



TBMs FOR MIXED GROUND

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Ground Conditions

▶ **Soft Ground**

- ▶ Cobbles and boulders (soft ground and rock cutting tools)
 - ▶ Stable or unstable face (positive face support)
 - ▶ Waterbearing ground below water table (face support pressure)
 - ▶ Coarse or fine grained ground (TBM type EPB, Slurry or VD)

▶ **Hard Rock**

- ▶ Fault zones, fractured rock
 - ▶ Stable or unstable face and tunnel wall, overbreaks (Gripper or shielded TBM, ground improvement)
 - ▶ Waterbearing rock below watertable (pre-excavation grouting, freezing, closeable or Multi-Mode TBM)

Mixed Ground Conditions

No common understanding in the TBM industry about mixed ground

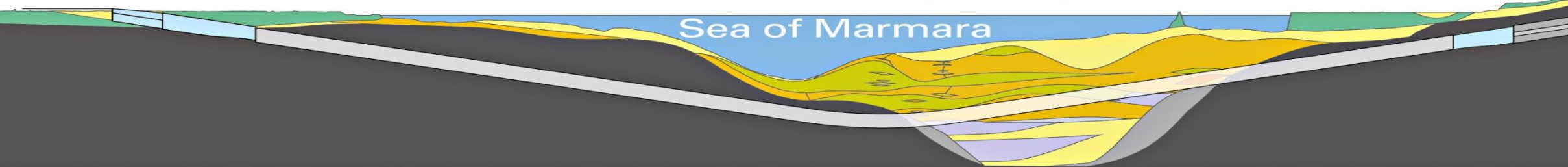
Variant 1, based on required cutter head tool dress

- TBM cutter head needs dual tool dress options of soft ground tools (scrapers) and rock cutting tools (disc cutters)
- ▶ Soft ground containing cobbles and boulders of a size too large for the downstream mucking system (cutting at the face required)

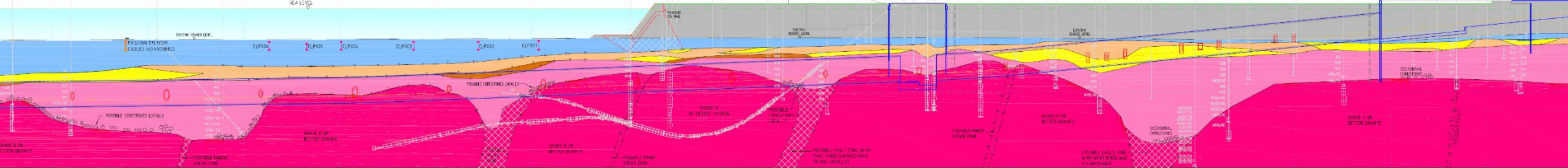
Variant 2, based on variable face ground conditions along the alignment

- TBM cutter head needs dual tool dress options of soft ground tools (scrapers) and rock cutting tools (disc cutters)
- ▶ Full face rock, full face softground and / or rock - softground transitions along the alignment
- ▶ Potential to change between closed mode and open mode operation along the tunnel alignment (Multi Mode TBMs)

Mixed Ground Conditions

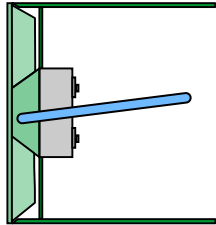


Istanbul Strait Crossing → Full face rock, full face softground and rock - softground transitions along the alignment



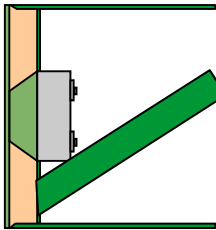
TMCLK Hongkong → Rock - softground transitions along the alignment

Existing Types of Shielded TBMs



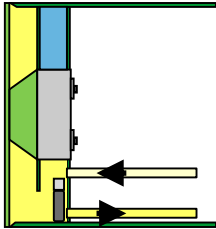
Open Shield TBM (Single or Double Shield)

Predominately stable face conditions, non pressurized excavation chamber, dry primary mucking system



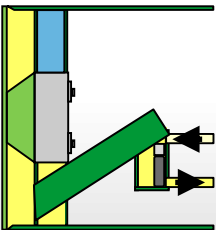
EPB TBM

Unstable face conditions, pressurized excavation chamber, fine grained material, screw conveyor as primary mucking system



Slurry TBM (Mixshield)

Unstable face conditions, pressurized excavation chamber, coarse grained material, slurry circuit as primary mucking system

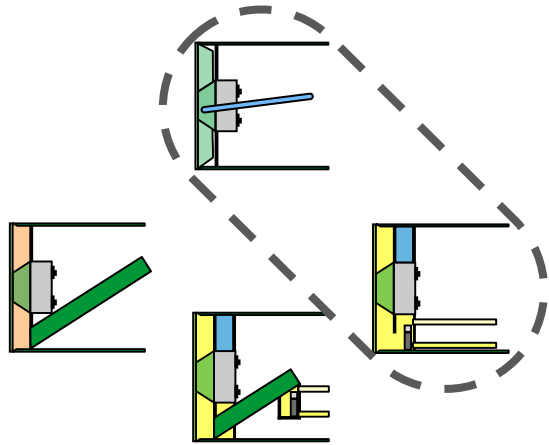


Variable Density TBM

Unstable face conditions, pressurized excavation chamber, fine to coarse grained material, screw conveyor and slurry circuit as primary mucking system

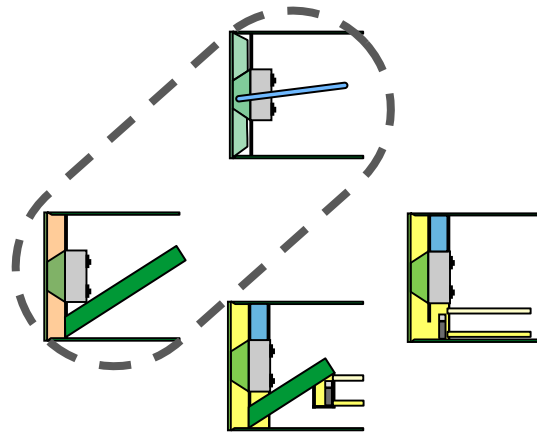
Convertible Machines, Multi-Mode Options

