Tunnel Construction Overview

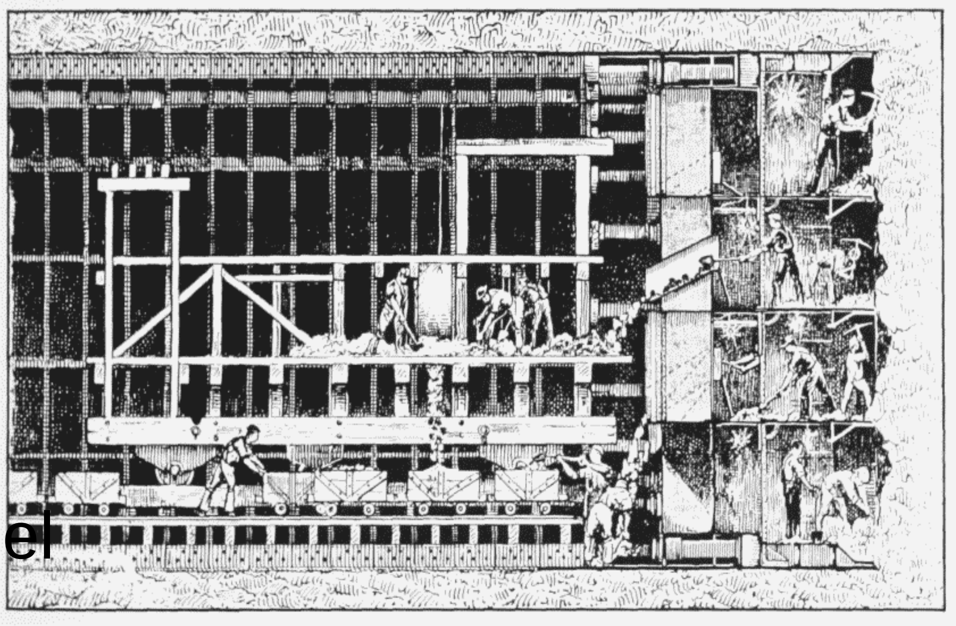
Ulrike Pelz, Engineering & Design Director, Lendlease, NorthConnex Project, Sydney

"It's always dark in front of the pick"
(German miners proverb)

HISTORY OF TUNNEL CONSTRUCTION

- In ancient times excavation of underground spaces was mainly used for burials and religious purposes, succeeded by construction of drainage, water supply and sewers.
- 18th century: “Modern” tunnel construction started, blasting using black powder, tunnel support with timber structures and sometimes final linings erected using bricks and cement.
- Tunnelling relied entirely on the experience of the people involved, no analytical methods to predict ground loads or define the required support were available.

- Majority of tunnels were constructed in rock.
- Late 18th century tunnelling under the Thames River in London was given consideration.
- A tunnelling ‘shield’ was patented by Marc Isambard Brunel in 1818. A shield, supporting the ground in front and around it was used to construct the Thames river crossing from 1825 – 1843, the advance was so time consuming and expensive, that no shield was used for the next few decades.
- Several further attempts to use shield machines were carried out more or less successful. Projects were often finished utilising alternative equipment
- Peter Barlow patented a shield machine with features close to a modern TBM in 1878.



- The invention of compressed air rock drills, use of dynamite, designed lining construction, introduction of ventilation and survey control revolutionised tunnel construction in the first half of the 19th century.
- The new methods allowed tunnel construction under conditions which were up to this time not accessible for tunnelling.
- Over 100 years up to the 1960s significant developments:
- Geotechnical engineering & subsurface explorations emerged, Ground behaviour could now be modelled confirmed through field observations, leading to support systems.
- Rock bolts were introduced to systematically reinforce the rock mass.
- “Modern Era” of tunnelling began in the 1970s.

Tunnelling Methods - General

Several tunnelling methods are available. The method selected for any specific project depends on multiple parameters as:

- Ground conditions (Geology, rock or soil, water pressure, contamination, etc.)
- Length and cross sectional area of the tunnel
- Tunnel depth
- Access options
- Logistical considerations
- Programme
- Cost and risk considerations

For relatively large cross sections, three basic types of tunnel construction methods can be distinguished:

- Bored tunnel
- Cut & Cover Tunnel
- Immersed tubes

Bored or Driven Tunnel

- Whole range of different methodologies
- Tunnel cross sections are typically circular, horseshoe or fish mouth shaped for optimal load transfer
- Depending on the prevailing conditions and constraints, the tunnel excavation can be carried out using methods close to traditional mining:
  New Austrian Tunnelling Method (NATM) or Sequential Excavation Method (SEM), mostly advanced by
  - Drill and blast or
  - Roadheader excavation
- or fully mechanised options using
  - Tunnel boring (Shield) machines

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New Austrian Tunnelling Method

- Limited rock deformations around the tunnel during the stress re-distribution phase after the tunnel advance are allowed.
- Leads to an adaptable, economic support system
- The self- supporting capability of the ground arch around the tunnel is mobilised to a large extent.
- Not suitable for very soft ground conditions.

Tunnel Boring Machines (TBMs)

Are commonly used where:

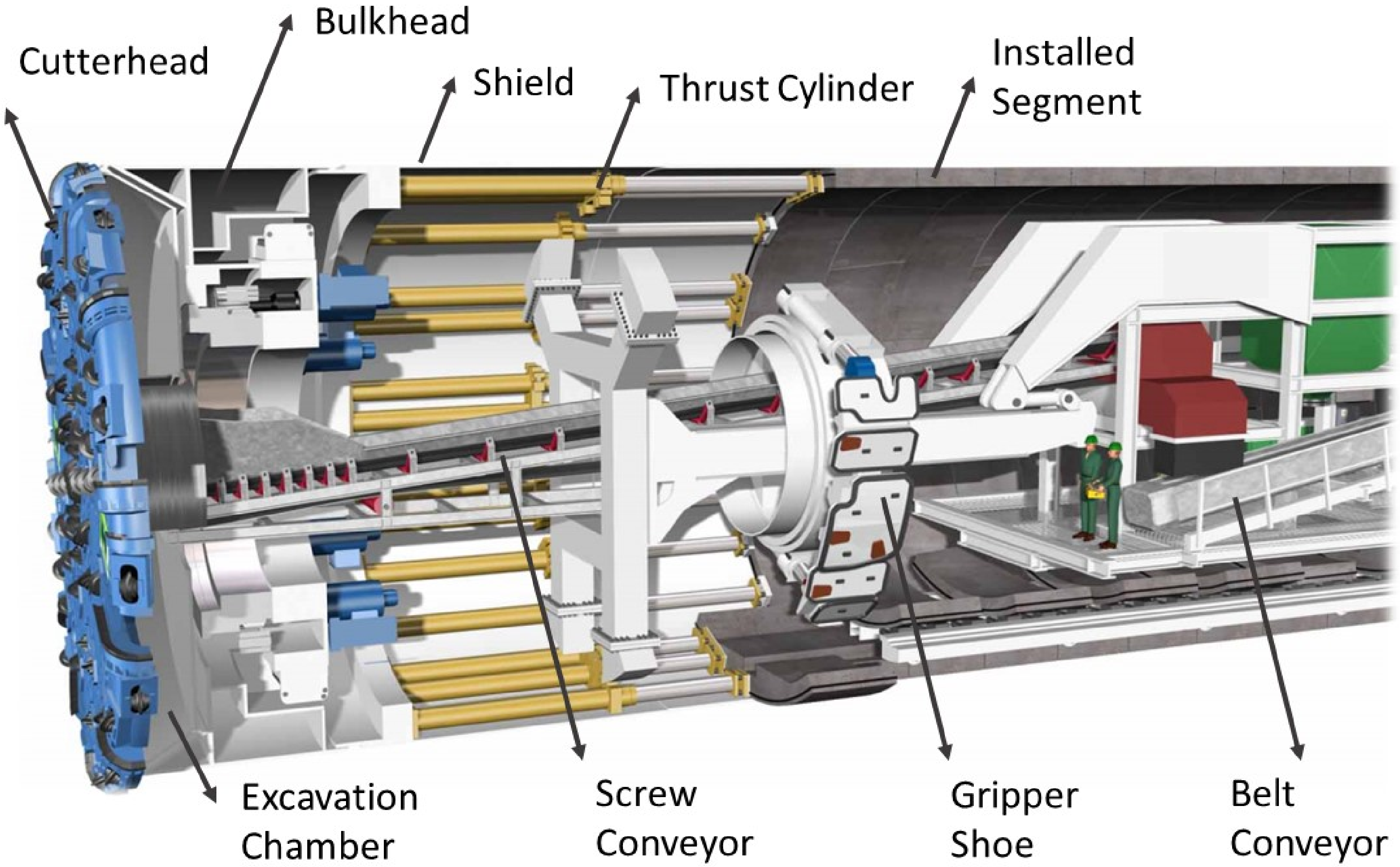
- the ground conditions do not allow for conventional mined tunnel excavation or
- long tunnels are constructed without intermitted access options from the surface.

