Case Studies in Challenging Geology:

Gerede Water Tunnel & Delaware Aqueduct Repair

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PRESENTATION OUTLINE

CHALLENGING GEOLOGY

- Robbins Case Studies
  - Gerede Water Transmission Tunnel: Fault Zones & High Water Pressure
  - Delaware Aqueduct Repair: High Volume Water
- Discussion

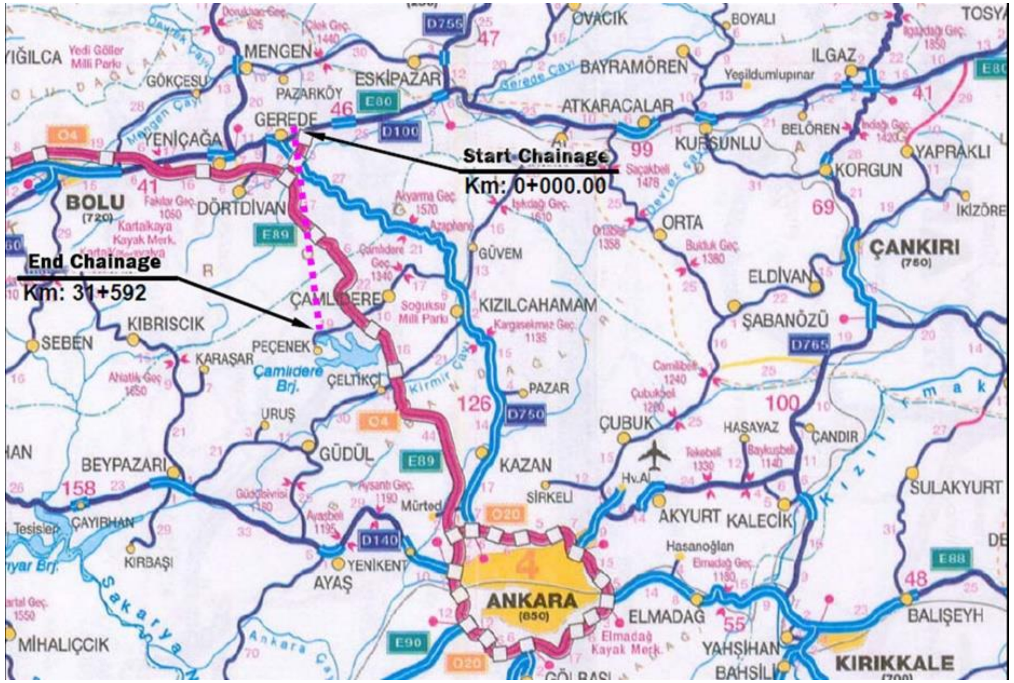
CASE STUDY:

Gerede Water Tunnel

CASE STUDY: GEREDE WATER TUNNEL

PROJECT FEATURES

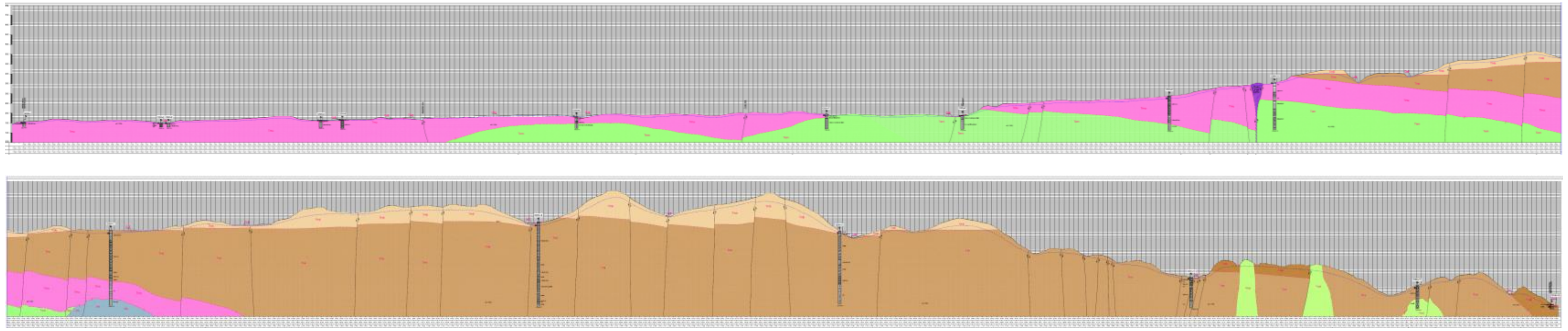
- 31.6 km water supply tunnel near Ankara,Turkey
- Deemed a national priority by the Turkish State Water Department (DSI) due to severe and chronic droughts in the area lasting years
- Tunnel draws water from the Gerede River to a water storage system near Ankara
- The longest water tunnel in Turkey
- JV contractor of Kolin/Limak responsible for tunnel construction



CASE STUDY: GEREDE WATER TUNNEL

GEOLOGY

- Geology consisting mainly of tuff, basalt, and breccia, giving way to sedimentary formations like sandstone, shale, and limestone
- Nearly 30 fault zones along entire length



CASE STUDY: GEREDE WATER TUNNEL

ORIGINAL TBM SUPPLY

- First attempt: Three standard 5.6 m Double Shield TBMs supplied by another manufacturer
- Each TBM would bore approximately 10 km of the tunnel

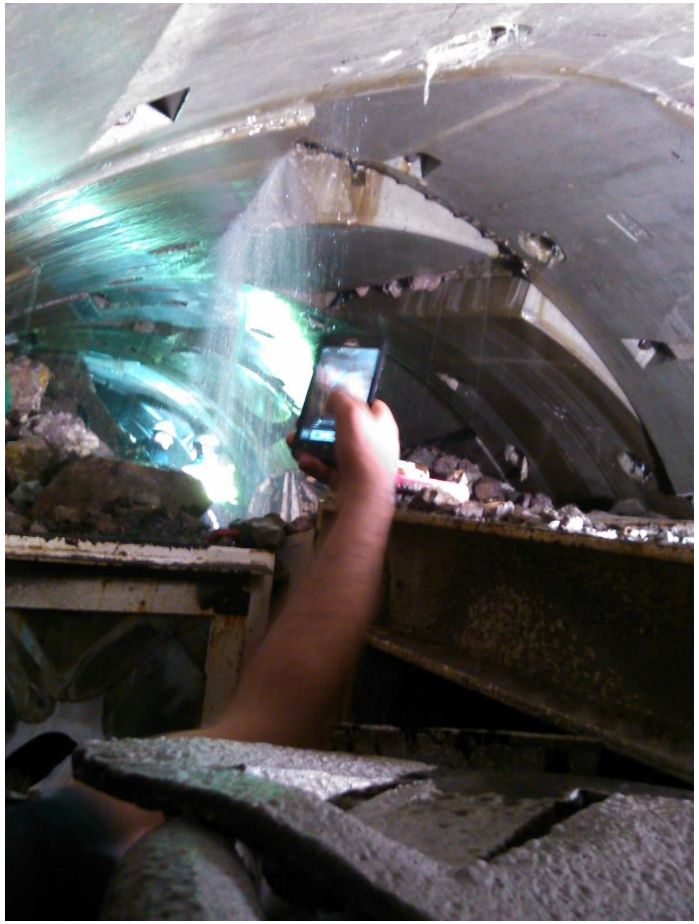
TBM 1 EXCAVATION

- TBM 1 completed 9,588 m of tunnel in relatively homogeneous rock under low cover
- Some water inflows and squeezing ground were encountered that caused delays, but did not trap the machine

CASE STUDY: GEREDE WATER TUNNEL

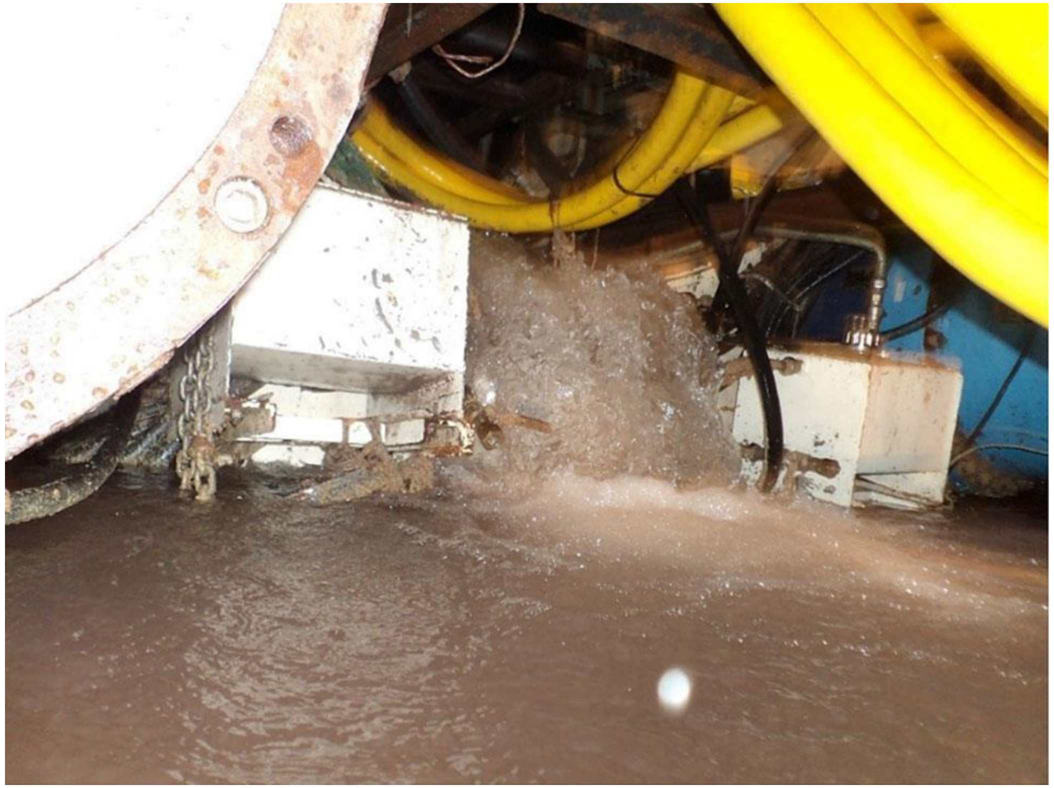
TBM 2 EXCAVATION

- TBM 2 had bored a significant section of its 10,339 m long tunnel when a massive inrush of water flooded the TBM and tunnel
- The TBM was boring downhill and the water had to be pumped out
- The TBM was deemed a loss
- Some parts were salvaged and the rest of the machine was removed



