Long and deep hard rock TBM Tunnelling under the Alps. Brenner Base Tunnel, Italian section

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ABSTRACT

Once completed, the Brenner Base Tunnel (BBT) will mark the record as the world longest railway tunnel, connecting Innsbruck in Austria and Fortezza (Bolzano) in Italy, with a 64km long complex underground infrastructure.

The paper describes the construction of the Italian stretch of the tunnel comprised between the Isarco River and the Italy-Austria border which includes 14km of twin main line tunnel excavated by two large diameter TBMs, 14km of emergency/exploratory tunnel with a smaller diameter TBM and 6km of twin main line tunnel excavated with conventional methods.

The complex logistic and the challenging underground activities are presented, with special consideration for the mechanized tunnelling works. The geology is extremely complex with different geological formation as granite, gneiss, marble and schist, interested by the “Periadriatic Fault”, an extended regional fault crossing the eastern alps caused by the collision of the African and European plate. Rock strength up 250 MPa and extreme abrasiveness, squeezing ground, aggressive waters pose severe challenges to the TBM advance.

Furthermore, the configuration and design of the tunnel boring machines for tunnels excavation is explained, including all the special plant and equipment required for the tunnelling works. Due the unforeseen geological condition and the squeezing rock with the overburden exceeding 1,600m, the paper describes the methodology to drive the TBM in these peculiar conditions.

1 INTRODUCTION

The Brenner Base Tunnel (BBT) is one of the most important infrastructures worldwide, when opened it will be the longest railway tunnel ever built with a total 64 km from entrance to exit portal. BBT is included in the Scandinavian-Mediterranean corridor, which is inside a wider continental project called Trans-European Transport Network (TEN-T). When completed in 2030, TEN-T will comprise a vast train network able to connect the most important nodes across Europe for freight and people transportation (European-Commission, 2020).
Lot Mules 2-3 is the biggest lot inside BBT, executed by the JV WeBuild-Ghella-Pac, therefore is considered one of the biggest sites in Europe at the time of its construction. This consists of the following (see Table 1):
- two Main Tunnels from Italian southern lot of Isarco until Italian-Austrian border. From Mules Adit towards north a 14 km stretch per tube, excavated with two TBM Double Shield of 10.71 m diameter and towards south with Drill & Blast;
- one Exploratory Tunnel, located in between the Main Tunnels and approximately 12 m below, for geological recognition is excavated from Mules Adit to Italian-Austrian border with a TBM Double Shield of 6.85 m diameter;
- an Access Tunnel excavated from Mules Adit to Trens Emergency Stop with Drill & Blast;
- an Emergency Stop, with cross passages for ventilation and evacuation purposes, excavated with Drill & Blast.

![Figure 1. Mechanized tunnels section view with cross passage.](image1)

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Method</th>
<th>Cross Section</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access to Trens Emergency Stop</td>
<td>Drill &amp; Blast</td>
<td>85-100 m²</td>
<td>4,500 m</td>
</tr>
<tr>
<td>Main Tunnels North</td>
<td>Drill &amp; Blast and TBM</td>
<td>90 m²</td>
<td>30,000 m</td>
</tr>
<tr>
<td>Main Tunnels South</td>
<td>Drill &amp; Blast</td>
<td>65-85 m² for single track</td>
<td>6,000 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>115-130 m² for double track</td>
<td></td>
</tr>
<tr>
<td>Exploratory Tunnel</td>
<td>Drill &amp; Blast and TBM</td>
<td>35 m²</td>
<td>15,000 m</td>
</tr>
<tr>
<td>Trens Emergency Stop</td>
<td>Drill &amp; Blast</td>
<td>90 m²</td>
<td>1,500 m</td>
</tr>
<tr>
<td>Cross Passages and Logistic Tunnels</td>
<td>Drill &amp; Blast</td>
<td>varies from 35 m² to 65 m²</td>
<td>7,000 m</td>
</tr>
</tbody>
</table>

![Figure 2. Lot Mules 2-3 layout.](image2)
Geologically, BBT is located between Austria (Innsbruck) and Italy (Fortezza). Tunnel runs beneath the Alps Mountain Range, specifically on the central sector of Western Alps, creating an alternative new route to the historically Brenner Pass.

