Hard rock extreme conditions in the first 10 km of TBM driven Brenner Exploratory Tunnel

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This first part of the Brenner exploratory tunnel was bored entirely through very hard granitic rocks under high cover. In certain locations extremely adverse geological events were encountered by the TBM. A long section of the tunnel was confronted by extensive rock burst phenomena. In another section of the tunnel the thrust of high pressure ground water on the tunnel walls caused the sudden collapse of 40 m of precast lining immediately behind the TBM. This paper describes in detail these occurrences as well as the methods and special design measures implemented to overcome them.

Along the entire tunnel the rock mass parameters were measured. RMR (Rock Mass Rating) and RME (Rock Mass Excavability) values and classes were determined and are presented here. The RMR and RME classifications are compared with and correlated to the TBM advances and penetration rates. The TBM advances were predicted using the formula based on RME and compared with the ones actually achieved.

More than 2500 cutter changes were performed and the relevant data are presented also in relation with the RMR and RME classes.

INTRODUCTION

The Brenner Pass is the most important North-South connection in the entire European Union. The Brenner Basis 55 km long Tunnel forms the central element of the Munich-Verona route, which in turn forms part of the railway route called TEN-T n.1 Berlin-Palermo.

In the context of the design and construction of the Basis Tunnel, the Exploratory Tunnel is of fundamental importance. Its function is to provide a continuous survey along the whole route of the Basis Tunnel, thus enabling a geological survey on the real scale, indispensable for the correct final design and for the planning of the best methods for boring the main tunnels. The surveys thus cover the most problematic sections from the geological and hydrogeological point of view; a detailed picture of the rock formations is obtained, which is useful for design purposes.

Furthermore, during the construction of the two main tunnels, the exploratory tunnel will allow for the transport of excavation material, the transport of construction material, the drainage of water and the eventual pre-consolidation of the rock formation in zones proving to be critical.
SURVEYS AND TESTS CONDUCTED

During the excavation of the tunnel, monitoring of the rock mass bored was conducted. This monitoring is first of all necessary to guarantee the safety of personnel, as well as to correctly identify the rock formation in order to collect data useful for the design of the two main tunnels. Table 1 shows a summary of the monitoring activities and tests which are described below in greater detail.

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<td>Survey of cutter parameters</td>
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<td>Incremental extensometers</td>
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<td>Hydrogeological monitoring with piezometers</td>
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<td>Pressure cells, extensometers with vibrating wire</td>
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</table>

The main surveys and tests conducted are described below in greater detail.

Survey of the boring machine parameters

The TBM (PLC) system is designed to record all the main parameters of the machine, and produce a “TBM file” recording the following information at regular intervals of 10 seconds: date, time, advance stroke [mm], extension of the thrust cylinders [mm], rotation speed of the cutter head [rpm], torque transmitted by the single motors and total [kNm], penetration rate [mm/min and mm/rpm], thrust of the jacks on the head and on the segments [kN], pressure of the grippers [bar], absorbed power at the cutter head [kW] and amps of each motor [A]. The information contained in the “TBM file” is used daily at the construction site to verify the data supplied by the operator in the excavation reports, the performance of the machine in special conditions and the use of the machine within the allowed limits of thrust and torque. The linear regression in Figure 1 shows a close relationship (R²=0.70) between the thrust applied and the penetration, showing the correct operation of the TBM.

Figure 1. Correlation of the boring Thrust with the Penetration Rate

Figure 2. A window for geologic mapping pk 8875
Geo-mechanical surveys of the face

The geological survey provides the basis of the geotechnical information used to study the interaction between the rock mass and the machine, besides being a means by which the owner and the contractor can quantify the expected rate of advance of the TBM for contract purposes.

In each work shift, a person in charge of the survey enters the cutter head to reach the excavation face and conduct there a survey. Furthermore, every 125 m the installation has been planned of a window opening on the right-hand sidewall (Figure 2) in order to take samples so that lab tests can be performed on the rock (UCS, Brazilian tensile strength, Cerchar Abrasivity Index).