TBM 3 EXCAVATION

- TBM 3 was several kilometers into its 11,653 m drive and struggling in karstic aquifer conditions that required polyurethane injection
- A sudden high inrush of water and mud, about 1,500 liters per second, flowed into the tunnel
- The pressure was enough to crush the TBM shields and send cylinders catapulting into the back-up
- Dye tests showed the water had come from a river overhead and was entering the tunnel through a cave system
- The machine was stuck in place



VIDEO

LESSONS LEARNED: DIFFICULT CONDITIONS

+ One machine hit a fault zone, flooding and damaging the machine and collapsing the shield
+ The flooded machine was deemed not suitable to finish the tunnel
+ Another machine was damaged, though not as extensively, and stuck in place
+ The standard Double Shield TBMs needed to be fully sealable against high water pressure

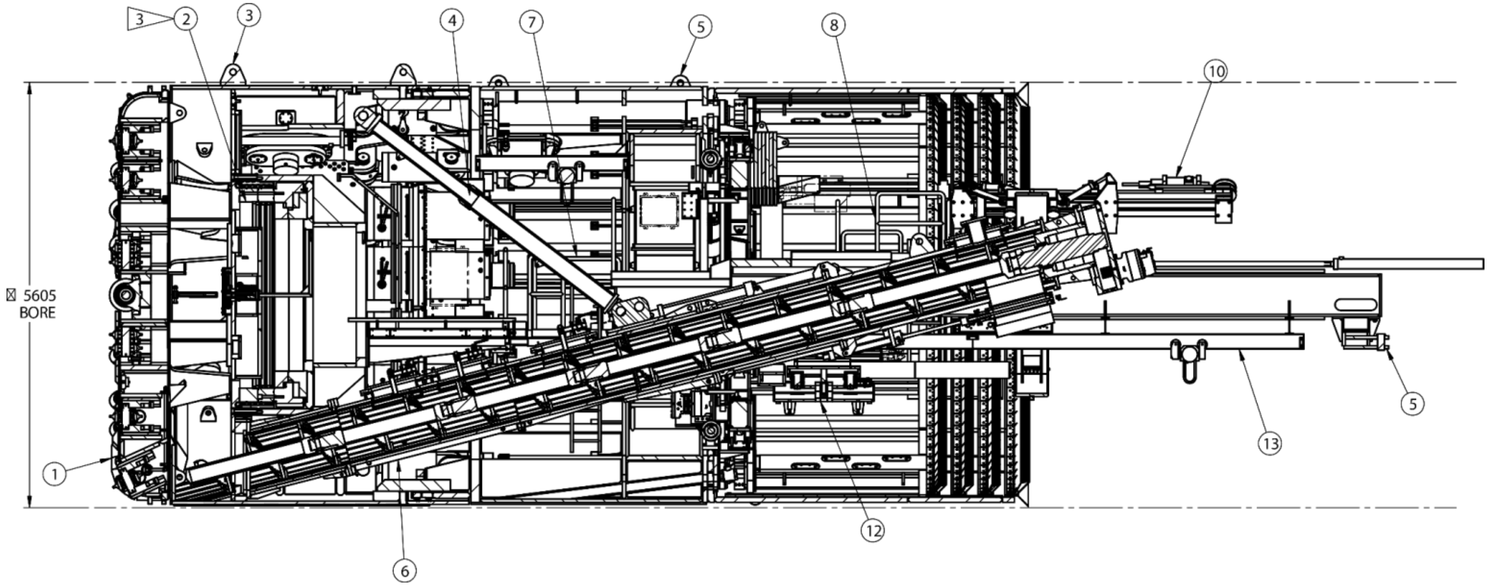
NEW TBM SUPPLY

Robbins
RELIABLE | RESPONSIVE

- Robbins was selected to supply a 5.6 m diameter Crossover (XRE) type TBM to excavate 11 km of faulted and fractured rock with pressure up to 20 bar
- Assembly of the machine onsite in the tunnel
- Reuse existing backup and system components

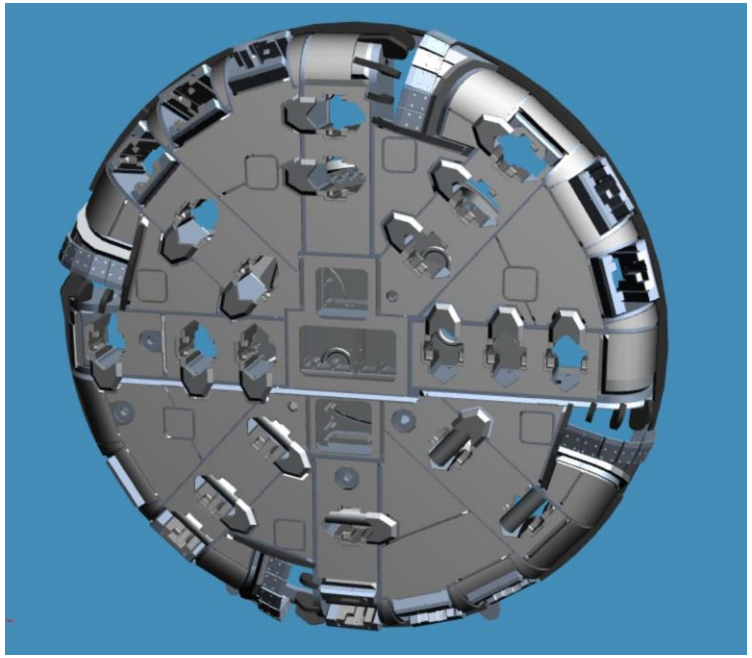
TBM FEATURES

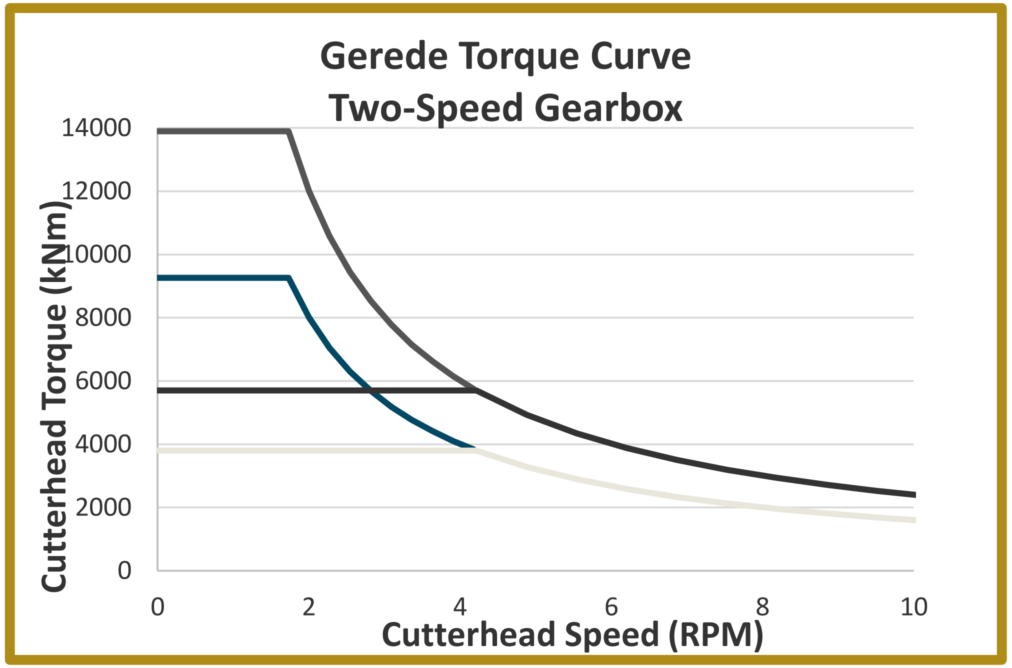
- Crossover (XRE) TBM with Single Shield and EPB TBM characteristics
- High strength shield with closed bulkhead to resist water and mud inflows
- Bottom screw conveyor
- High pressure articulation and tail seals
- High thrust capacity
- Multi-position probe drilling



CUTTERHEAD

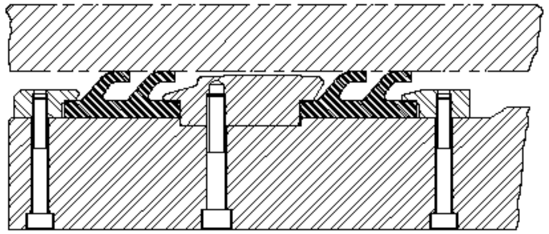
+ Single-direction rock cutterhead
+ Dual ratio transmission for high torque capability

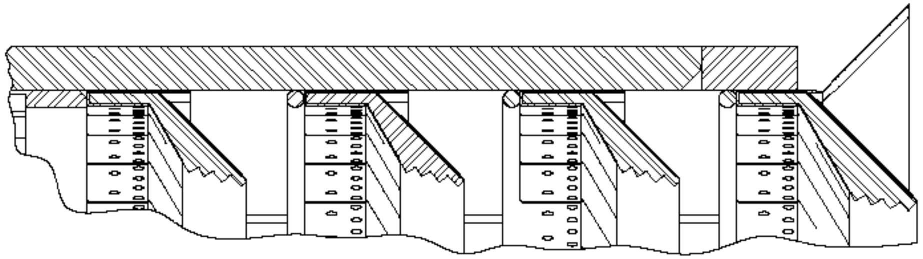


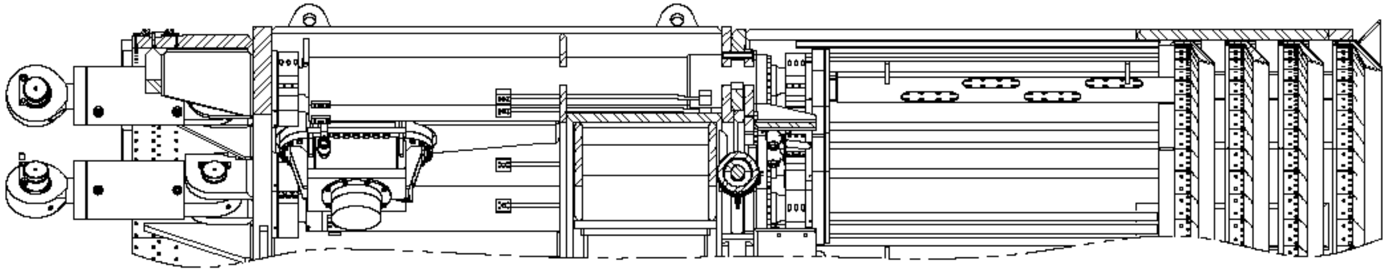


GEREDE SEAL DESIGN

- TBM could statically hold up to 20 bar pressure in event of water inflow
- Extensive sealing system in place
- Sealing around main bearing, articulation joint, gripper and stabilizer shoes
- Between each seal, grease ensured constant pressure
- Pressure sensor to detect water and continually grease seals