TBMs are classified as hard rock or soft ground machines.

Three general types of TBMs can be distinguished:

- Earth Pressure Balance Machines (EPBs)
- Slurry Shield Machines (SSM)
- Open Face Machines

- Slurry Shield and Earth Pressure Balance types use thrust cylinders to advance forward, pushing against rings of precast concrete segments
- EPB machines use the excavated material to balance the earth pressure at the tunnel face.
- In conditions with higher pressure due to very soft ground / high water pressure, Slurry Shield machines are utilised.
- Open face TBMs (Main Beam machines) can only be utilised if the excavation face will stand up without support for a short period of time.


Cutterhead
Bulkhead
Shield
Thrust Cylinder
Installed Segment
Excavation Chamber
Screw Conveyor
Gripper Shoe
Belt Conveyor

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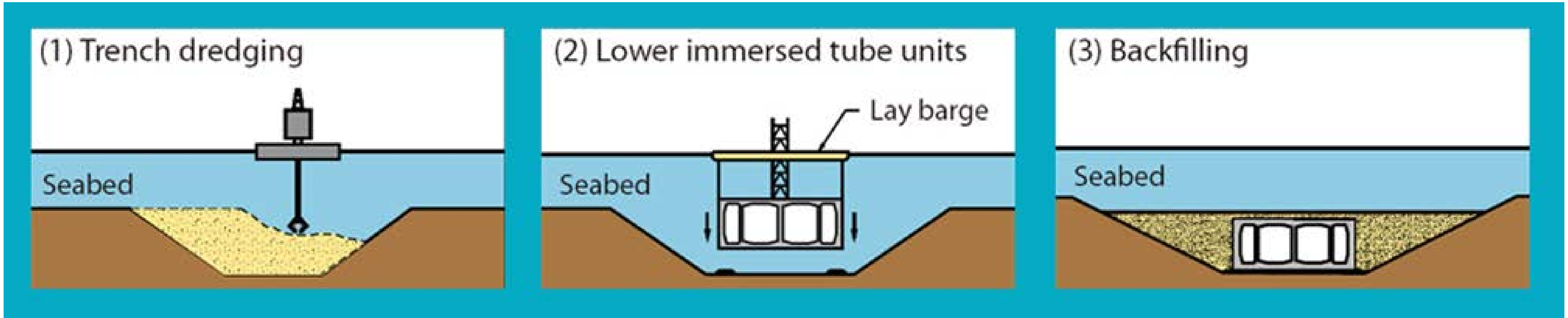
Cut & Cover Tunnels

- Tunnel structure is excavated between pre- constructed walls and finished with a roof which is covered with backfill material.
- 2 Methods:
  - bottom- up in an open cut
  - top- down with a roof being constructed and excavation taking place underneath.

Immersed tubes

- Used for tunnel crossings of rivers or sea channels
- Are assembled from pre-fabricated segments which are floated to the intended location, sunk into place, interlinked and sealed.
- Steel or concrete segments are typically used.



TUNNEL SUPPORT

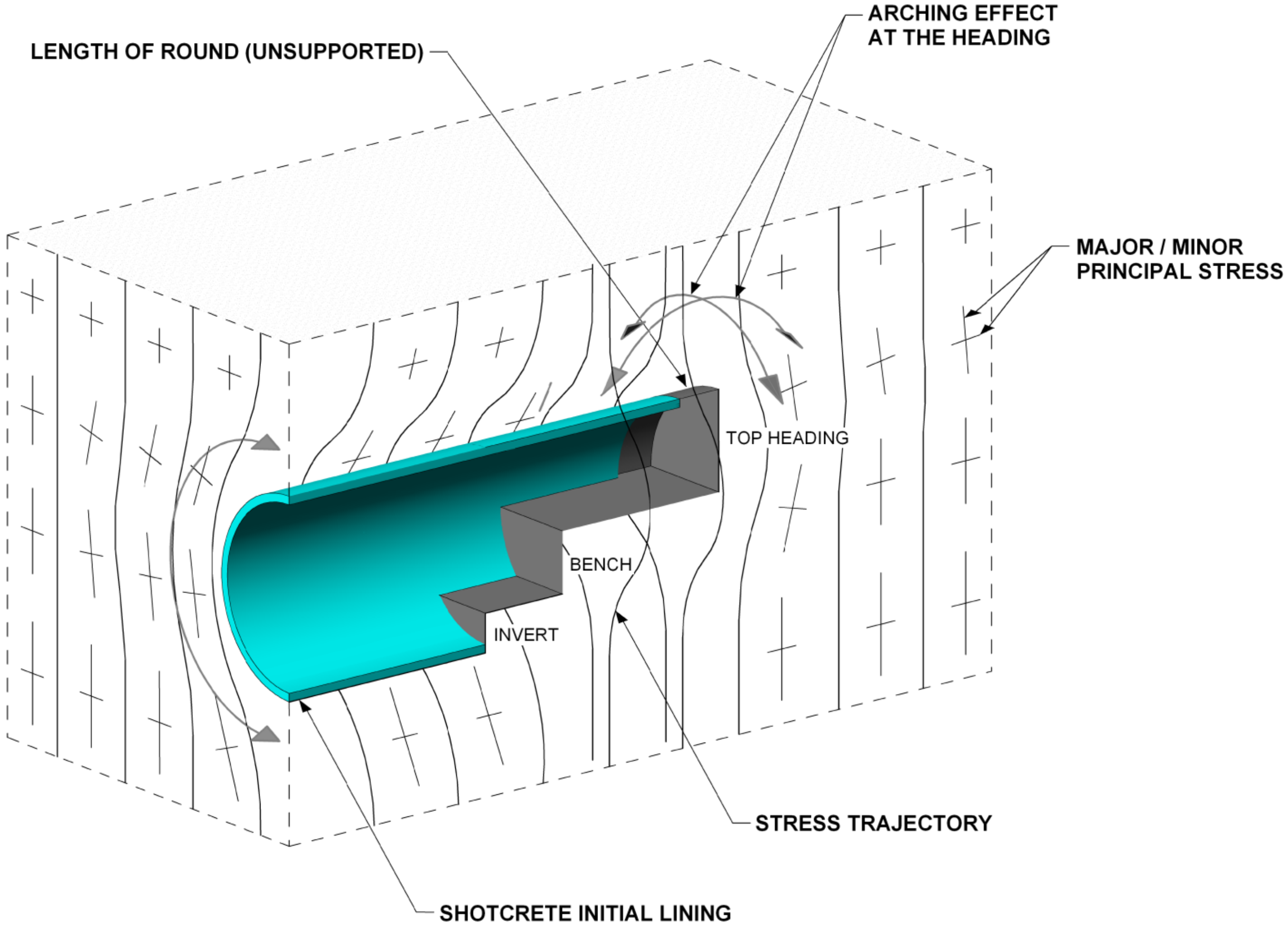
Several support classes are designed and are implemented depending on:

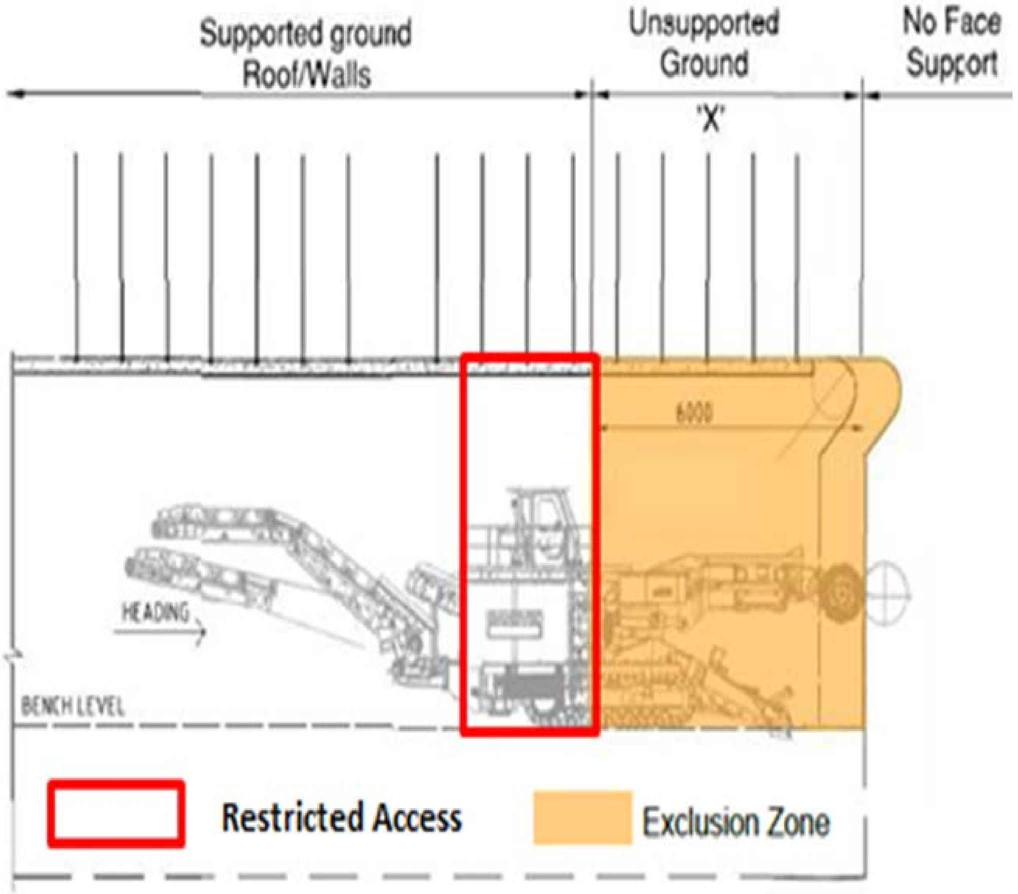
- Tunnel profile
- Cross sectional area
- Tunnel depth
- Expected ground conditions
- Surface loads for any section of the tunnel
- Other conditions

In conventional tunnelling (NATM) three stages of support can be differentiated:

- Temporary Ground Support
- Primary Lining
- Secondary Lining

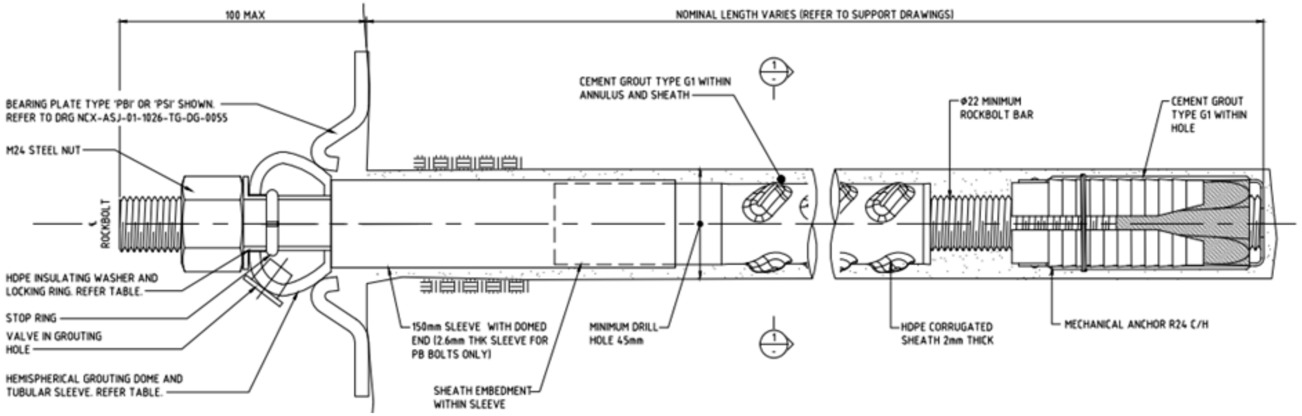
Excavation Sequence





Active and Passive support systems

- **Active support systems**
  Elements are activated as soon as installed and often impose a predetermined load onto the substrate at the time of installation.
  Examples are tensioned rock bolts, pre-stressed anchors or cable bolts.
- **Passive support systems**
  Support elements are reactive, they take over load as the rock mass deforms. Examples are non-tensioned rock dowels, lattice girders and reinforcement.



