Challenges of Large Diameter TBM Tunnels

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Tuen Mun–Chek Lap Kok Link (TM-CLK) Hong Kong – 17.6m
Challenges of Large Diameter Soft Ground TBM Tunnels

Presentation Outline
- Background and Historical Perspective
- Challenges and Mitigation Measures Associated with Large Diameter TBMs
- Case Histories:
  - Alaskan Way Tunnel SR-99, Seattle, USA
  - Eurasia Tunnel
- Conclusions and Future Outlook

“Bertha” – Alaskan way Tunnel, Seattle, USA 17.5 m diameter – Second largest TBM in the world
Historical Perspective

What was before mechanized excavation (TBM)?

- 19th Century and up to 1950s and 60s soft ground tunneling was done by hand excavation, open shield, or compressed air.
- Brunel Shield (1818) - Never open more than is needed, can be excavated rapidly, and supported quickly.
- Nearly all soft ground tunnels built up to the early 1970’s were mostly constructed using the basic concepts of the Brunel tunnel shield, with compressed air; compartmentalization, face breasting with timber and lots of hand labor.

Marc Brunel 1818 Patent Application

“Open... the ground in such a manner that no more earth shall be displaced than is to be filled by the shell or body of the tunnel.”
Historical Perspective (cont’d)

- Late 1950’s and 1960’s
  - Emergence of mechanical mining
  - Rock Tunnel Boring Machines (TBMs)
  - Rotating Cutter Head (The Robbins TBM)

- Changes for Tunnel Shields in 1960’s
  - Mechanical excavators start being used replaced hand excavation and miners replaced at tunnel face

- Starts in 1960’s Tunnel Face Closed to Control Water
  - UK, Europe, Japan, Canada
  - Earth Pressure Balance (EPB), Slurry TBM, Hydroshield, Mixshield etc.
  - Trenchless Technology - Microtunneling

- Pressurized Face Tunneling
TBMs are Getting Bigger and Bigger...

- Microtunneling (usually less than 3 m)
- Metro/subway size (6 to 7 m)
- Railroad single tracks (8 to 10 m)
- Railroad double tracks (10 to 12 m)
- Road tunnels 2 or 3 lanes > 12m


M-30 Madrid – 15.2 m dia. (2005)
First TBM larger than 14m Tokyo Bay Tunnel (1994)
Large Diameter Soft Ground TBMs

Courtesy of Herrenknecht
More Challenges with Large Diameter

TBM Torque - EBP / Slurry

Courtesy of Herrenknecht
And the World Largest TBM...

Tuen Mun – Chek Lap Kok Link (TM-CLK) Hong Kong – 17.6m (2015)
Large Diameter TBM Challenges

- Large Diameter Tunnel Configuration
  - Differential pressure within the excavation chamber
  - Gap size
  - Potential over-excavation
  - TBM maneuverability and maintaining horizontal and vertical alignments

- Geological and Geotechnical Conditions and Potential Mixed Face Condition
  - Variable ground conditions within the excavation and around excavation
  - Mixed face conditions (rock/soil; clay/sand; fractured/solid rock; intrusions; etc.)
Large Diameter TBM Challenges (Cont’d)

- Ground Water
  - High ground water pressure
  - Quantity of water intake
  - Ground water control – transient lowering water table level on adjoining facilities

- Large Overcut
  - Accommodate thickness of shield, brushes, gap, outer gage cutters, etc...
  - For 15m (50ft) dia tunnel the gap can be about 38 cubic meter/meter (15 CY/ft) – 3 times bigger than a typical metro tunnel – 90 CY/shove
  - Need to fill the gap
  - Potential settlement
Large Diameter TBM Risk Issues (Cont’d)

- **Ground Loss**
  - Ground and ground water control
  - 1% of ground loss on a 15m diameter will yield 1.8 cubic meter/meter of ground loss – over 4.5 times ground loss from a metro size TBM
  - Potential significant settlement
  - Wider settlement trough
  - Impact on existing structures and utilities

