GEOTECHNICAL CONTROL DURING THE EXCAVATION OF THE TUNNEL OF GUADARRAMA

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ABSTRACT: The tunnels of Guadarrama are new twin tunnels crossing the Central Range between Madrid and Segovia, as part of the new High Speed Railway Line to the NW of Spain. Their length is 28,3 km with a maximum overburden of 900 m. The geology consists mainly of crystalline rocks, gneiss and granites, with a main graven in the Lozoya valley where poor quality sedimentary rocks from the Cretaceous are crossed. Nevertheless several faults have also been detected with mylonites and water. The tunnels have been done using four double-shield TBMs, all of them with an excavation diameter of 9,5 m. The information that can be accessed from the face during its excavation with a Double-Shield TBM is generally limited. Nevertheless during Guadarrama tunnels excavation a close control of the excavated ground has been carried out, in order to allow the prediction of ground conditions ahead the TBMs. The applied methodology consists in: - geotechnical face characterization – inspection of the excavated chips – analysis of TBM drilling parameters. In relation with face characterization, conventional mapping of the face has been done as well as short boreholes (<1 m) through the lining segments. These cores have provided samples for laboratory conventional tests (UCS, PLT, Vp,…). The inspection of the waste chips has consisted not only in the weight in the belt but also in the size and shape of the waste. Finally, the drilling parameters controlled were: - rate of advance – time of excavation – weight of material in the belt – thrust – rotation speed – torque. These basic drilling parametes have been used to obtain the drilling specific energy, that has shown to be a very powerful index to predict ground conditions in the face. By means of this analysis the prediction of ground conditions ahead the TBM face was successfully done, specifying discontinuities spacing and condition.

1 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.

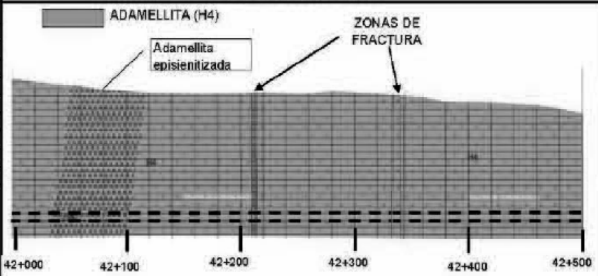
Following that methodology for the each 500 m of tunnel that roughly correspond to a month of advance a prediction sheet was done. Figure 1 shows an example of this prediction sheet.

TUNELES DEL GUADARRAMA BOCA NORTE	PREVISIÓN GEOLÓGICA SEGÚN RECONOCIMIENTO SUPERFICIAL Y RECOMENDACIONES	LOTE Nº 3 Del PK 42+000 al PK 42+500	FICHA Nº3 10-sep-03

DATOS DEL TRAMO

COTA TERRENO	
PK 42+000	PK 42+500
1202,45	1123,84
COTA RASANTE	
PK 42+000	PK 42+500
1227,07	1124,85
RECUBRIMIENTO (m)	
PK 42+000	PK 42+500
32,62	9,01
OBSERVACIONES DEL TRAMO	

PERFIL LONGITUDINAL



OBSERVACIONES

El túnel en este tramo se excavará, en general, en **adamellita porfídica "Tipo La Granja", muy competente y poco fracturada**, excepto:

- Entre el PK 42+340 y el PK 42+330
- Entre el PK 42+215 y el PK 42+205

donde se prevé que se atravesarán dos zonas fracturadas.

También se prevé atravesar una zona episienitizada a partir de PK 42+100.