Open Shield ↔ Slurry



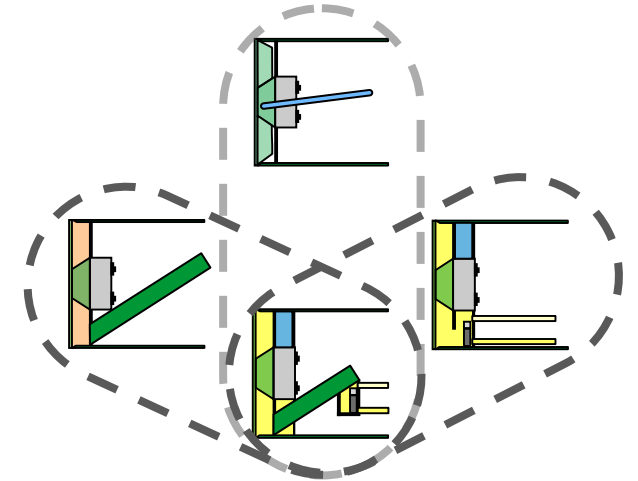
- ▶ State of the Art Technology
- ▶ First Application for Grauholz Tunnel in 1989
- ▶ Retractable muckring
- ▶ Two tunnel mucking systems (wet – dry)

Open Shield ↔ EPB



- ▶ State of the Art Technology
- ▶ First Application for Glattstollen in 1991
- ▶ EPB open mode or retractable muckring

Slurry ↔ EPB



- ▶ Variable Density TBM
- ▶ First Application for Klang Valley KL in 2012
- ▶ Seamless transition from EPB to HD-slurry to LD-slurry

Saverne TGV Rail Tunnel

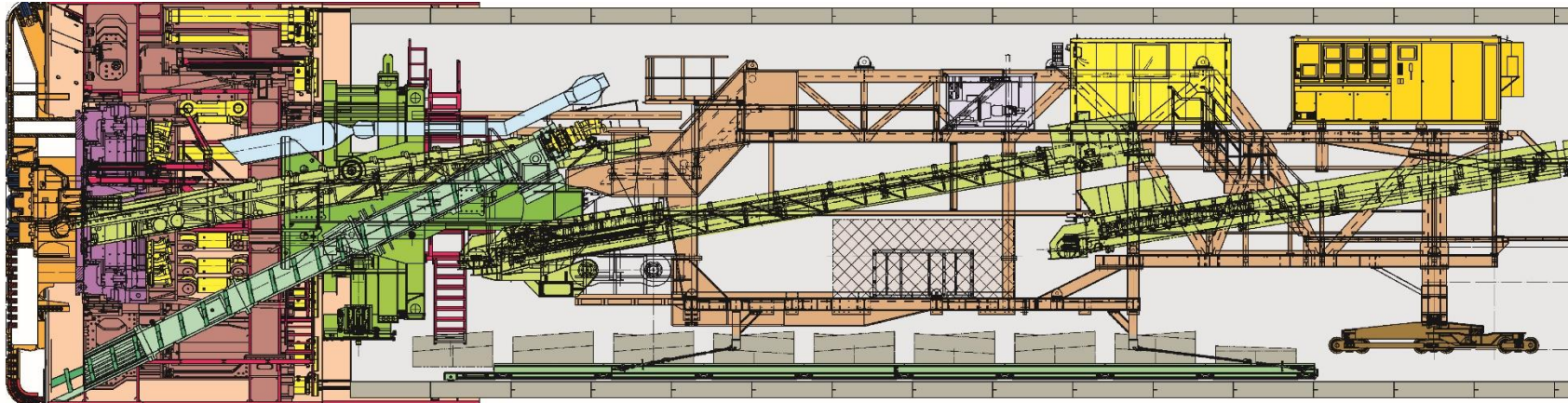
Saverne, France



- ▶ Multi Mode TBM (EPB – open mode) Ø 10,01 m
- ▶ Tunnel length 2 x 4 km
- ▶ Water pressure max. 3 bar in soft ground section

Saverne - Change Between Open Single Shield and EPB

Center Belt Conveyor And Screw Conveyor As Primary Mucking System



Closed Mode - Earth Pressure Balance

- Screw conveyor in forward position for full capacity
- Center belt and muck hopper retracted, rotary installed
- Cutterhead muck transport channels partially removed

Open Mode

- Screw conveyor in retracted position (limited capacity)
- Center belt and muck hopper in forward position, rotary removed
- Cutterhead muck transport channels installed

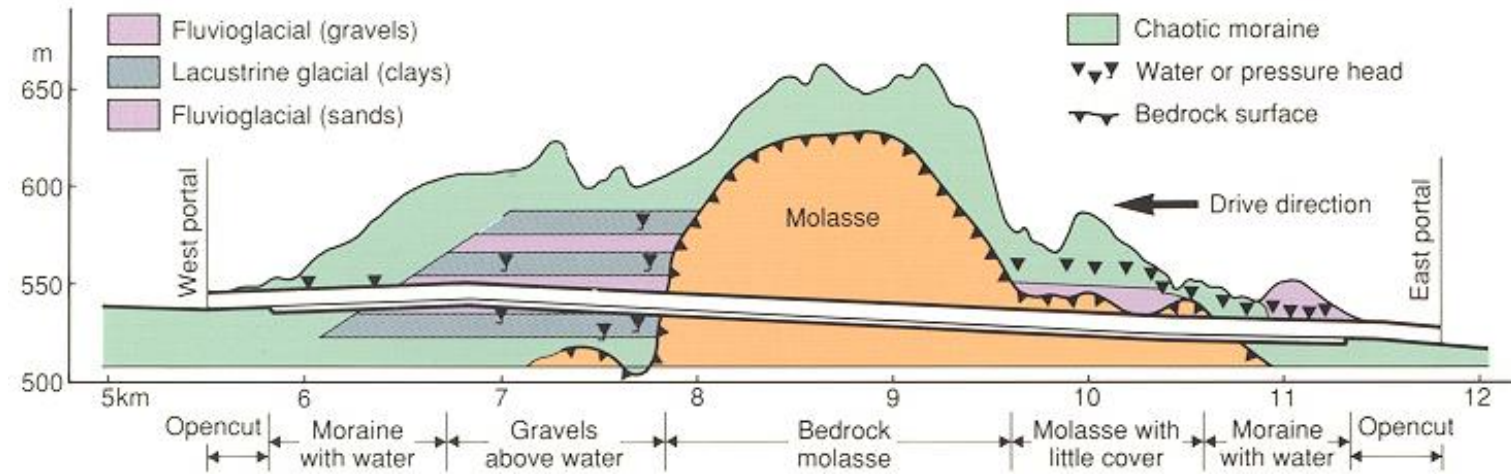
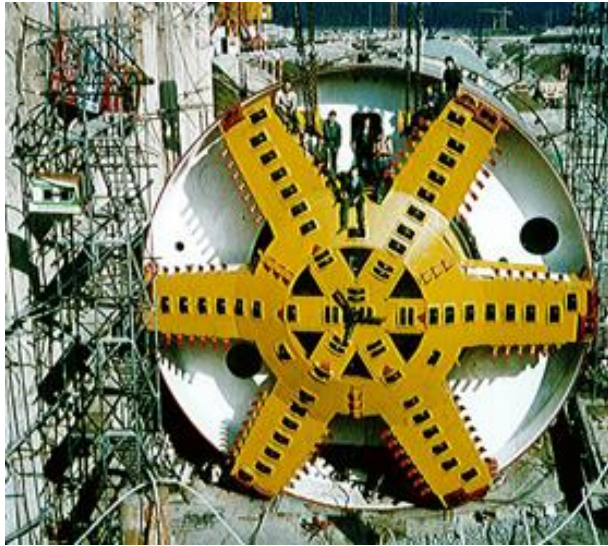
Saverne - Change Between Open Single Shield and EPB



