Case history of hard rock TBM

La Maddalena exploratory adit for the Turin-Lyon high speed railway base tunnel

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The HSR network in Europe: like a giant Metro-System connecting main cities
The “Mediterranean Corridor” will connect Seville (Spain) to Budapest (Hungary).
The Turin-Lyon high-speed rail project is halfway along the future “Mediterranean Corridor” from Seville (Spain) to Budapest (Hungary).
The Turin-Lyon HSR project includes:

- **French section**, between Saint-Didier-de-la-Tour (East Lyon) and Saint-Jean-de-Maurienne, managed by RFF;
- **International section** (France-Italy), which crosses the Alps between Saint-Jean-de-Maurienne (France) and Susa (Italy), managed by a bi-national agency (TELT - Tunnel Euralpin Lyon Turin) governed by Italian and French gov.;
- **Italian section**, from Susa to outskirts of Turin, managed by Italian RFI.

**Mechanized Tunnelling:**

- **Open air section**
- **Tunnel section**
- **New stations**
- **Safety site**

The project includes a 57 km-long Alpine base tunnel, whose construction will be starting soon.
The base tunnel has four adits:
- three in France (all completed)
- one in Italy (under completion) – La Maddalena.
Scope of «La Maddalena» exploratory adit:

- **Investigation** of rock mass and TBM performance for detail design of base tunnel
- **Construction** of «Clarea» safety cavern on base tunnel
- **Access** to base tunnel for maintenance or emergency
### «GEA» Main Beam TBM (Robbins MB1812-299-2)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Machine Diameter</td>
<td>6.30m</td>
</tr>
<tr>
<td>Overboring</td>
<td>0.1- 0.2m</td>
</tr>
<tr>
<td>Number of disc cutters</td>
<td>43 (17”)</td>
</tr>
<tr>
<td>Maximum Recommended Individual Cutter Load</td>
<td>311kN</td>
</tr>
<tr>
<td>Normal Operating Cutterhead Thrust @4200PSI</td>
<td>12,756kN</td>
</tr>
<tr>
<td>Periodic Maximum Cutterhead Thrust @4500PSI</td>
<td>13,667kN</td>
</tr>
<tr>
<td>Cutterhead Drive</td>
<td>7 electric motors, gear reducers and brake</td>
</tr>
<tr>
<td>Cutterhead Power</td>
<td>2,954HP</td>
</tr>
<tr>
<td>Cutterhead Speed</td>
<td>0-10.8rpm</td>
</tr>
<tr>
<td>Cutterhead Torque @ 10.8 rpm</td>
<td>2,083kNm</td>
</tr>
<tr>
<td>Stroke</td>
<td>1.83m</td>
</tr>
<tr>
<td>Number of Main Thrust Cylinders</td>
<td>4</td>
</tr>
<tr>
<td>TBM weight (approx.)</td>
<td>250 ton</td>
</tr>
</tbody>
</table>
Main beam TBM assembly under telescopic shed at tunnel entrance
Present state of “La Maddalena” construction

6,500 m excavated
Quaternary deposits
- Tectonic carbonatic rocks
- Ambin Rock complex (Aplitic Gneiss)
- Ambin Rock complex (Quartzitic Micaschists)
- Clarea Rock complex (Micaschists)

Schematic geological profile

chainage 6+500
Overburden approx. 1,910 m

Max overburden 2,012 m

Overburden approx. 1,910 m

Quaternary deposits
MAX RMR: 98
MAX GSI: 98

MAX $\sigma_c$: 236MPa (lab test)

AS-BUILT – RMR

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>I</td>
<td>6.1%</td>
</tr>
<tr>
<td>II</td>
<td>46.1%</td>
</tr>
<tr>
<td>III</td>
<td>47.1%</td>
</tr>
<tr>
<td>IV</td>
<td>0.7%</td>
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</tbody>
</table>

Extremely hard and abrasive rock mass
Rock mass rated fair (III) to good (II)
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- 19.1% Occasional Bolting
- 21.6% Systematic Bolting
- 38.5% Light Steel Ribs
- 20.8% Heavy Steel Ribs

Longitudinal Steel Re-bars at Tunnel Crown
## Mechanized Tunnelling: Challenging Case Histories – 01 December 2016 - Rome

<table>
<thead>
<tr>
<th></th>
<th>Weekly Hours Available for Excavation</th>
<th>Hours Worked per Week</th>
<th>Labour Availability</th>
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</thead>
<tbody>
<tr>
<td>3 Shift Teams (exc. 24h/d 6d/w)</td>
<td>168</td>
<td>124</td>
<td>73.8%</td>
</tr>
<tr>
<td>4 Shift Teams (exc. 24h/d 7d/w)</td>
<td>168</td>
<td>168</td>
<td>100%</td>
</tr>
</tbody>
</table>

4 Shift Teams vs. 3 Shift Teams:
Hours Available for Excavation

**+35,5%**
Observed behaviour of rock mass
Effects from stress release were evident even with relatively low overburden (less than 400m).