BEAM

In order to ensure the safety of personnel and the TBM from any sudden worsening of the stability of the rock mass or from unfavorable hydrogeological conditions, an advanced state of the art continuous monitoring system has been implemented: the BEAM (Bore Tunneling Electrical Ahead Monitoring) based on the emission of weak alternate electric current enabling the monitoring of a prism of rock up to a maximum depth of approximately 3 diameters in front of the cutter head. The instrument is positioned on the head of the TBM. The monitoring records the permeability of the rock (porosity) and the fracture status by means of two parameters:

- PFE (%) = Percentage Frequency Effect - this is the capacity of the rock mass to store electrical energy and is mutually related to the porosity of the rock.
- Resistivity (Ohm) - provides additional information on the presence of fractures and underground cavities (Gas/water or air).

Seismic investigation

The purpose of seismic investigation in advance of boring is to make an indirect geological and geomechanical survey of the rock mass near the cutting face by seismic reflection. The results of the investigation enable us to verify the model of the rock where the tunnel is excavated and, if necessary, to update it. This information can help us decide if and to what extent excavation strategy must be adjusted to the real geomechanical conditions. The capacity of investigation of this survey is 100 – 150 m, and the overlapping of the areas surveyed is in any case ensured.

This is achieved by drilling holes approximately every 50 m on the sidewall (depth 2 m, diameter 42 mm), and the placing of geophones or acceleration sensors, with subsequent measurement of the signals deliberately produced near the cutting face and reflected by the geological formations. Three single-component sensors are installed in each section in three separate borings. Six active sections are used. An impulse charge is applied approximately every 6 m by an explosive inserted in other holes of the same diameter and length.

Prospecting during advance

Approximately every 50-60 m of excavation, starting from the shield tail, a 51 mm diameter hole is made, with measurement of the drilling parameters (dac-test) above the top of the tunnel. The length and the pitch of the drillings are such that they are positioned to have at least 5m of drilling already undertaken in front of the cutting face. The dac-test consists in the continuous recording of the main drilling parameters, conducted with destruction of the core, in order to recognize the basic stratigraphic features of the rock mass and make a direct verification of the geology encountered.

The necessary equipment consists of:

- Rotary percussion drilling machine;
- Electronic device for the measurement, amplification and recording on magnetic support of the following drilling parameters: thrust applied to the cutting tool [MPa]; speed of advance [m/h]; rotation torque [MPa]; slurry pressure [MPa]; rotation speed [rpm]

When drilling, maximum steadiness is sought. In particular, the thrust applied to the tool is kept constant, when possible, kept constant for the entire drilling and such as to ensure that the most resistant levels can be overcome without too much loss of consistency of the results.
The analysis of the excavation surface is conducted daily during maintenance shift of the machine and during work shifts at least once at the beginning of the shift, or several times between boring operations if the conditions of the rock mass change (according to the parameters of the TBM and/or the consistency and condition of the material removed by the conveyor belt). The survey consists in the drawing up of a printed report showing the characteristics of the rock mass for which parameters are assigned, the sum of which defines the RMR quality index (Bieniawski 1989). Table 2 shows the distribution of the RMR classes of rock encountered. The RMR index is by definition a single survey of the rock face, so that it is not directly related to the average penetration rate for the day when the survey was made. If, on the other hand, we consider the parameters of the machine for each one of the advance stroke on which the geotechnical survey of the face has been made, we obtain definitely improved relations between RMR and TBM parameters. Table 3 and Figure 3 show how the main excavation parameters depend on the geological conditions and with respect to theoretical performance the better results are in class IV rather than in class III. However it should be observed that rock classes IV and V have been encountered much less frequently than the other classes, and therefore the statistical analysis is less reliable. For a comparison that best illustrates how the performance of the TBM depends on geological conditions, the average value of the RMR index, and the corresponding excavation parameters for 50 m stretches of tunnel, have been calculated. It was thus possible to compare the parameters and the geological conditions with spatial regularity, and create representations showing how the excavation parameters depend on the geological conditions (Figure 4). The geotechnical conditions of the rock also vary considerably in 50 m excavation stretches with considerable swings occurring in the values corresponding to the excavation parameters and to the RMR index. In order to reduce these swings, the trend in mobile averages made on 15 values was determined, in order to better observe these ratios over the series. The comparison between the penetration rate and the RMR quality index shows symmetry along a horizontal axis, while the thrust applied to cutter head, excluding the initial learning phase, showed trends almost parallel to the RMR index (Figure 5).