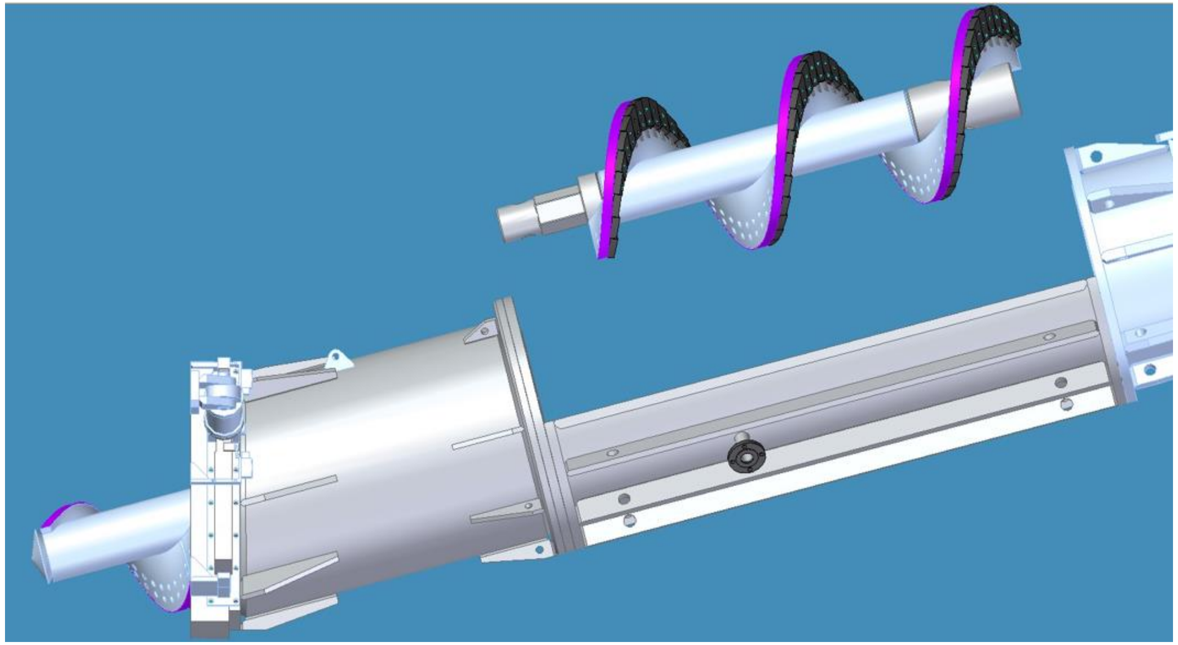






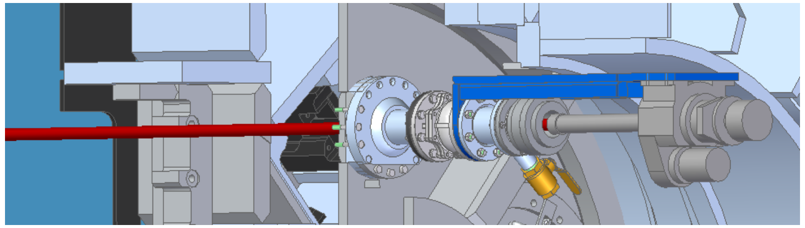
SCREW CONVEYOR DESIGN

- Sealing system to seal itself off so TBM could continue boring through fault zones
- Replaceable wear plates to protect against highly abrasive rock
- Removable sectional casings that could be replaced if needed

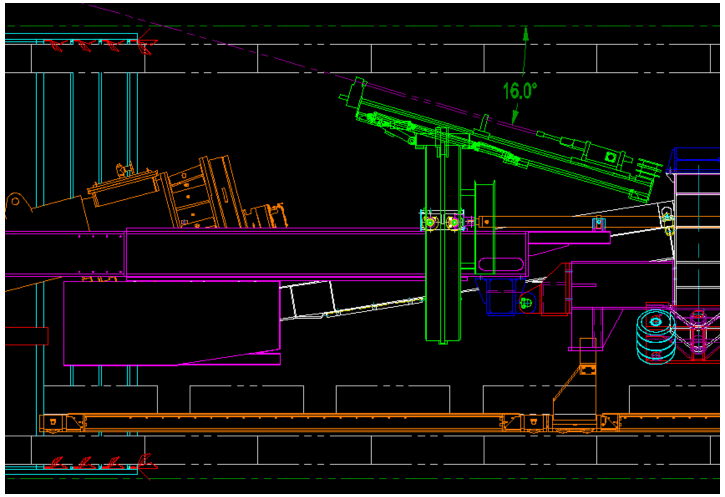


PROBE DRILL DESIGN

+ Necessary to detect and grout off zones of concern
+ TBM has twelve Ø100 mm sealed ports angled at 7° that are equally spaced around the rear shield and ten Ø100 mm ports through the forward shield
+ There are six hatches built into front of machine
+ In emergencies, the drill can pull back behind the tail shield at an angle of 16°, so it can drill behind the shields and into the segment lining