- **Other Potential Issues:**
  - Transition areas near surface
  - Break-in and break-out
  - Operation and maintenance of the TBM – “safe havens” and maintenance in free air
  - Potential needs for saturation diving
  - Required cover over the TBM
Controlling Ground Behavior at the Source

- Control overcut gap
  - Minimize the shield gap
  - Bentonite injection & pressurization immediately and as close to the face as possible
  - Pressure cells on shield perimeter
  - Tail shield grouting

- Close spacing of extensometers and piezometers to determine ground behavior at the source

- Continuous monitoring
  - Correlate the TBM performance parameters and ground behavior – impact on facilities
  - Construction “Monitoring Task Force” for collaboration

- Collaboration among contractor, designer, owner, and stakeholders
Controlling Overcut Gap

- Control the face pressure to prevent over-excavation
- Monitor for evidence of larger volumes of over-excavation and void formation:
  - Reconcile weight and volume of excavated material with volume of advance - Targets +2 to -4%. This requires accurate measure of additives and more accurate belt measurements
  - Large diameter tunnels may yield 1000 tons per shove, this may represents 100 tons over excavation (10%) and a large void
- Check grouting (use secondary grouting) through the segmental lining to fill all gaps as soon as possible if needed.
- Polymer additives for EPBs to control sands and significant bentonite conditioning to make sand and water form a viscous fluid could add significant bentonite solids
  - On a 1000 tons excavated per advance: up to 2 tons of bentonite solids could added
Case History

Alaskan Way Tunnel – SR99 – Seattle, USA
New SR 99 Corridor - Alignment

- 158 buildings within influence zone
- Passes under historic building zone
- Under freight rail tunnel
- Passes under significant utilities
## Cross Section

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation diameter (TBM)</td>
<td>17.48 m (57’4”)</td>
</tr>
<tr>
<td>Internal diameter</td>
<td>15.85 m (52”)</td>
</tr>
<tr>
<td>Segment thickness</td>
<td>610 mm (24”)</td>
</tr>
<tr>
<td>Grouting thickness</td>
<td>200 mm (8”)</td>
</tr>
<tr>
<td>Average ring length</td>
<td>2 m (6’ 6”)</td>
</tr>
<tr>
<td>Number of segments</td>
<td>7+2+1</td>
</tr>
<tr>
<td>Tunnel length</td>
<td>2800 m (9300’)</td>
</tr>
</tbody>
</table>

- **Electrical rooms**
- **Equipment rooms**
- **Egress corridor**
- **Utility corridor**
- **Pump station**
- **Ventilation duct**
Tunnel Profile and Geological Setting

- Poor, unconsolidated soils
- Till deposits
- Cohesionless sand and gravel – regional aquifer
- Cohesionless silt and fine sand
- Cohesive clay and silt
- Till-like deposits
“Big Bertha” – Hitachi Zosen EPB

- Diameter: Ø17.480 m (57.35 ft)
- Length: 110.642m (363 ft)
- Total weight: 6,700 t
- Design pressure: 7 bar (10 bar emergency)
- Max Thrust: 392,000 kN
- Max Torque: 147,400 kNm
- Breakout torque: 206,360 kNm
- Total installed power: 22,600 kW
- Ribbon Screw Conveyor 2 x Ø1,500 mm
- Design cycle: 62 min. (32 min exc.+ 30 min ring building)
Cutterhead Features

- Weight: 886 t
- Opening rate: 37%
- Rotational speed: 0.8 to 1.2 rpm
- Max. size boulder to pass: Ø 1m
- Max. CHD thrust allowed: 196,000 kN
- 55 face double disc cutters 17”, 47 of them to be changed at atmospheric pressure
- 4 copy cutters (50 mm)
- 10 center disc cutters
- 101 fixed pre-cutting bit
- 260 cutter bits
- 12 Bucket teeth (trim bits)
- 32 scraper bits
- 45 emergency bits (150 mm)
- 34 foam injection ports
## Sequence of Precarious Events