<table>
<thead>
<tr>
<th>Class</th>
<th>Frequency of the Classes</th>
<th>Penetration rate [mm/rpm]</th>
<th>Boring Thrust [kN/cutter]</th>
<th>Torque [kNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>178</td>
<td>2.5</td>
<td>214.282</td>
<td>923.8</td>
</tr>
<tr>
<td>II</td>
<td>512</td>
<td>3.7</td>
<td>199.578</td>
<td>1141.2</td>
</tr>
<tr>
<td>III</td>
<td>236</td>
<td>6.1</td>
<td>161.781</td>
<td>1272.4</td>
</tr>
<tr>
<td>IV</td>
<td>41</td>
<td>8.1</td>
<td>127.725</td>
<td>939.5</td>
</tr>
<tr>
<td>V</td>
<td>12</td>
<td>5.8</td>
<td>145.276</td>
<td>974.6</td>
</tr>
</tbody>
</table>

Table 2. Distribution of RMR classes

Table 3. RMR Classes – TBM Parameters

Figure 3. RMR Classes – TBM Parameters
EVALUATION OF THE RME INDEX (ROCK MASS EXCAVABILITY)

As above mentioned, a window was installed every 125 m on the right-hand sidewall in order to take samples and thus conduct lab tests. The RME index was calculated near these windows, since sufficiently reliable UCS values were only available in these positions. Lab results showed that the UCS varies in a range between 75 MPa (pk 8500) and 195 MPa (pk 2100).

The Drilling Rate Index value of each section analyzed was estimated by applying the empirical formula proposed by Palmström (1995), deriving the DRI value from the UCS value:

\[ DRI = E \cdot \sigma_c^{-0.6} \]  

where \( E = 1000 \) (hard non-schist rock, \( \sigma_c > 45 \))

The number of irregularities and their orientation with respect to the direction of the tunnel, the homogeneity of the face, the water flow rate at the face and the stand up time were assessed by direct inspection of the cutting face and the windows. The calculation of the rates assigned to the partial indexes, the total of which defines the RME index, was conducted with reference to the graphs proposed by Bieniawski (Bieniawski et al. 2008), shown in Figure 6.
The RME values have been compared with the values of the main TBM parameters measured, and the results are shown in the following graphs (Figure 7). We can see that the linear regression applied shows good results with regards to the penetration, with an increasing trend as the RME increases. In other words, it shows greater penetration as the boreability of the rock increases while there is little correlation with regard to thrust values.

**RME - Forecast and observed penetration rates**

In order to use RME as a tool to forecast rates of advance of the TBM, the concept of average rate of advance, better known as ARA, has been applied. The ARA was calculated taking into consideration the sections adjacent to the open windows where the RME was calculated.

It should be stressed that the sections considered to obtain the ARA are subjected to the following conditions (Bieniawski, 2008):
1. Length of the section >30 m
2. No significant variations of the RME and a representative RMR value (not varying by more than 10 points)
3. No extraordinary repairs to the TBM
4. Coefficient of utilization (efficiency) of the TBM between 30% and 60%.