Probe drilling through a port in the machine shield



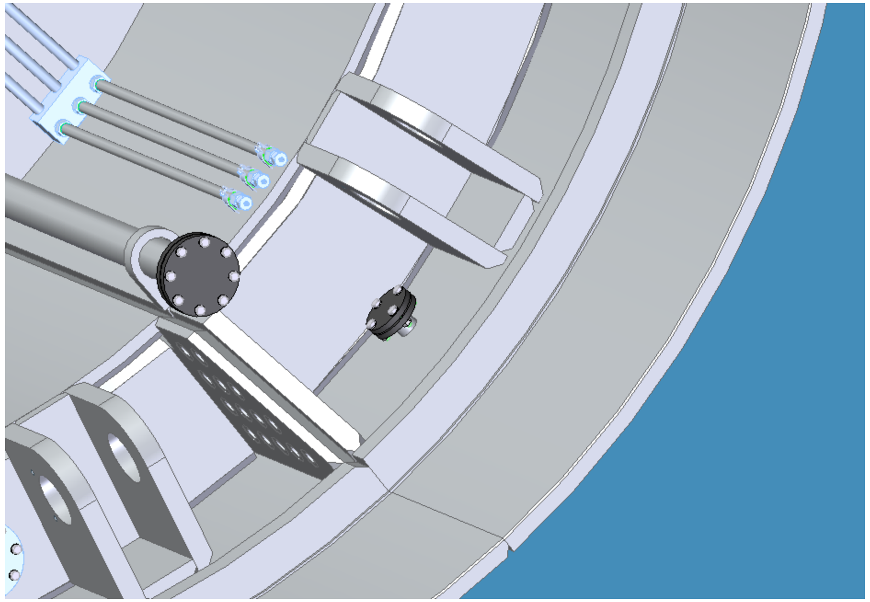
Probe drilling behind the tail shield

CASE STUDY: GEREDE WATER TUNNEL

RAPID ADVANCE SHIELDS

+ Stepped shield design
+ Peripheral shield lubrication

View of stepped shields

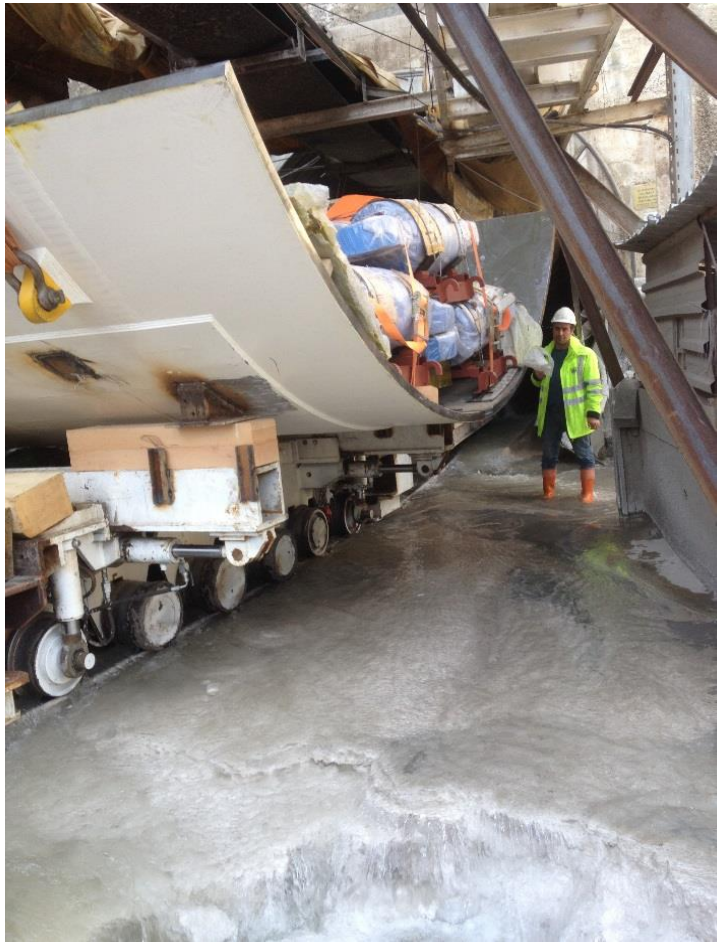


Peripheral shield lubrication port

CASE STUDY: GEREDE WATER TUNNEL

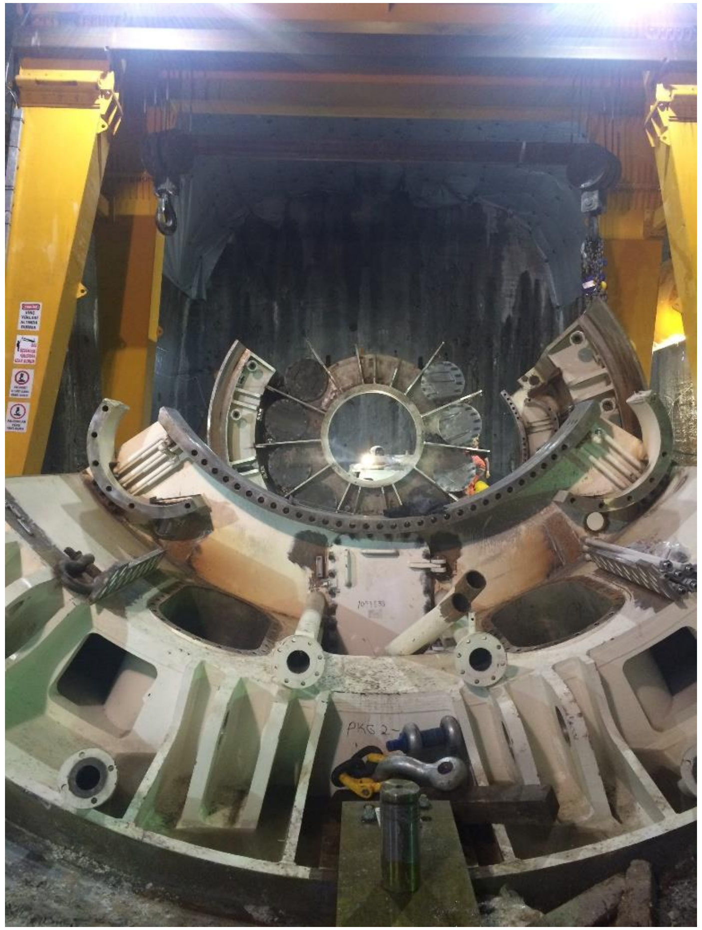
TBM ASSEMBLY

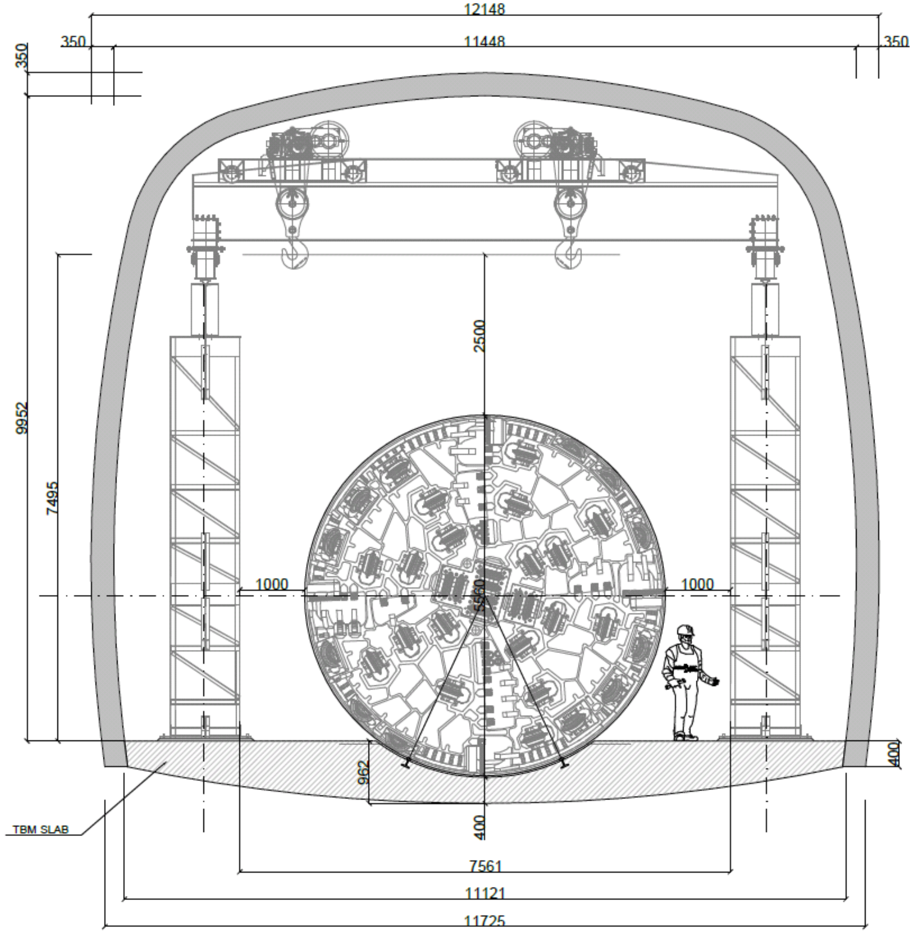
- TBM was assembled in a chamber 7 km from the tunnel portal
- Segment ID 4.5m
- Water flow inside the tunnel averaged 500 l/s during the assembly process
- Existing machine and back-up were still in place



CASE STUDY: GEREDE WATER TUNNEL

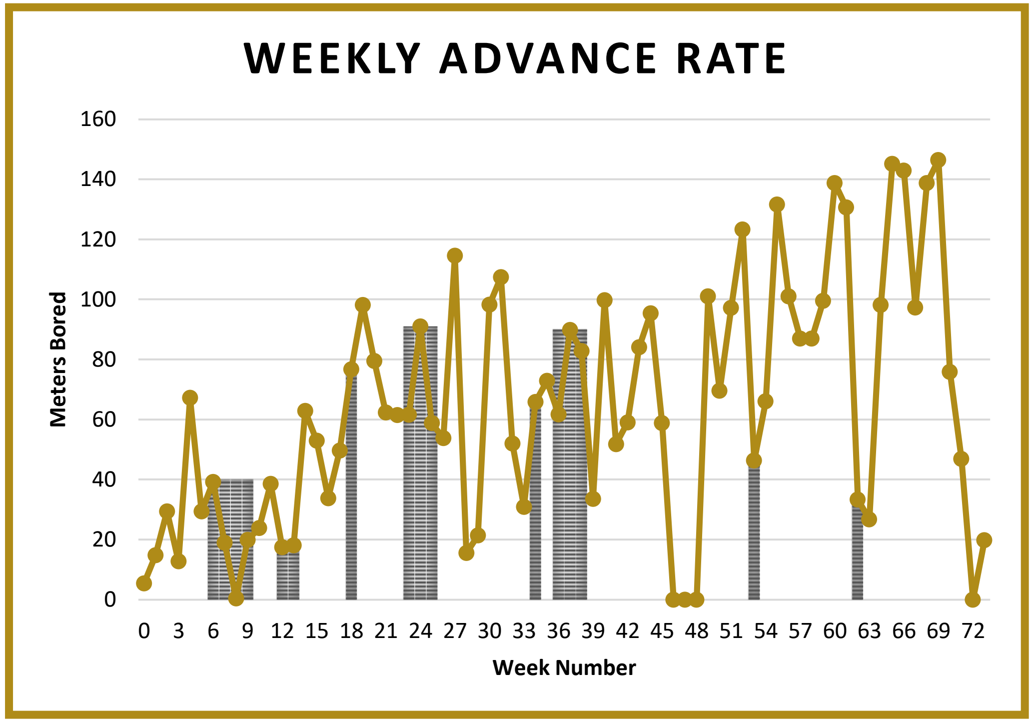
ASSEMBLY INSIDE CHAMBER





TBM ADVANCE

+ Machine launch was in summer 2016
+ The geology was variable and the TBM was boring basalt, tuff, medium to hard clay, and sandy clay with excessive groundwater
+ Water flow inside tunnel was 450-570 l/sec and strained logistics including rail transport
+ First 72 weeks of tunneling, noted in chart, were highly variable



TBM ADVANCE

Robbins
RELIABLE | RESPONSIVE

- TBM ultimately bored through 48 fault zones
- Statically held water pressures up to 26 bar, as well as alluvial material in fault zones
- Ground pressure on the shield body caused squeezing conditions in clay
  - TBM was able to pass through squeezing ground by keeping TBM advance rate, Cutterhead RPM, and screw conveyor rotation speed at optimal levels

BREAKTHROUGH

- Breakthrough occurred on December 18, 2018
- Machine achieved good advance rates for the conditions, up to 484 m in one month

Best Day	29.4 m	**Average Day**	9.49 m
Best Week	134.6 m	**Average Week**	71.14 m
Best Month	484.0 m	**Average Month**	284.54 m