ANILLO COLOCADO		PK DEL FRENTE		LITOLOGÍA BÁSICA	CARACTERIZACIÓN		GRADO DE FRACTURACIÓN	PRESENCIA DE AGUA	RECOMENDACIONES						COD.
Desde	Hasta	Desde	Hasta		Dureza	Abrasividad			M. Oper.	Emp. Total	Emp. Contacto	Penetración	Rpm rueda	Insp. Rueda corte	
2844	2945	42+500	42+340	Adamellita	Alta	Muy alta	Poco fracturado	Seco	DOBLE ESC.	19000-21000 kN	-	6-10 mm/rpm	5	2-3 avances	
2950	2950	42+340	42+330	Adamellita	Alta	Muy alta	Fracturado y muy fracurado	Seco	DOBLE ESC.	16000-18000 kN	-	8-12 mm/rpm	3,5 - 4	2-3 avances	
3020	3020	42+330	42+215	Adamellita	Alta	Muy alta	Poco fracturado	Seco	DOBLE ESC.	19000-21000 kN	-	6-10 mm/rpm	5	2-3 avances	
3025	3025	42+215	42+205	Adamellita	Alta	Muy alta	Fracturado y muy fracurado	Poco caudal	DOBLE ESC.	15000-16000 kN	-	8-12 mm/rpm	3 - 3,5	2-3 avances	
3025	3091	42+205	42+100	Adamellita	Alta	Muy alta	Poco fracturado	Seco	DOBLE ESC.	19000-21000 kN	-	6-10 mm/rpm	5	2-3 avances	
3091	3125	42+100	42+030	Adamellita episienitizada	Muy alta	Alta	Localmente fracturado	Seco	DOBLE ESC.	20000-22000 kN	-	4-8 mm/rpm	4 - 4,5	2-4 avances	
3125	3153	42+030	42+000	Adamellita	Alta	Muy alta	Poco fracturado	Seco	DOBLE ESC.	19000-21000 kN	-	6-10 mm/rpm	5	2-3 avances	

Figure 1. Example of a prediction sheet for the ground conditions ahead the TBM face.

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_{S50}).
- RMR determination (Bieniawski, 2003).
- Discontinuities (strike, dip, spacing, roughness, filling).
- Photos.

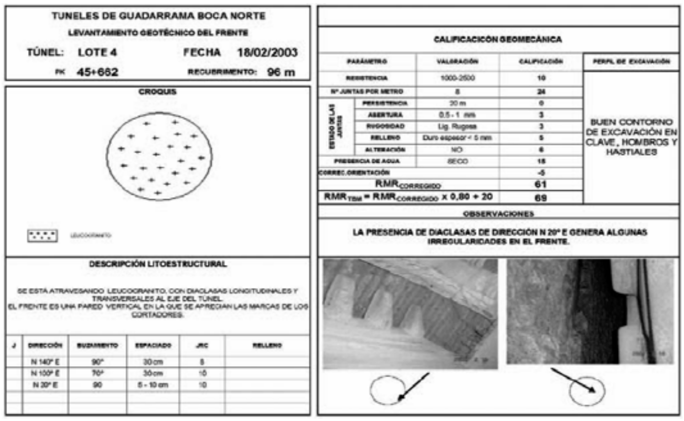


Figure 2. Example of the geotechnical information obtained from the mapping of the face.

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.

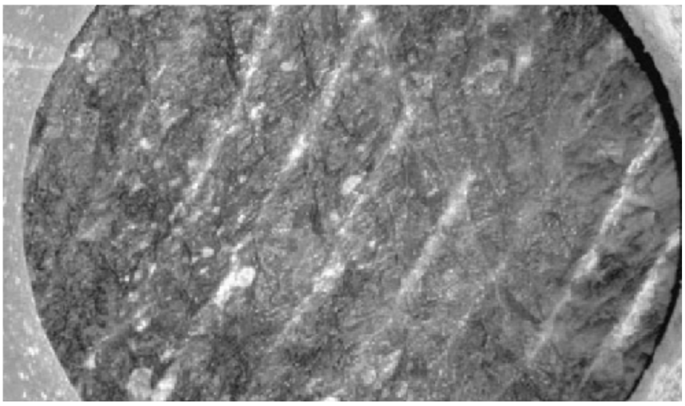


Figure 3. Face view taken through the man window in the TBM head.