It was not possible to respect all the above conditions on all the sections analyzed, since the rock mass in some sections was characterized by rapid changes and limited by the geological conditions. In order to have sufficiently homogeneous sections, in some cases sections of less than 30 meters long were considered.

### Table 4. Distribution of RME classes

<table>
<thead>
<tr>
<th>Class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>48</td>
<td>396</td>
<td>252</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>%</td>
<td>7.0%</td>
<td>56.8%</td>
<td>36.2%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

The geology (and thus the RME index) is not the only factor influencing the excavation advance rate. The factors listed below also have significant influence on the advance of the TBM (Grandori 2007):

1. Diameter of the TBM:
   a. the rotation speed of the head (and thus the penetration rate of the TBM) decreases in a linear manner with the diameter of the machine;
   b. the time for the installation of the prefabricated tunnel segments increases with the diameter of the TBM.

The influence of these two factors is due to the fact that with geological conditions being the same, the use of a TBM with a diameter of 12 m results in penetration rate 50% lower with respect to diameters of 3.5m.

2. Efficiency of the site:
   a. the experience and know how of the construction company;
   b. the quality and expertise of the personnel;
   c. the location of the site.

These three factors have an approximately equal weight, and can reduce the advance rate of the TBM by up to 50%.

3. The learning phase. In the first months of tunneling, lower rates of advance are observed due to a lower coefficient of utilization, because of the adjustment of the equipment and the excavation organization to those specific geotechnical conditions.

The ideal conditions for reaching the maximum advance rate are:

a) RME = 100;
b) TBM diameter of 3.5 m
c) Full efficiency of the site

Under these ideal conditions the machine can achieve a maximum theoretical production of 120 m/d and therefore an average production of 60 m/d. In relation to these hypotheses, the following formula was proposed:

\[
ARA\, [m\, /\, d\, ] = 60 \cdot \frac{RME}{100} \cdot C_D \cdot C_E \cdot C_L + 0.23 \cdot RME - 14.5
\]

(2)

where,

- RME is the index forecast or measured in a given section of tunnel;
- \( C_D \) is the coefficient for the diameter of the TBM (D) calculated with the formula:
  \[
  C_D = 1.2058 - 0.0588D
  \]

(3)
- \( C_E \) is the coefficient for the efficiency of the site and can be estimated by the following formula:
  \[
  C_E = 0.5 + C_c + C_m + C_a
  \]

(4)

where the following coefficients appear:

- \( C_c \) takes into consideration the experience of the contractor undertaking the works, and can have values ranging from 0 to 0.2:
Table 5. Cc index on the experience of the contractor undertaking the excavation

<table>
<thead>
<tr>
<th>Experience Level</th>
<th>No TBM Projects</th>
<th>1-5 TBM Projects</th>
<th>5-10 TBM Projects</th>
<th>10-20 TBM Projects</th>
<th>&gt;20 TBM Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cc</td>
<td>0.00</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
<td>0.20</td>
</tr>
</tbody>
</table>

- Cm refers to the quality of the personnel and ranges from 0 to 0.15:

Table 6. Cm index on the quality of the personnel

<table>
<thead>
<tr>
<th>Quality Level</th>
<th>Poor quality</th>
<th>Average quality</th>
<th>Good quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cm</td>
<td>0.00</td>
<td>0.10</td>
<td>0.15</td>
</tr>
</tbody>
</table>

- Ca refers to the logistic conditions of the site and can have values ranging from 0 to 0.15. This coefficient depends on the following factors: the transport time to the site including customs procedures (0.075 for times less than one month, 0 in other cases), availability of local suppliers (0 for absence of suppliers, 0.075 otherwise);

- C_L is the coefficient taking into consideration the effect of the learning phase on the total time for completing the works. This coefficient varies according to the length of the tunnel to be excavated:

Table 7. CL index for the effect due to the learning phase

<table>
<thead>
<tr>
<th>Tunnel Length</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 4 km</td>
<td>0.85</td>
</tr>
<tr>
<td>4 to 8 km</td>
<td>0.90</td>
</tr>
<tr>
<td>8 to 12 km</td>
<td>0.95</td>
</tr>
<tr>
<td>&gt; 12 km</td>
<td>1.00</td>
</tr>
</tbody>
</table>

On the basis of what has been said previously, the following values have been assigned to the Brenner construction site:

Table 8. Brenner coefficients

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_D (D=6.3 m)</td>
<td>0.84</td>
</tr>
<tr>
<td>Cc</td>
<td>0.2</td>
</tr>
<tr>
<td>Cm</td>
<td>0.15</td>
</tr>
<tr>
<td>Ca</td>
<td>0.15</td>
</tr>
<tr>
<td>C_L (length 10 km)</td>
<td>0.95</td>
</tr>
</tbody>
</table>

The real advances reached indicate that the model has a reasonable correspondence to reality, as shown in the graph in Figure 8.
Theoretic trend

Real Trend

R² = 0.29

Figure 8. Correlation between the RME and the ARA (average rate of advance)

From the figure above, it is confirmed that a linear and unique correlation exists between the RME and the ARA, therefore the proper use of the RME index in the characterization of a rock mass from the point of view of the TBM excavation is justified.

Most probably, the observed difference between the ARA and the actual advance rate could be a result of the following aspects:

1) the DRI has been calculated according to the empirical formula (1) and the results are too much approximate, so that the RME index is overestimated: lab tests to determine DRI in 8 of the considered stretches have given an average value of 35 in respect of a value of 48 estimated via the empirical formula. This difference gives a value of the RME index overestimated of 5 points;

2) the tunnel has been excavated inside a rock mass characterized by very high stresses generated by very high overburden and tectonic phenomena: the TBM has was able to excavate in a rock mass with an higher strength than that determined in laboratory tests. An introduction in the ARA calculation of an additional corrective coefficient, based on the overburden, should be considered to include this special aspect.

EXCEPTIONAL EVENTS: THE COLLAPSE OF THE LINING AND ROCKBURST

Collapse of lining pk 6.150

The excavation of the tunnel started in June 2008. At the start of the works, during the so-called “learning phase”, lasting about 1 month, the TBM went through a very hard (Bieniawski Class I and II) and highly abrasive (CAI> 5) rock mass, very different from that forecast in the planning phase. The difficult conditions have made it impossible to achieve extensive penetration rates, as well as causing a substantial increase of replacements of cutters. These conditions persisted for the first 2 km, where the rate of advance was approximately 9.5 m/day and efficiency about 50%. From January 2009, production improved considerably although the sections crossed by the TBM were characterized by alternating zones with intact rock and zones with fractured rock (Figure 10). In the zones where the rock mass was less intact / more and more fractured, the TBM reached a production of 30 m/day.
Figure 10. Monthly production at the Brenner Exploratory Tunnel

Unfortunately, on 9 August 2009 at km 6+151, the day after the TBM had passed, the left-hand sidewall lining of the tunnel partially collapsed for a length of approximately 30 meters. This incident led to a stoppage of work lasting about 5 months. Thanks to the reconstruction of the geological model, the presence of a sub-vertical fault was identified parallel to the direction of excavation, not forecast in the design phase. The interaction between deforming stresses due to the excavation and stresses due to the particular features of the fault lead to a highly asymmetrical load on the tunnel section, thus damaging the lining and causing its collapse (Figure 11).

Figure 11. Detail of lining collapse

After the TBM stopped, a number of activities were undertaken with the following objectives:

1. Ensuring the safety of the tunnel
2. Restoring the internal section so that the TBM could resume operation
3. Start up of the TBM again in the stretch involving the fault sub-parallel to the excavation
4. Defining the procedures and the instruments for ensuring greater safety for the continuation of the advance until the Mules access tunnel was reached.