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 July 2013</td>
<td>TBM Launch</td>
</tr>
<tr>
<td>20 Aug 2013</td>
<td>Breakout of labor dispute with Longshoremen’s union over muck handling at the wharf</td>
</tr>
<tr>
<td>23 Sep 2013</td>
<td>Drive restarts</td>
</tr>
<tr>
<td>31 Oct 2013</td>
<td>Stoppage for machine adjustments and fitting new cutting tools</td>
</tr>
<tr>
<td>14 Nov 2013</td>
<td>Drive restarts</td>
</tr>
<tr>
<td>03 Dec 2013</td>
<td>“Bertha” hit a piezometer steel casing (left in place from the investigation phase).</td>
</tr>
<tr>
<td>05 Dec 2013</td>
<td>TBM reaches 1,000ft (300m) milestone</td>
</tr>
<tr>
<td>06 Dec 2013</td>
<td>High temperature readings prompt precautionary machine shutdown and 158 hours worth of hyperbaric inspections are carried out between Jan 17–28</td>
</tr>
<tr>
<td>28 Jan 2014</td>
<td>Drive restarts</td>
</tr>
</tbody>
</table>
## Sequence of Precarious Events

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 Jan 2014</td>
<td>TBM advances 2ft (60cm) before same heat readings prompt shutdown. <strong>Main bearing seal damage is diagnosed, plus possible damage to main bearing itself</strong></td>
</tr>
<tr>
<td>May 2014</td>
<td>Excavation of 36.5m x 24.4m (120ft x 80ft) recovery shaft begins</td>
</tr>
<tr>
<td>02 Sep 2014</td>
<td>TBM advanced 3ft (1m) to rest against the outside of the piles of the recovery shaft</td>
</tr>
<tr>
<td>18 Feb 2015</td>
<td>Drive restarts</td>
</tr>
<tr>
<td>02 Mar 2015</td>
<td>TBM shut down after being driven through 57ft (9 rings) into recovery shaft</td>
</tr>
<tr>
<td>30 Mar 2015</td>
<td>TBM lifted out of recovery shaft over a 2-day period using specialist hoisting equipment</td>
</tr>
<tr>
<td>05 Jun 2015</td>
<td>Newly designed outer and inner seal systems installation begins; repairs include a new main bearing plus other major modifications</td>
</tr>
</tbody>
</table>

### April 2014 - Repair
- Replace broken seal
- Replace main bearing
- Install enhanced motoring systems
- Add steel to stiffen the TBM
# Sequence of Precarious Events

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<tr>
<th>Date</th>
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</tr>
</thead>
<tbody>
<tr>
<td>25 Aug–8 Sept 2015</td>
<td>TBM lowered in pieces back into recovery shaft</td>
</tr>
<tr>
<td>12 Nov 2015</td>
<td>TBM testing program begins – on Nov 24 the cutterhead is tested to sustained rotation</td>
</tr>
<tr>
<td>22 Dec 2015</td>
<td>Drive resumes, with TBM breaking out of the recovery shaft – progress of 12 rings is made</td>
</tr>
<tr>
<td>12 Jan 2016</td>
<td>Sinkhole 4.6mx10.7m (15x35ft) 250 m3 of concrete after 100ft (30m) advance made by the TBM out of the recovery shaft</td>
</tr>
<tr>
<td>14 Jan 2016</td>
<td>WSDOT issues a forced stop order, pending an independent safety and operational review</td>
</tr>
<tr>
<td>23 Feb 2016</td>
<td>Drive resumes after STP’s management modifications and additional operational protocols</td>
</tr>
</tbody>
</table>

*Total Days Lost = 817 days*
TBM Recovery and Repair Shaft

- 24.3m (80ft) diameter x 36.5 m (120ft) recovery shaft
- Secant piles in conjunction with the existing protection piles and closed with jet grouting
- Compression ring
- Dewatering to reduce pressure
- Started shaft construction May 2014
TBM Repair