- ▶ Screw conveyor and center belt / muck hopper for primary mucking system
- ▶ Approx. four days required for open – closed mode change
- ▶ Two short closed mode sections along the alignment (approx. 5%)
- ▶ Very high rock/soil abrasivity

Grauholz Tunnel 1989

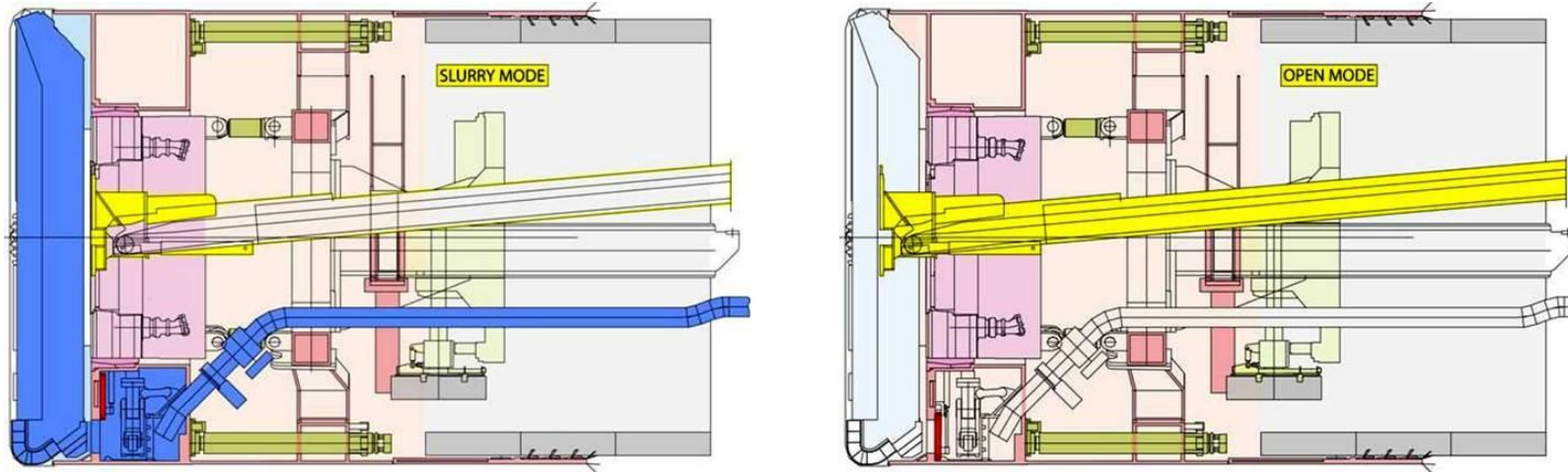
Bern, Switzerland



- ▶ Multi Mode TBM (slurry – open mode) Ø 11,6 m
- ▶ Tunnel length 5,6 km
- ▶ Water pressure max. 4 bar

Change Between Open Single Shield and Slurry

Center Belt Conveyor And Slurry Circuit As Primary Mucking System



Closed Mode – Slurry machine

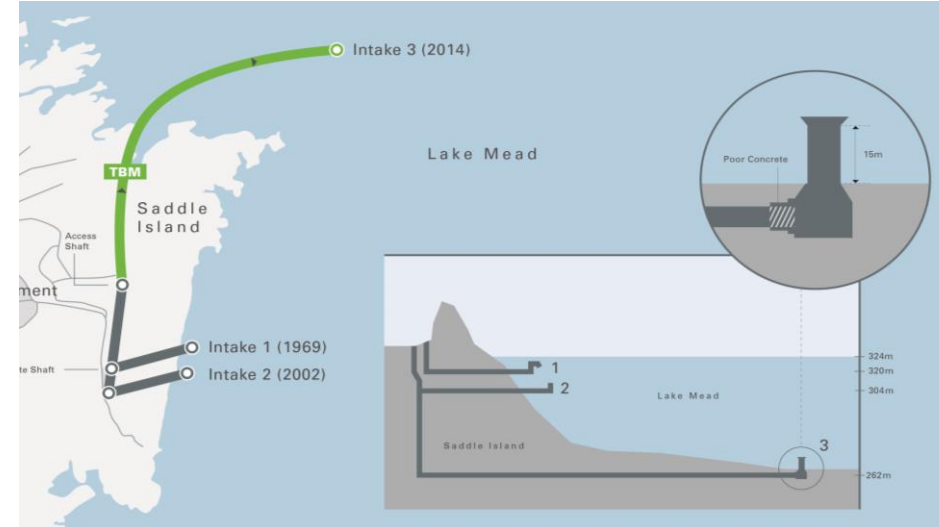
- Submerged wall gate open
- Center belt and muck hopper retracted and sealed
- Slurry circuit and treatment plant in operation

Open Mode

- Submerged wall gate closed
- Center belt and muck hopper in forward position
- Closing / Mode change within 2 - 4 hours

