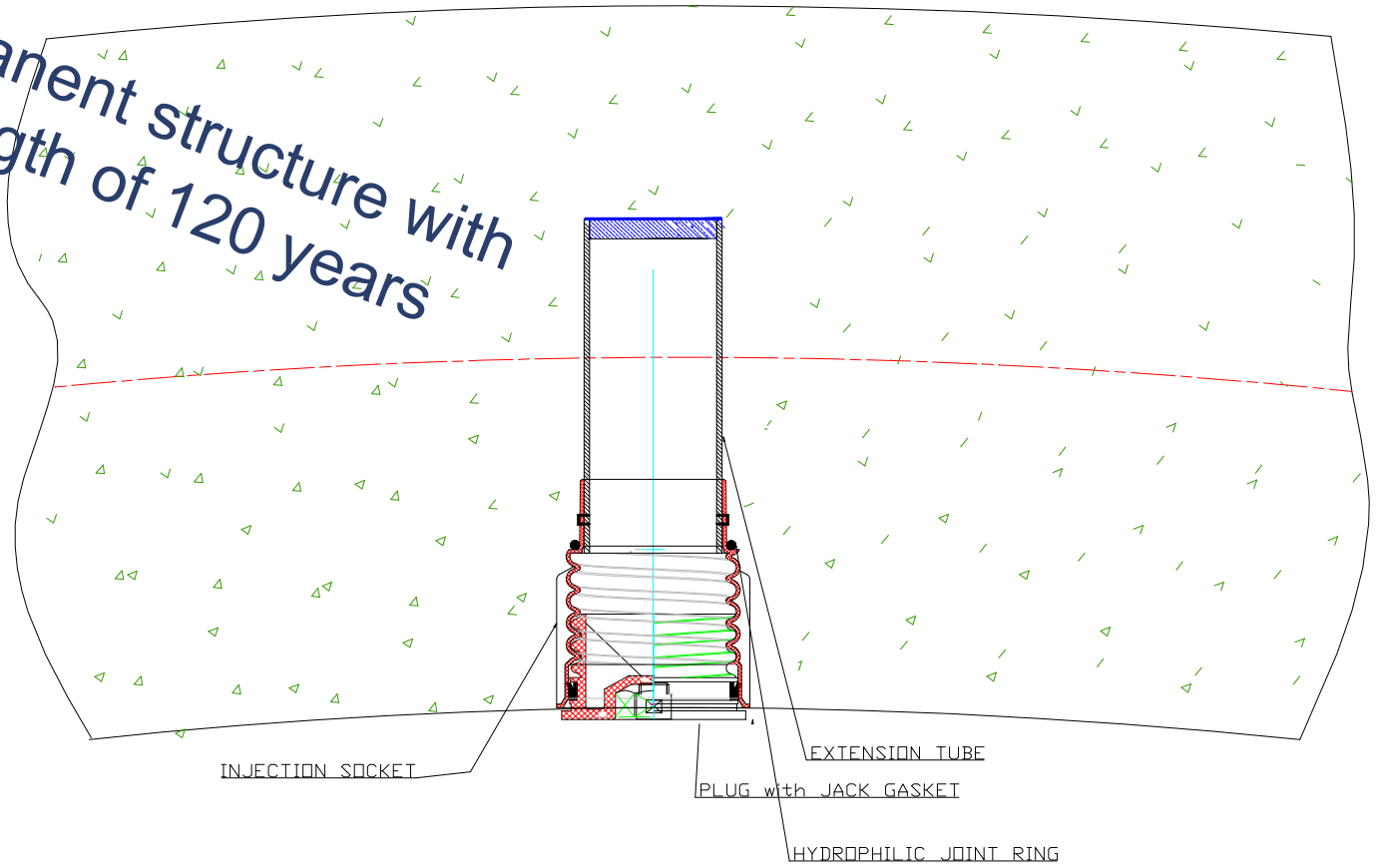
