GEODATA ENGINEERING

Cross Passages : Design and Construction

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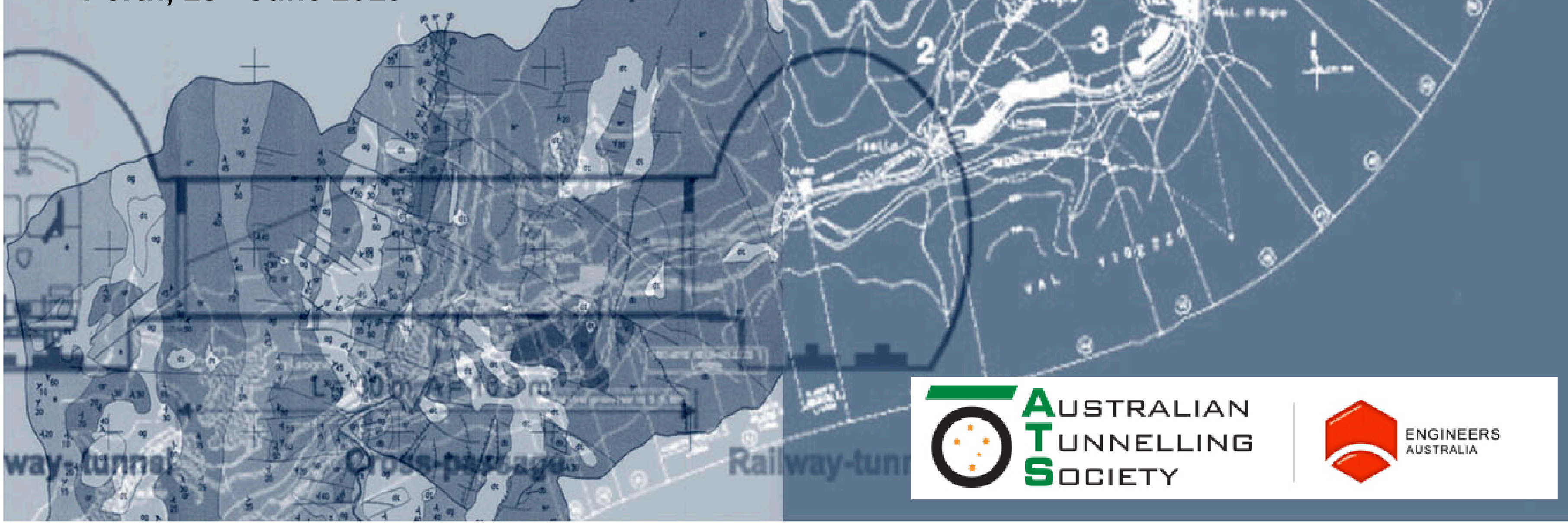
Tunnel Design & Construction - Short Course

Perth, 18th June 2019



AUSTRALIAN TUNNELLING SOCIETY

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Cross Passages (CPs)

- Critical component in any twin tunnel transportation project: their design and construction is often the most channeling element of the project
- Typically mined tunnel with comparatively small cross section and restricted access
- Design involves various disciplines and requires significant interface management
- Managing groundwater and keeping excavation dry and safe
- In soft ground additional problems of ensuring strength to enable stress redistribution around the excavation and face stability
- Planning – work stages mainly after main tunnel drive result in CPs typically being on critical path for construction

A - Design Criteria and Considerations

1. Cross Passage spacing - Fire Life Safety
2. Sizing of CP
3. Connection to running tunnels

B - Design of Cross Passages

1. Ground Conditions and Treatment
2. Methods of Analysis
3. Construction Sequence
4. Temporary Support for running tunnel lining
5. Primary Lining design
6. Waterproofing
7. Final Lining design

C – Forrestfield-Airport Link

- Twin tunnels for transportation infrastructures provide inherently higher safety

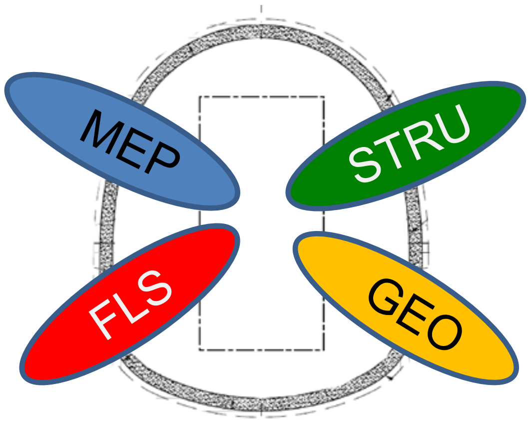
- Cross Passages and Emergency Egress Shafts enable egress to non-incident tunnel and eventually to safe area at surface in emergency events

- Worldwide reference guidance by US agency National Fire Protection Association
  - NFPA 130 for railway/metro tunnels
    - Distance between emergency exit to surface < 762 m
    - Distance between CPs < 244 m
    - Fire rated doors to 1 $^{1/2}$ hrs and self closing
  - NFPA 502 for road tunnels
    - Distance between exit to place of safe refuge < 300 m
    - Distance between CPs < 200 m
    - Fire rated to 2 hrs, self closing and two-way opening doors

- Alternative detailed risk-based approach design comparing the risk profile with the NFPA benchmark

- Specific FLS equipment in CPs – gas suppression system, fire rating internal wall separating equipment cabinet from evacuation path

- Interdisciplinary effort



- Ground and groundwater conditions largely drive design of temporary elements and construction sequences

Functional space required

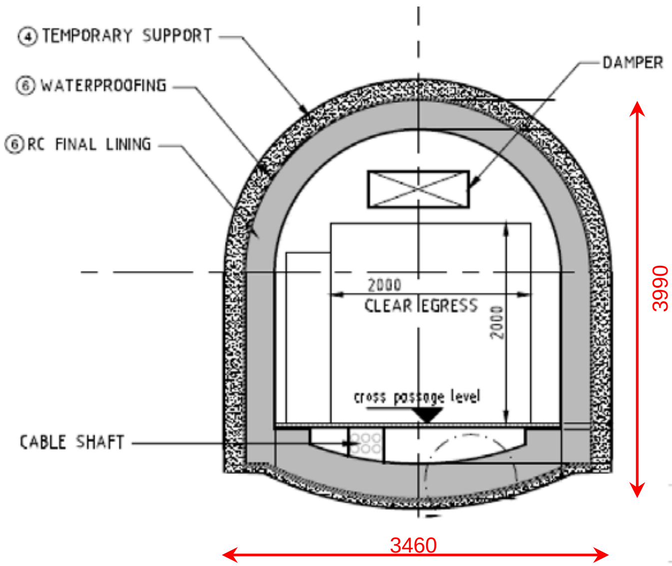
- Evacuation
- Ventilation
- Drainage out or in + sump
- MEP

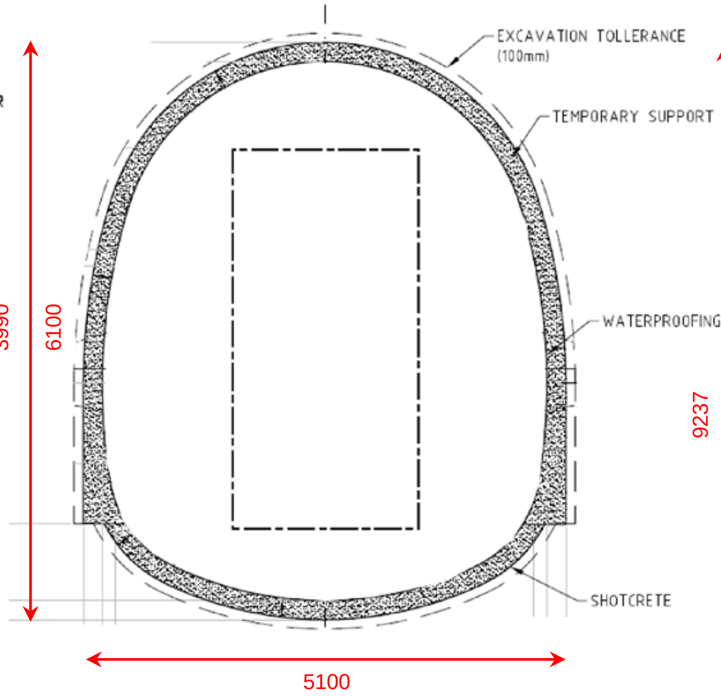
Selection of suitable shape and lining

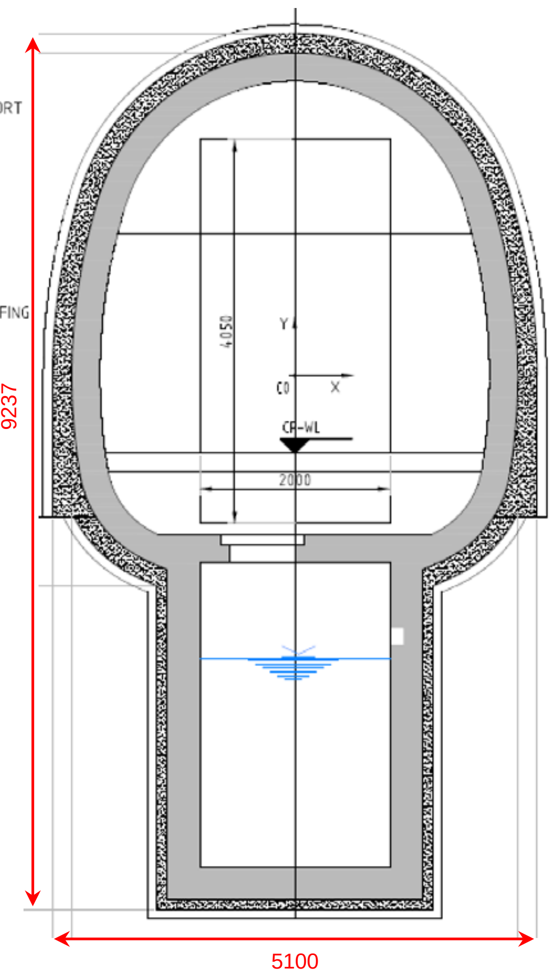
- Construction tolerances
- Primary support requirements
- Thickness of final lining
- Excavation profile (E-line)