Lake Mead Intake #3

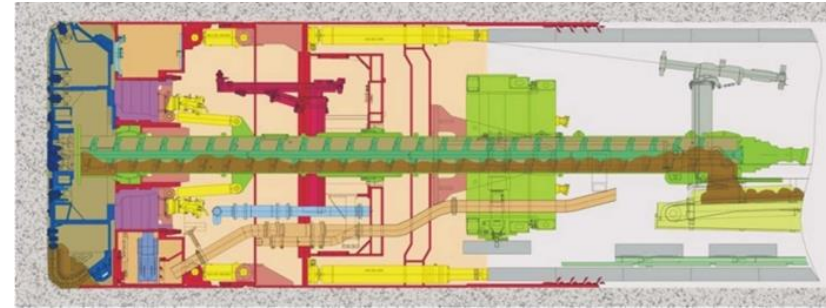
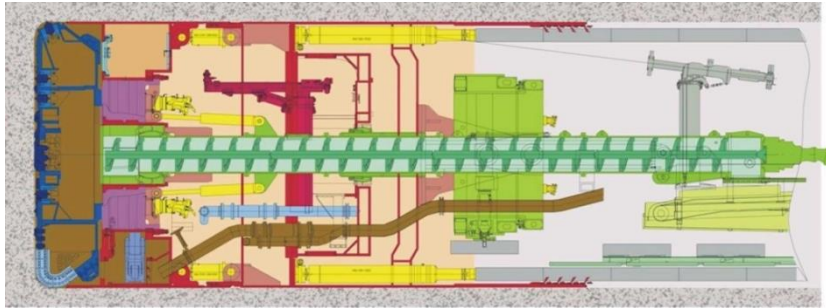
Las Vegas, NV



- ▶ Multi Mode TBM (slurry – open mode) Ø 7,18 m
- ▶ Tunnel length 4,8 km
- ▶ Water pressure max. 15 bar

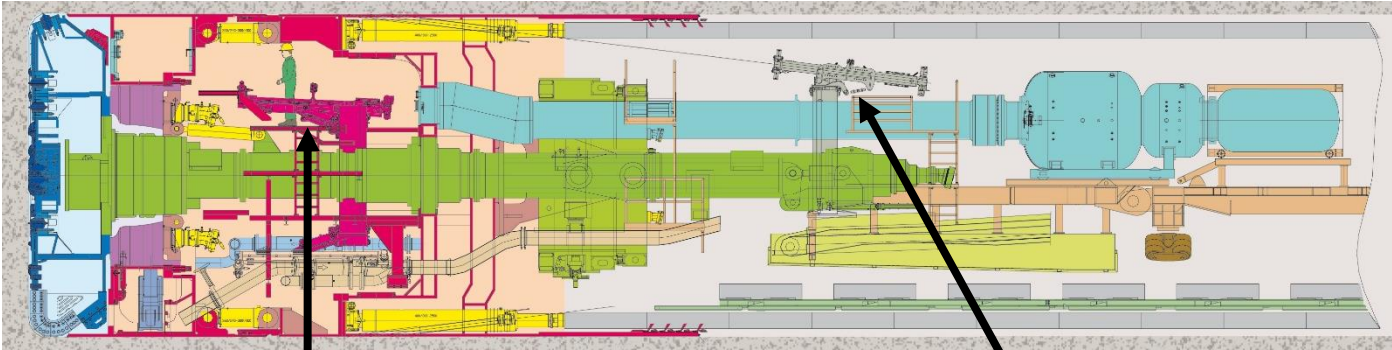
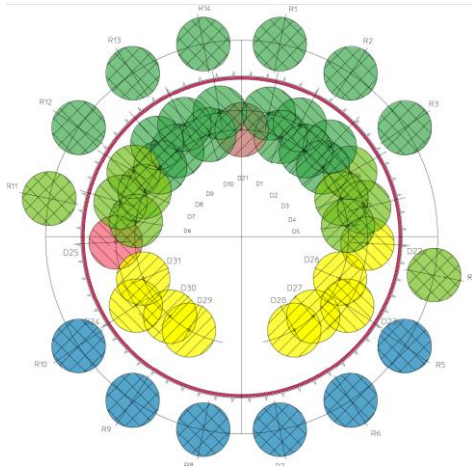
Change Between Open Single Shield and Slurry

Center Screw Conveyor and Slurry Circuit as Primary Mucking System
(Special Version for Lake Mead Intake No. 3 Tunnel)

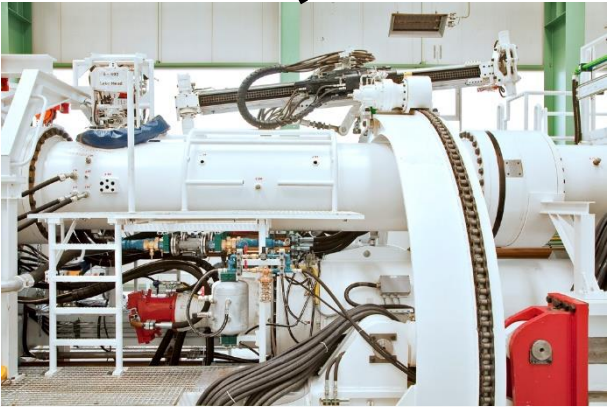


- ▶ Open mode with dry primary muck discharge system (screw conveyor)
- ▶ Open mode with cyclic pre excavation grouting
- ▶ Open mode with cyclic per excavation grouting in closed static conditions
- ▶ Closed mode with hydraulic muck discharge system under reduced face pressure and atmospheric chamber access
- ▶ Closed mode with full face pressure, potential for positive face support and pressurized chamber access