The following activities were undertaken to ensure the safety of the tunnel:

1. Installation of 2.2m long steel bolts secured with resin between points km 6+103 and 6+127, to sustain the crown of the lining
2. Transfer of the back-up decks back from km 6+105 to point 6+080
3. Installation of no.2 HEB100 ribs for each ring of lining between points km 6+087 and 6+105.

Following the phase described above, the situation in the tunnel was as follows (Figure 12):

- km 6+151 – 6+139: face position
- km 6+139 – 6+105: beam connecting the back-up decks and the TBM with the below segment carrier partially blocked by shifts in the lining
- km 6+139 – 6+120: segment carrier
- km 6+139 – 6+128: portion of segment carrier blocked by shifts in the lining
- km 6+105 – 6+080: portion of tunnel substantially free from blockages

Figure 12. Outline of the collapse of the segments

The following measures were undertaken to remedy this situation:

1. Dismounting of the portion of the segment carrier not blocked by the shifts in the lining
2. Injections of organic-mineral expansive resins to fill the area most subjected to loosening, just behind the segments between points km 6+104 and 6+139 on the left-hand sidewall, a process preparatory to subsequent injections
3. Injections of organic-mineral resins in 3m thick layer (maximum drilling depth possible using a self-supporting drill bit) between points km 6+104 and 6+130 on the left flank (Figure 13)
4. Execution of radial nails with 6m or 3m long self drilling bars (according to whether a drilling machine or a self supporting drill bit can be used) between points km 6+080 and 6+139 in the portion of lining from the invert segment up to 2 o’clock, except for the areas of lining to be demolished and replaced
5. Execution of core boring for checking and eventual drainage 4-6m along the left-hand sidewall
6. Cutting, demolition and replacement of the reinforced concrete segments showing excessive shifts and/or breakage, for subsequent smaller portions, with steel panels (Figure 14) and subsequent rear filling of panels with cement, and the installation of radial nails with 3 m long self drilling bars.

This activity, conducted on no.17 rings, was completed on 15/11. Four pairs of extensometers with vibrating wire were installed on two replaced segments to verify their behavior with resuming of tunneling operation.
Once the lining of the tunnel was restored, the HEB100 ribs were removed between points km 6+087 and 6+105, to make it possible to shift the back-up decks forward again and to restore the hydraulic and electric connections with the TBM. However, the TBM, after being trapped for 3 months in the fault area, proved to be blocked; after several attempts to restart it using high pressure, it was decided to make an “unlocking” tunnel on the left-hand sidewall (Figure 15).

This tunnel was made with the following work phases:
1. Injection with stabilizing resins
2. Excavation with manual sledgehammer
3. Installation of ribs (10 HEB100 ribs)
4. Installation of no.30 6 m long self drilling nails
5. Advance with wooden spile drivers
6. Installation of wooden struts

After the tunnel for “unlocking” was completed, it was necessary to repair the parts of the TBM damaged due to the heavy pressure to which it had been subjected. The grippers showed widespread deformation of both shoes, a puncture on the front part of the shoe and the collapse of a supporting flank. It was necessary to remove part of the shoe, rebuild the damaged flank and restore the correct functioning of the grippers.

The shield showed widespread elasto-plastic deformation on the entire left side with considerable denting on the lower zone. The gravel sealing brushes were also damaged and had to be replaced. The elastic component of the deformation was eliminated once the shield was freed by means of the tunnel, and the plastic component was recovered with the use of hydraulic jacks. The tunnel was then filled with pea gravel,
and stabilizing resin was then injected. The total filling of the tunnel was ensured by using tubes with different lengths for the resin and the gravel.

Before resumption of boring, an investigation was conducted at the face with 2 continuous drillings with recovery of cores and monitoring by georadar. The first 50 m of tunnel were built by placing special steel rings, and a further type of lining was designed and installed, consisting of concrete segments reinforced with 20 mm dia. re-bars. On the basis of the incident, specific risk management was developed.