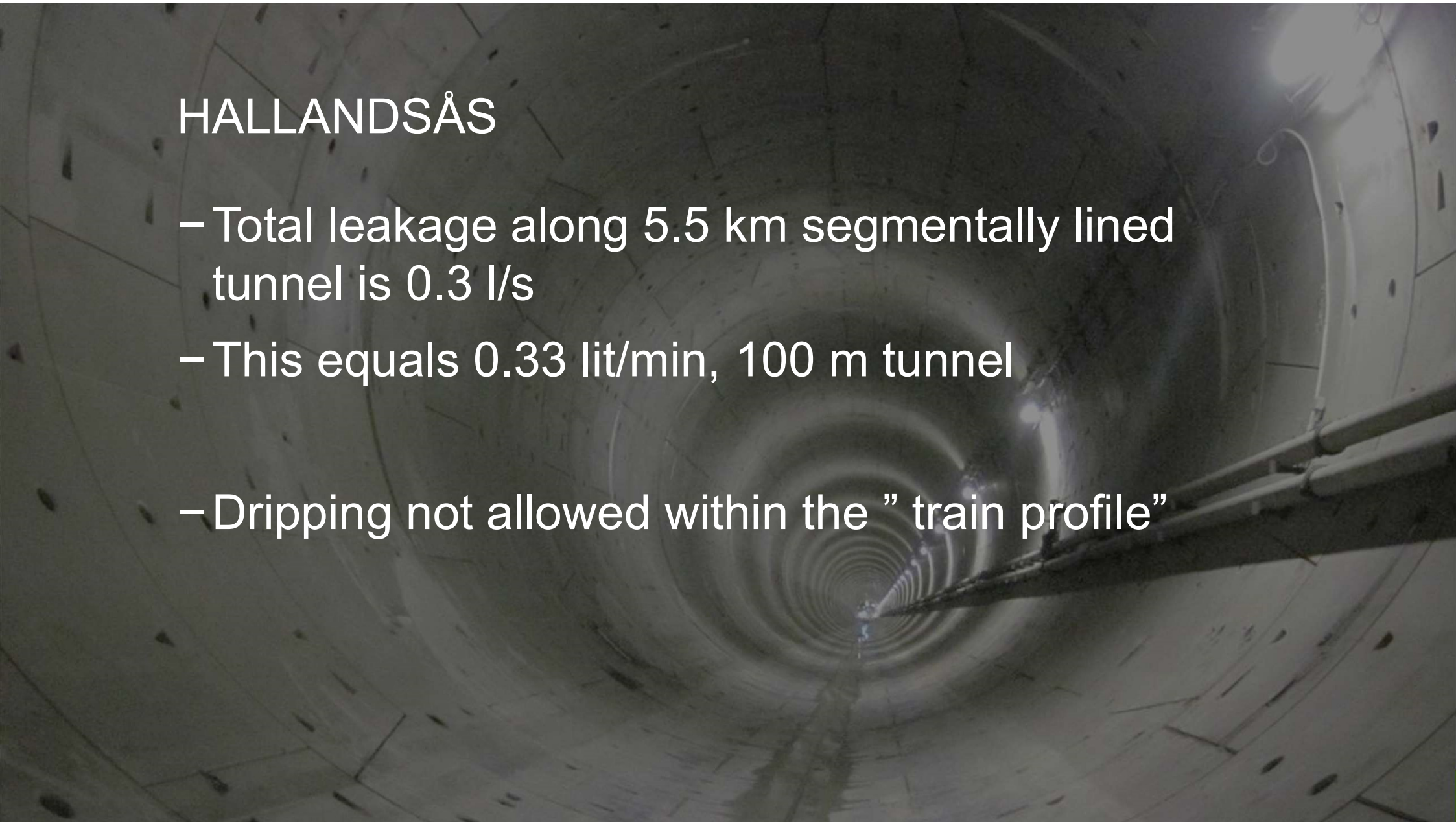