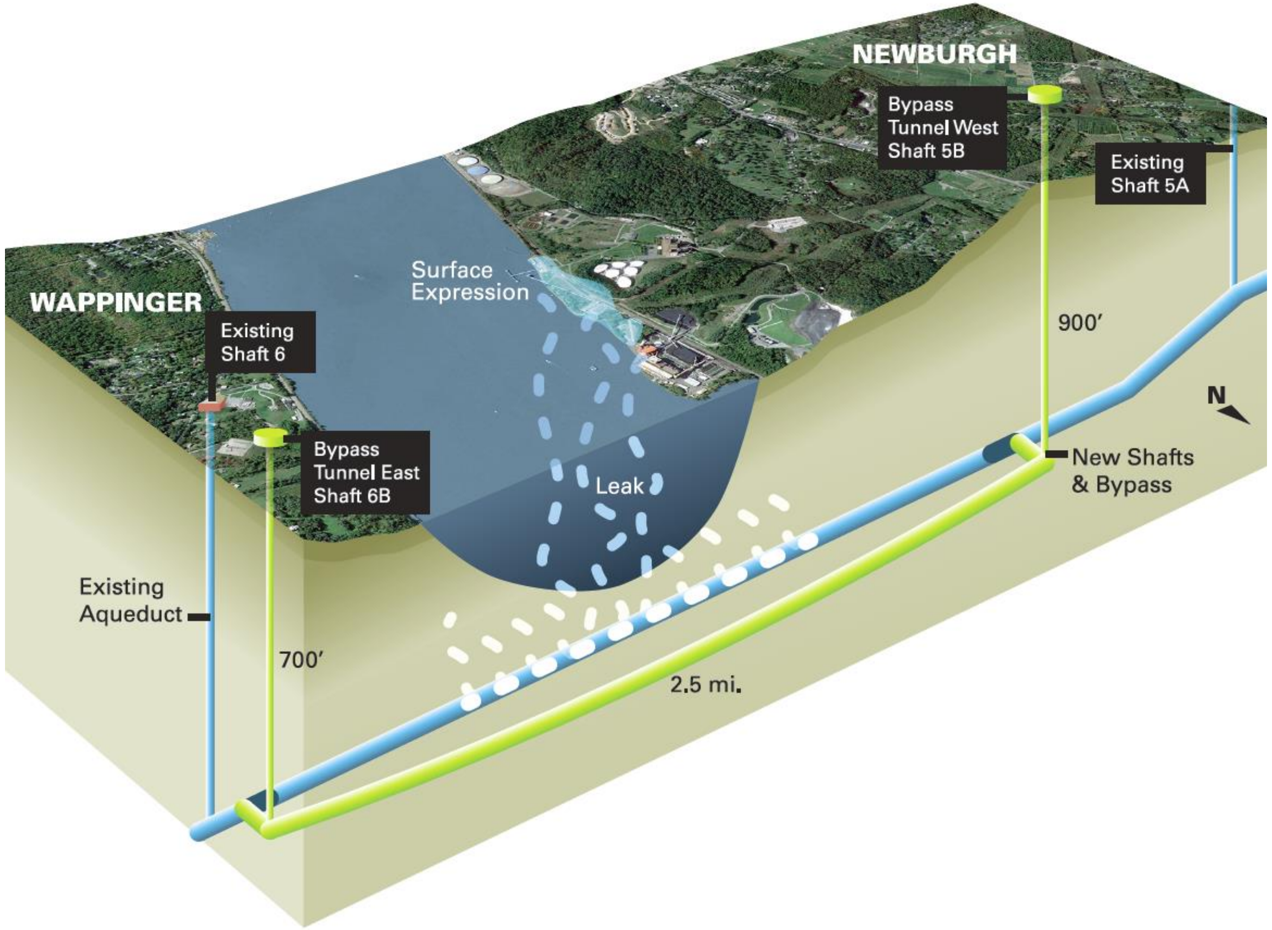
CASE STUDY

Delaware Aqueduct Repair

Delaware Aqueduct Repair

Project Background

+ Delaware Aqueduct supplies 50-60% of the drinking water for New York
+ 85 mile long tunnel was placed in service in 1944
+ Tunnel is currently leaking up to 35 million gallons per day
+ Bored tunnel bypasses leaking



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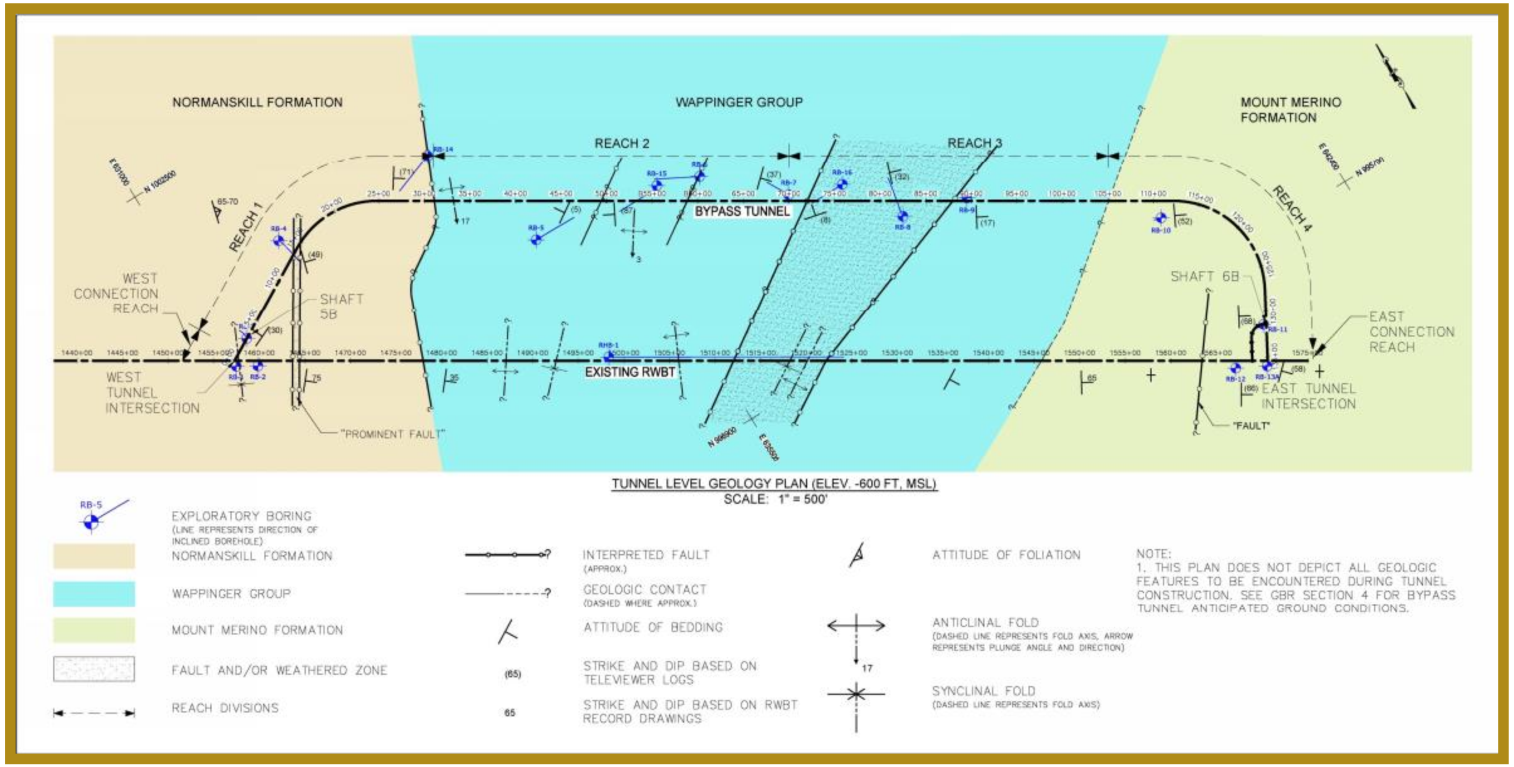
Geology

- Reach 1-780m Shale
- Reach 2-1189m Limestone
- Reach 3-1067m Limestone
- Reach 4-774m Shale
- Hard Rock Tunnel
  - Maximum UCS of 54 ksi (372 MPa)
  - Average UCS of 35 ksi (241 MPa)
- Fault Zones
- Squeezing Ground



HIGH VOLUME WATER

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Robbins
RELIABLE | RESPONSIVE

Project Challenges

+ Ground Water Pressure
  + 675 - 875ft (205 - 267m) of head
  + Machine designed to resist 30 bar (435psi)
+ Ground Water Inflows
+ Muck and Water Handling
+ Sealing systems
+ Drilling and Grouting systems

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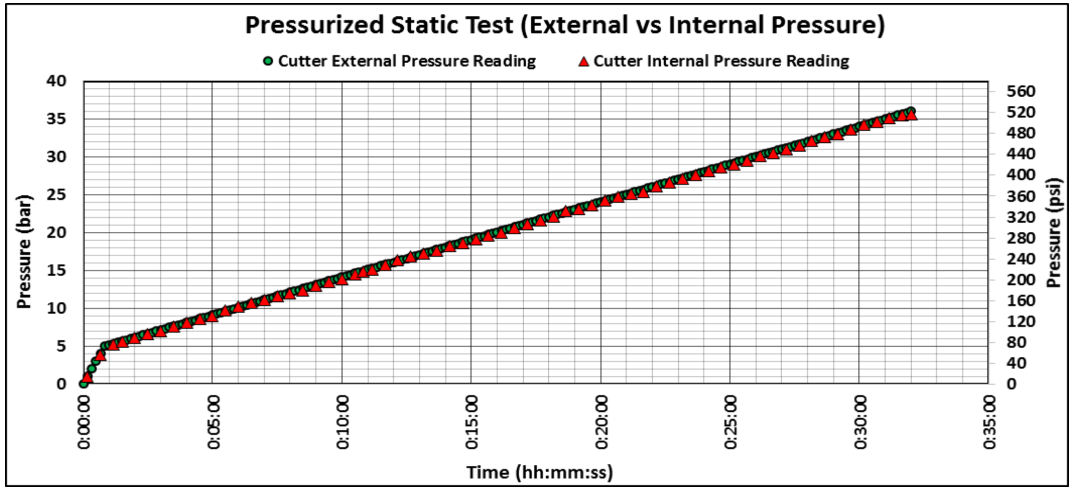
Operational Challenges

- Main bearing seals capable of withstanding 35 bar (435psi) static pressure
- Pressure compensated disc cutters installed
  - Testing surpassed 30 bar static capability



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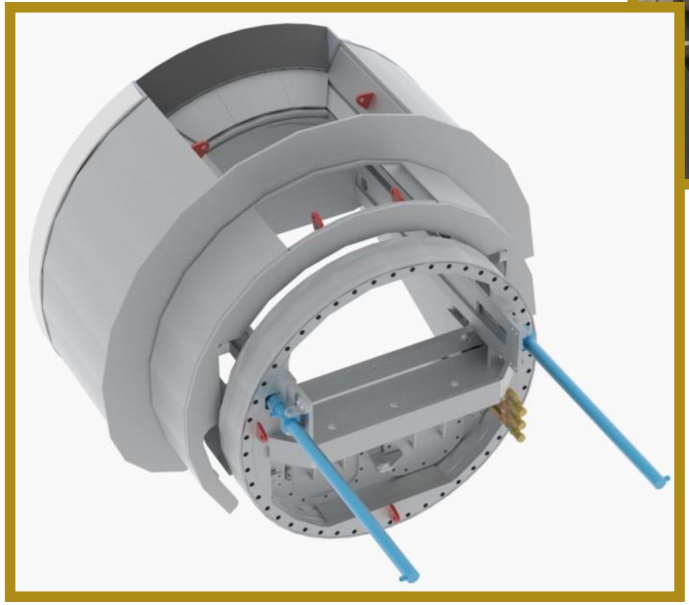
Sealing of Conveyor Opening

+ Knife gates to block incoming muck
+ Retractable conveyor
+ Retractable gate with inflatable seal
+ Provisions made to pull extra belt out of the way