- ***Shotcrete***
  Shotcrete is used as primary support measure in conjunction with rock bolts as the tunnel is advanced, but has found recently in reasonably good ground conditions more application as final lining structure as well.
- ***Rock reinforcement***
  Different types of rock reinforcement are used in tunnel construction.
  Rock-bolts, dowels, cable-bolts and rock anchors are the most common ones.

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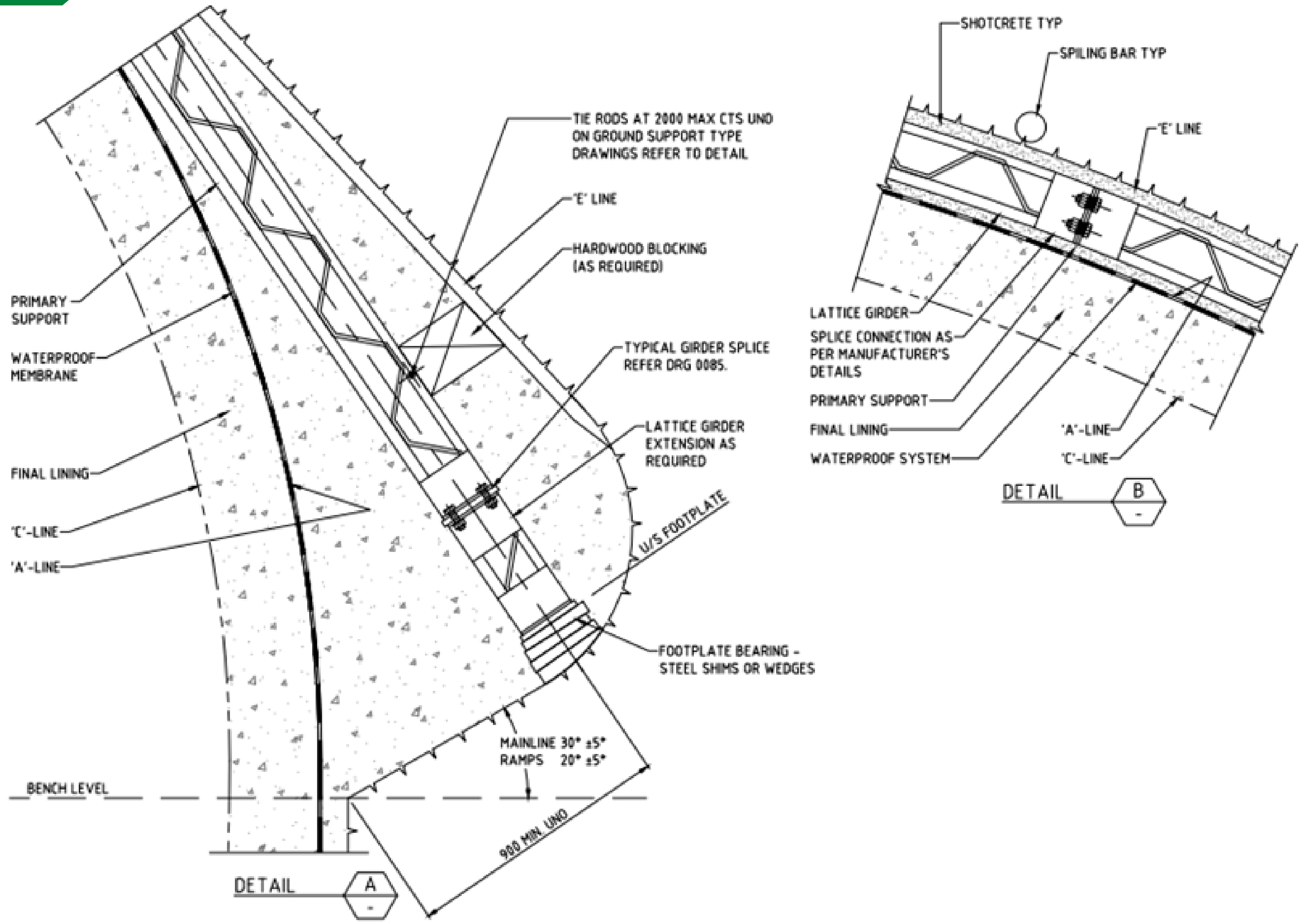
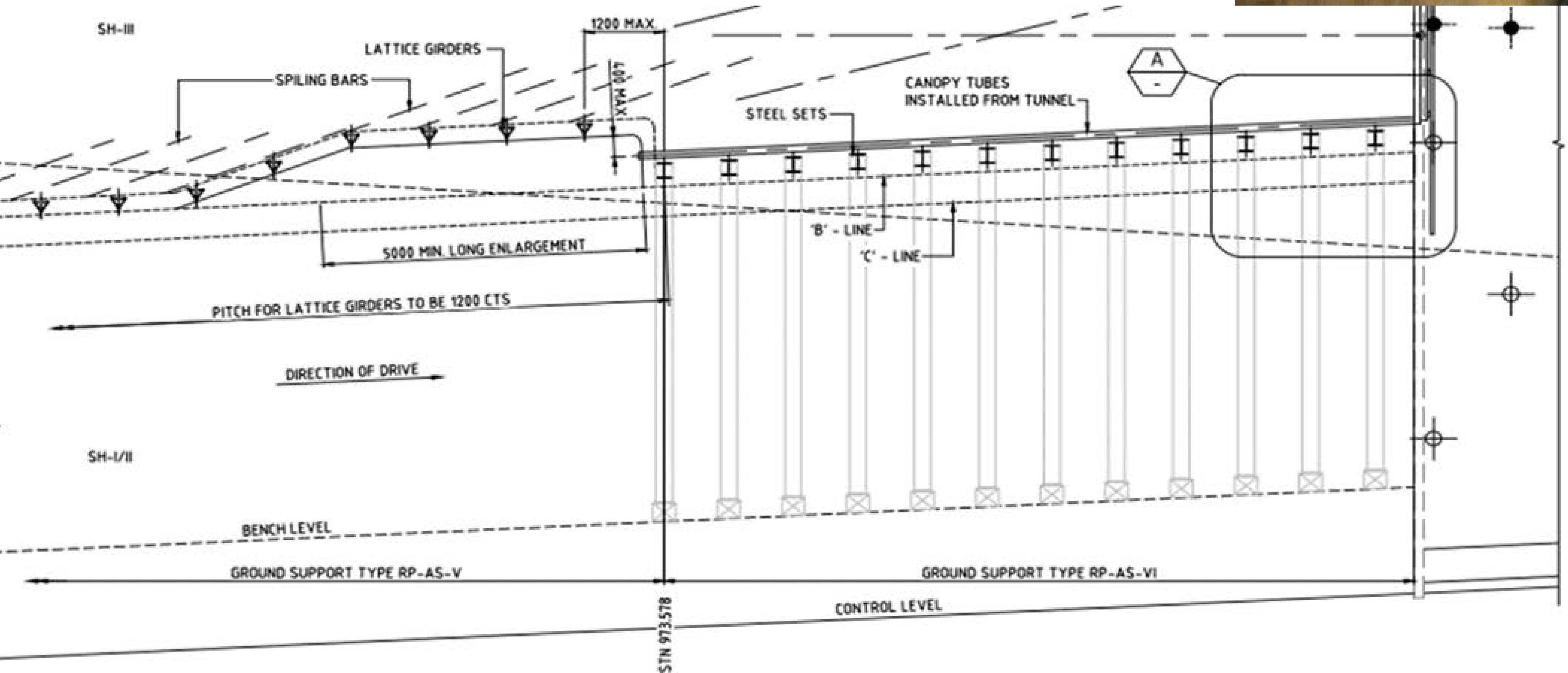
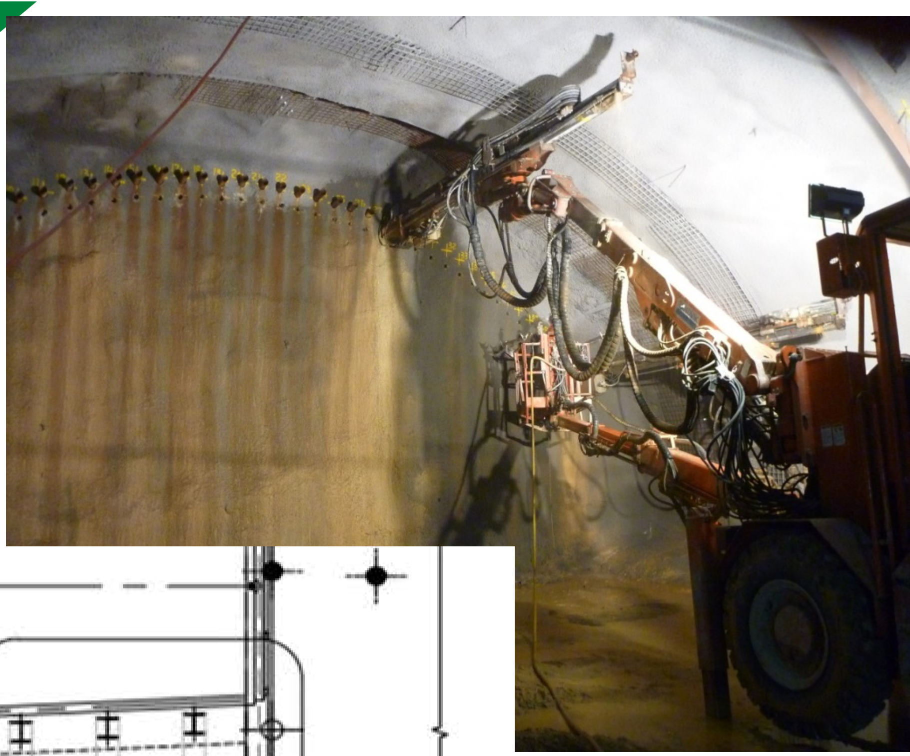
- ***Lattice girders / Steel sets***
  Lattice girders or heavier steel sets are a passive support system used in areas of weak rock, fault zones or low cover sections.
- ***Spiling bars***
  The installation of spiling bars, often referred to as forepoling, is used where the ground is so fractured or weak that rock bolts do not provide the necessary support.