Lake Mead Intake No. 3 – Pre Excavation Grouting Drill Pattern

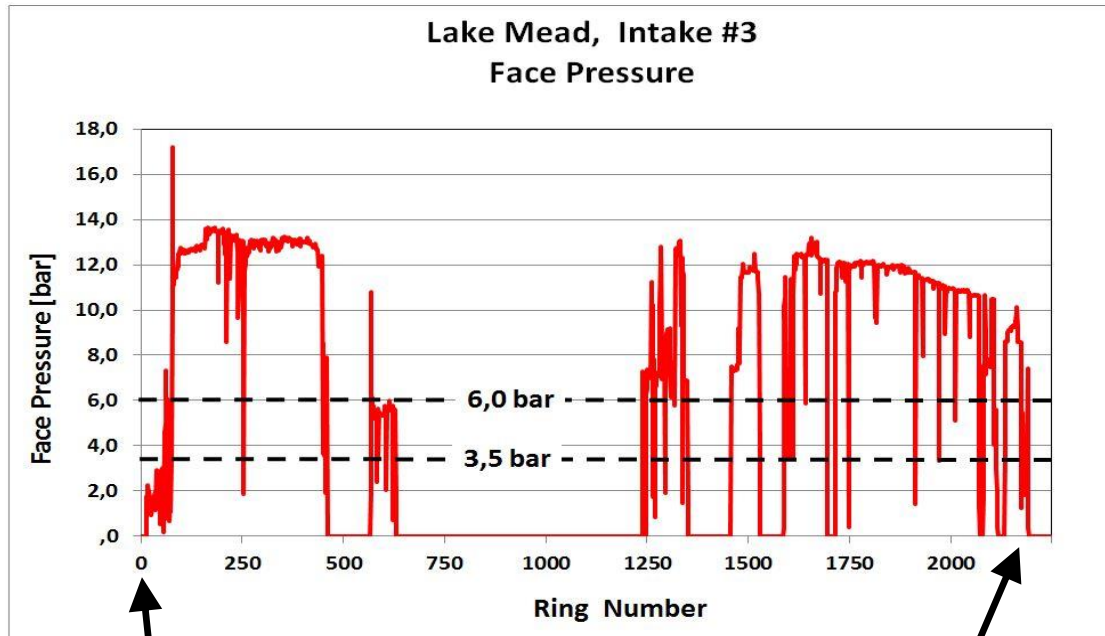


Two permanent installed front drills for face drill pattern



One permanent installed rear drill for periphery drill pattern

Lake Mead Intake No. 3 – Closed Mode vs. Open Mode



Real site experience:

- ▶ Several attempts for pre-excitation grouting with limited success
- ▶ Closed mode at full water pressure of 10 – 13bar as preferred mode of operation along high water inflow sections

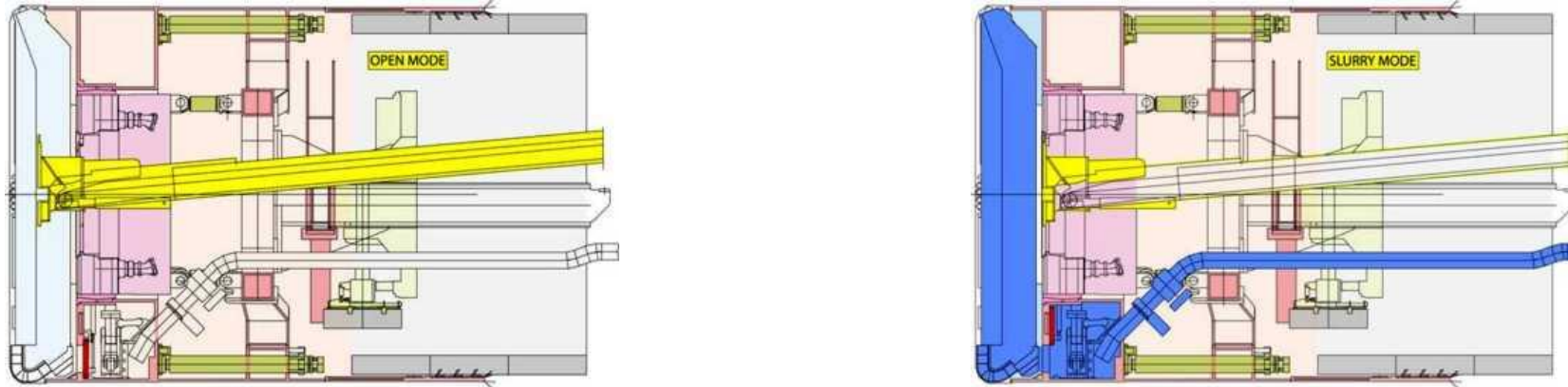
Hallandsås Tunnel

Båstad, Sweden



- ▶ Multi Mode TBM (slurry – open mode) Ø 10,53 m
- ▶ Tunnel length 2 x 5,6 km
- ▶ Water pressure max. 13 bar

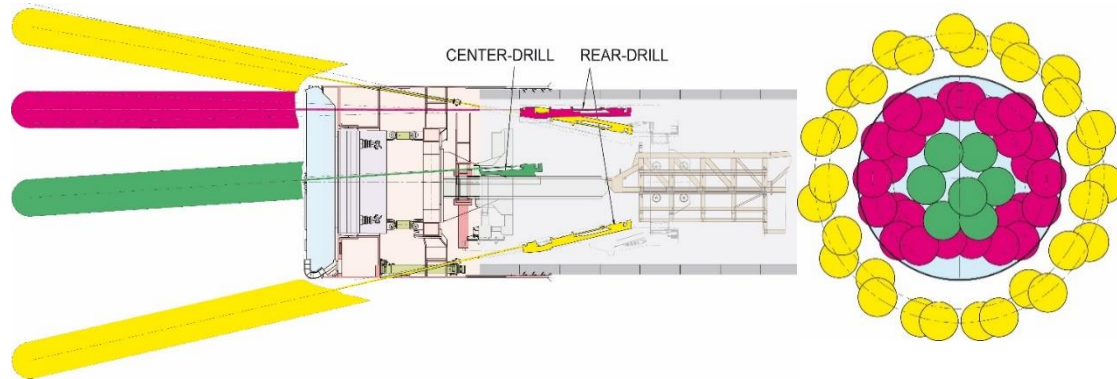
Hallandsås Tunnel – The Multi Mode TBM concept



- ▶ Open mode with dry primary muck discharge system (belt conveyor)
- ▶ Open mode with cyclic pre excavation grouting
- ▶ Open mode with cyclic per excavation grouting in closed static conditions
- ▶ Closed mode with hydraulic muck discharge system under reduced face pressure and atmospheric chamber access
- ▶ Closed mode with full face pressure, potential for positive face support and pressurized chamber access