SPACE PROOFED CROSS PASSAGE

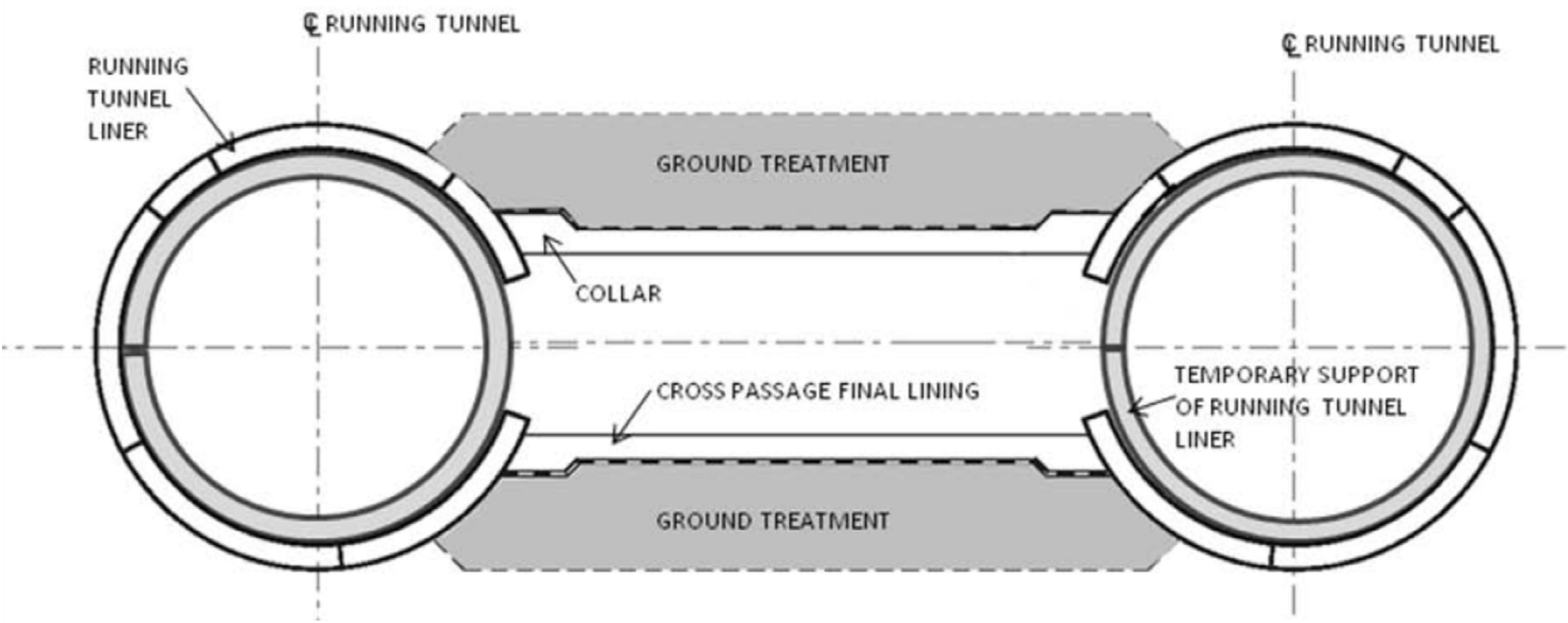
How can space proofing affect CP sizing



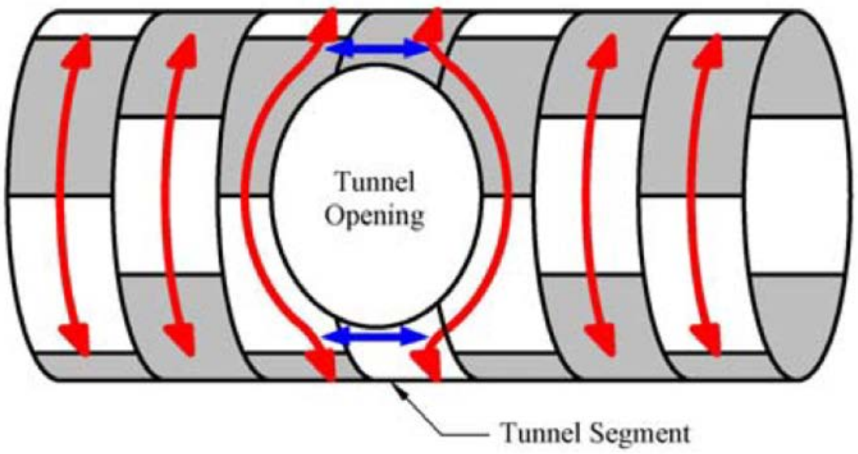




Cross Passage main elements



- CP opening results in change in stress distribution in the cut and adjacent rings
- Common practice to use CP for evacuation purposes and for housing systems equipment, thus requiring more space
- Ideal configuration is with CP opening relatively smaller than tunnel diameter, with similar axis elevation and 90° orientation
- Elevation of CP walkway is driven by that of evacuation walkway in tunnel
- Complex structure required when running tunnel and CP have similar size or axes have significant difference in elevation



Barcelona Metro Line 9

B.1 - Ground Conditions and Soil Treatment

- Two main issues associated with ground conditions for CP excavation are:
  1. Control stability and deformation of soil during excavation
  2. Control of groundwater limiting inflow into excavation

- Most soils – except stiff clays and naturally cemented soils – require some sort of ground treatment for excavating CPs by mining.

- Selection of suitable and effective ground treatment is paramount to reduce risk

- Most common Ground Treatments in soil are :
  - Grouting – Permeation grouting, Chemical grouting, Jet Grouting
  - Ground Freezing
  - Pre-support in soft, low permeability geotechnical units

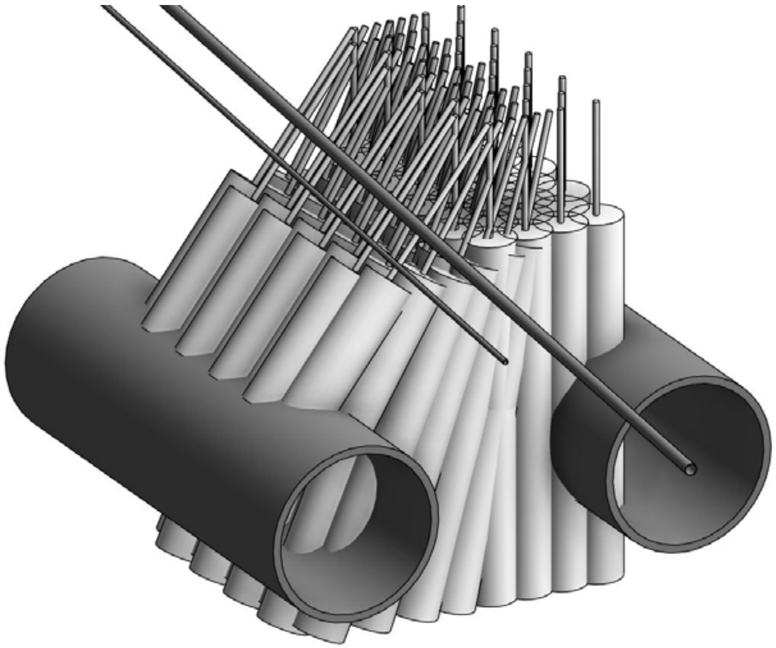
- Ground treatment selection is largely driven by:
  - Particle Size Distribution of soil
  - Availability of area at surface for intervention

Grouting

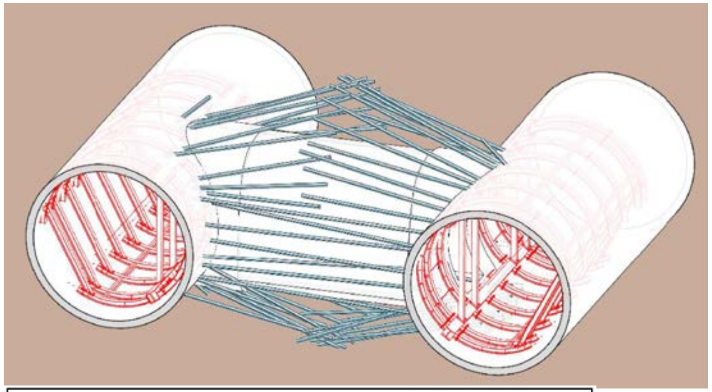
- Injection of grout mix in the soil mass with the purpose of reducing permeability and enhancing strength and stability for excavation

- **Permeation Grouting** – injection of chemical or high-penetrability cement grout mix to fill the soil pores
  - Range applicability fine sand to coarse gravels
  - Low pressure injection

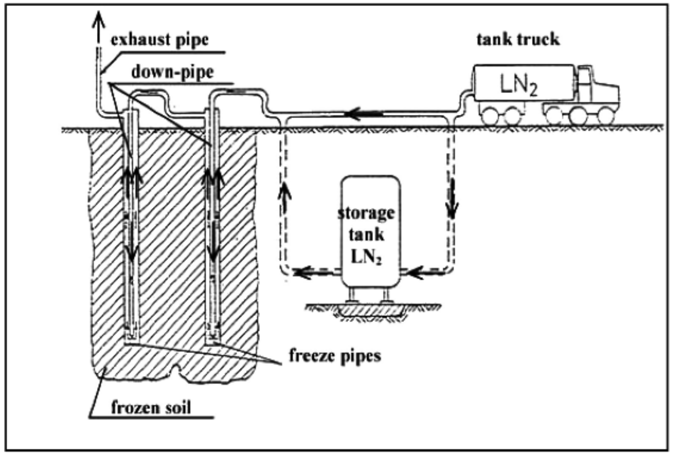
- **Jet Grouting** – high pressure jets to break up soil and replace with mixture of soil and cement.
  - Range applicability clay to fine gravels
  - Injection from nozzles on withdrawal with monofluid (grout), bifluid (water and grout) or tri-fluid (air, water and grout)
  - Interlocked columns diam up to 2.0-2.2m in sand, 1.0m in clay
  - Pre-washing in clayey soils helps breaking up structure
  - Required access at ground surface

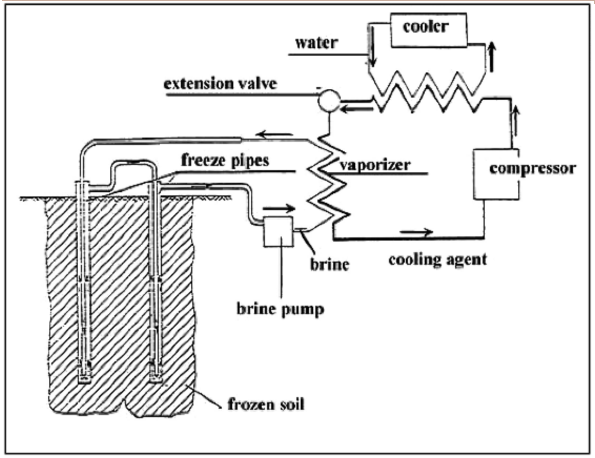


Ground Freezing



- Freezing the groundwater by means of circulation of a refrigerating fluid in pre-installed freezing probes
- Two methods
  - Liquid Nitrogen – open circuit, quick freezing up
  - Brine – closed circuit, slower heat exchange
  - Two stages: freezing and maintenance

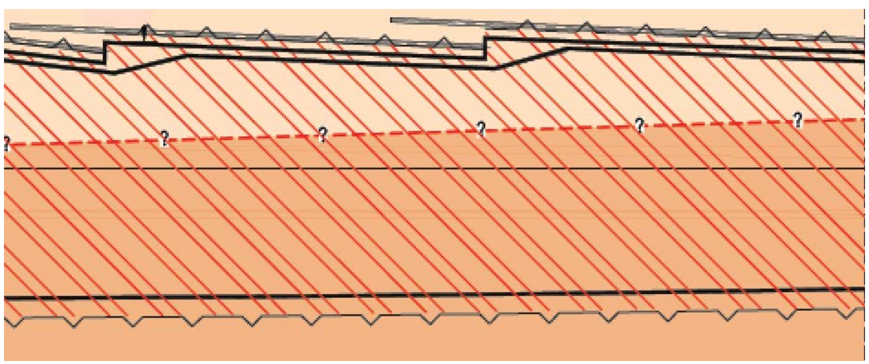


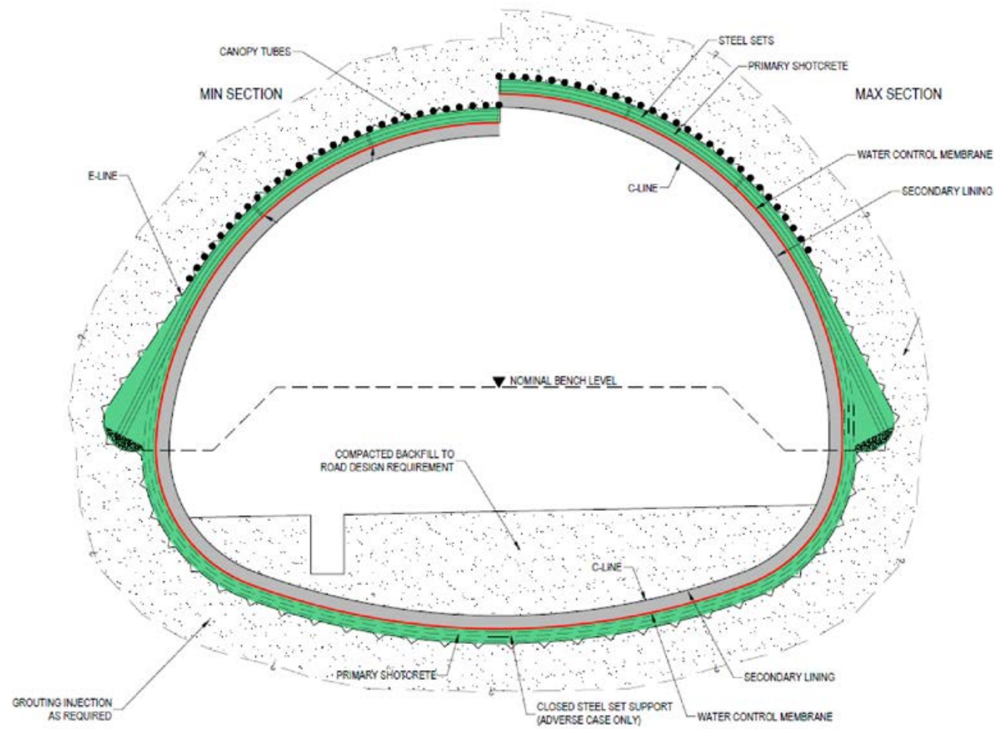


- Advantages
  - Impermeable barrier with increased strength in any type of soil
  - Effectiveness is temperature controlled and easily monitored with thermocouples at critical locations
- Limitations
  - Only applicable below GW table and where GW flow is not too high
  - Carried out from inside tunnels to limit length of pipes – impact on planning
  - Thawing may reduce the strength and deformation characteristics below those of original soil

Pre-support

- Canopy tubes (Umbrella pipe arch) provide support at the excavation face
- Steel pipes diam 70-150mm grouted in place, length 12-15m
- Required tapered tunnel section for installation of canopy tubes in rounds
- Supported by the lattice girder or steel sets





B.2 - Methods of Analysis

- 2D or 3D soil-structure interaction numerical modelling is used to determine:
  - Internal forces developing in the linings
  - Overall stability of excavation – FS reduction methods
  - Seepage analysis during excavation

- Structural design of CP to running tunnel connection and support frame is carried out with 3D structural modelling software packages

