Introduction

The construction of a tunnel using a TBM requires an accurate knowledge of the rock mass as the face is almost inaccessible and therefore the information that can be obtained from it is limited. Also because the TBMs are very sensible to the rock mass characteristics and its possibilities to adaptation to other conditions not foreseen is quite difficult.

In Guadarrama tunnels one of the tunnels (In the North Portal, the eastern one) goes always ahead the other. This circumstance makes very interesting to make a precise supervision in the first one, in order to:

- Foreseen the ground behaviour in relation with the TBM performance.
- Extrapolate the TBM behaviour from one tunnel to the parallel one.

The methodology set up includes the following activities:

- Geological and geomechanical prediction.
- Information collected from the tunnels excavation.
- Data storage and exploitation.

2 Geological and Geomechanical Prediction

The main objective of this activity is to have a prediction of the ground conditions ahead the TBM face.

In Galera et al. (2006) it has been explained the importance of geological mapping as well as geophysical prospecting and in situ testing, for this purpose.

Following that methodology for the each 500 m of tunnel that roughly correspond to a month of advance a prediction sheet was done. Figure 1 shows an example of this prediction sheet.
It can be observed that this prediction sheet includes the following information:
- Geological profile and description.
- Lithology.
- Discontinuity spacing.
- Hardness and abrasivity.
- Water presence.

Also in the right hand side it includes the recommendations for the TBM, as follows:
- Working mode (Double or Single Shield TBM).
- Thrust (kN).
- Penetration (mm/rpm).
- Rotation speed (rpm).
- Time for inspection of the cutter wheels (TBM head).

3 INFORMATION COLLECTED FROM THE TUNNEL EXCAVATION

3.1 Tunnel Face
The access to the tunnel face in a Double-Shield TBM is very restricted. Nevertheless in some maintenance gaps, it is possible to access to it. Usually this access is done through the windows included in the TBM head (cutter-wheels, bucklets or man windows).

The information collected from the face is shown in the sheet included in Figure 2, that contains the following:
- Face scheme, mapping lithologies and geological structures.
- UCS estimation, using point load tests ($I_{550}$).
- RMR determination (Bieniawski, 2003).
- Discontinuities (strike, dip, spacing, roughness, filling).
- Photos.

Figures 3, 4 and 5 include photos taken on the tunnel face.
These photos have been systematically taken from the three different available windows at the TBM head.

Exceptionally it has been possible to visit the face of the tunnel while some maintenance stops. Figure 6 shows the aspect of the face in one of these occasions.
3.2 Chip inspection

The most usual way to analyse the ground condition in a tunnel excavated using a TBM, is following the chips coming from the TBM head. Figures 7, 8 and 9 show the way in which the cutter wheel creates different types of chips, depending on the kind of ground.

Figures 10, 11 and 12 include photos showing the type of chips coming from a homogeneous face, fractured face and faulted-gouge.
3.3 TBM drilling parameters

The following TBM drilling parameters have been systematically recorded:
- Advance rate (ARA)
- Time of excavation
- Weigh of the debris in the belt
- Thrust (total/contact) (F)
- Rotation speed (N)
- Torque (T)

Two different interpretations can be done:
- Qualitative
- Quantitative

In the first type the following circumstances have been noticed:
- A significant increase in the rate of advance with an decrease in the geomechanical ground quality.
- An increase in the debris weight with a face instability.
- Instantaneous torque increase with a face instability.
- The difference between the applied and the contact thrust is equivalent to the TBM friction. If this value increase the TBM can get stucked.

In relation with a quantitative interpretation, the following values have been considered:
- Penetration rate (p)

\[
p (mm / r) = \frac{V (mm / m)}{N (rpm)}
\]  

(1)

that gives the ground resistance to be excavated.
- Penetration index (\(I_p\))

\[
I_p = \frac{F (kN)}{p}
\]

(2)

that proportionates the thrust per cutter to penetrate 1 mm per revolution.
- Specific energy of excavation (\(E_s\))

\[
E_s (kJ / m^3) = \frac{F}{A} + 2\pi \cdot N \cdot T \cdot A \cdot ARA
\]

(3)

where \(E_s\) = specific energy of excavation (kJ/m³), 
\(F\) = total cutterhead thrust (kN), 
\(A\) = excavated face area (m²), 
\(N\) = cutterhead rotation speed (rps), 
\(T\) = applied torque (kN·m) and 
\(ARA\) = average rate of advance (m/s).

As it can be observed there are two addends, the first one corresponds to the thrust energy \((E_{st})\) while the second one corresponds to the rotation energy \((E_{sr})\).

- Correlation between \(I_p\) vs. \(E_{sr}\).

Figures 13 and 14 shows the existing relation between the penetration index and the specific rotation energy of excavation.

![Figure 13. Relationship between \(I_p\) and \(E_{sr}\) for 500 segments rings.](image)

![Figure 14. Correlation between \(E_{sr}\) and \(I_p\) \((E_{sr} = 8 \cdot I_p^{0.52})\).](image)

In the first one it can be observed the direct relation between both parameters considering 500 segment units. From this relation it can be concluded that the specific energy depends on the
geomechanical quality of the rock mass as the penetration index does.

3.4 Discontinuities at the excavation face

The Norges Lekmsk-naturritenskaplig Universitet (NTNU, 1994) made a classification (see Table I).