On 3 December 2009, the TBM resumed excavation. The production rates in the month of December were adversely affected by the installation of the steel rings, requiring very long installation times, and by the execution of advance monitoring by georadar. In the first 20 days of January, the TBM recorded an average production of over 17 meters per day, thus resuming its normal work cycle.

Rockburst pk 6.700

On 01 February 2010, just 560 m from the restarting of the excavation, the TBM had to face another geological event. At 8:30 p.m., during the excavation phase, a serious rockburst occurred, followed by the release of considerable portions of rock mass, with the immediate blockage of the cutter head. In the days before the blockage of the TBM, the conditions of the rock remained almost constant, without any warning of the event that was to occur. On the other hand, by definition there is no advance warning of this phenomenon, involving the sudden release of energy and causing the subsidence in the rock mass with serious deformations of the excavation even in rock with favorable mechanical characteristics. The penetration rates and thrust pressures before the event indicated that the rock was of medium to high strength, as also confirmed by the RMR classification of the excavation face. The thrust pressures for the regripping phase indicated that the excavation was not subjected to deformations.

The rock mass stratification presented three different families of discontinuities: one family on the tunnel crown with an average spacing of about 40 cm and altered joints; a second one on the left side parallel to the tunnel axis also with altered joints; the third one on the right side of the tunnel with the same characteristics of the second.

The first operation conducted, after the occurrence of the blockage of the cutter head, was to free the TBM head from the weight of the rockslide. Smaller blocks of rock were removed manually, as much as possible, through the openings at the front loading buckets, while microcharges were used to break and remove larger blocks. After each blast, the rock fragments were removed manually through the housings of the cutters previously dismounted. Operations continued slowly, because of the difficulty of the work and the small spaces where personnel had to work until the cutter head was freed; after 2 days of work, the cutter head could rotate again. However, the front shield was also blocked by the collapsed blocks after the rockburst. After the remounting of the cutters on the cutter head, attempts were made with high pressure thrust, but without success.

In order to free the upper part of the front shield, subject to the pressure of the rock, drillings were made from the upper part of the telescopic shield so that small charges could be exploded. Because of the lack of results of the thrust attempts after the first blast and after the removal of the rock fragments, a second series of drillings was undertaken, again from the upper part of the telescopic shield, but despite thrusts at more than 22000 kN the blockage situation was unchanged.

However, the use of small blasts gave excellent results in terms of freeing the front shield, since each explosion brought loose material in front of the head, and this material was then removed (Figure 16).

![Figure 16. View from above the TBM](image)
The first phenomenon was not followed by further collapses and therefore the rockslide was limited to a certain area. The removed material was not substituted by new collapsing portion of rock mass and, therefore, the cavity around the cutter head was made bigger step by step and allow the head to be freed. The material produced by the small blasts of the second phase was directed towards this cavity and with the rotation of the cutter head it was easily removed front the face.

Given these results, the technical staff decided to continue in this way to avoid excavating another “unlocking” tunnel, involving considerable costs and time.

New hatches measuring approximately 300mm on the side were opened in the zone of the telescopic shield, in order to check the condition of the rock and allow the execution of further blasts (Figure 17).

Figure 17. TBM profile – borings from the gripper shield

The procedure for freeing the front shield by microcharges continued by shifting the zone of intervention to the lower part of the shield.

By continuing work in this direction, and making thrust attempts after each blast, the personnel finally freed the TBM.

Figure 18. Last borings made

Excavation resumed with reduced advance rates (“half strokes” have been used) to avoid inducing instability in the rock mass with excessive stress releases. The cavity behind the lining was filled with gravel. Pipes were inserted in the section affected by the rockburst for subsequent filling with resin or cement.