- Face Stability check – analytical methods

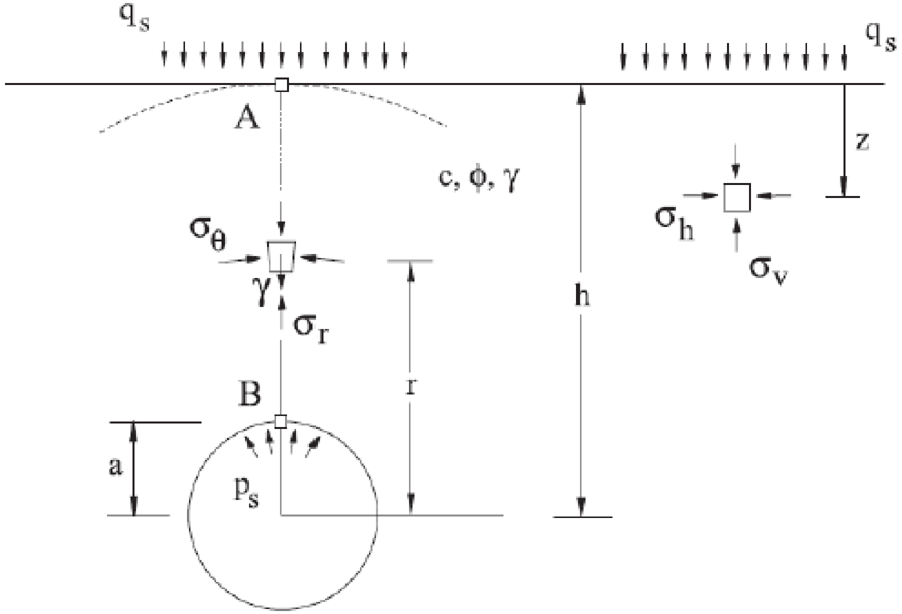
- Heave and Flotation of tunnel – analytical method with highest GW level for design life
  - Design Action S* =γR with γ= 1.2 Design Resistance R* =FR with F= 0.9

- Footing bearing capacity for lattice girders / steel set – analytical method
  - Determination of load transferred from lining to
  - Brinch-Hansen or similar method to determine q_u
  - $q_{all} = q_u/\gamma$

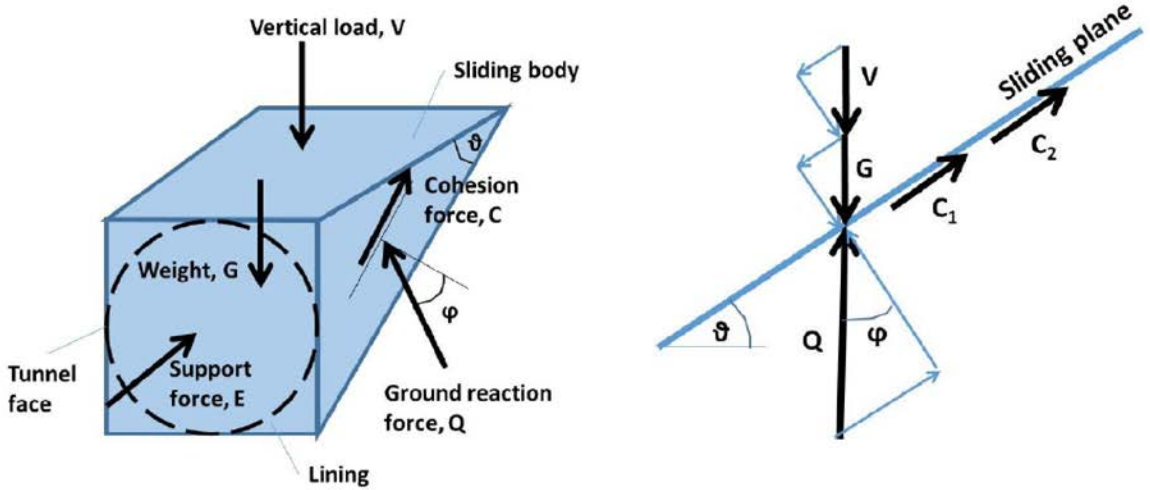
Face Stability verification – Analytical methods based on limit equilibrium

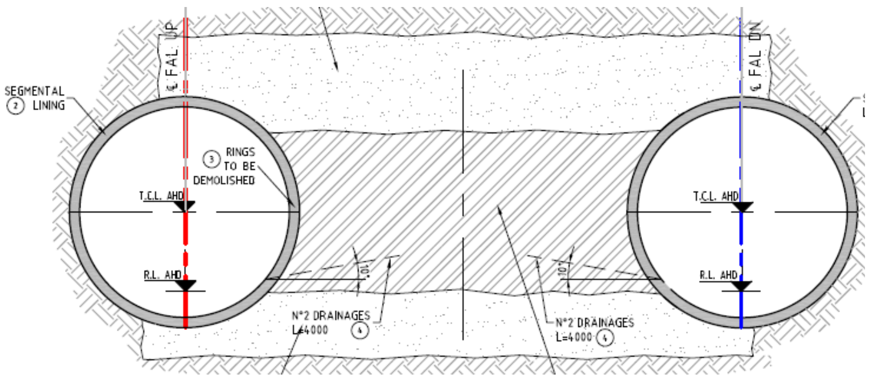
- Caqout & Kerisel method modified Carranza Torres (2004)

$$\frac{p_s}{\gamma a} = \left(\frac{q_s}{\gamma a} + \frac{c}{\gamma a} \times \frac{1}{\tan\phi}\right)\left(\frac{h}{a}\right)^{-k(N_\phi - 1)} - \frac{1}{k(N_\phi - 1) - 1}\left[\left(\frac{h}{a}\right)^{1-k(N_\phi - 1)} - 1\right] - \frac{c}{\gamma a} \times \frac{1}{\tan\phi}$$

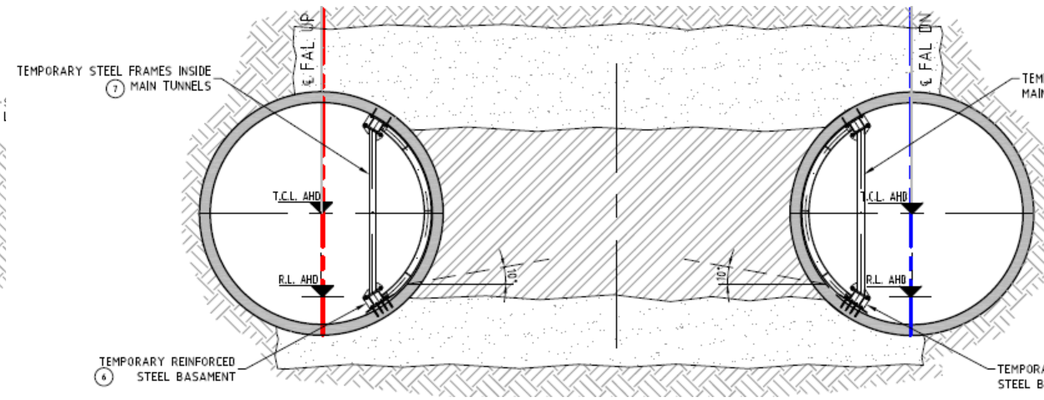


- Wedge method

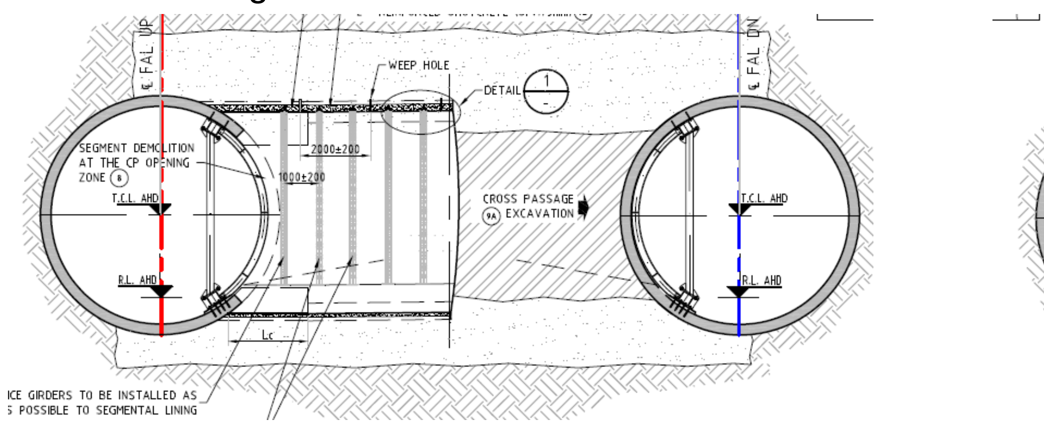




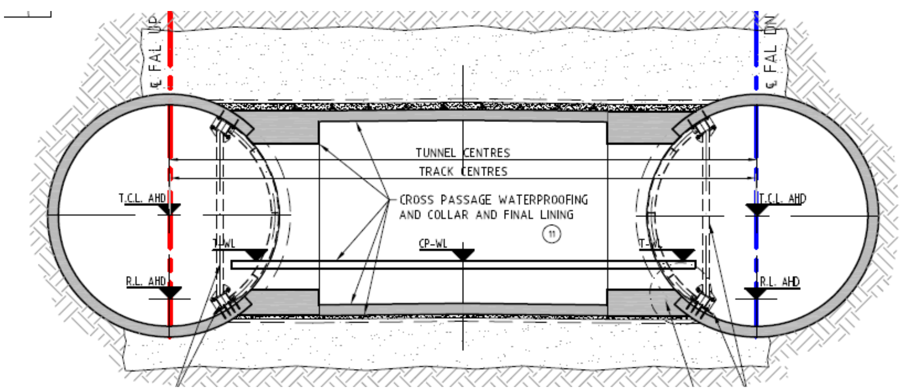
1A – Ground treatment (prior to TBM tunnel)
1B – TBM tunnels construction
2 – Mark position for CP opening
3 – Drainage installation in central chamber



4 – Installation Temporary support
5 – Face Consolidation



6 – Segment lining cutting and demolition
7 – Excavation in round lengths with application of primary lining support
8 – Invert excavation and primary lining completion



9 – Installation waterproofing
10 – Construction of collars and CP perm lining
11 – Removal of Temporary support
12 – CP fit out

1 – Special segments

- Special permanent steel segments with framing designed to:
  - Provide any required drilling windows for ground treatment or pre-support from tunnel
  - Create a portal frame supporting hoop force from the opened rings
- Ease of removal of segmental lining at CP position by unfastening the central segment
- Disadvantages
  - No flexibility in position of CP after TBM tunnel construction
  - Higher cost

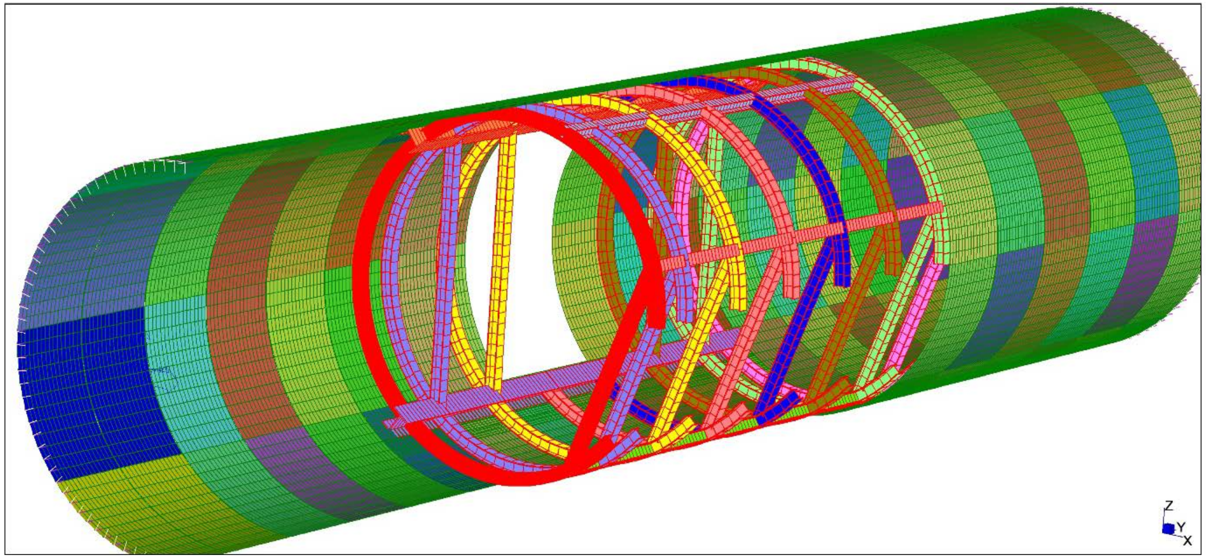
Steel set adopted in the Channel Tunnel Rail Link (UK)

B3 – Temporary support for running tunnels

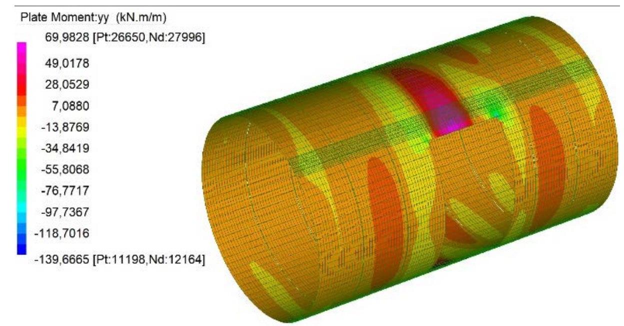
2 – CP opening steel sets

- Internal temporary structure to transfer the hoop force across the opening
- Complex installation with significant drilling in segments
- Advantages
  - Flexibility in adjusting CP position
  - Enabling skew junction design (although not desirable)