Canopy Tubes

- Where spiling bars are not strong enough to provide the support required, tubes are drilled into the ground along the tunnel perimeter to act as a canopy above the tunnel.
- System is sometimes also referred to as “pipe umbrella”.
- Installation with adequate drilling equipment or self-drilling tubes
- The tubes are installed in sections with screw connections.
- Tubes are filled with grout and the annulus is also grouted.
- If several rounds of tubes are installed, they overlap with the previous umbrella. Their underside is exposed during excavation and lattice girders or steel sets are typically placed to support the tube canopy.

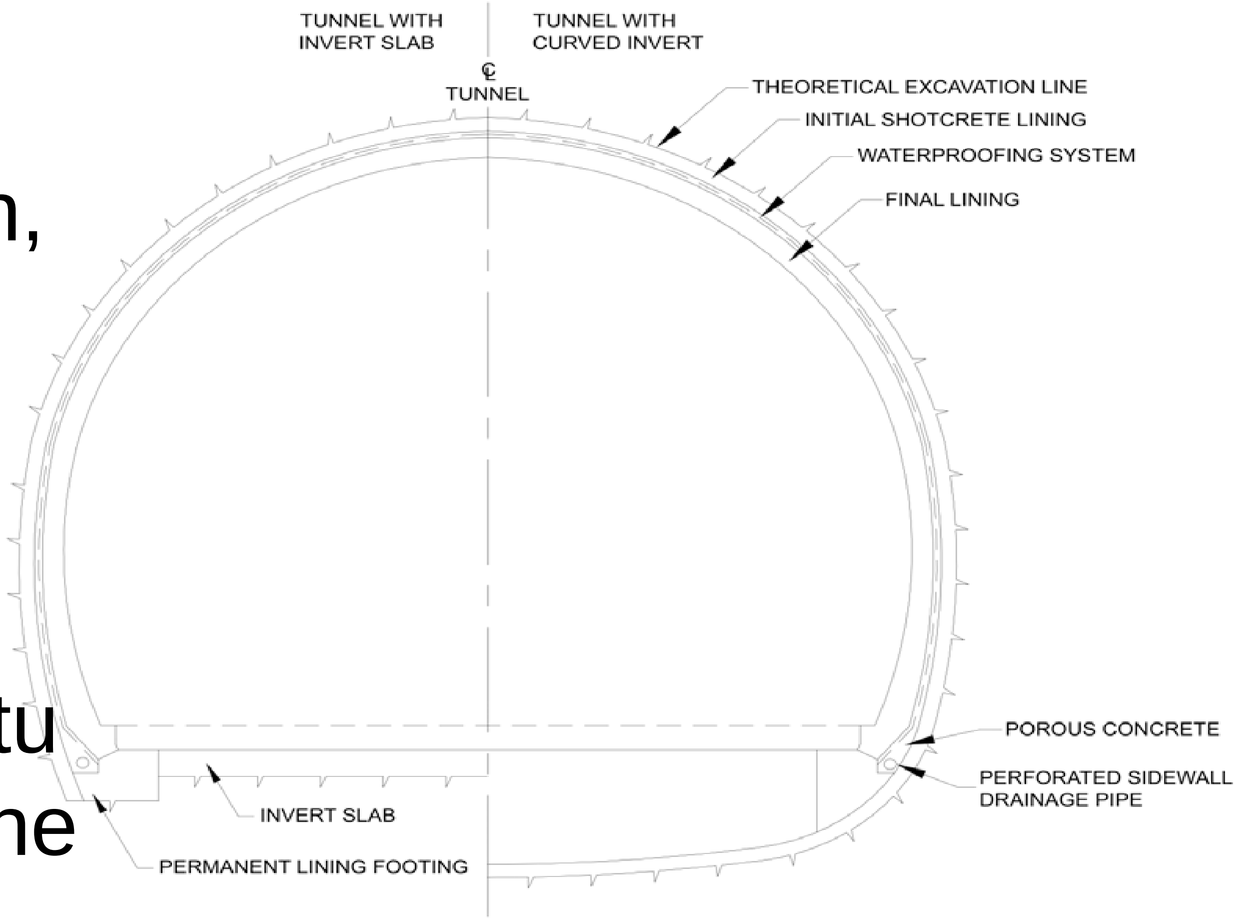

SH-III
1200 MAX
LATTICE GIRDERS
SPILING BARS
400 MAX
CANOPY TUBES
INSTALLED FROM TUNNEL
A
-
STEEL SETS
'B' - LINE
'C' - LINE
5000 MIN. LONG ENLARGEMENT
PITCH FOR LATTICE GIRDERS TO BE 1200 CTS
DIRECTION OF DRIVE
SH-I/II
BENCH LEVEL
GROUND SUPPORT TYPE RP-AS-V
GROUND SUPPORT TYPE RP-AS-VI
CONTROL LEVEL
STN 973.578



Tunnel Linings

After the primary lining installation, waterproofing and final lining applications follow.