Hallandsås Tunnel – Probing And Pre-Excavation Grouting

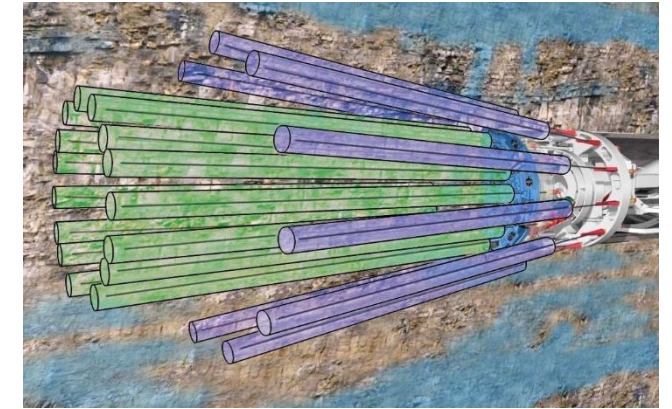
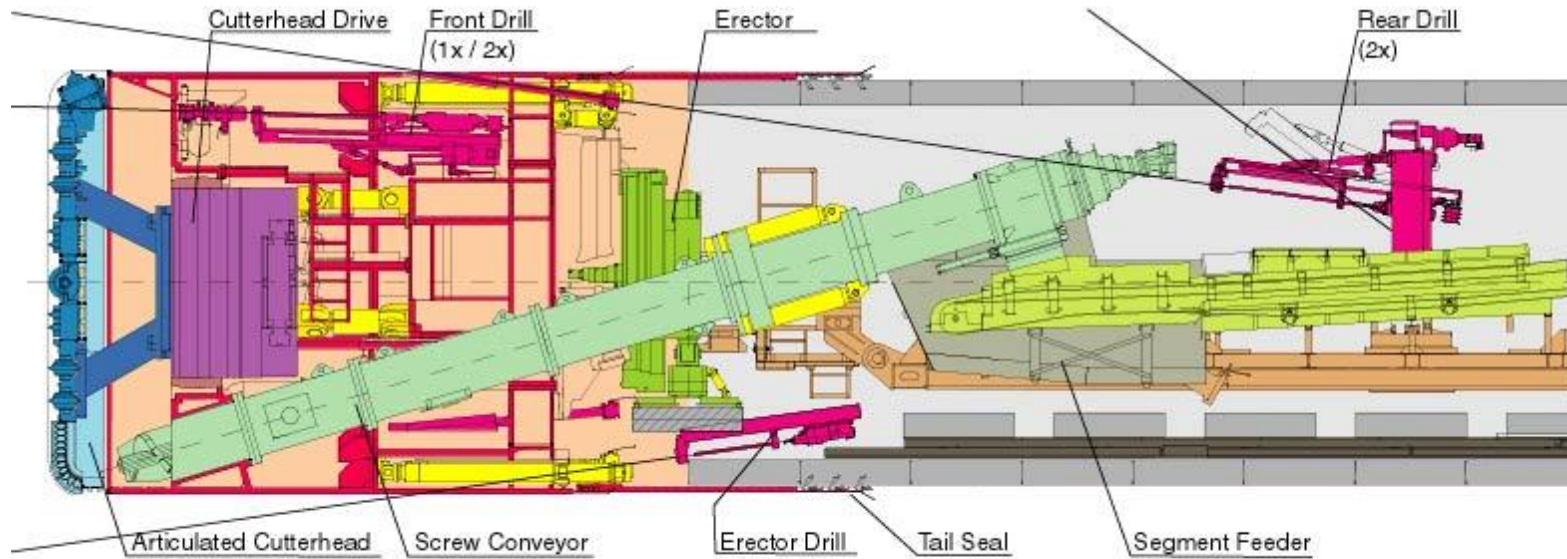
- ▶ Three permanent drills behind shield for periphery and outer face coverage
- ▶ Two temporary drills in shield
- ▶ Temporary mounted drill in center area and erector



Real site experience:

- ▶ Predominately open mode operation with frequent pre-excavation grouting
- ▶ Very limited use of closed mode option due to severe blocky face conditions
- ▶ Closeable TBM concept beneficial in order to provide static water conditions for pre excavation grouting, rear barrier construction and inflow reduction during standstill periods

Arrowhead Tunnels, San Bernardino CA

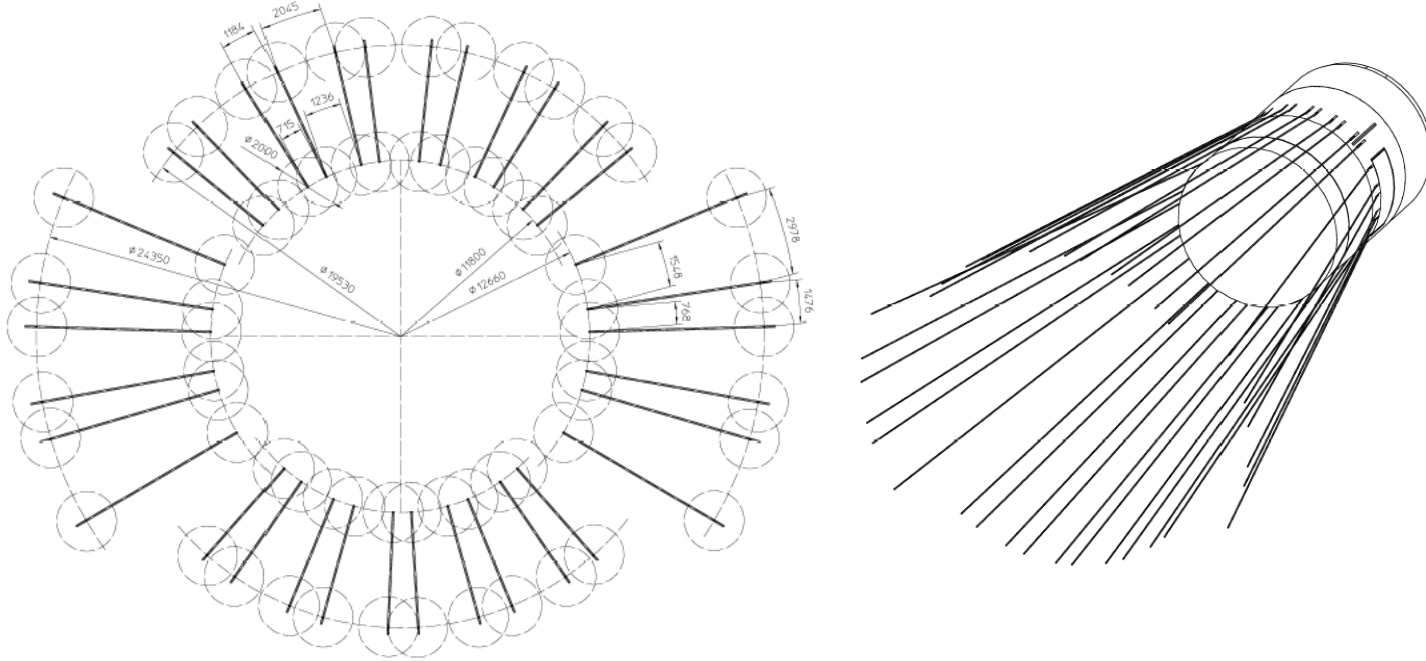


Two in standstill mode closeable single shields, 10 bar static, excavation diameter 5,79m