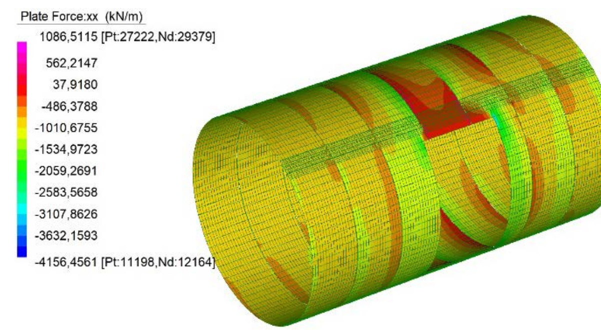
3D Structural Modelling and Verifications



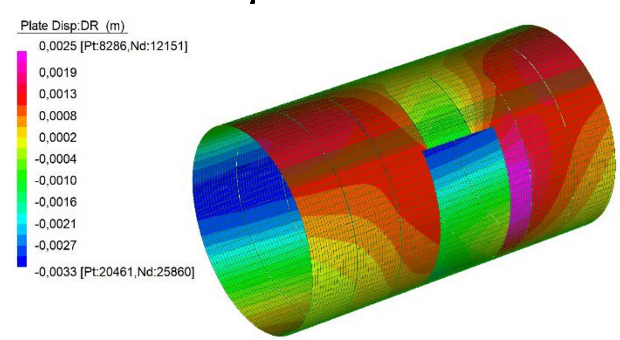
Bending Moment



Axial Force



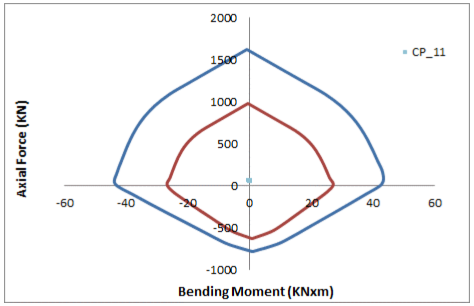
Radial Displacement



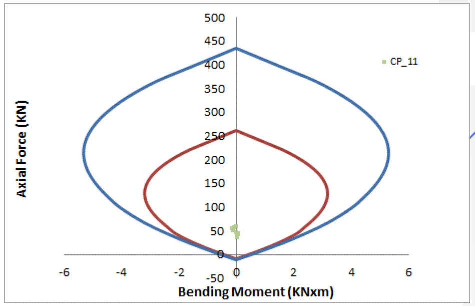
- Interaction between segmental lining and steel frame and how this is loaded
- Shell-spring : soil-structure interaction through calibrated elastic springs (compression only)
- Loading condition on extrados of segmental lining from soil-structure interaction software $q = 2Nk/D$
- Structural verification of steel frame elements and connections
- Structural verification of internal forces distribution generated in segmental lining

- Temporary or Permanent structural element
- 2D/3D soil-structure interaction FE analyses
  - 2D FE model plain-strain analysis, advance, 3D effects and progressive deformation of ground and loading of primary lining through Relaxation Factor – λ
  - ULS design for Temporary lining

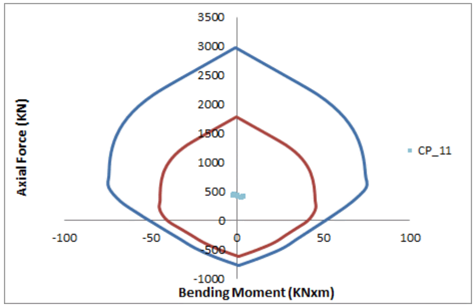
8 hrs – Crown & Side wall



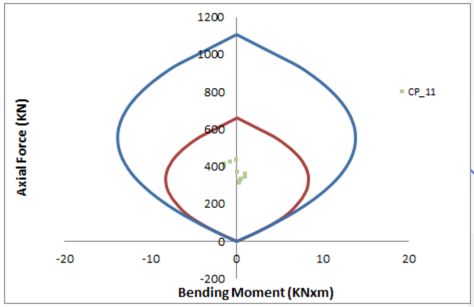
8 hrs – Invert



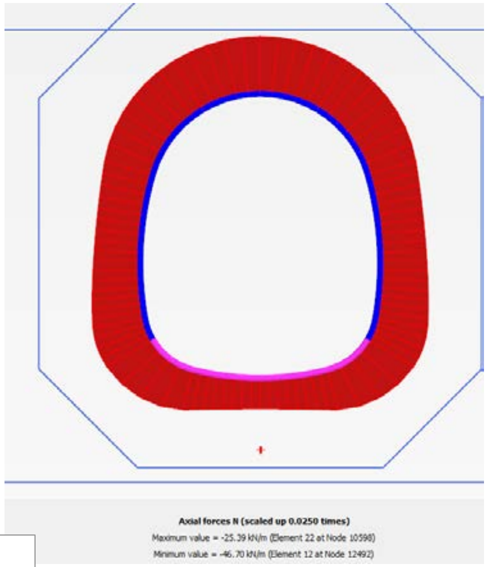
24 hrs – Crown & Side wall

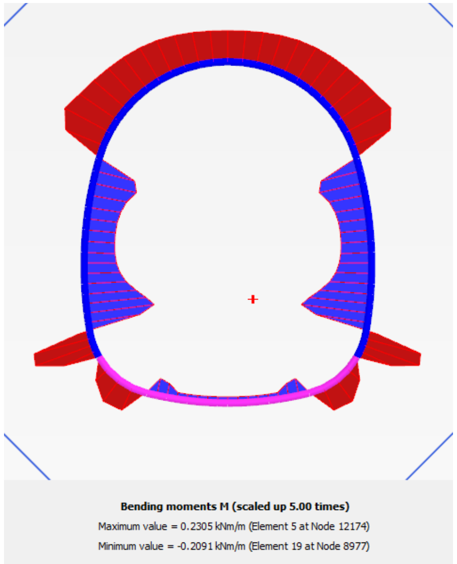


24 hrs – Invert

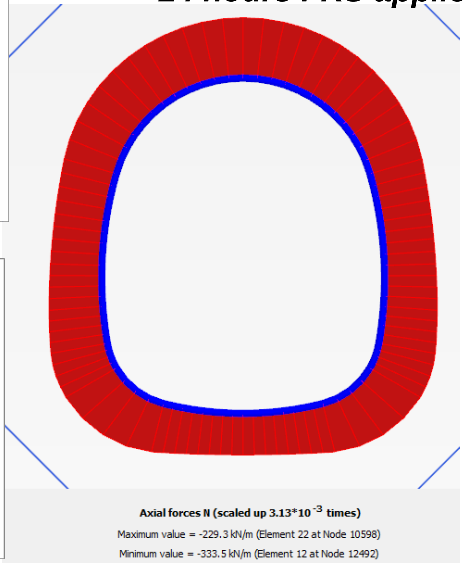


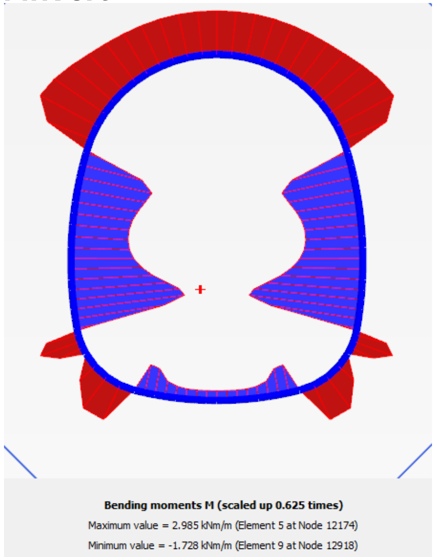
8 hours FRS application invert





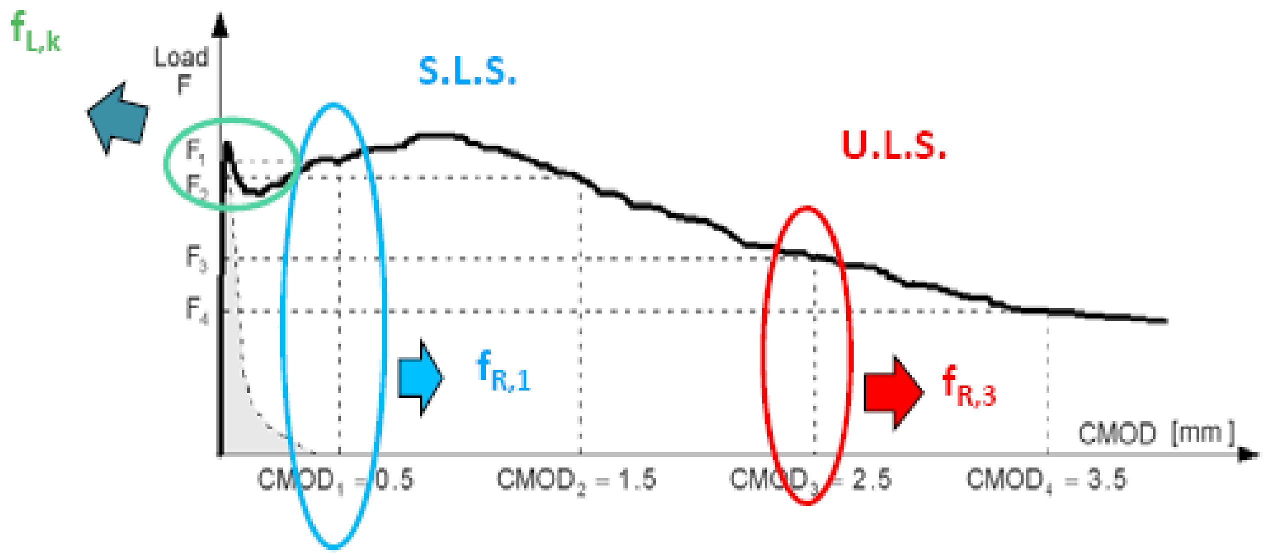
24 hours FRS application invert





Fibre Reinforced Shotcrete (FRS)

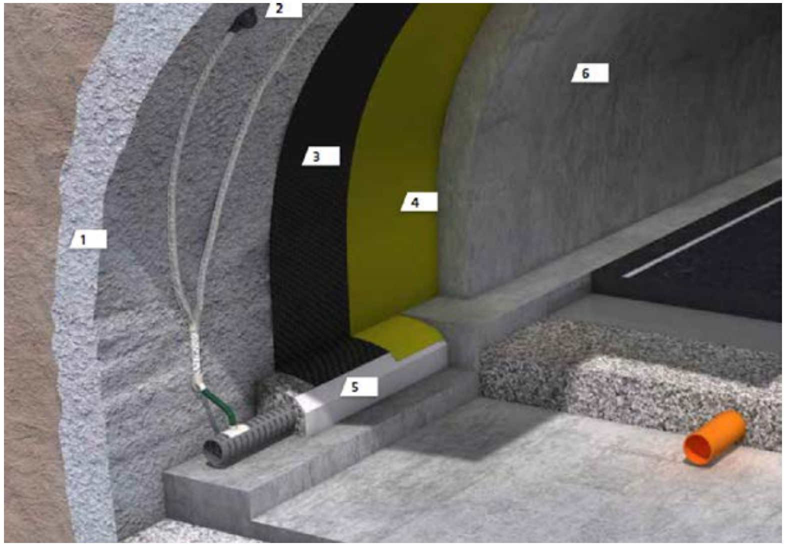
- *Model Code 2010* international reference
- Steel Fibres provide significant improvement in post-cracking behaviour with increase in toughness of concrete and ductility
- Residual Flexural Tensile Strength ($f_{R,x}$) v Crack Mouth Opening Displacement (CMOD) determined from testing on v-notched beams

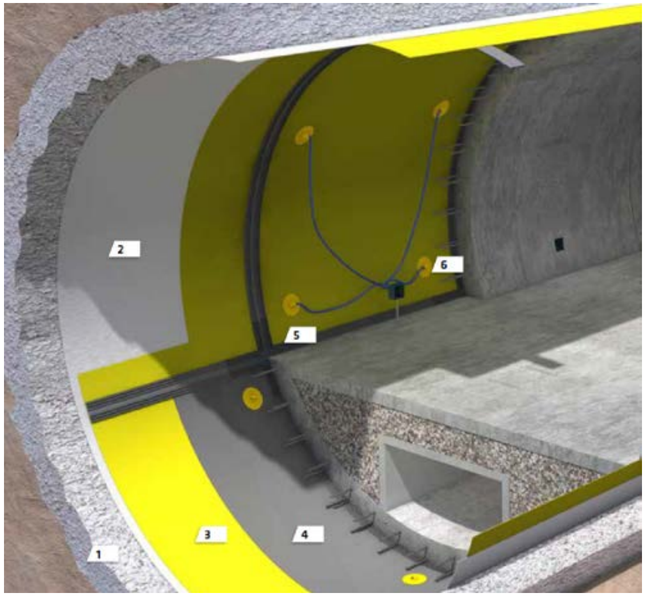


- Key parameters
  - Fibres type and dosage
  - Concrete class f'_c
  - $f_{R,1}$ and $f_{R,3}$