Stand-up time in unsupported rock began to be systematically shorter than usually experienced (Bieniawski, 1989). Excavation often proceeded with relatively low TBM thrust on the face, leaving broken rock at tunnel crown.
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Z.T. Bieniawski, 1989
Bieniawski '89 – Stand-up time

Stand-up time for 6 m roof span (hrs)

RMR

0 1 2 3 4 5 6

10E+00 10E+01 10E+02 10E+03 10E+04 10E+05 10E+06
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![Graph showing RMR vs. Stand-up time for 6 m roof span (hrs) with different markers for Brittle failure, Stable, and Unstable wedges.](image-url)
Production now safely proceeds with installation of circumferential steel ribs connected with 120°arch of longitudinal steel re-bars

**Lesson learnt:** new type of support with circumferential steel ribs and longitudinal steel re-bars
Less work required to excavate with brittle failure at face
The most important brittle failure event occurred at 11 p.m. of 21/12/2015 around ch. 4+200 having a visible effect on support for a length of 10-12m of excavated tunnel.

The rock mass, classified RMR = 61-72 and GSI = 62-75, presented subhorizontal schistosity and open discontinuities often with carbonate fill. Overburden was of about 1,000m.

Workers heard a sudden smash. This was accompanied by large deformation of supports.
Significant rock fragmentation at crown (result of failure between new/existing discontinuities and schistosities)

Lesser disturbed conditions with generally stable sidewalls
Rock fragmentation and observed behaviour correspond to a **Bulking without ejection** event (CRRP, 1996): the stored strain energy was consumed in the fracturing process, with significant increase of volume due to dilatancy.

There was no significant release of kinetic energy (rock ejection at high velocity).
Numerical modelling

← Step 1: parametric analysis
  \( ko=0.3-0.8-1.2; \ldots \)

Likely scenario:

- Failure criterion
  "spalling" (Diederichs)
- \( ko = \frac{\sigma_h}{\sigma_v} = 1.2 \)

Step 2: based on CSIRO tests results (niche 3) →
Deviatoric stress (σ1-σ3)

a) Fracturing starts («damage»)

\[ \sigma_1 - \sigma_3 \approx 0.4 \text{ UCS} \]

b) Potential rockburst conditions

\[ \sigma_1 - \sigma_3 \approx 0.7 \text{ UCS} \]

(*) Castro, McCrath & Kaiser (1995)

3D NUMERICAL ANALYSIS
**OBSERVED MECHANISM**

- Fracturing (damage) starts near excavation face at crown and invert
- Potential rockburst conditions from about one diameter behind face
- Depth of damage is at max 1-1.5m from excavated profile
Brittle failure events, from ch. 4+200 onwards, were less intense

Change in morphology/stress

Event at ch. 4+200

Niche 3
ch. 2+805
SUMMARY AND CONCLUSIONS

• The main beam hard rock TBM used for La Maddalena exploratory adit has excavated 6.5km in a rock mass (gneiss and micaschists) rated from fair to good and has reached the exceptionally high overburden of 2,000m under Mount Ambin.

• Stress release effects, with fracturing and failures especially at tunnel crown, have accompanied excavation since overburden exceeded about 400m, when it was observed that stand-up times in unsupported rock began to be systematically shorter than usually experienced (Bieniawski, 1989).

• Another side effect from stress release, with fracturing at tunnel face rather than at tunnel crown, was the reduction of TBM thrust, torque and head rotation velocity required for excavation.

• The type of brittle failure observed is of dilatant fracturing (or “bulking without ejection”), a rockburst mechanism without significant release of kinetic energy.
SUMMARY AND CONCLUSIONS

• Only on one occasion, at the end of 2015 when overburden was of the order of 1,000m, rock mass bulking provoked large deformations of tunnel steel rib supports.

• Even now, with 2,000m overburden, minor brittle failure continues to take place, always without violent rock ejections.

• Tunnel profile supports have since been adapted, by using systematic protection with a 120° arch of longitudinal steel rebars supported by circumferential steel ribs, a solution which allows to continue excavation even when the rock mass at crown has broken into fragments.

• The new supports brought to an immediate sustained increase of percentage of use of TBM (efficiency), from under 35% to over 55%, allowing productions of about 12m/day as opposed to about 4m/day in unstable crown conditions.
Mechanized Tunnelling: challenging case histories

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