From a geological point of view, BBT will pass through the major and most relevant tectonic units of the Alps. These units constitute the residual of the collision between the European and Adriatic (African) plate, forming a multiple overlapping stratum. Due to the extent of the entire project, different rock formations are expected to be encountered with variable rock mass resistance from 15 MPa up to 220 MPa and different mechanical behaviours.

Inside these different rock formations, is located one of the most critical areas of the entire project, the Periadriatic Fault which is the contact zone between European and African plate moving towards each other. This fault is part of the Periadriatic Seam which constitute a larger geological fault of 1000 km, running from the Tyrrhenian Sea along the Alp Mountain Range until Eastern Europe. Rock genesis can be divided in three main epochs:

- Cretaceous subduction,
- Collision between plates in the early Tertiary, and
- Tauer window formation in the lower early Tertiary.

From Mules Adit, excavation proceeds towards North with Drill & Blast until the chainage of the Assembly Chambers which have a cross section of 350 m². From this location to the Italian-Austrian border excavation proceeds with TBMs. Towards North, excavated material can be classified in two major categories:

- Metamorphic rocks such as Calcschists, Amphibolite and Marble encountered on the first 10 km, with variable UCS from 30 MPa up to 120 MPa, relatively low abrasion CAI index, high foliation and intercalation of fault zones. Depending on its geological composition, JV classified these materials as B+C spoil type, muck from these rocks could eventually be reused only for fill purposes;
- Metamorphic rocks on the last 5 km composed mostly by Gneiss, with high UCS from 50 MPa up to 250 MPa, high abrasion CAI index and high risk of interception the Brenner Thermal Waters, a precious resource to protect, nonetheless precious for local communities. Due to its geological composition, these rocks can be classified as A type of spoil, therefore reusable for many purposes.

Major risks faced by TBMs on the first 10 km were mostly identified in three main categories:

- Risk of TBMs blockage due to caving phenomena in fault zones and sectors with low RMR,
- Risk of TBMs blockage from rock-burst phenomena due to rock dip angle, rock’s geological composition and high overburden up to 1,700 m,
- Risk of encounter high water pressure flows, mostly in the areas with the lowest overburden in the entire project and in the transition area between Gneiss and Calcschists. These areas, due to high content of calcium and presence of high aggressive waters, are subjected also to low chemical dissolution inducing karst formation.

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**GEOLOGICAL PROFILE – TBM**

<table>
<thead>
<tr>
<th>Overburden (m)</th>
<th>1715 - 945</th>
<th>1010 - 755</th>
<th>1255 - 615</th>
<th>1610 - 1190</th>
<th>1500 - 905</th>
<th>1200 - 1095</th>
<th>1135 - 700</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_v$ (MPa)</td>
<td>218 - 47</td>
<td>117 - 15</td>
<td>106 - 54</td>
<td>117 - 15</td>
<td>98 - 54</td>
<td>140 - 75</td>
<td>116 - 72</td>
</tr>
<tr>
<td>RMR</td>
<td>75 - 60</td>
<td>65 - 30</td>
<td>65 - 30</td>
<td>60 - 30</td>
<td>60 - 30</td>
<td>70 - 60</td>
<td>70 - 42</td>
</tr>
<tr>
<td>CAI</td>
<td>4 - 6</td>
<td>1 - 4</td>
<td>2 - 3</td>
<td>2 - 3</td>
<td>2 - 4</td>
<td>3.5 - 4.5</td>
<td>4.5 - 5.5</td>
</tr>
</tbody>
</table>

Figure 3. Geological profile.
MECHANIZED TUNNELLING

Towards North from Mules Adit excavation is proceeding with 3 TBMs. For the Exploratory Tunnel, JV decided to use a Double Shield TBM with 6.85 m diameter; similarly, for the East and West Main Tunnels JV is using two Double Shield TBMs of 10.71 m diameter (see Table 2). TBMs were designed by JV and manufacturer to overcome intrinsic difficulties of the different rock masses to be excavated, such as:

- Squeezing rock,
- Caving,
- Fault zones,
- High water pressures inflows.