Sheet Membranes

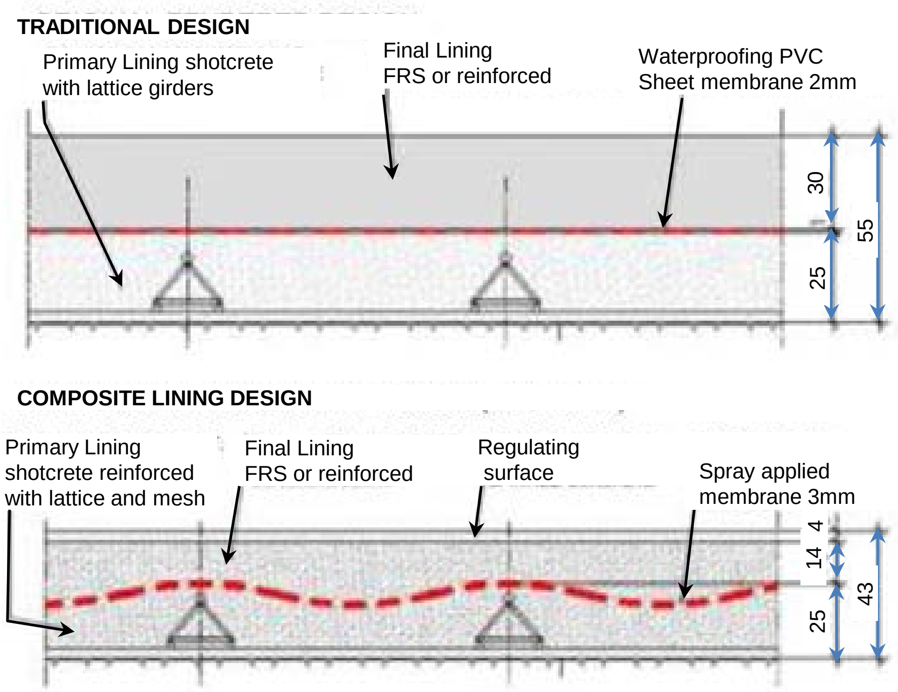
- PVC-P or FPO membranes with protective geotextile layers
- Drained of fully-tanked (undrained) tunnels
- Main characteristics are
  - Thickness
  - Tensile Strength
  - Elongation at break
  - Resistance to puncture
  - Resistance to chemical attacks
  - Reaction to fire
- Durability
  - Good ageing of membrane in place – conditions and testing of membranes excavated after 45 years confirmed they still possess characteristics that exceed the design requirements
  - membrane properties will fulfil their waterproofing function for many more decades
  - Design Life exceeds 100 years





Spray-applied Membranes

- Fully-bonded membrane to substrate of primary lining and to the inner final lining
- No migration of water leakage
- Has shear resistance which enable composite lining design between primary and final linings
- Very fast to install, particularly advantageous in complex geometry like niches, sumps, small adits and CPs
- Effectiveness of sprayed waterproofing systems very much dependent on the condition of the substrate for bond
- It requires high quality primary lining to ensure its own durability as it remains outside of the waterproofing layer

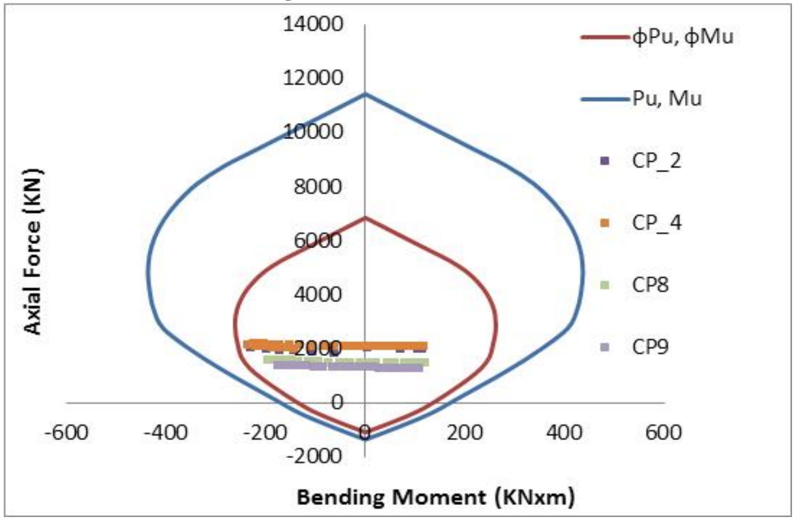


B6 – Final Lining Design

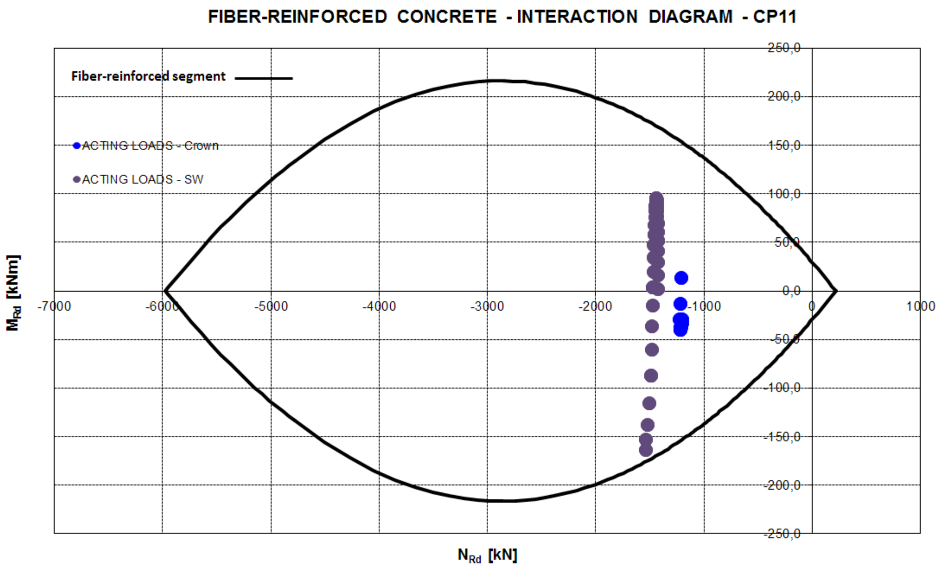
- ❑ Cast-in-situ or shotcrete
- ❑ Traditional rebar reinforcement required where high bending moments are involved
- ❑ Loading considered for Final Lining design:
  - Soil – only in association with Temporary Primary Lining and for portion of load transferred to this latter
  - Groundwater max design life
  - Future Development Loads
  - Creep
  - Seismic

- ❑ Define require reinforcement based on for BM, axial force and shear ULS verifications
- ❑ Check of SLS for max crack opening allowed
- ❑ Check of minimum reinforcement required for concrete shrinkage control

Interaction diagram for rebar reinforcement



Interaction diagram for fibre reinforcement

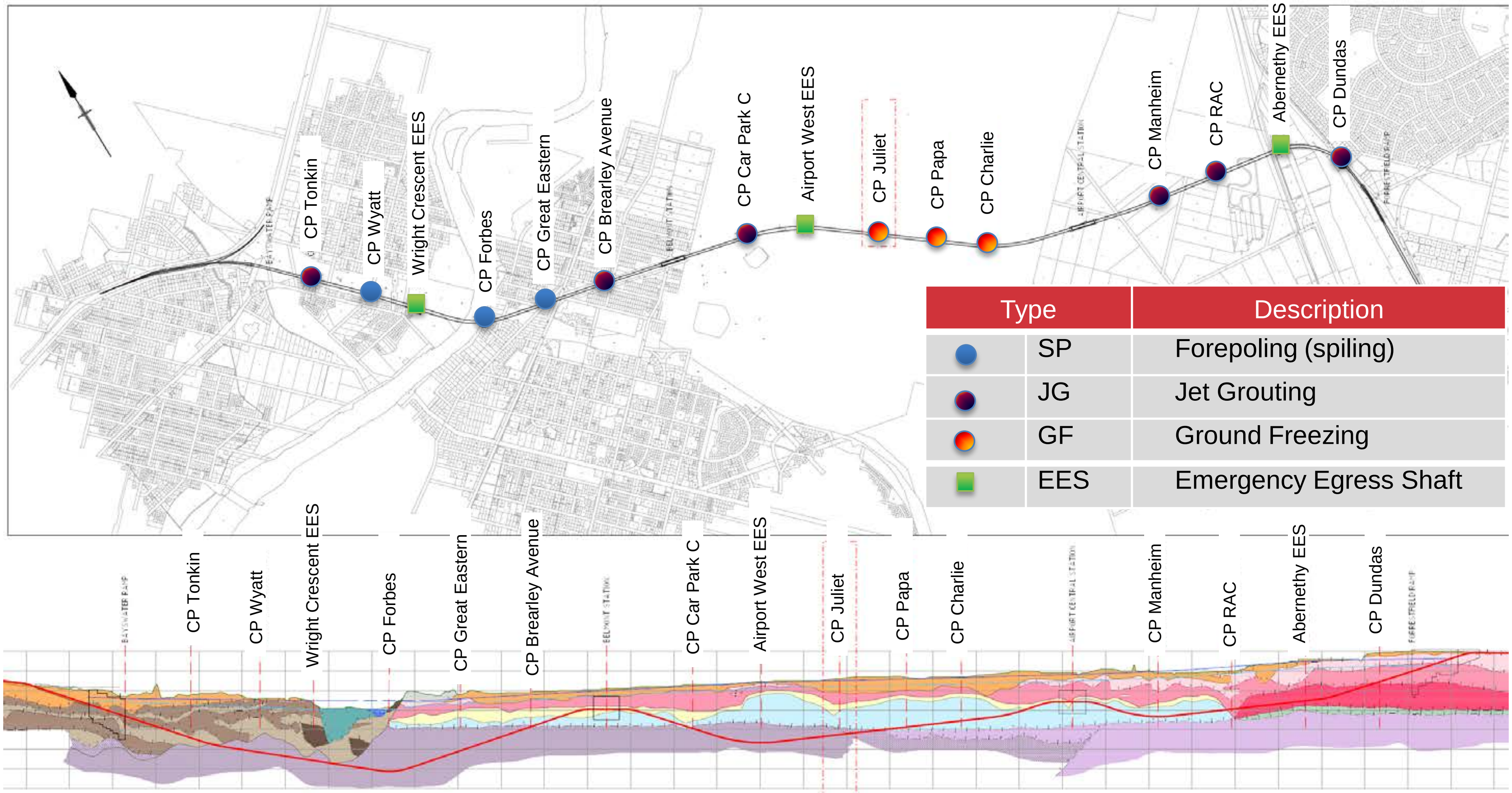


Forrestfield-Airport Link - Geology

Geological Unit		Typical Description	Depositional Environment	Approximate Age
Name	Unit Colour			
Fill (MG)		Primarily fine to medium grained yellow to brown sand. Also road base and other types of fill.	Controlled and uncontrolled sand fill in recent history.	< 200 years
Swan River Formation (SF)		Silty clay, clayey silt, silty sand and sand, dark grey, dark brown to black with shells and organic material, low to high plasticity fines, very soft to firm, or very loose to loose.	Palaeochannel deposits in marine, estuarine and fresh water conditions.	0 to 30 ka
Perth Formation (PF)	PF / PFs	PFs: Sand to silty sand, yellow, brown and grey, fine to coarse grained, medium dense to dense. Some fine to coarse gravel, generally rounded to sub-rounded quartz, may be present.	Palaeochannel deposits in marine, estuarine and fresh water conditions.	80 to 150 ka
	PF / PFc	PFc: Clay, some silt and sand, blue-grey, mottled red, yellow, brown, generally low to medium plasticity and generally stiff to hard some soft to firm materials close to the Swan River.		
Bassendean Sand (BS)		Sand, light grey, yellow, dark brown, fine to medium grained, loose to dense, fining upwards where fluvial in origin, with thin (up to 1 to 2 m) localised iron cemented layers. May contain peaty sand, silty and clay associated with wetland or dampland interdunal deposits.	Mixed fluvial and aeolian orign.	80 to 750 ka
		transitional boundary / facies change		
Guildford Formation (GF)		Clayey sand, silty sand, sand and clay, brown, pale grey, orange, fine grained layers stiff to hard and low plasticity, coarse grained layers are medium dense to very dense. Includes potential sand deposits of the Yoganup Formation east of the RAC driving centre (~ CH7600).	Fluvial origin generally deposited as part of alluvial fan system. Yoganup formation is a littoral (coastal) deposit	170 ka to 2 Ma
		transitional boundary / facies change		
Gnangara Sand (GS)		Sand and silty sand, blue-green, dark green, fine grained, loose to dense.	Freshwater and marine deposit in nearshore coastal environment	170 ka to 2 Ma
Yoganup Formation (YF)		Sand, fine to coarse grained, yellow to orange, medium dense to very dense.	Fluvial origin generally deposited as part of alluvial fan system.	170 ka to 2 Ma
Ascot Formation (AF)		Ascot Beds (AFa): Carbonate sandy gravel, gravelly sand and sand, fine to medium grained sand, grey, yellow, medium dense to dense, some siliceous calcarenite layers.	Inner shelf, nearshore marine environment, deposited during multiple marine transgressions.	750 ka to 3 Ma
		Jandakot Beds (AFj): Carbonate sand, sandy gravel and gravelly sand , fine to coarse grained, grey, dark grey and blue-grey, medium dense to very dense, some siliceous calcarenite. Polished rounded black phosphatic gravel often found at the base. High strength conglomerate boulders may also be present at the base of this unit but have only been noted in the vicinity of the Perth Airport air traffic control tower to date.		
			Major unconformity	
Osborne Formation (OF)	OFm	Mirrabooka Member (OFm): Sand, silty sand and clayey sand, dark green to dark grey, medium to coarse grained, dense to very dense, siliceous and glauconitic. Includes the Molecap Greensand	Shallow-marine origin.	100 to 120 Ma
		Kardinya Shale Member sand dominated (OFs): Silty sandstone, fine-grained, layered, dark green and black, moderately weathered to fresh, extremely low to medium strength		
		Kardinya Shale Member fines dominated (OFf): Sandy mudstone and sandy siltstone, black and dark green, moderately weathered to fresh, extremely low to medium strength.		