Waterproofing is usually either a sheet membrane with a cast in-situ final lining or a spray-on membrane with a shotcrete lining.



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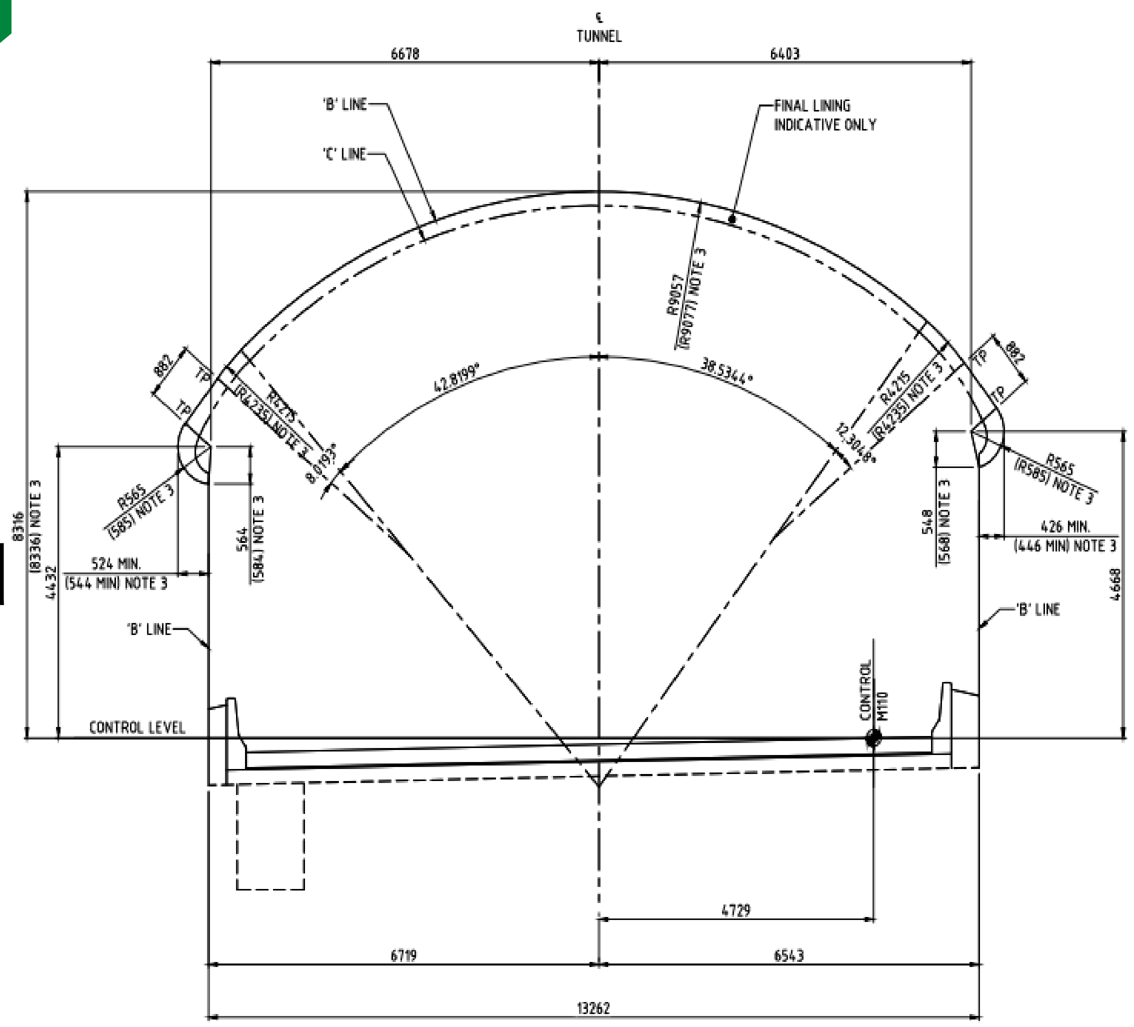
Cast in-situ lining construction sequence

- Sheet membranes are manually placed, pinned and welded from a specifically designed, movable working scaffold
- Casting of a kicker which serves as the foundation for the arched lining
- Installation of the lining reinforcement if required.
- Lining formwork is moved into place and the lining cast.

Shotcrete lining construction sequence

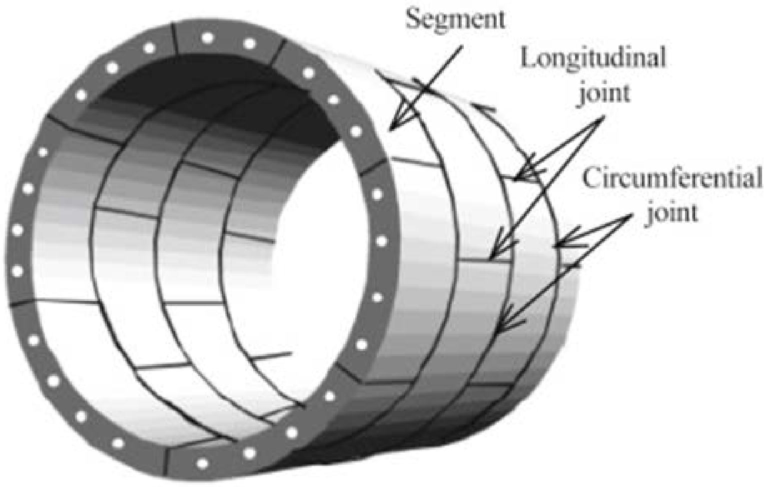
- Smoothing shotcrete layer is placed on top of the primary lining
- Waterproofing membrane applied in two to three thin layers
- Application of final shotcrete lining after the waterproofing membrane has dried
- In less stable ground conditions the lining is design as a full arch
- Where the arch action is only required in the tunnel crown, a so called “hitch”- profile is often used for a shotcrete lining.

- The hitch geometry needs to be designed carefully
- Needs to provide the necessary contact area between the lining and the ground for safe load transfer
- Needs to take the radii and tolerances the utilised cutting equipment can achieve into consideration
- Strict geometric control during the shotcrete application is required.