Moreover, due to the selection of a Double Shield TBM, if is considered the total extend of the thrust and auxiliary cylinders, shields have a total length of almost 15 m, this extended length could increase significantly the risk of TBM blockage under squeezing rock conditions.

Table 2. TBM technical data

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>TBM for Exploratory Tunnel</th>
<th>TBM for Main Tunnels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal boring diameter (m)</td>
<td>6.85</td>
<td>10.71</td>
</tr>
<tr>
<td>Shield length + Tail Skin (m)</td>
<td>12.3</td>
<td>12.7</td>
</tr>
<tr>
<td>Back-up total length (m)</td>
<td>275</td>
<td>205</td>
</tr>
<tr>
<td>Nominal thrust force (kN)</td>
<td>45,000</td>
<td>95,000</td>
</tr>
<tr>
<td>Exceptional thrust force (kN)</td>
<td>97,000</td>
<td>210,000</td>
</tr>
<tr>
<td>Nominal torque (kNm)</td>
<td>8,600</td>
<td>24,000</td>
</tr>
<tr>
<td>Breakaway torque (kNm)</td>
<td>14,000</td>
<td>30,600</td>
</tr>
<tr>
<td>Total power (kW)</td>
<td>4,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Max. theoretical advance rate (mm/min)</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Max. theoretical cycle time (ring/h)</td>
<td>5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

To overcome this potential risk, JV with manufacturer decided to increase TBMs conicity up to almost 0.017 for the Exploratory Tunnel and 0.019 for the Main Tunnel. TBM operators needed to be high qualified and high experienced because this out-standard conicity influence TBMs guidance.

Additionally, TBMs where manufactured with the possibility of increasing tunnel profile by lifting the Main Drive and changing cutting tools configuration of the Cutterhead. This procedure is programmed to be executed with the TBMs already assembled and could be performed at any stage of the project from inside TBMs. The maximum overcut designed is of 112 mm in diameter, resulting in an increase of the shield-rock gap on the crown of 224 mm after Main Drive vertical displacement.

This increase on the tunnel profile is calculated to be enough to permit rock mass to relax and give enough time to the TBMs to reach tunnel profile with precast rings before rock mass closure, thus preventing TBM blockage.

Despite to have an Exploratory Tunnel for geological recognitions of rock mass, despite JV performs regularly 150 m of probe drills in addition with a Tunnel Seismic Prediction (TSP) on the Exploratory Tunnel, Alps Geology is extremely variable and unforeseen to have different geological conditions at the same chainage for the three TBMs.

Even though all the measures taken to avoid TBMs blockages due to squeezing rocks, TBM for the Exploratory Tunnel suffered an extreme fast closure of tunnel profile at 1,600 m below the surface, forcing the construction of a rescue lateral tunnel of 15 m length and 3.5 m² cross section, with Drill & Blast to release TBM shields. In case of caving in fault zones, TBMs were equipped with 2 different probe drills, one installed on the Bridge and a second smaller removable probe drill to be installed on the Erector when needed.
TBM shields were configured with two sets of probe holes to allow the execution of eventual consolidation campaigns, from Gripper Shield and Front Shield. Additionally, a set of holes were placed near the Main Drive to allow the consolidation of tunnel face from the Cutterhead.

Figure 4. View of lateral rescue tunnel under construction in squeezing rock mass.

Figure 5. Position of drilling machines inside TBM (Herrenknecht AG, 2017).

Figure 6. TBM drilling pattern (Herrenknecht AG, 2016).
For these situations, TBM were designed to exert an extraordinary force with the auxiliary cylinders up to 200,000 kN on the last installed ring in single shield mode. Additionally, Main Drives were designed with a low gear able to overcome Cutterhead blockages able to resist 31,000 kNm for the Main Tunnels and 14,000 kNm for the Exploratory Tunnel.

Moreover, to control eventual rock mass lying on shields, a set of extension pistons were installed in specific positions. This data is used to verify real shield-rock gap, afterwards real tunnel profile is used to estimate real amount of spoil extracted per meter of advance. Furthermore, this information is compared with data available from belt scales installed inside TBM to identify over excavation of tunnel profile. Furthermore, a set of pressure earth sensors were installed around shields to control eventual rock lying on TBM surface shields. Data from pressure cells and extension pistons are used to identify eventual closure of tunnel profile in squeezing rock conditions.