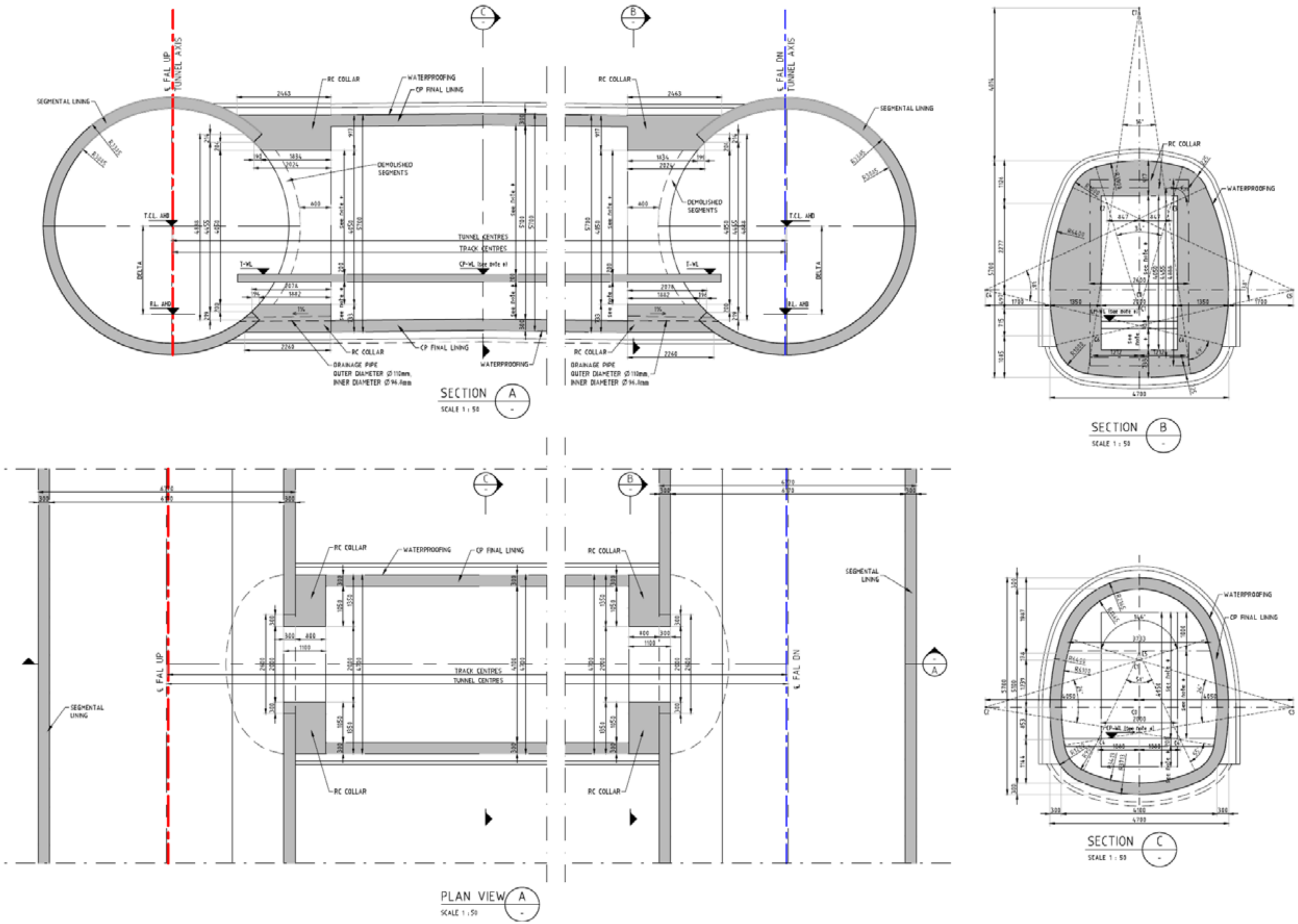
Forrestfield-Airport Link – Plan-profile

Cross Passages and Emergency Egress Shafts

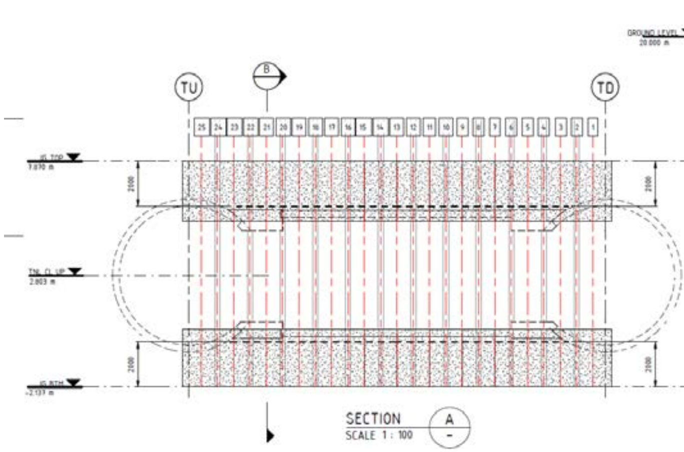


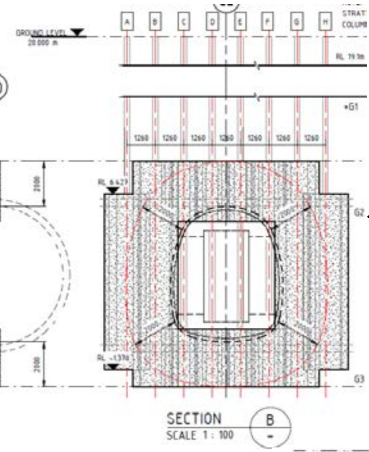
Type		Description
● (blue)	SP	Forepoling (spiling)
● (dark red)	JG	Jet Grouting
● (orange)	GF	Ground Freezing
■ (green)	EES	Emergency Egress Shaft

Cross Passages: Typical Layout, Sections and Elevation



Cross Passages: Ground Improvement



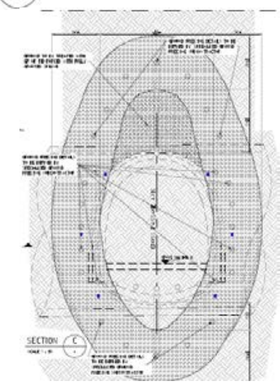


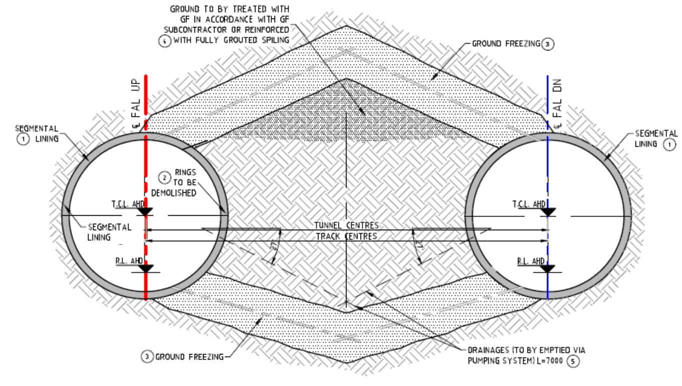
Jet Grouting

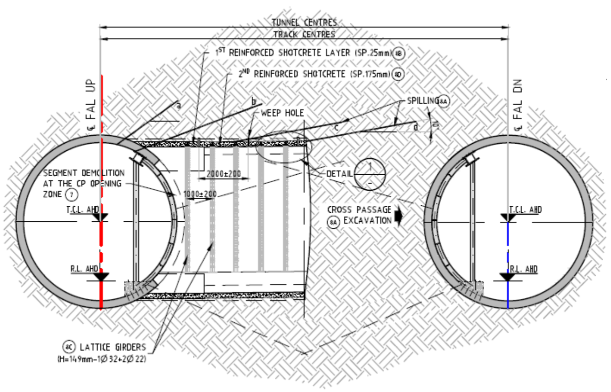
CP1 Tonkin, CP5 Brearley Av, CP6 Car Park C, CP10 Manheim, CP11 RAC, CP12 Dundas Rd

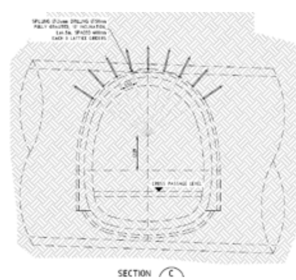
Ground Freezing (PAPL airside)

CP7 Juliet, CP8 Papa, CP9 Charlie





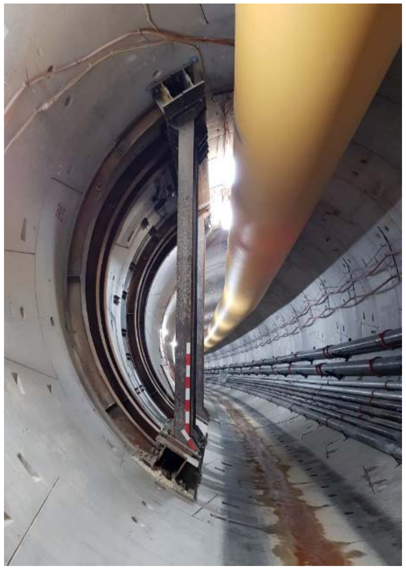




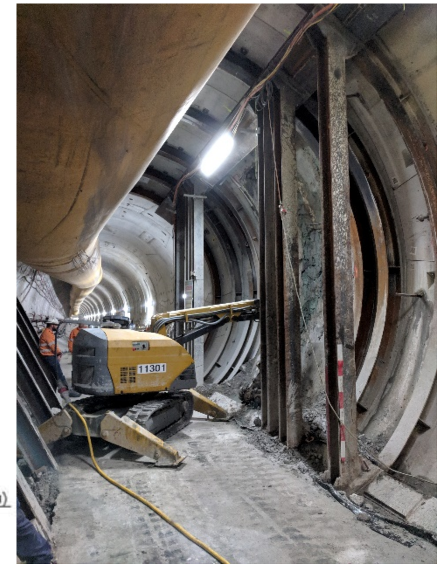
Forepoling (spiling)

CP2 Wyatt, CP3 Forbes, CP4 Great Eastern Highway

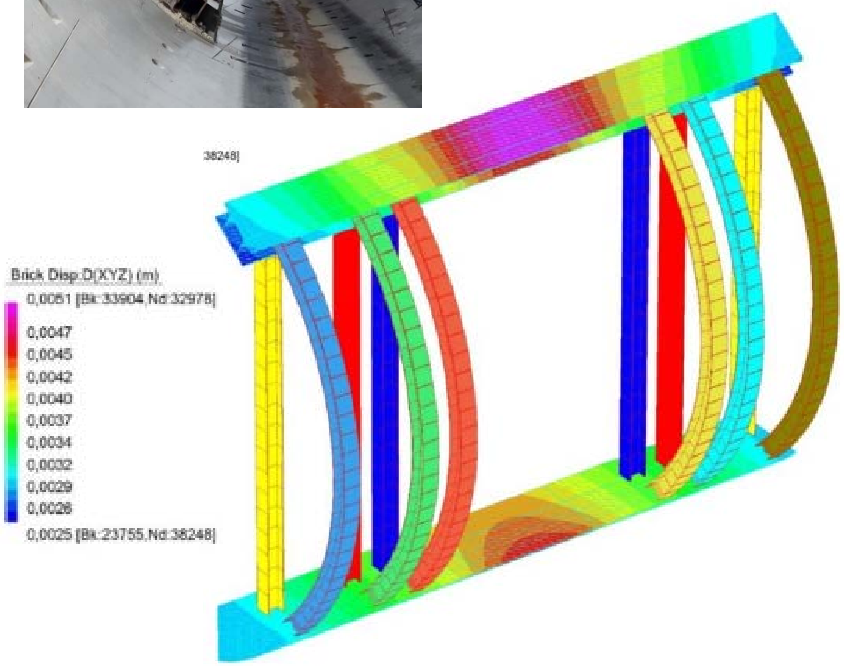
Cross Passages – Temporary Support for Segmental Lining