In the Guadarrama tunnels the discontinuities spacing has been determined:
- Directly from the mapping of the face.
- Indirectly from the debri type at the belt.
- Indirectly from the TBM drilling parameters.

Table I. Rock Mass Classification, considering discontinuities spacing (NTNU, 1994).

<table>
<thead>
<tr>
<th>ROCK MASS CLASSIFICATION</th>
<th>DISCONTINUITIES SPACING (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Massive</td>
</tr>
<tr>
<td>0-I</td>
<td>160</td>
</tr>
<tr>
<td>I</td>
<td>80</td>
</tr>
<tr>
<td>I-II</td>
<td>40</td>
</tr>
<tr>
<td>II</td>
<td>20</td>
</tr>
<tr>
<td>III</td>
<td>10</td>
</tr>
<tr>
<td>IV</td>
<td>5</td>
</tr>
</tbody>
</table>

In Table II it is shown the relation between them.

Table II. Criteria to establish the rock mass spacing discontinuities at the excavation face, considering different criteria.

<table>
<thead>
<tr>
<th>Rock Mass Type</th>
<th>Spacing (cm)</th>
<th>Joints/m</th>
<th>I_p</th>
<th>E_u (kJ/m²)</th>
<th>Debris</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>&gt;40</td>
<td>4</td>
<td>20-30</td>
<td>40-60</td>
<td>chips</td>
</tr>
<tr>
<td>II</td>
<td>20</td>
<td>4-8</td>
<td>10-15</td>
<td>20-30</td>
<td>chips and occasional blocks</td>
</tr>
</tbody>
</table>

3.5 Rock sampling

The aim of this activity was to obtain information about basic rock mechanics properties of the excavated rock mass.

Each 125 m of tunnels a small borehole (70 cm aprox.) was drilled, obtaining samples to carry out the following tests: density, sonic velocity, UCS, brazilian, point load test, petrographical analysis, DRI and Cerchar abrasivity.

In Table III it is shown the average parameter obtained for the different lithologies excavated in the tunnels of Guadarrama.

4 CONCLUSIONS

The methodology followed during the excavation of the tunnel of Guadarrama for its geotechnical control, has consisted on:
- Mapping of the tunnel face.
- Chips inspection.
- TBM drilling parameters record.
- Discontinuities spacing at the excavation face.
- Rock sampling.

This methodology has proved to be efficient for the geological and geomechanical prediction of the rock mass to be excavated.

Table III. Geomechanical properties of the Guadarrama lithologies.

<table>
<thead>
<tr>
<th>LITHOLOGY</th>
<th>Density (gr/cm³)</th>
<th>UCS (N/mm²)</th>
<th>Is50</th>
<th>σ_t (N/mm²)</th>
<th>V_p (m/s)</th>
<th>Qz (%)</th>
<th>Quartz equivalent (%)</th>
<th>DRI</th>
<th>CLI</th>
<th>Cerchar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthogneiss</td>
<td>2.703</td>
<td>89.6</td>
<td>8.30</td>
<td>9.5</td>
<td>5100</td>
<td>33</td>
<td>53</td>
<td>46</td>
<td>13.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Adamellite</td>
<td>2.625</td>
<td>85.9</td>
<td>7.50</td>
<td>7.6</td>
<td>5095</td>
<td>33</td>
<td>55</td>
<td>55</td>
<td>11.7</td>
<td>3.1</td>
</tr>
<tr>
<td>Leucocratic Granite</td>
<td>2.591</td>
<td>95.1</td>
<td>7.71</td>
<td>9.0</td>
<td>4737</td>
<td>33</td>
<td>57</td>
<td>42</td>
<td>9.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Episienite</td>
<td>2.582</td>
<td>75.6</td>
<td>4.50</td>
<td>5.6</td>
<td>4686</td>
<td>3</td>
<td>34</td>
<td>55</td>
<td>18.6</td>
<td>2.4</td>
</tr>
<tr>
<td>Granitic Porphyr</td>
<td>2.598</td>
<td>125.0</td>
<td>9.18</td>
<td>13.0</td>
<td>5530</td>
<td>22</td>
<td>47</td>
<td>37</td>
<td>12.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Diorite</td>
<td>2.723</td>
<td>152.1</td>
<td>10.34</td>
<td>-</td>
<td>5577</td>
<td>1</td>
<td>32</td>
<td>38</td>
<td>27.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Paragneiss</td>
<td>2.759</td>
<td>-</td>
<td>9.00</td>
<td>10.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Marble</td>
<td>2.711</td>
<td>-</td>
<td>5.30</td>
<td>7.3</td>
<td>-</td>
<td>0</td>
<td>9</td>
<td>71</td>
<td>64</td>
<td>1.4</td>
</tr>
<tr>
<td>Skarn</td>
<td>2.726</td>
<td>-</td>
<td>8.10</td>
<td>9.9</td>
<td>-</td>
<td>3</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pegmatite</td>
<td>2.756</td>
<td>110.3</td>
<td>-</td>
<td>9.7</td>
<td>-</td>
<td>47</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Quartz</td>
<td>2.657</td>
<td>76.0</td>
<td>6.84</td>
<td>-</td>
<td>5805</td>
<td>99</td>
<td>99</td>
<td>47</td>
<td>5.3</td>
<td>3.1</td>
</tr>
</tbody>
</table>

5 BIBLIOGRAPHY