Heavy Lift – 2000 tons
Damage

Main bearing

Main bearing seal

Damaged Pinion

Damaged Rollers

Damaged Disk Cutters
Repair
TBM Crosses the Viaduct

- May 11\textsuperscript{th}, 2016 TBM mined the full reach of 171m (385ft)
- 4.5m (15ft) below the viaduct’s foundation piles
- Run 12 days of 2-12 hrs shifts
- Settlement of the viaduct was 1.5 to 3 mm
Instrumentation and Monitoring

- Total Stationing
- Settlement points
- Inclinometers
- Deep Extensometers
- Tiltmeters
- Liquid Level sensor
- Crack gauges
- Compensation Grouting
Surface Settlement

Ground Loss 0.5%

Surface Settlement Criteria

Measured Surface Settlement varied from 0 mm to 2.5 mm
Deep Extensometer settlement 1.5 m above TBM

Settlement, mm

SURFACE SETTLEMENT 0 - 2.5 mm

EXTENSOMETER SETTLEMENT 1.5 m ABOVE TBM

Courtesy Prof. Edward Cording Muir Wood Lecture April 2018
Why Measured Settlement Was Less than Predicted?

- Overcut gap closure
  - Bentonite injection & pressurization
  - Pressure cells on shield perimeter
  - Immediate and continuous grouting
  - Shield gap pressure: volume injected to fill 30 mm gap + 35%
- Borehole Extensometers 50 ft (16m) on center to measure settlement at the source
- Piezometers in all extensometer boreholes
- Construction Monitoring Task Force

BENTONITE SLURRY INJECTED THROUGH PORTS INTO 30-mm GAP

CHAMBER PRESSURIZED WITH CONDITIONED MUCK

Courtesy Prof. Edward Cording Muir Wood Lecture April 2018
Construction Monitoring Task Force – Collaborative Approach

- TBM Work Plan
- Daily TBM Parameter Log
  - TBM Torque, Thrust, Rotation, Penetration Rate, etc.
  - Face Pressure
  - Shield gap
  - Pressure between advances
  - Tail grout injection and volume
  - Soil conditioning
  - Muck weight and volume

- Real time machine instrumentation
- Ground and structure displacements
- Correlated with TBM pressures

---

### Daily TBM Parameter Log

<table>
<thead>
<tr>
<th>Report #</th>
<th>135</th>
<th>revision #</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Station</td>
<td>25838</td>
<td>Current Ring #</td>
<td>977</td>
</tr>
<tr>
<td>Date From</td>
<td>12/9/16</td>
<td>Time From</td>
<td>5:00 AM</td>
</tr>
<tr>
<td>Date To</td>
<td>12/10/16</td>
<td>Time To</td>
<td>4:59 AM</td>
</tr>
</tbody>
</table>

#### TBM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target Advance Speed (mm/min)</th>
<th>40</th>
<th>Target Total Thrust Force (kN)</th>
<th>45,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target CHD Torque (%)</td>
<td>40%</td>
<td>Target Total CHD Force (kN)</td>
<td>153,000</td>
</tr>
<tr>
<td></td>
<td>Target CHD Rotation Speed (rev/min)</td>
<td>1.0</td>
<td>Penetration Rate (mm/rev)</td>
<td>40</td>
</tr>
</tbody>
</table>

#### WORKING PRESSURE

- **TOP Target Earth Pressure (bar)**: (average of sensors 11 & 12)
  - 3.2 Green Range
  - Lower 3, Upper 3.05

- **Keep System Settings (bar)**: (based on average of sensors 11 & 12)
  - Lower 3, Upper 3.05

- **GROUT PRESSURE**
  - **TOP Target Grout Line Pressure (bar)**: 5.5
  - **MID. TOP Target Grout Line Pressure (bar)**: 6.1
  - **MID. BOT. Target Grout Line Pressure (bar)**: 7.1
  - **BOTTOM Target Grout Line Pressure (bar)**: 7.5