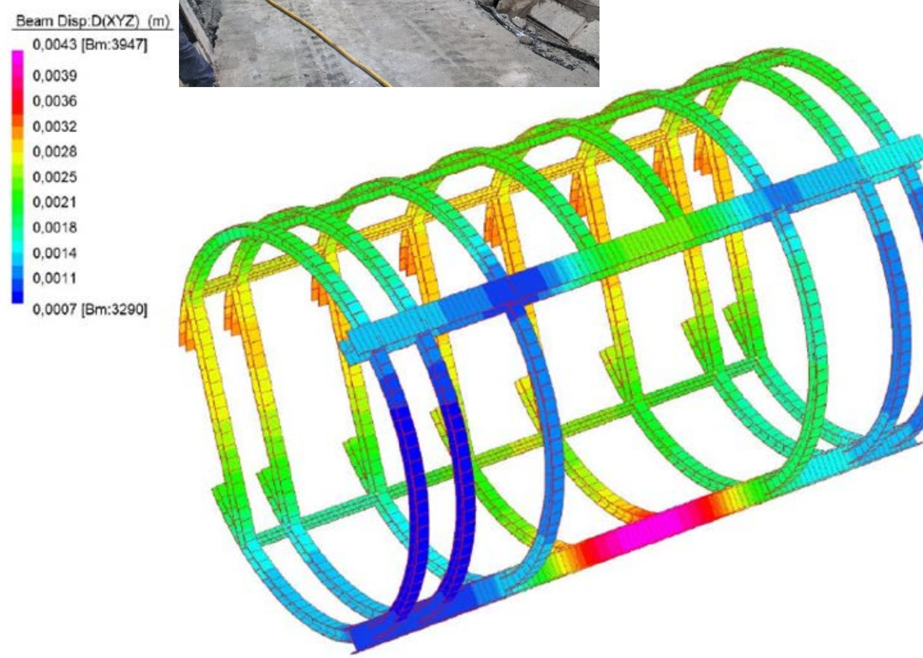


Half-moon steel frame

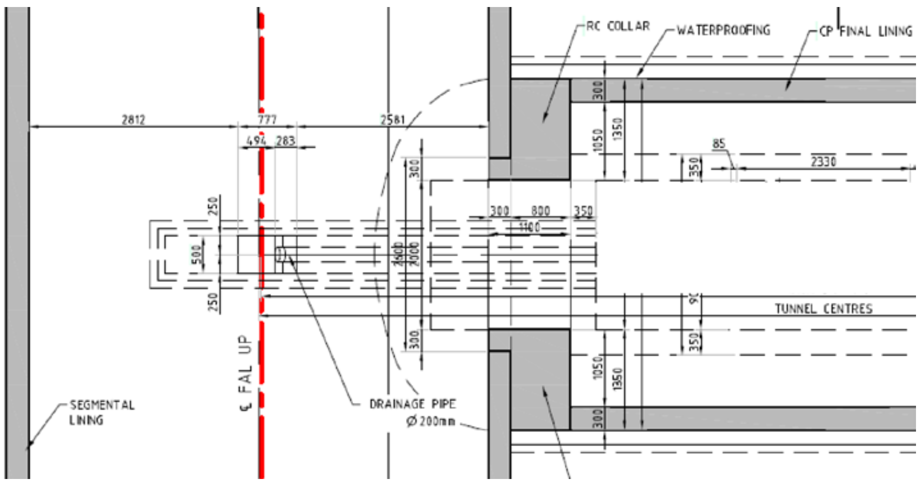


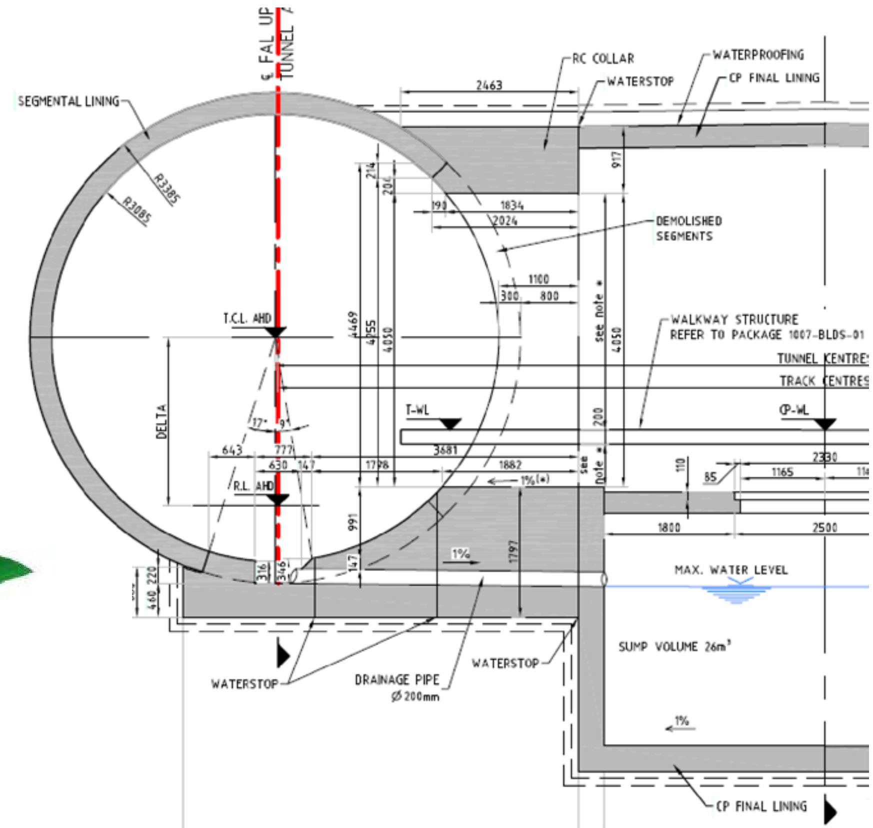
Full-round “Hamster cage” steel frame

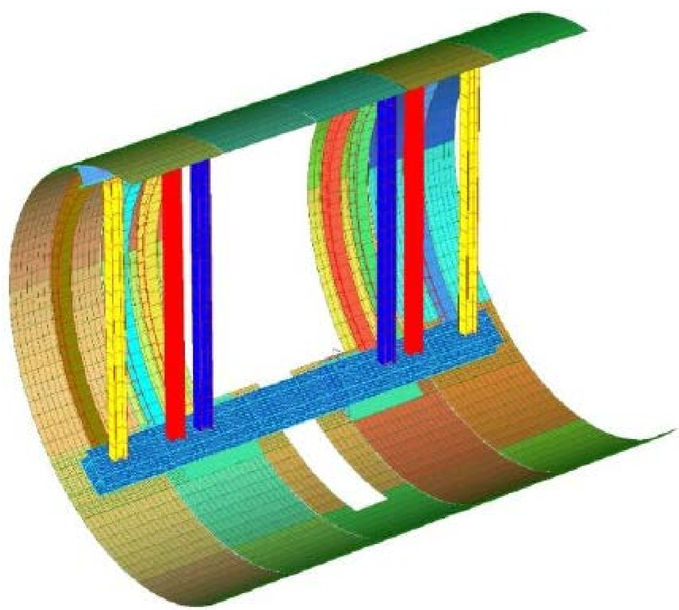




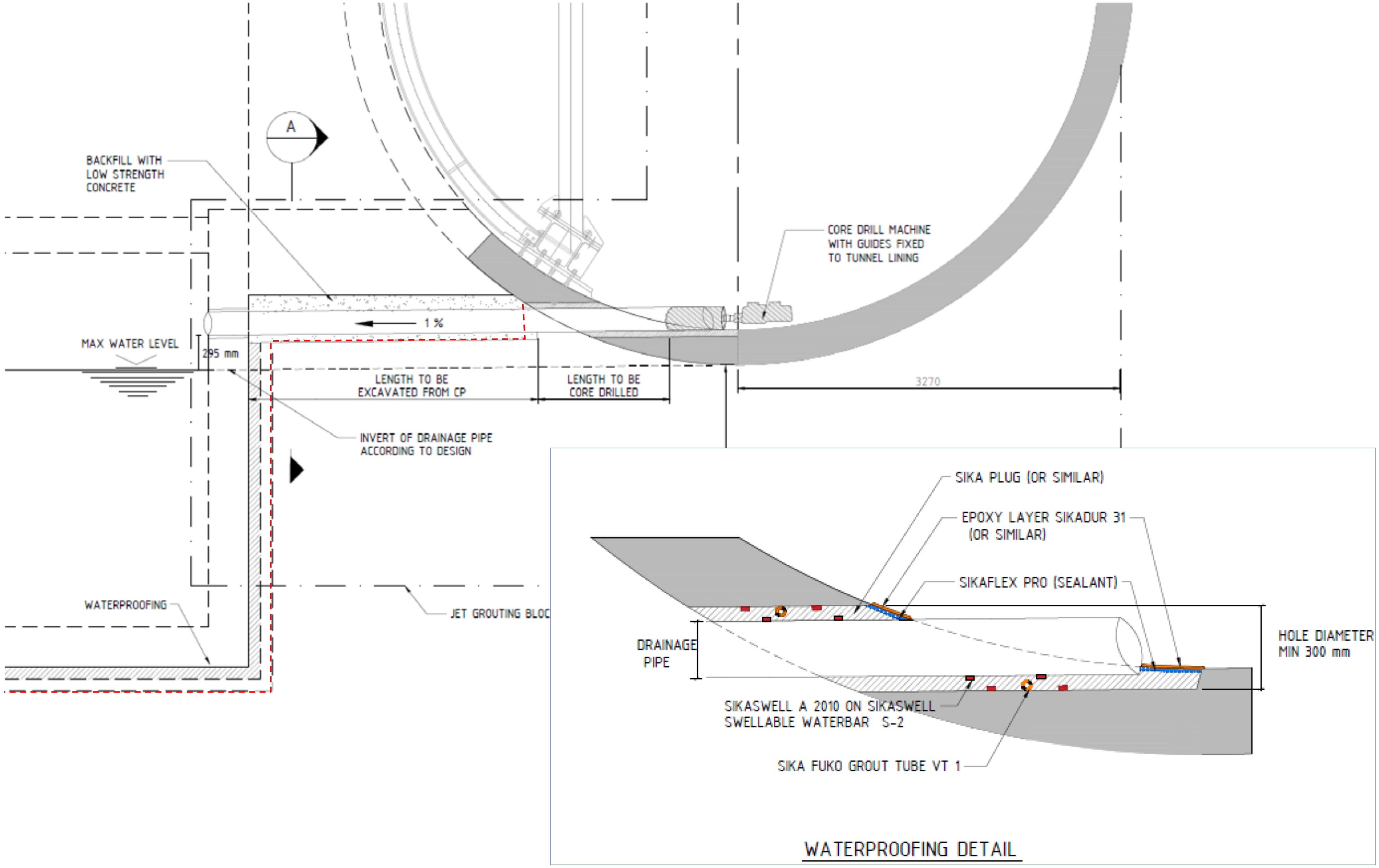
Cross Passages: Drainage solution to sump - IFC design





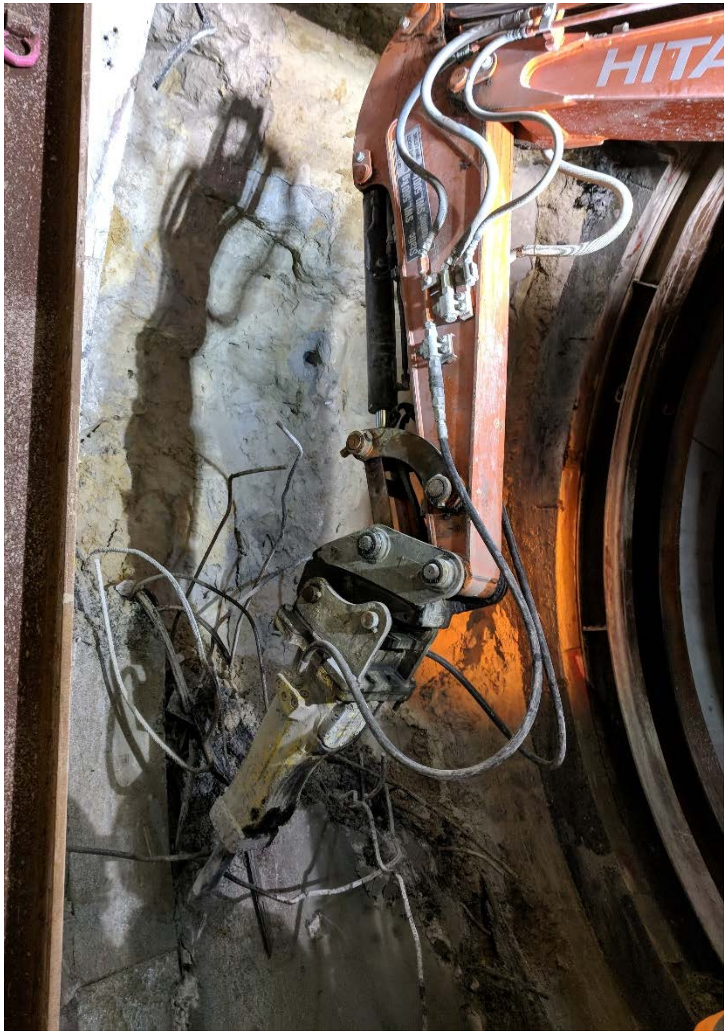


Drainage solution to low level sump in CP implemented in construction



Forrestfield-Airport Link – Break through tunnel lining

- Controlled demolition to ensure safety of operation and preserve structural integrity of segmental lining
- Ahead of CP opening, probing through segmental lining to control ground conditions and install drains to dewater central chamber
- Diamond-impregnated saw cutting
- Demolition of cut segmental lining