TBM Driven Tunnel Support

- Support installed using open body hard rock machines is similar to the support mentioned for RH driven tunnels
- Lining used in shielded machines are typically rings consisting of precast segments. These linings have multiple purposes for instance:
  - Absorbing the forces to press the TBM forward
  - Securing the tunnel space against rock falls
  - Taking multiple forces as self-weight, ground loads, groundwater loads, grouting pressure, loads from in-tunnel equipment
  - Sealing the tunnel against groundwater ingress
  - Mounting surface for tunnel equipment (fans, lighting, etc.)



IMPORTANT CONSIDERATIONS OF TUNNEL CONSTRUCTION

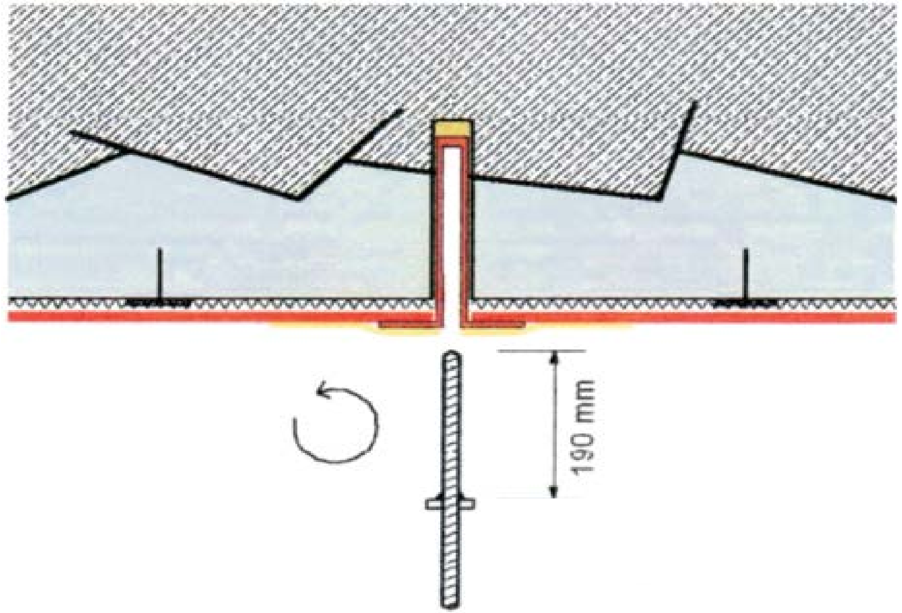
- Ground investigations to understand the project requirements.
- Surface conditions
- Site locations in relation to the alignment are critical. The launch and retrieval of TBMs need to be considered.
- Accessibility to the tunnel for spoil removal; shotcrete and material deliveries during excavation and to allow for multiple fit out activities
- Temporary intermediate access points in form of shafts or declines are often established to meet all requirements.
- Machine and equipment selection is crucial and needs to take place at a very early stage so that the details can be considered in the design approach

Waterproofing

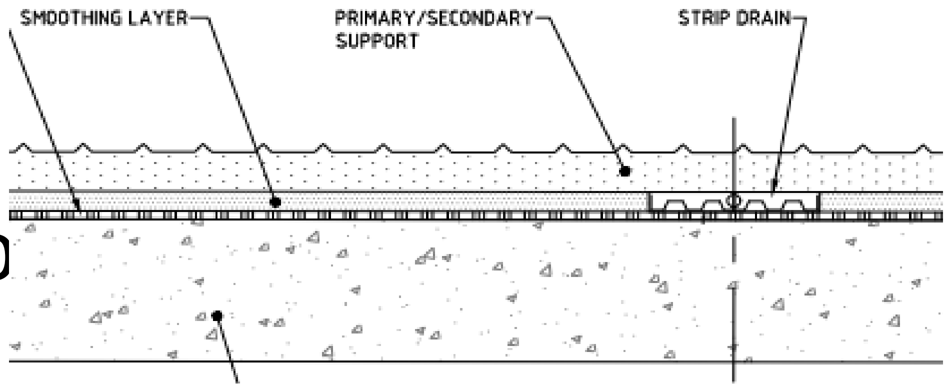
- Drained and tanked tunnels are differentiated.

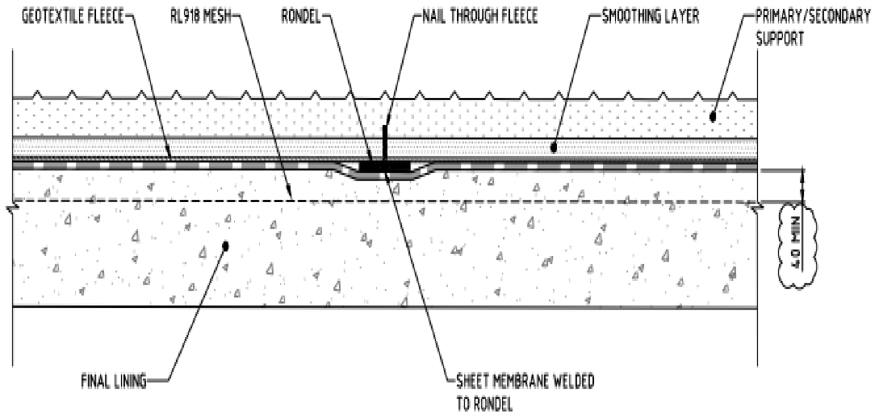
Drained tunnels:

- Waterproofing is applied to the lining
- Water is channelled by the means of strip drains or dimple sheets into the tunnel drainage system.
- Cast in-situ final lining: PVC or VLDPE membrane with geotextile underlay, using pins whose heads can be welded onto the membrane.
- Closed BA-anchors, also welded to the membrane, are used where anchorage is required which would otherwise penetrate the membrane.



- As shotcrete does not stick to this type o membrane, a spray-on membrane product is used where a shotcrete lining in used as final lining.
- The spray-on membrane is applied usually in two passes to a thin layer of smoothing shotcrete, which does not contain any fibre, to avoid damage to the membrane.
- Spray-on membranes are to a certain degree elastic and can bridge cracks

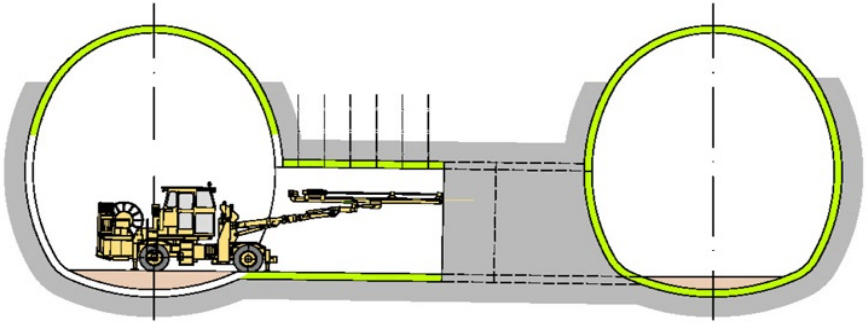




SHEET MEMBRANE FIXING DETAIL

- The disadvantage of a drained tunnels:
  - Tunnel drainage system including the sump needs to allow for the total water volume.
  - Leads to a permanent drawdown of the groundwater table surrounding the tunnel.
- Construction of a tanked tunnel requires sealing the entire tunnel by installing a complete waterproofing system.
- TBM tunnels which are segmentally lined are tanked via compressive gaskets placed in the segment joints around the segments.