- **GAP VOLUME**
  - **Grout Volume Target (m^3)**: 26
  - Green Range 22.1 to 31.2

- **SOIL CONDITIONING**
  - **Planned Ground Conditioning Recipe**:
    - Recipe 1: SLF (3.0%) plus Rehosoil 211 (0.5%)
  - **FER Target**: 3.0%
  - **FER Range**: 2.8% to 3.2%
  - **FIR Target**: 85%
  - **FIR Range**: 80% to 90%
  - **Target Advance Speed (mm/min)**: 40
  - **Target Total Thrust Force (kN)**: 153,000
  - **Target Total Thrust Force (kN)**: 45,000

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**Courtesy Prof. Edward Cording Muir Wood Lecture April 2018**
- Pressure across full face of ~ 2 bars
- Upper face pressure controls
- Between advances: maintained at 0.2 bars below target by pumping bentonite slurry which replaces air coming out of foam so that density and pressure in lower face increase
Lessons Learned on SR-99

- Closely spaced instrumentation provides unique assessment of the tunnel performance
- Ground movement & dynamic groundwater pressures to be monitored at the source
- Bentonite injection through the shield:
  - Shield pressures and volumes as indicators
- Minimize ground loss
  - Gaps filled & pressurized immediately
  - Elastic Settlement, settlement at the surface is minimal (0 to 2.5 mm)
  - Deep settlement is proportional to differential between overburden & TBM face/shield Pressure

April 4th, 2017
Project Description

- **Model:** Build – Operate – Transfer
- **Total Investment:** ~$1.3 Billion
- **Construction Period:** 55 Months
- **Operation Period:** ~ 26 Years
- **Total Project Length:** 14.6 km
  - Part-1: Europe side (5.4 km)
  - Part-2: Bosphorus Crossing (5.4 km)
  - Part-3: Asian side (3.8 km)

- **1st and 2nd bridges (total 7x2 lanes)**
  - 180,000 (1st) and 220,000 (2nd) crossings per day
- **Eurasia Tunnel (2x2 lanes)**
  - 110,000 crossings per day (both directions)
- **1st and 2nd bridges (total 7x2 lanes)**
  - 180,000 (1st) and 220,000 (2nd) crossings per day
- **Eurasia Tunnel (2x2 lanes)**
  - 110,000 crossings per day (both directions)
Connectivity of Istanbul

- Provides shortcut between Bakirkoy and Fatih regions in the European side and Uskudar and Kadikoy regions in the Asian side
- Considerable relief of traffic on the Bosphorus bridges
- Significant time savings for travelers - Reduce travel time from 100 min to 15 min each way
- Significant net savings in fuel consumption, emission, air pollution
- Shortest distance between Ataturk and Sabiha Gokcen airports
- Minimal visual impact - No effect on the appearance or the silhouette of Istanbul
- Respect to cultural heritage (UNESCO Surveillance)
**TBM Bored Tunnel**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel Cross Section</td>
<td>13.2m (43’-4”) outer diameter and 12.0m (39’-4”) inner diameter Double Deck</td>
</tr>
<tr>
<td>Water Pressure</td>
<td>11.0 bar</td>
</tr>
<tr>
<td>Tunnel Alignment</td>
<td>±5% - Depth 106m</td>
</tr>
<tr>
<td>Seismic Design</td>
<td>Consideration of Mw= 7.5 on main Marmara fault</td>
</tr>
<tr>
<td>Design Life</td>
<td>100 years</td>
</tr>
<tr>
<td>Segment Liner</td>
<td>60 cm precast concrete (8+1 configuration) (C50)</td>
</tr>
<tr>
<td>Upper Road Deck</td>
<td>Cast in-situ concrete (C50)</td>
</tr>
<tr>
<td>Lower Road Deck</td>
<td>Precast concrete (C40)</td>
</tr>
<tr>
<td>Tunnel Ventilation</td>
<td>Longt. Ventilation: Jet-fans and Vent Shafts at Portals 20Km/hr vehicle speed</td>
</tr>
<tr>
<td>Emergency Egress</td>
<td>1.12m wide Emergency Walkway / Escape Stairways at every 200m</td>
</tr>
<tr>
<td>Emergency Stops</td>
<td>At every 600m</td>
</tr>
</tbody>
</table>
Challenges