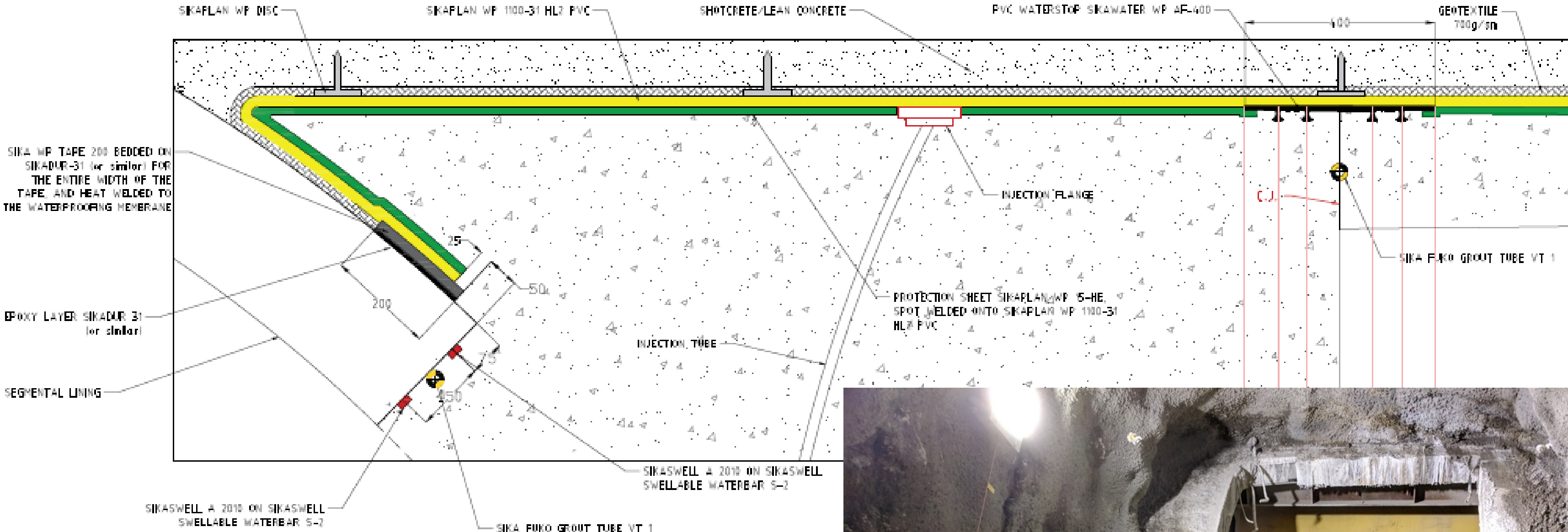


Forrestfield-Airport Link – Excavation and Support

Installation of lattice girder upon completion of excavation round of top heading

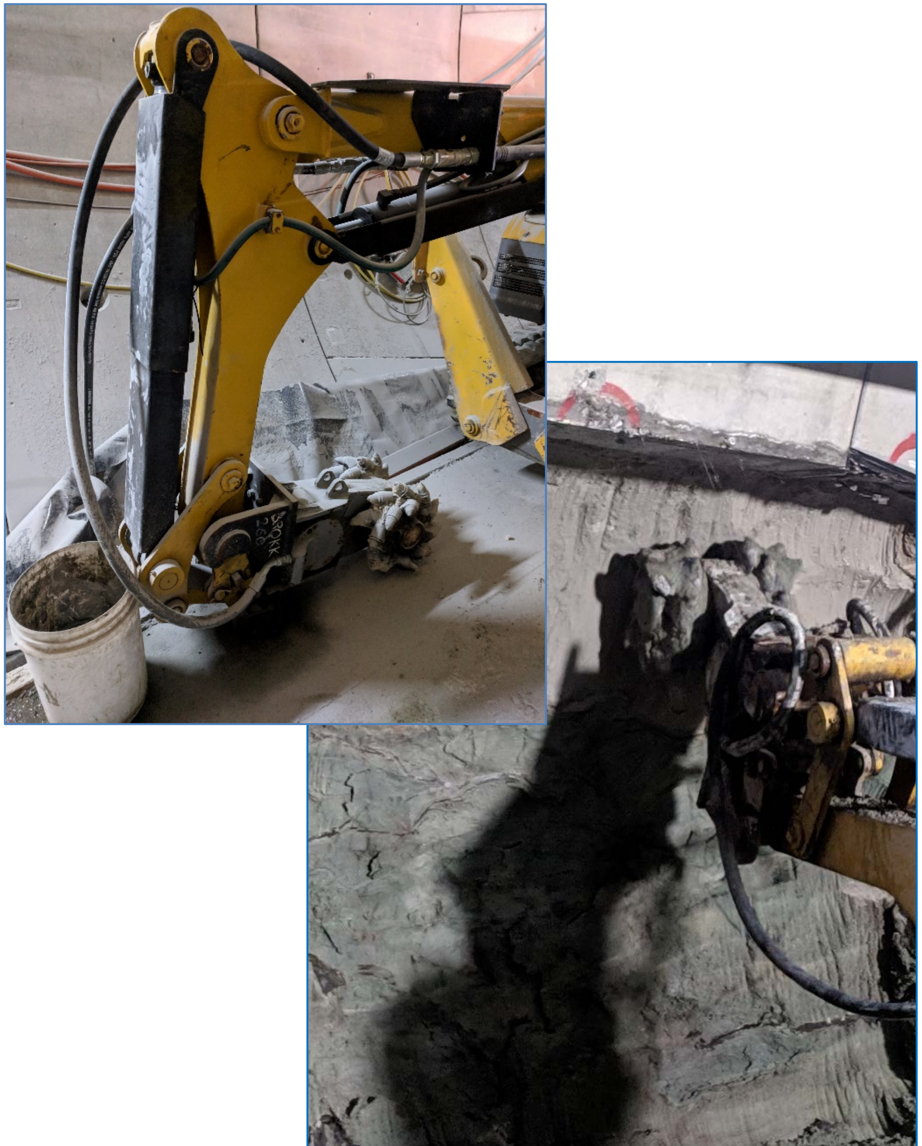
Bench excavation and support extention

PVC Membrane with geotextile protection

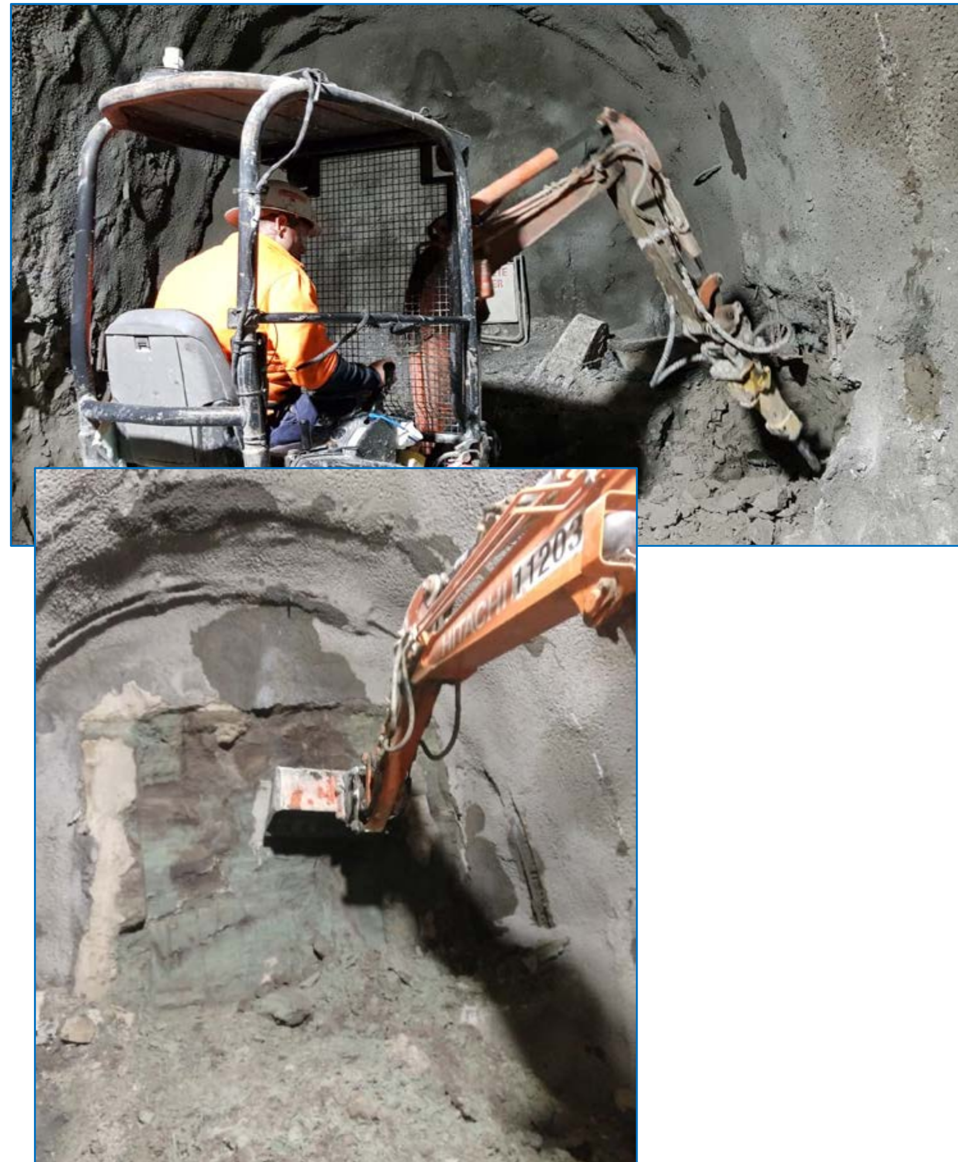


Forrestfield-Airport Link – Excavation Equipment

Small roadheader

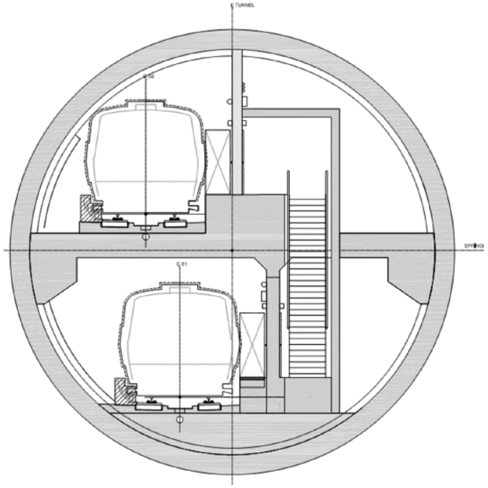


Hydraulic breaker and excavator



- CPs critical component in transportation twin tunnel infrastructure which often provide the most channeling element in the project
- Deep understanding of ground conditions and selection of most suitable ground treatment in soft ground is paramount to reduce risk during excavation
- The behavior of soil and structures is highly 3 dimensional and suitable FE modelling is essential

BART extension San Jose California



- Recently developed alternative - single large diameter tunnel with separated operational levels
  - two levels act as two separate tunnels for emergency purposes.
  - advantage of the cost reduction of using a single tunnel, together with the safety advantage of two separate tunnels (although strict requirement are set for the structural design of the ceiling slab).

Barcelona Metro Line 9 Spain

TBM: 12.04m

Thanks for your attention

External Sources

- Lawrence C, Taylor J (2012) : *Design of Tunnel Cross Passages*
- Agus S.S., Enferadi N., Amon A. (2016) : *Aspects of Design of Tunnel Cross Passage*
- Lee T., Choi T. (2017) : *Numerical Analysis of Cross Passage Opening for TBM Tunnel*
- Chapman D., Metje N., Stark A, (2010) : *Introduction to Tunnel Construction*