Cross passages



- The cross passage opening weakens the main tunnel structure in the junction area and increased support in the intersection and around the cross passage opening is required.
- Care needs to be taken that equipment and plant sizes and the geometry of the structure are coordinated and the construction sequence planned in detail.

Cross passages in soft ground for TBM driven tunnels provide a particular challenge:

- Cross passages need to be excavated with conventional plant and ground stabilisation and the prevention of water inflow needs to be achieved by other means.
- Ground stabilisation using grouting or ground freezing are methods which are often utilised.
- To open a TBM tunnel for cross passage excavation, lining segments need to be removed.

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Ventilation

- Tunnel need to be ventilated and dust to be extracted to provide fresh air and protect the crews in the tunnel from excessive dust inhalation, fumes, oxygen depletion and excessive heat.
- The ventilation system needs to be designed to suit all stages of the tunnel construction

Backend Works and Fit out

- Sequencing and coordination of a multitude of tasks crucial
- The installation of pavement or track- laying, mechanical and electrical installations need to be considered in the planning and construction programme.

Spoil removal and treatment

- Spoil management is a crucial component of any tunnel construction.
- A spoil management plan required prior to any excavation.
- To find spoil disposal sites is always a challenge.

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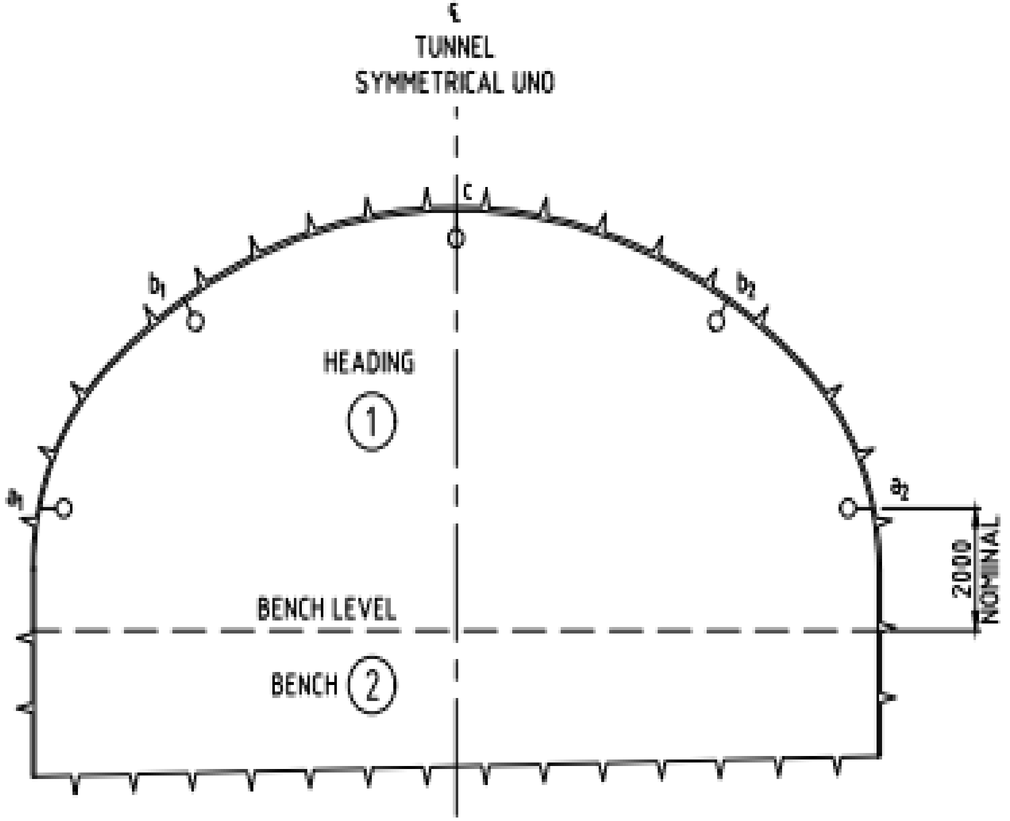
Instrumentation and Monitoring

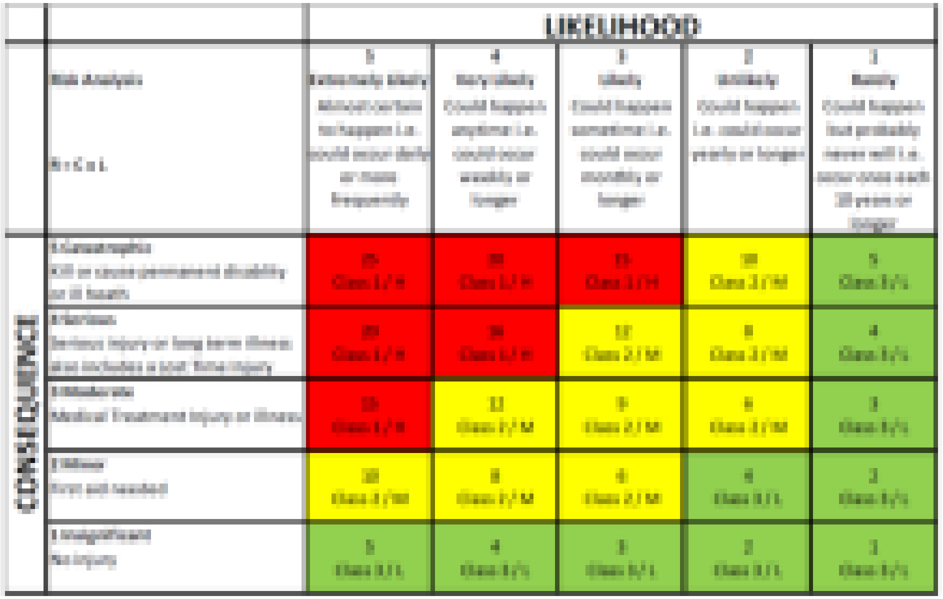
- Monitoring Plan outlining the installation and monitoring of movement within the tunnel and on the surface
- Groundwater monitoring is carried ou to observe changes in groundwater levels as well as the water quality.



Permit to Tunnel (PTT)- Process

- Permit to Tunnel process has been developed on Australian Tunnelling Projects over approximately the last 15 years.
- A PTT is required for each excavation location (heading, bench) and is typically valid up to a certain chainage or for 24 hours.
- The PTT is an instruction outlining all requirements during the timeframe of its validity.

Safety in Design (SiD)



- The risk assessment and mitigation approach starts with the design.
- All identified risks are evaluated for likelihood and consequence prior to and after introduction of the mitigation measure in accordance with a risk matrix.
- Risk for which design considerations alone are not sufficient level become handed over to the construction team.

Fire Safety

- Fire safety is an important consideration not only for an operating tunnel but also during construction.
- Emergency evacuation and egress schemes need to be in place for all stages of construction.
- Tag- in and –out procedures, often automated by the use of sensors, track and record tunnel entry and egress of personnel.

THANK YOU !

ANY QUESTIONS ?