ImpactEchoQfactor110103
Impact Echo
File: I2409
Open
Save
Record
DAQ Set-Up
Report
Amplitude (V)
Time (s)
x 10^-3
ZOOM
fr=4325
Q=6.77
Amplitude
Frequency (Hz)
Q=6.77, fr=4325 Hz, Energy=25
Poor backfill
Good backfill
Frequency (Hz)
Q-factor
POOR BACKFILL
Copyright Nils Ryden
start
ImpactEcho
ImpactEchoQfactor1...
1:03 PM


Inserts and plugs

A permanent structure with life length of 120 years




Is it tight?

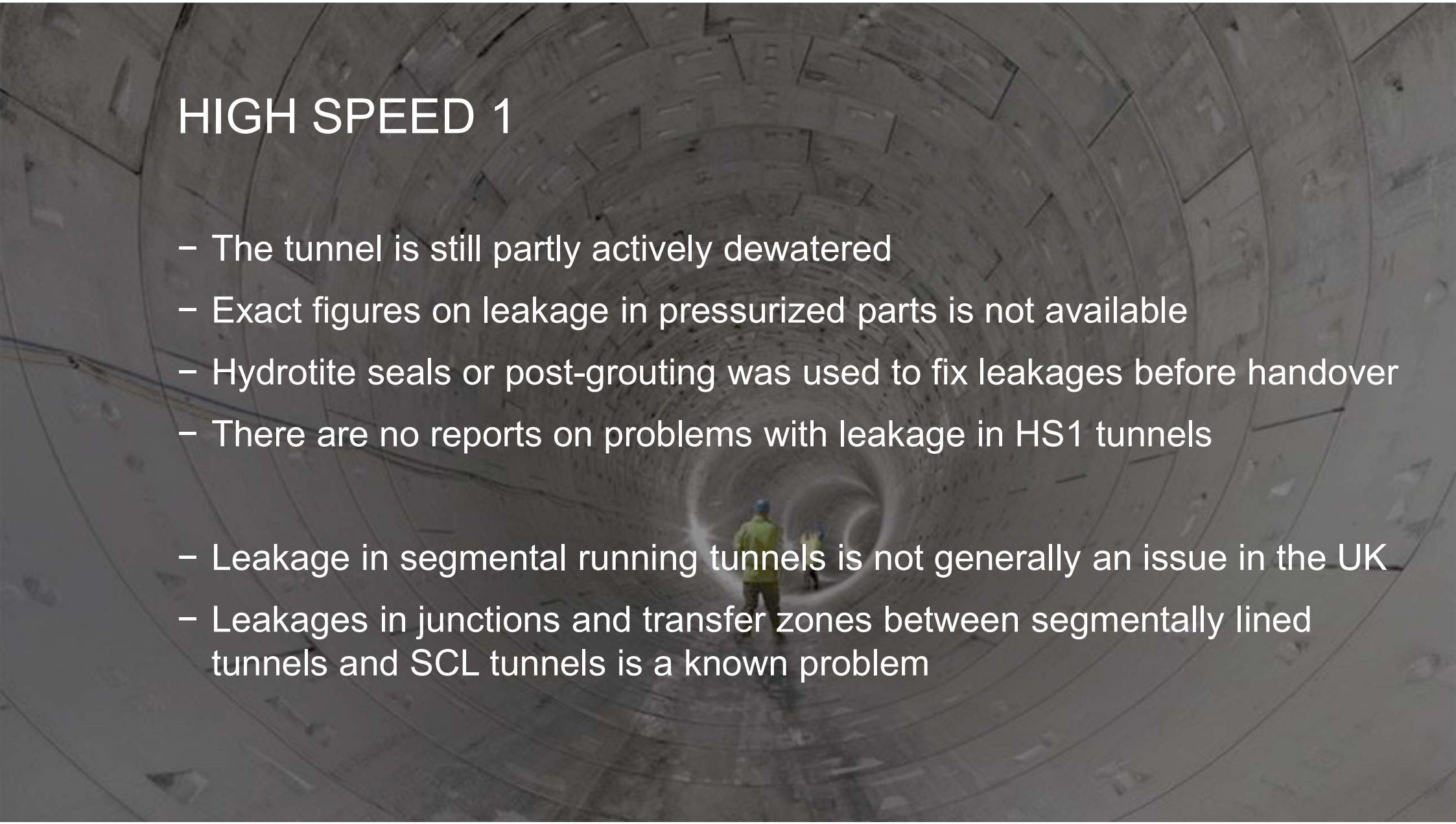


HALLANDSÅS

- Total leakage along 5.5 km segmentally lined tunnel is 0.3 l/s
- This equals 0.33 lit/min, 100 m tunnel

- Dripping not allowed within the ” train profile”


~13 kg/m tunnel
Working with
ISOCYANATE



HIGH SPEED 1

- The tunnel is still partly actively dewatered
- Exact figures on leakage in pressurized parts is not available
- Hydrotite seals or post-grouting was used to fix leakages before handover
- There are no reports on problems with leakage in HS1 tunnels

- Leakage in segmental running tunnels is not generally an issue in the UK
- Leakages in junctions and transfer zones between segmentally lined tunnels and SCL tunnels is a known problem


Tight lining – the result of an interacting system with several parts
- Segments/Concrete
- EPDM gasket
- Inserts and plugs
- Backfilling
- (Rock/soil mass)