- Large-diameter/double-deck tunnel configuration
- Complex and variable geology and hydrology
- Mixed face conditions
- High water pressure (11 bars)
- High seismic zone
- Complex Transition Structures on Both Sides
**Complex Geology**

- **Bedrock:** Trakya formation sedimentary inter-layered sandstone, siltstone and mudstone. Highly fractured, folded, faulted, weathered, and intruded with volcanic dykes.
- **Soft ground:** is alluvial deposits consisting of coarse-grained soils (gravels and sands) to fine-grained soils (silts and clays) with beds of gravel and cobbles.
- **Mixed Face Conditions:** The tunnel passes through mixed face conditions rock to soft ground, soft ground to rock, and within the rock strata itself.
Geotechnical Investigations

GEOLOGICAL PROFILE OF BOREHOLE (BH1-2) EXPECTED HIGHEST FACE PRESSURE

- Rock Quality:
  - RQD < 25% – very weak
- Rock Mass based on Geological Strength Index (GSI):
  - Fractured – Weak locked and extremely fractured rock mass with angular and round rock particles
Mixed Face Tunneling

- Rock/soft ground interfaces
- Volcanic Dyke Intrusions of diabase, andesite and dacite up to 100m thick
- Highly variable rock strengths, abrasive mineralogy, and presence of stiff blocks embedded in soft matrix
- Faults at various locations across the tunnel alignment
- Sand, Gravel, and Cobbles
- Soft Silts and Clays

(From The nearby Marmaray Tunnel)
In Trakya Formation, dykes (andesite and diabase) cut through the sandstone/Mudstone layers. Such a geological setting creates a different rock mass medium with variable stiffness. Andesite/Diabase dykes have uniaxial compressive strengths more than 200 MPa. (30,000 psi). Cherchar Abrasive Index (CAI) is an indication of cutter disc/tools wear rate and in the case of dykes, this index increases up to 4.5 (extremely abrasive).

Pink color in geological profile corresponding to dyke zones faced during excavation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Asia Side Trakya Formation</th>
<th>Europe Side Trakya Formation</th>
<th>Overall Trakya Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Dyke Zones</td>
<td>6</td>
<td>23</td>
<td>29</td>
</tr>
<tr>
<td>Total Dyke Length (m)</td>
<td>28</td>
<td>397</td>
<td>425</td>
</tr>
<tr>
<td>Average Dyke Length (m)</td>
<td>5</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Average Dyke Frequency (m)</td>
<td>113</td>
<td>83</td>
<td>90</td>
</tr>
</tbody>
</table>

Note: Longest dyke is 120.0 m.
Tunnel Boring Machine (TBM)

Outer Diameter: 13.71m, Length: 120.0m, Weight: 3,300 ton, Water Pressure: 13 bar
## TBM Parameters

### TBM - GENERAL
- Maximum Face Pressure: 13 bar
- TBM Diameter: 13.7 m
- Length of the TBM: 120.0 m
- Weight of the TBM: ~3,300 t
- Installed Total Power: 10,330 kW
- Nominal Torque: 23,289 kNm (17,000 K-ft)
- Thrust Force: 247,300 kN (55,600 K)

### TBM – SPECIAL EQUIPMENT
- Φ2000mm Man Lock: 2 units
- Φ1600mm Center Lock: 2 units
- Material Lock: 3 units
- Shuttle (3200 x 1600 x 1600 mm): 1 unit