[Image: Extension pistons & Pressure cells scheme installed on TBM of Exploratory Tunnel (Herrenknecht AG, 2016).]

Even though these measures against fault zones and caving risk areas, TBM for the Exploratory Tunnel suffered a blockage due to poor rock mass conditions in fault zone. However, JV conducted successfully a consolidation campaign with self-expanding one component cement injected through VTR à manchettes pipes inserted on bore holes made with probe drills installed on the Bridge and Erector.

Purpose of an exploratory tunnel is to retrieve useful information regarding rock mass conditions and eventually presence of water prior the excavation of the Main Tunnels. Contemporary, a probe drill of 150 m had to be made from the TBM of the Exploratory Tunnel at every 125 m of advance, leaving 25 m of overlapping from two consecutive probe drills.

Data like thrust, rotation speed, torque from probe drills and information from Tunnel Seismic Prediction like Static and Dynamic Young modulus, shear Modulus and waves seismic speed were processed to estimate rock mass condition of the Exploration Tunnel prior its excavation with TBM.

These crucial information about rock mass that TBM will face in the following advances, influence excavation approach and parameters like Cutterhead rotation speed or for example in condition of unexpected risk of squeezing (define by probe drilling and TSP) some adjustment could be implemented, like installation of 20” cutters in the gauge area and increase tunnel profile by lifting the Main Drive and Cutterhead.
As already discussed, all this information obtained during the Exploration Tunnel excavation plus the ones retrieved by pressure earth sensors and extensions pistons on the shield are producing a large set of data that are being used during Main Tunnels excavation.

This standard drilling procedure led to a major risk of water interception, in sensitive predefined areas on tunnel alignment. These zones were identified by Client and a risk analysis was made, JV proposed a procedure to protect precious water sources for local communities such as the Brenner Thermal Waters and Kaltwasser source, nonetheless to keep undisturbed the fragile environmental equilibrium of the Alps biodiversity.

In fact, to guarantee any disruption to the surrounding environment, JV along with specialist on the oil and perforation sector designed a Blow-Out-Preventer (BOP) able to resist 150 bars of pressure to be used while probe drills execution. BOP is lifted employing TBM’s Erector and allocated in position to allow drilling and control water inflows.

4 TBM DISASSEMBLY

Since the TBMs involved on the Mules 2-3 Lot reached (S-1054 for the Exploratory Tunnel) and will reach (S-1071 & S-1072 for the Main Tunnels) the Italian-Austrian border before the consecutive lot on the Austrian side, the TBMs don’t have a typical breakthrough with the entrance of the TBM in station or cavern.

The end of Mules 2-3 Lot on the norther side is located 1,600 m below the border at the Brenner Pass and approximately 19 km from the portal, therefore the TBMs have to be the disassembled in the tunnel from the inside without the standard heavy equipment used in a typical disassembly like cranes and/or overhead cranes.

The disassembly of a TBM from the inside of the tunnel requires detail program in order to:

1) Ensure the safety of all the personnel involved in the tunnel at any time,
2) Complete the disassembly on time to move forward with the finishing works.

The TBM used to excavate the Exploratory Tunnel (S-1054) reached the Brenner Pass in November 2021, however a series of preparatory works was needed in order prior the TBM disassembly.

A substantial challenge involved the disassembly of the Cutterhead due to the confined space and the dimensions of approximately 7 m diameter. Also, for safety reasons and Italian regulation no workers were allowed to work in front of the Cutterhead in between the tunnel face and the TBM, forcing the entire disassembly of the Cutterhead from inside the Cutterhead. Several options were studied: overturn the
Cutterhead, cutting the Cutterhead steel structure in small size and anchor the Cutterhead to the tunnel face to cut it vertically at the final stage of the disassembly.

However, the solutions mentioned involved a substantial working hour and also the risk for the workers was considerable high. Therefore, a different solution was adopted that involved the utilization of the hydraulic system and the power of the TBM to reduce the safety risks involved in such task and to shorter the schedule for the TBM disassembly.