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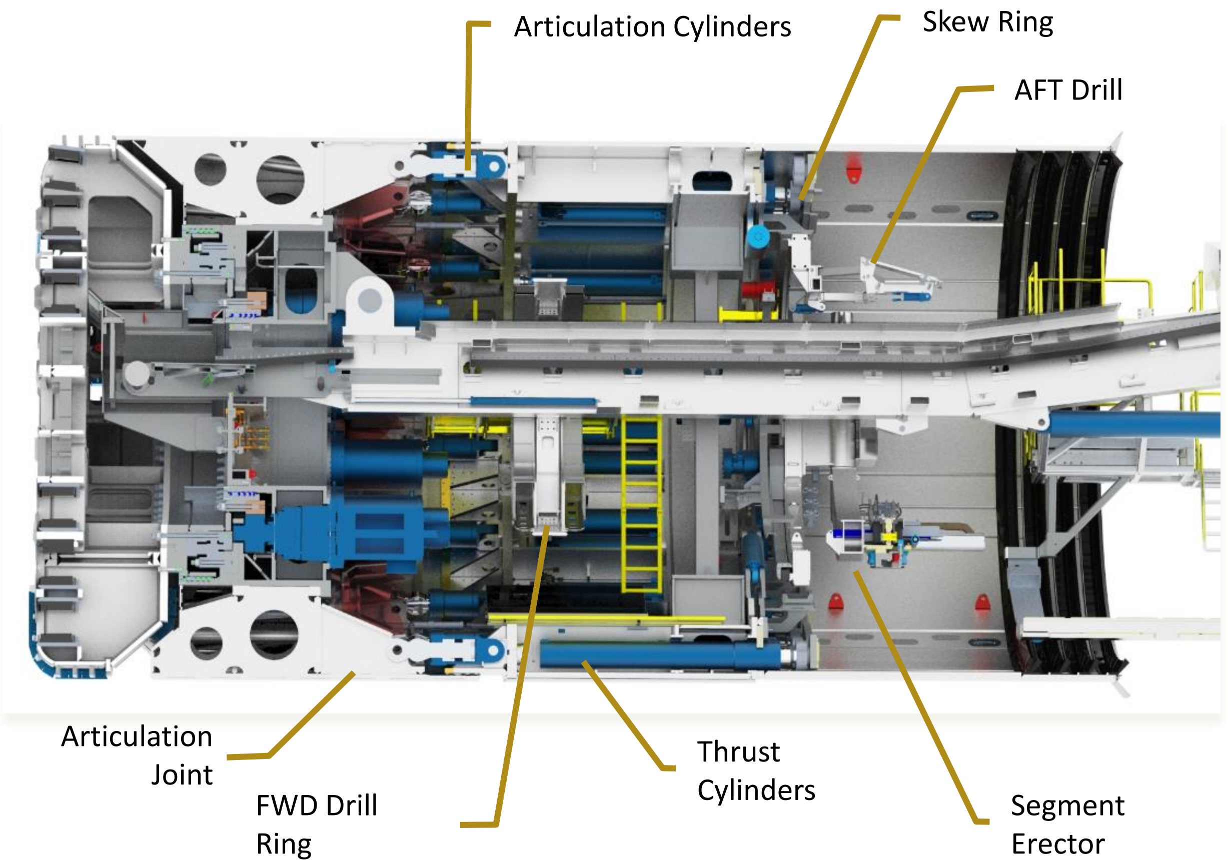
Shield Sealing

- Three articulation seals required
- Four tail seals
  - Erector is designed to remove segments so all four brushes can be removed from inside tunnel
- Sealed stabilizers and grippers



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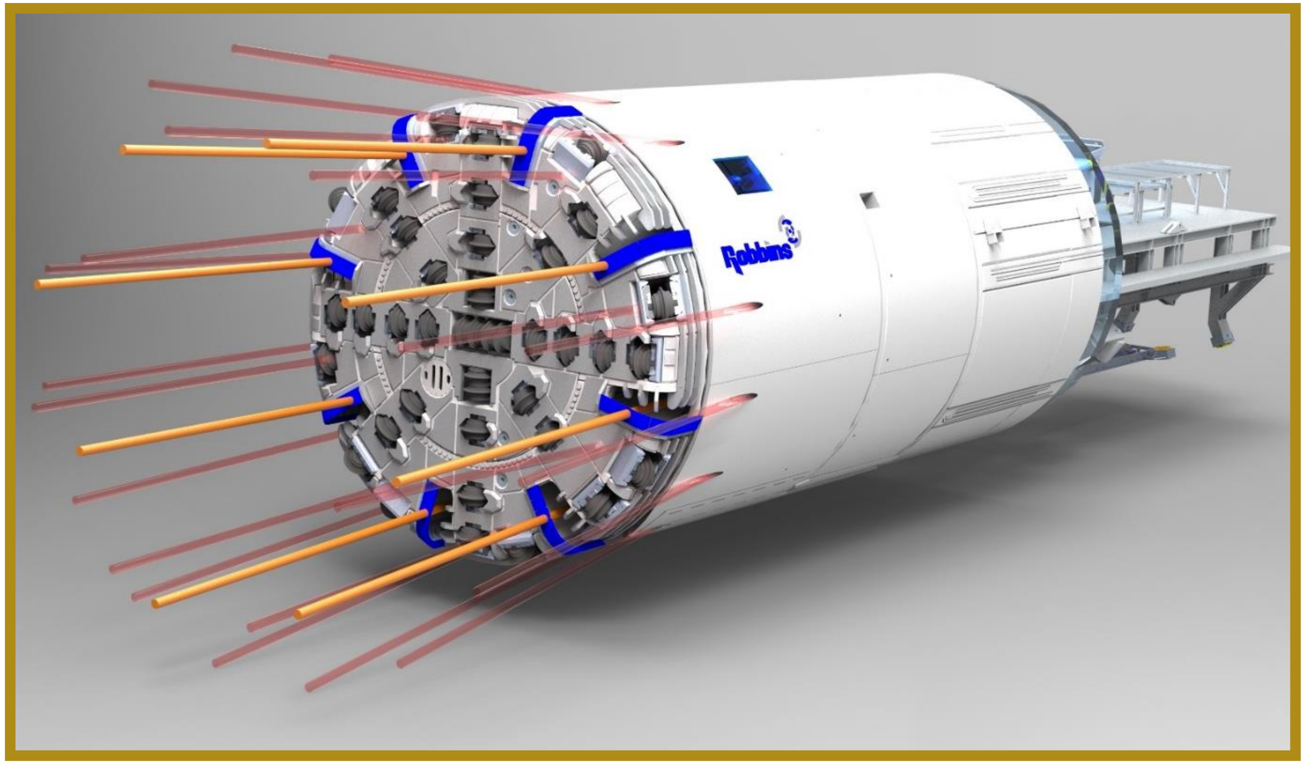
Drill Ports

- Cutterhead
  - 4 ports at 0 degrees to alignment
  - 12 ports at 4 degrees to alignment
  - Cutterhead automatically positions it self between two different drill positions
- Radial Ports
  - 14 ports at 7 degrees



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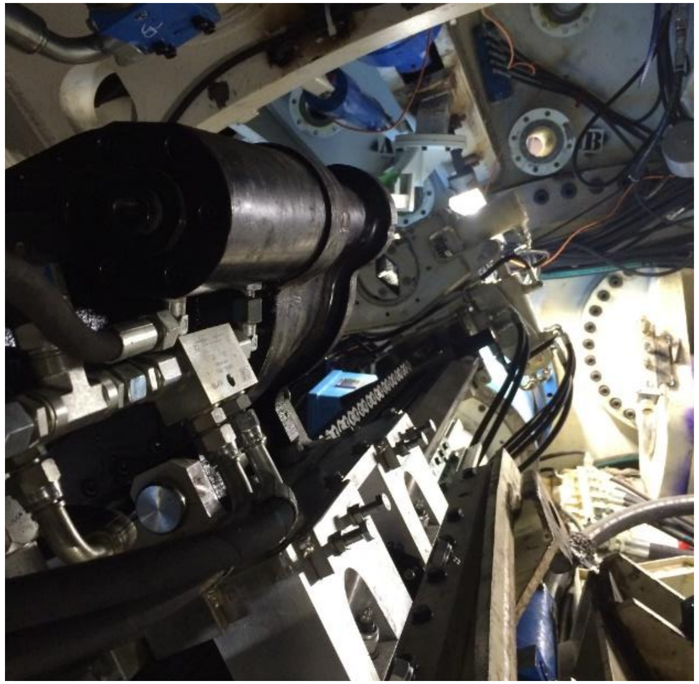
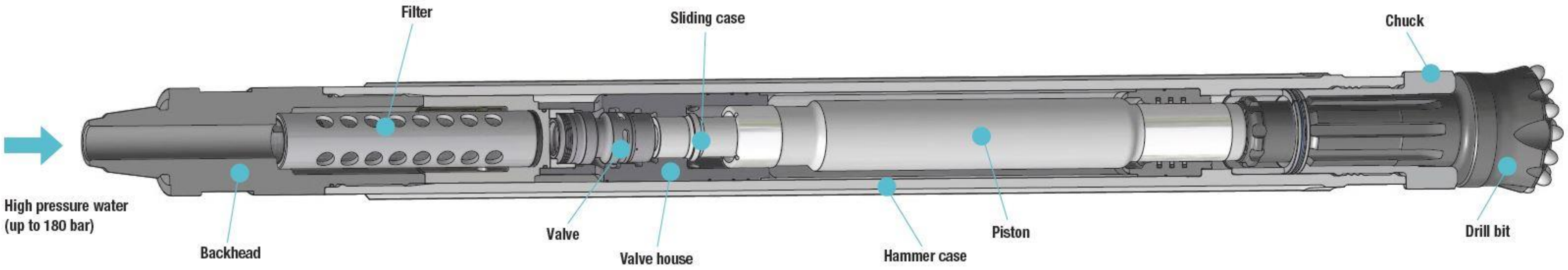
Drills

+ Down-the-hole water hammers
  + Straighter drilling vs top hammer drifters
  + Advantageous for longer holes





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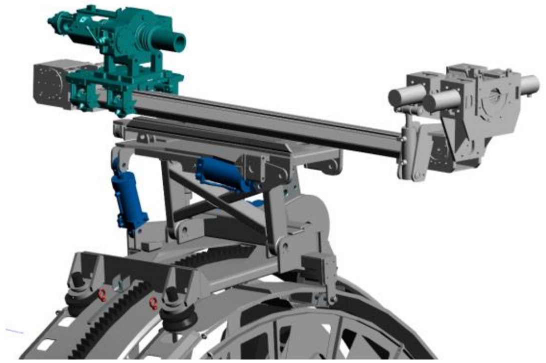
Forward Drills

- Contained inside of rear shield
- 2 separate drills with 360-degree freedom of movement
- Can drill in both the horizontal and 4-degree ports
- Large freedom of movement for locating drills
- Special provisions made during plumbing to avoid contact with drills
- Bulk of drilling duties will be carried out by forward drills