### CUTTING TOOLS
- Number of Total Disc Cutters: 35 (double)
- Diameter of Disc Cutters: 19 inch
- Atmospheric Changeable Cutting Knives: 48
- Hyperbaric Changeable Cutting Knives: 144
- Buckets: 12

### ENTS
- Outer Ring Diameter: 13.2 m (43'-4"
- Inner Ring Diameter: 12.0 m (39'-4"
- Ring Arrangement: 8+1 keystone
TBM Tunnel

- Designed to handle mixed-face conditions
- Operates in closed face mode to minimize uncontrolled ground losses and to avoid potential loss of face stability
- Most cutters can be replaced under atmospheric pressure
- A special lock system allows access under pressurized air at over 5 bars
- Launched on April 19, 2014; completed the drive on August 22nd, 2015
- Average daily advancement (working days) is at 9 m (29.5 ft) – Maximum 18 m (59 ft)

Rock Disc Cutter (19 inch Monoblock)
35 pieces

Soil scrappers (192 pieces)

12 Buckets

Jaw crusher

Avrasya
Cutter Change under Atmospheric Condition

- Spoke access under atmospheric conditions
- Tool exchange without working at tunnel face
- Back knives cutting replacement
- Back loaded Disc cutter replacement

- Double disk cutters (atmospherically changeable) 35qty
- Cutting knives (scrapers) (atmospherically changeable) 48qty
- Cutting knives (scrapers) (changeable under hyperbaric) 144qty
- Buckets (changeable under hyperbaric) 12qty
Saturation Diving
Saturation Diving

- 7 hyperbaric maintenance interventions and repair. Some are:
  1. 10.8 bars (Suction grid)
  2. 10.3 bars (Cutter-head)
  3. 9.8 bars (Suction grid)
  4. 8.5 bars (Stone crusher)
- Divers worked up to 12 days under hyperbaric conditions at a time
- Up to 7 days decompression period was needed
TBM Performance

- TBM is equipped with more than 300 sensors/parameters & online monitoring
- Major monitored TBM excavation parameters
  - Daily advance rates \((m/day)\)
  - Thrust forces \((kN)\)
  - Torque \((kNm)\)
  - Penetration \((mm/rev)\)
  - Revolution per minute \((rpm)\)
  - Face Pressure \((bar)\)
  - Utilization (%) 
  - Downtimes and root causes
Cutterhead Torque and Speed

- **Limit Torque**
- **Nominal Torque**
- **Breakage Torque**

**Source:** Yapı Merkezi R&D Department, 2015
**Face Pressure and Thrust Force**

- **3rd Hyperbaric Maintenance** for "Suction Grid Repair" at 9.8 bar
- **4th Hyperbaric Maintenance** for "Boulder Crusher Repair" at 8.5 bar
- **2nd Hyperbaric Maintenance** for "Cutterhead Inspection" at 10.8 bar
- **1st Hyperbaric Maintenance** for "Suction Grid Repair" at 10.8 bar

**Pressure at Tunnel Axis (bar)**

- 10.8 bar (90% of design capacity)
- 10.3 bar (90% of design capacity)

**Total Thrust Force (kN)**

- 239000 kN (97% of design capacity)

**Face Pressure and Thrust Force**

- Above 4.5 bar, saturation diving is required for maintenance/repair operations

**Excavation Direction**
Opening Day December 20th, 2016
Conclusions

- Tunnel construction technologies have advanced significantly in the last 20 years -- Further advancements are anticipated
- Tunnels are becoming larger, longer, in more challenging grounds and conditions
- Detailed risk assessment and risk management must be fully implemented taking into consideration all potential risks
- Risks are best managed by design of mitigation and reduction measures in a systematic way
- Aggressive, innovative thinking, and a cooperative partnering approach among various project stakeholders are essential for a successful project
- Set backs should not hinder the development or advancement of tunneling technologies or executing challenging projects
“Open... the ground in such a manner that no more earth shall be displaced than is to be filled by the shell or the body of the tunnel.”

Marc Brunel

Thank You
Questions?