The concept of the new idea for dismantling the TBM ‘s Cutterhead was studied together by the JV and the TBM manufacturer. The idea was to use the advantages of a Double Shield TBM in which, with the employ of the gripper shoes located at the Gripper Shield and the stabilizers located on the Front Shield, it is possible to move the TBM forward in while building the tunnel, but also allows the TBM to move backwards if needed.

With this option, it was possible to section Cutterhead structure from the inside of the Cutterhead, the procedure followed was to:

1) Reach the final chainage of the tunnel,
2) Disassembly the entire accessories from the Cutterhead (cutters, bucket, etc.),
3) Remove the Muck Ring,
4) Anchor the bottom part of the cutterhead to the tunnel,
5) Cut the first piece at the bottom,
6) Move the TBM backwards approximately 2 m,
7) Turn the Cutterhead in order to have the second piece to cut at the bottom,
8) Anchor the second piece to the first piece already disassemble,
9) Cut the second piece at the bottom,
10) Move the TBM backwards approximately 2 m,
11) … repeat the process until the last part is disassembled.

To have a clearer understanding of the process see sequence on Fig 9.
While driving the TBM backwards it was needed to demount the rings in order to move allow the shields translate. This should have been a relatively easy operation; however, this was not allowed since while disassembling the shield, workers will have face the tunnel profile without any support, hence in direct contact with the rock. This situation was not allowed for safety reasons, therefore the JV had to apply a new solution for this problem.

The solution adopted comes from a Gripper/Open TBM where the support is composed by rock bolt and steel mesh installed immediately at the rear of the TBM’s Shields. This meant that a Double Shield TBM was converted into a Gripper TBM for the last meters of tunnel excavation. This allowed to place the Shields below a consolidated tunnel profile while moving backwards, to ensure a safe work environment for workers while dismantling the Shields of the TBM. For a better understanding of this procedures see Fig 11.
The concept of a Double Shield TBM is well known in the tunnelling industry, this type of machine allows the installation of a ring while proceeding with the excavation. Once the last ring is installed and the excavation is finished, the backups, the Gripper Shield and the Tail Skin are translated with a phase called Regrip. During this phase the Primary Thrust Cylinders retract and the Auxiliary Thrust Cylinders extend. This is allowed because the last installed ring support the force of the regrip phase.

For the last few meters of excavation, where no rings were installed, the JV had to modify the hydraulic scheme in order to complete the regrip phase to proceed with the next advance in Double Shield Mode. The modification consisted in using the Stabilizers on the Front Shield as a second pair of Grippers Shoes, which anchor the Front Shield to the rock, these created enough friction to avoid any displacement of the Front Shield. Afterwards the pressure lines and tank lines were inverted electronically and allowed to retract the Primary Cylinders with the result of pulling the backup, Gripper Shield and Tail Skin instead of pushing them on the last ring.

After cutting the first piece of the Cutterhead, the hydraulic scheme was modified in order to displace the TBM backwards. In this case the Stabilizers of the Front Shield were anchored to the rock in order to avoid any displacement of the Front Shield. Afterwards, the Primary Cylinder were set in the Double Shield excavation mode and allowed to push backwards the backup, Gripper Shield and Tail Skin, until the Primary Cylinders reached their maximum extension. Then the inverse of the regrip phase was conducted by anchoring the Gripper Shield with the Grippers Shoes to the rock and the Primary Cylinders were set to retract by modifying the hydraulic scheme electronically, this allowed the Front Shield to move backwards until the Primary Cylinders were completely closed. This process was repeated until the Tail Skin reached the last installed ring.

After the disassembly of the Cutterhead, the operations for disassembly the back-ups of the TBM were followed. The back-ups were detached and transported by rail to the assembly chamber 14 km away where it was possible to install a crane suitable for heavy lifts.

5 CONCLUSIONS

When completed and in service, BBT will be the longest tunnel rail link in the world, its importance will not only be measured from its length but also for the complexity of the logistics, variable geology encountered and environmental risk mitigation while its construction.

JV along with its partners where able to stand out and fulfil Client’s requirements by proposing innovative engineering methodology and environmental solutions to a massive project such as the Brenner Basis Tunnel.

6 REFERENCES