- ▶ Two permanent drills on ring carrier behind erector
- ▶ Two permanent drills in the shield
- ▶ Option for one temporary drill on the erector

Follo Line Double Shields (Oslo, Norway)

B-B

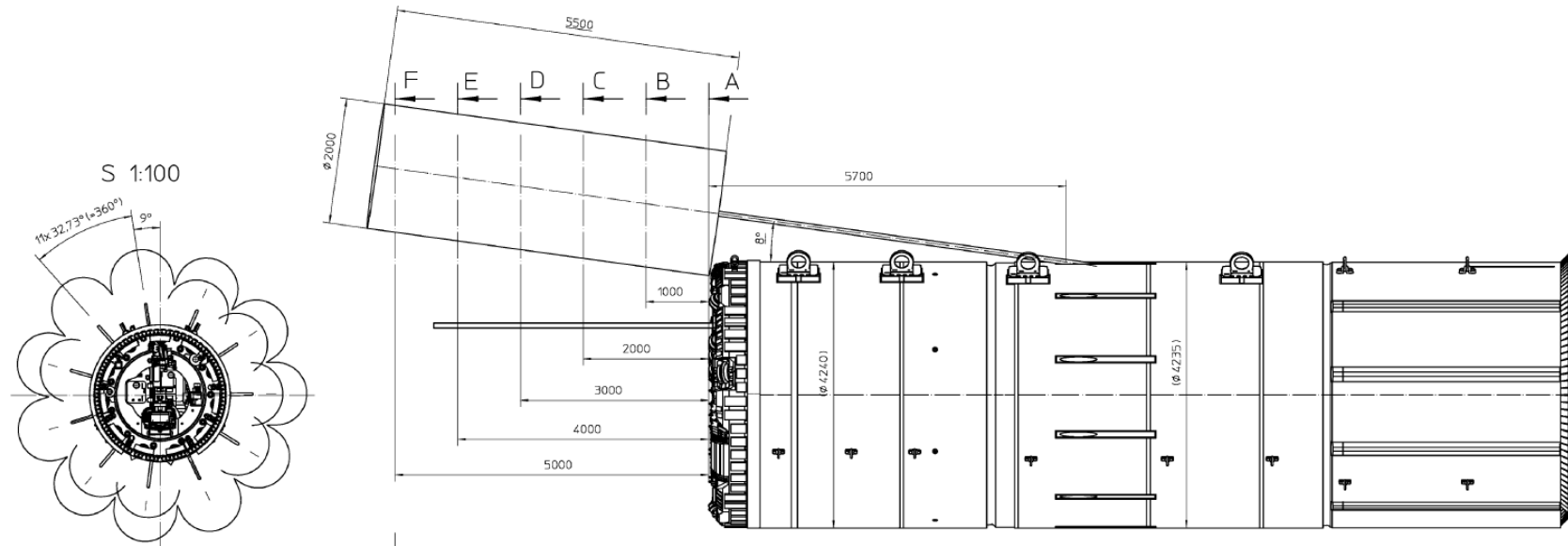


4 Double shields, excavation diameter 9,96m

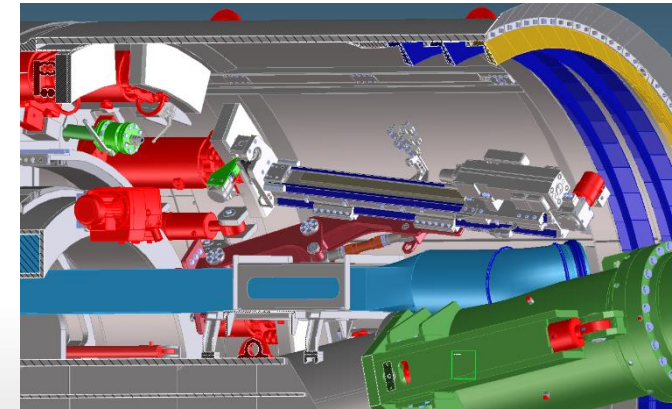
- ▶ 2 permanent drills incl. drill rod magazine on ring carrier behind erector
- ▶ 2 permanent core drills in the shield