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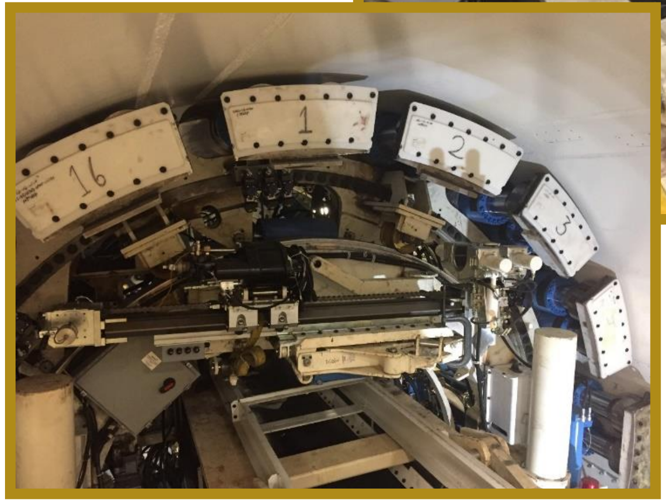
Rear Drill

+ Mounted on erector
+ Positioned to drill through 14 radial ports located evenly spaced around 360 degrees
+ Folds to stored position close to erector



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PEG Drilling

Drilling requirements

- 2 probes in reach 1 and 4
- 4 probe holes in reach 2 and 3
- 200 ft hole depth
- 20ft overlap
- 5 ft drill steel

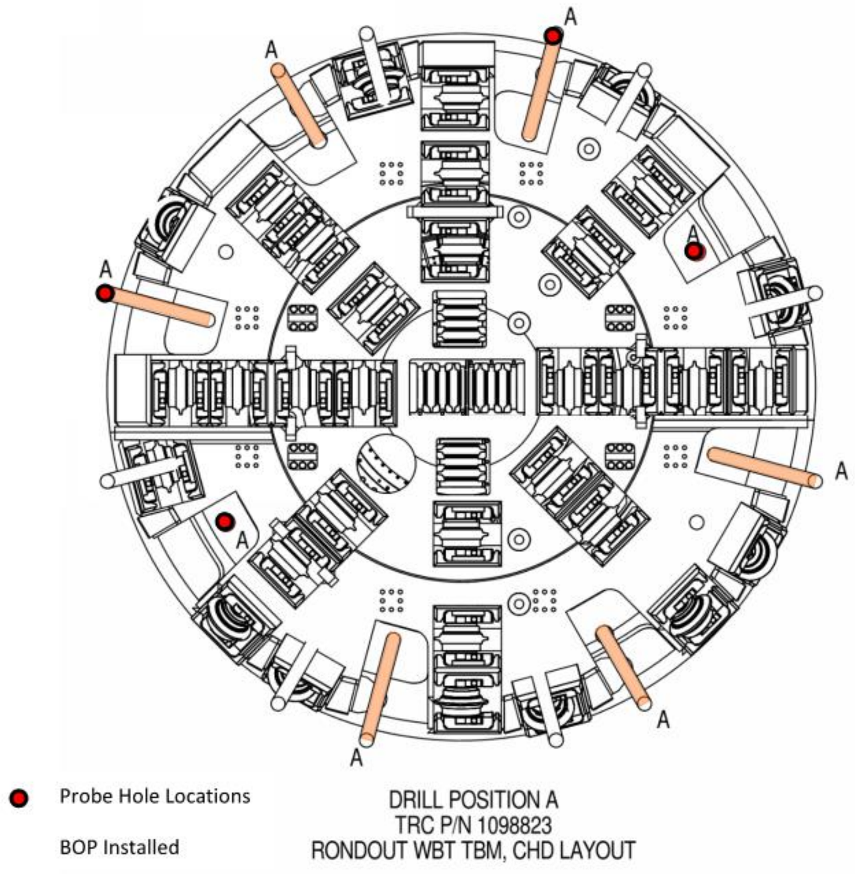

Figure 1. BOP Locations on drill position A

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Drilling Sequence

+ Use W70 (89mm) to drill 6-10ft
+ Install tail pipe packer and clamp with BOP
+ Use W50 to drill through packer

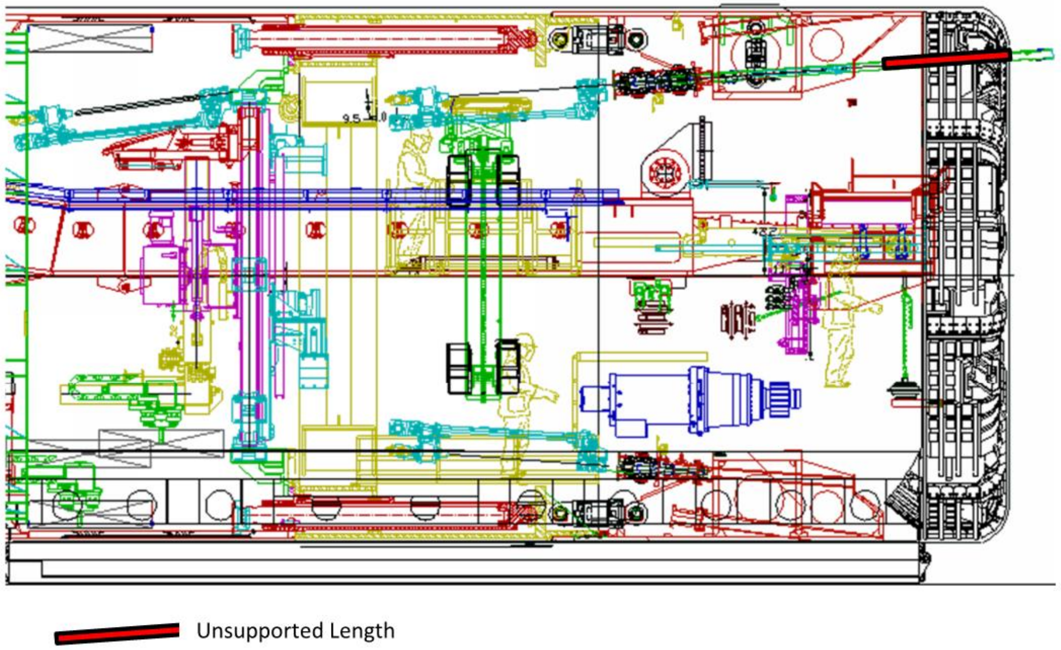

Figure 2. TBM Cut Section Drilling locations.

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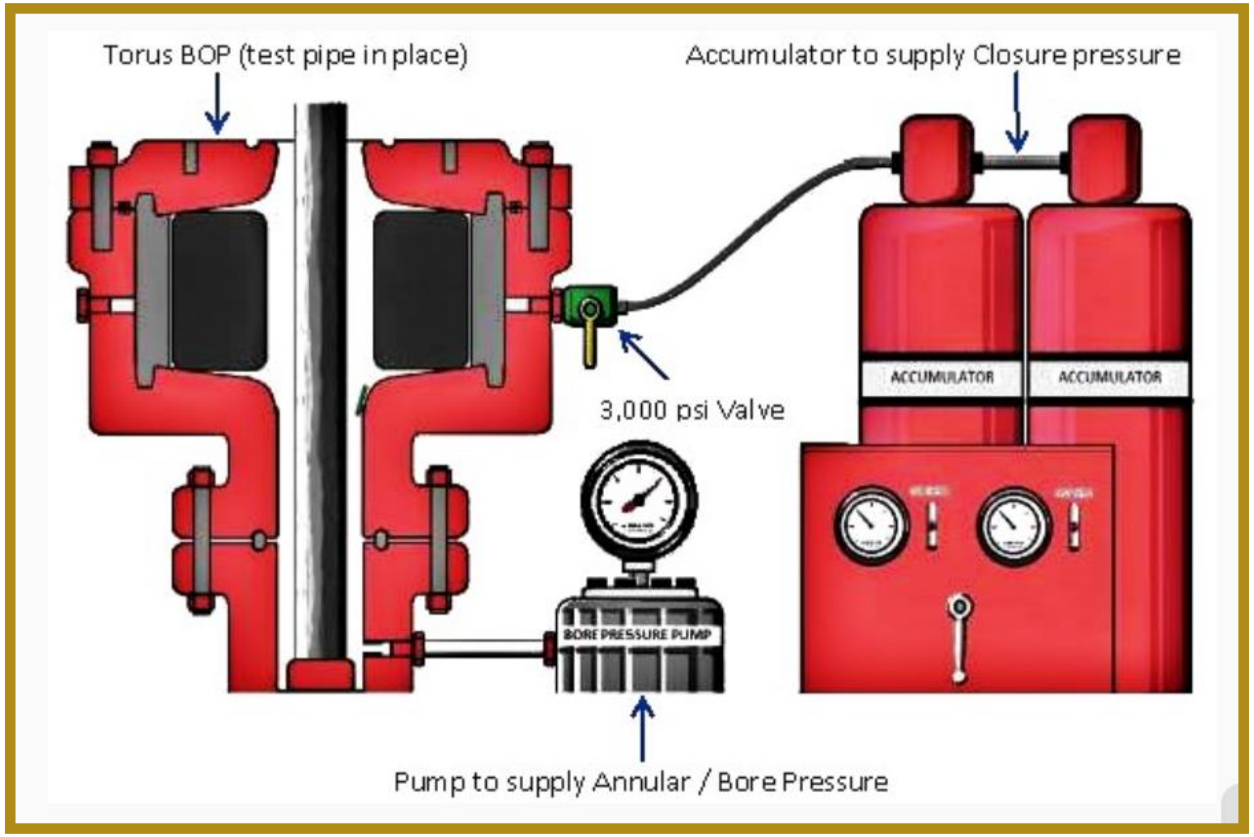
BOP

5-inch Regan Torus
valves on drill ports



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PEG Grouting

- 30 GPM grout trigger
- Grouting material
  - Type III cement
  - Ultrafine if needed
- Grouting procedure
  - Mix 4:1
  - 15 min < 10% pressure build
  - Grout pressure 50 psi over hydrostatic
  - Typical max grouting pressures 1psi/ft overburden