INFLUENCE OF GEOLOGICAL CONDITIONS ON REPLACEMENT OF CUTTERS

The wear of the cutter is highly important in mechanized excavation, especially in hard and abrasive rock, as was the case of the Brenner exploratory tunnel. At the end of the excavation, 2,556 cutter replacements were recorded for a total length of 10,419 m of excavation, corresponding to a performance rate of 4.07 m/cutter which, multiplied by an excavation area of 31.2 m² means a performance of 127 m³/cutter.

It is thus highly important to evaluate the influence of the geological conditions on the wear of the cutters; an attempt has thus been made to correlate the RMR and RME indexes with cutter replacements.

The graph in Figure 19 was made by using an RMR value (average RMR) every 50 m and the number of cutters replaced in the same 50 m, in order to have a statistical sample of the same size between RMR and the number of cutter replacements.
The analysis shows that the number of cutter replacements undoubtedly depends on the geological conditions of the rock mass: as the RMR increases, and therefore as the compactness of the rock formation increases, the number of cutters replaced also rises, and on the contrary falls with the RMR when the rock formation becomes less compact. The graph in Figure 19 shows that this relation is also numerical but the correlation is not especially strong ($R^2=0.29$) because on the one hand the RMR value depends solely on the conditions of the rock mass and not on its excavability, and on the other hand on the number of cutter replacements depends on additional factors. Table 9 shows the link between cutter performance and the RMR class.

Finally, a comparison has been made between the theoretical estimate of cutter wear on the basis of the RME index and actual wear. Although the RME structure includes the DRI index, in order to make an estimate of cutter wear, it is necessary to take into consideration a specific abrasivity index. The best and most convenient one is the Cerchar Abrasivity Index (CAI) (Bieniawski et al. 2009). In the tunnel concerned, 55 CAI values were recorded, distributed continuously along the tunnel. The average value calculated is 4.2 and no test gave values lower than 3.5, thus indicating the presence of moderately to high abrasive rock. On all the sections considered for the calculation of the ARA, the number of changed cutters was determined and the performance was calculated, expressed as changed cutters/excavated m$^3$.

The graph in Figure 20 shows the results obtained in relation to theoretical performance (for CAI $>3$) expressed by the following relation (Bieniawski et al. 2009):

\[
\frac{\text{Changed \_Cutter}}{\text{Excavated \_m}^3} = 7 \cdot 10^{6} \cdot \text{RME}^{-5.3} \tag{5}
\]

Only performance rates for RME values higher than 60 were considered, since the exponential trend suggests an excessive number of cutter changes for RME less than 60. For this relation (5), values of RME ranging higher than 60 were therefore used.

As we can see, the values measured are scattered, but in any case they show that as the RME index, in respect of the RMR index, can better represent the phenomenon of an exponential increase of the cutter changes in the “less boreable” rock mass.
CONCLUSIONS

The surveys and tests conducted during the excavation of the Brenner Exploratory Tunnel, together with the collected TBM parameters and the experience gained in the overcoming of exceptional events, provided invaluable information to optimize the design and the excavation methods for the construction of the Brenner main tunnels.

Also in this project, it clearly appears that the RMR system is an optimum method to classify a rock mass and to define the design requirements of a tunnel but, on the other hand, it is less reliable/representative to forecast the TBM advance rate.

The RME index which is very easy to determine uses some of the same parameters as the RMR index, and represents an excellent means to assess a rock mass in respect of its excavability with a TBM. The correlation between the RME index and the advance rate is, in fact, linear.

The difference highlighted in the comparison between estimated ARA and the actual advance rate is to be found in the in-situ rock mass conditions, specifically related to the stress field in the rock resulting from the high overburden and by tectonic occurrences. Whether, an additional coefficient should be introduced in the formula of the ARA, to consider the above special effects is being discussed.

Regarding the overcoming of the encountered exceptional events, it is emphasized that in a deep tunnel with very high overburden the forces of the nature can generate unforeseeable and extremely critical conditions and that, at the same time, such conditions can be faced and overcome by innovative technologies and the expertise and the devotion of the specialized personnel.

REFERENCES