Pre-Excavation Grouting for Small Diameter TBM



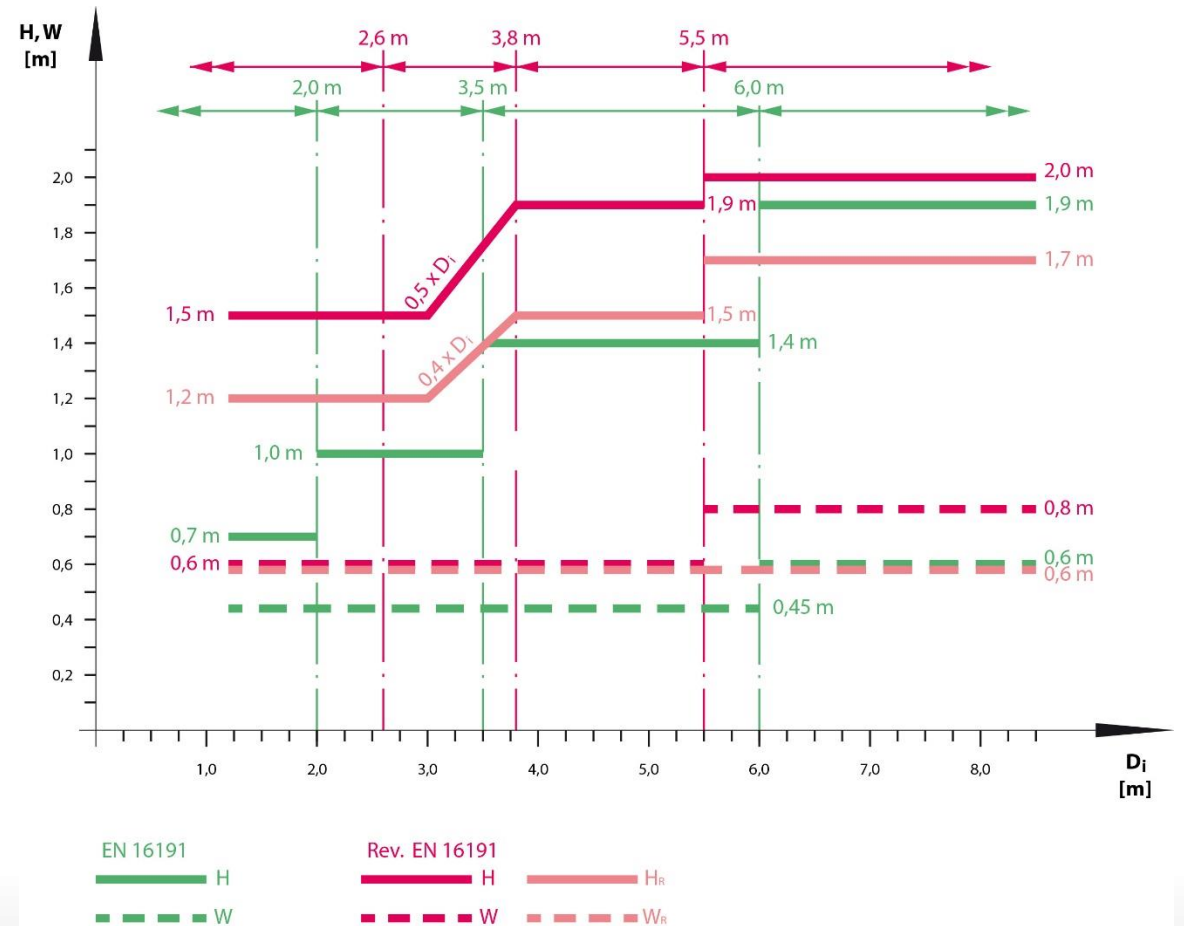
- ▶ 360° periphery drill pattern with approx. 8° lock-out angle feasible for a 4m TBM
- ▶ Drill rig temporary erector mounted for periphery drill pattern
- ▶ Permanent mounted drill in shield for 1 or two face positions feasible



Pre - Excavation Grouting for Medium to Small Diameter TBMs - Future Limitations

Increased Safety requirements

- ▶ More restricted exposure of personnel to moving or rotating parts of drill rigs (ref. EN16228)
- ▶ Increased requirements on ergonomic aspects in EN16191 revision (dimension of walk- and access ways, operators position etc.)



Walk- and access way dimensions existing vs. revised EN 16191 (Draft)

Closed Mode Slurry Operation for Water Pressure Balance in Rock

Istanbul Strait Crossing:

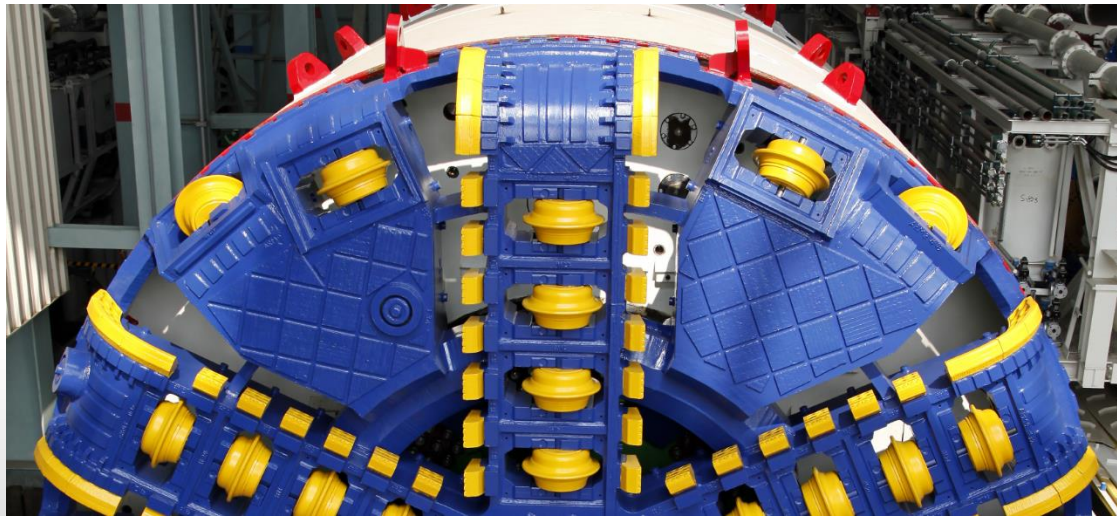


Tunnel alignment

Muck pile at the STP
in full face rock
sections



Tunnelling in Bukit Timah Granite, Singapore:

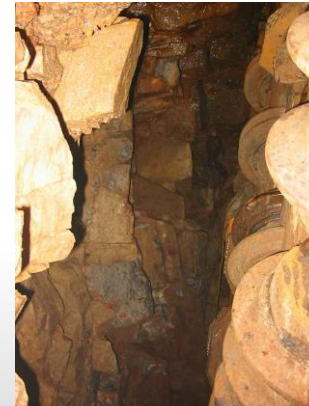


Muck pile at the STP
in full face rock
sections



TBM For Mixed Ground Conditions

- ▶ Four basic shielded TBM types for different ground conditions are available
- ▶ Mixed ground conditions may force into compromises or be addressed with a combination of the different TBM types → Multi Mode TBM
- ▶ Pre-excavation grouting for ground improvement and / or control of water inflow can be a solution or additional “on - board” tool
- ▶ Closed mode excavation with slurry TBM may be an alternate solution for ground water regime in permeable fractured rock below the groundwater table
- ▶ For difficult mixed ground conditions the provision of a variety of different “on-board tools” can be the key to success (Multi-Mode concept, pre-excavation grouting, closeability, different backfill systems, excess water handling systems...)



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