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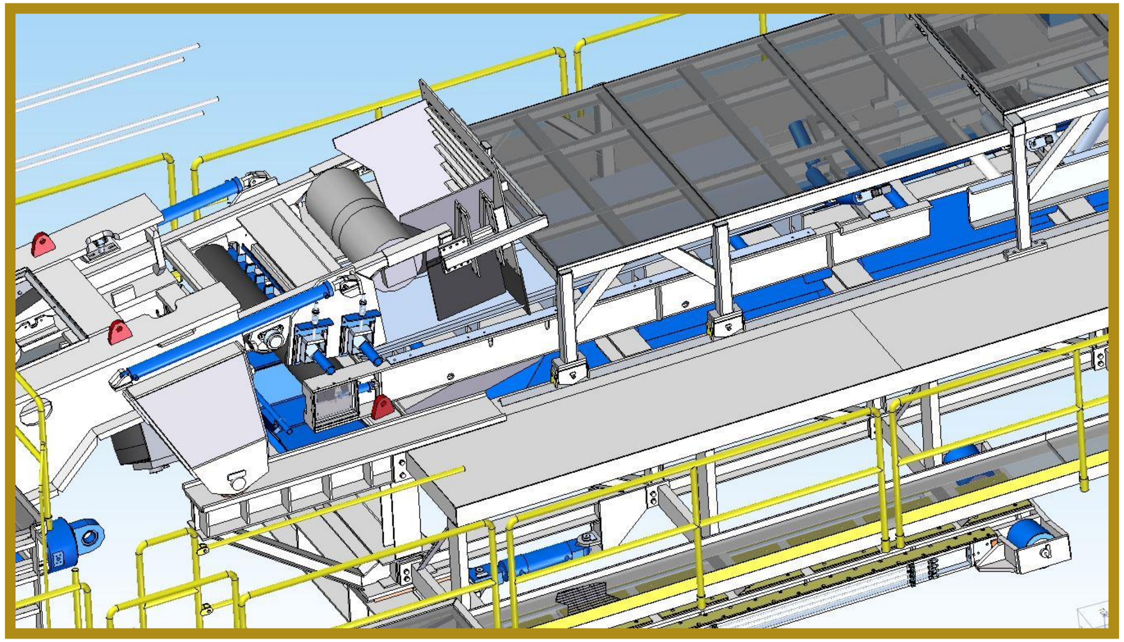
Rear Drill

- Open Conveyor
  - Troughed rollers
  - Full flashing
- Catch basin at transfer point to catch water runoff



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De-watering | De-mucking

+ Controls water inflow in two conditions
  + Boring: 0 – 800 gpm
  + Emergency: 1700 gpm
+ Pickup locations:
  + Cutting chamber
  + Drill water
  + Invert of TBM
  + Ring build area
  + Catch basin below conveyor transfer

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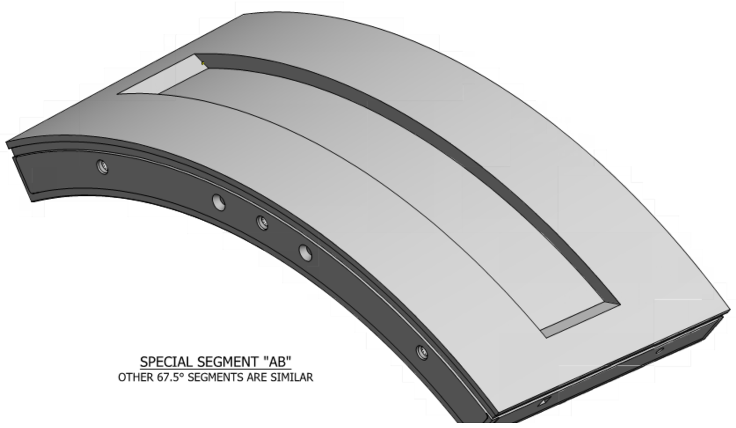
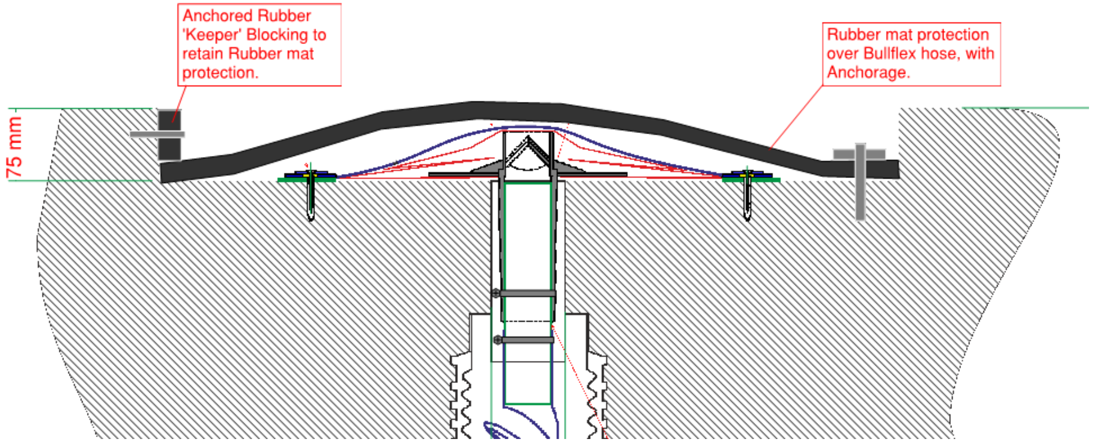
Bullflex Ring

+ Built with erector
+ Once exposed, grout will be used to inflate hose
+ Seals annulus to resist water/grout forward when TBM is sealed up





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Assembly & Launch from Deep Shaft

- Components were lowered down the 270 m deep Newburgh shaft
- TBM was assembled in a bell-out chamber with 12 m high ceiling

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Launch & Water Mitigation

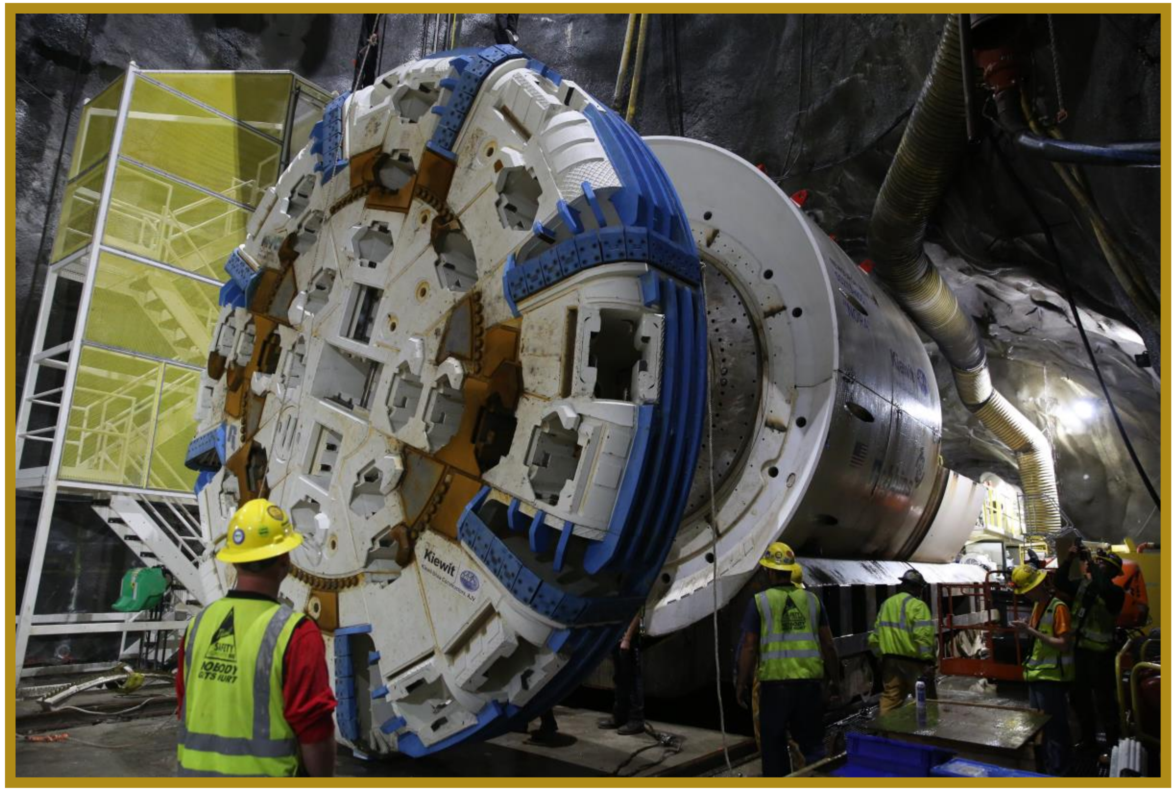
- The TBM was launched on January 8, 2018
- Contractor KSC performed extensive pre-excavation grouting to mitigate the 4,900 l/min predicted in the GBR
- The highest inflows encountered were 1,300 l/min and 200 psi was the highest pressure, a good result in part because of the dewatering effort

TUNNELING

Delaware Aqueduct Repair

Grouting

+ In the first two reaches of shale and limestone, no pre-excavation grouting was needed
+ All pre-excavation grout was done in reach 3, also consisting of limestone, beginning in January 2019
+ A stretch of approximately 530 m of the total 3,800 m tunnel length had to be grouted
+ Grout consisted of water cement type grout progressively thickened from 4:1, to 3:1, to 1:1 mix



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DTH Hammers

+ Used throughout the drive
+ Probed 120 m ahead of the TBM at 115 m intervals
+ Upkeep was challenging as the drill water had to be kept clean and filtered like hydraulic fluid, but ultimately the crew overcame the learning curve
+ Saved time and had less deviation from tunnel alignment than top hammer drills

Delaware Aqueduct Repair

Excavation Rates

+ TBM bored at rates of 100 mm/min
+ However, the shaft became a bottleneck particularly towards the end of tunneling because of the train travel time and muck cars, which were lifted out of the shaft
+ The TBM achieved 27.4 m in one day, 108.1 m in one week, and 288 m in its best month
+ Breakthrough occurred in August 2019
+ Work is ongoing to install a steel interliner in 2,800 m of the tunnel as well as a final concrete lining

DIFFICULT GEOLOGY

Conclusions

HIGH VOLUME WATER

Conclusions

- Several Methods and processes are available to address the issues of water inflows, high pressures, and fault zones
- Methods to be used need to be identified early in the process so machine design can be tailored to best support operations
- TBMs are often the only solution in tunnels in high overburden, and in such long and deep tunnels, surprises often occur
- A thorough geological analysis prior to boring is required for proper machine design and pre-planning
- Although cost for additional probing and drilling is initially higher, its payoff is substantial

HIGH VOLUME WATER

Conclusions

- An action plan should be made to cover all eventualities, and necessary equipment should be kept onsite
- An experienced team and continual communication with the surface office make a big difference when resolving issues
- Safety must be kept a priority when in water flows or fault zones as there are many hazards to workers

CHALLENGING GEOLOGY

QUESTIONS AND DISCUSSION