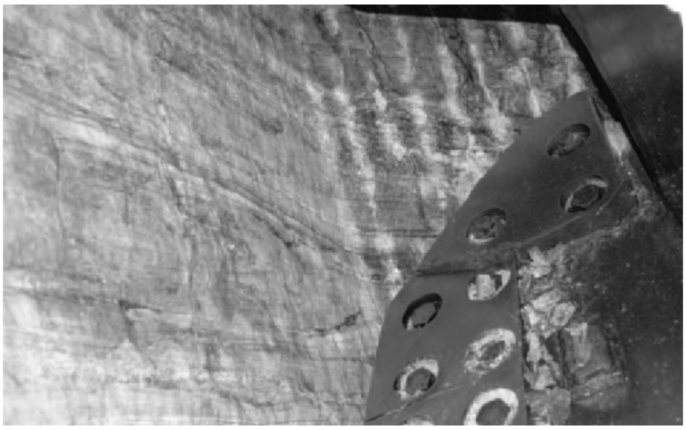


Figure 4. Face view taken though the bucklet window in the TBM head.

Figure 5. Face view taken through the cutter-wheel window in the TBM head.

Figure 6. Face of the tunnel taken during one maintenance stop.

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 shows 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.

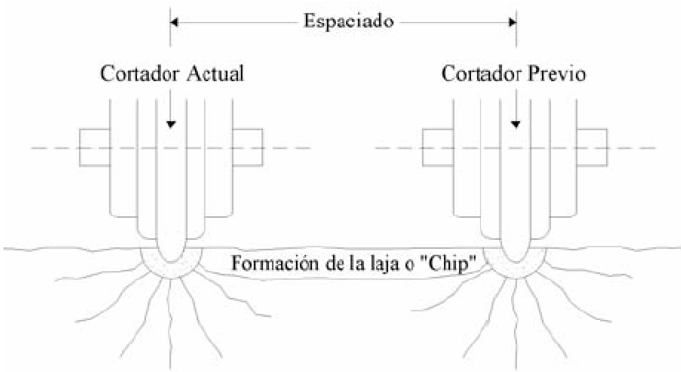


Figure 7. Chip created in a homogeneous ground.

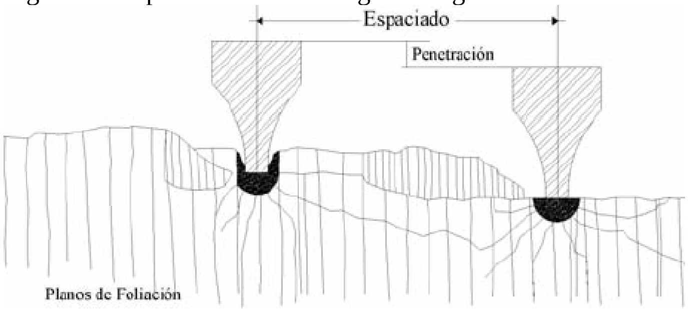


Figure 8. Chip created in a ground foliated longitudinally.

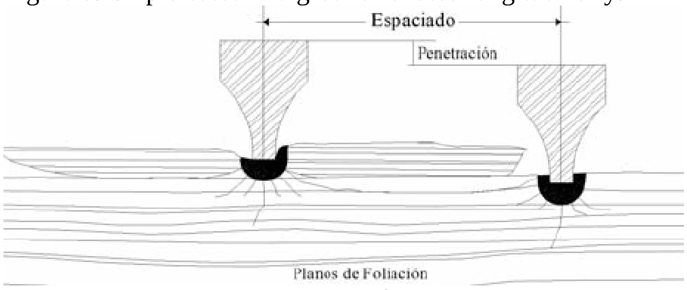


Figure 9. Chip created in a ground foliated perpendicularly.

Figure 10. Chips coming from a homogeneous ground.

Figure 11. Chips coming from a fractured face.

Figure 12. Chips coming from a faulted face.

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)

$$p\ (mm/r) = \frac{V\ (mm/m)}{N\ (rpm)} \tag{1}$$

that gives the ground resistance to be excavated.

- Penetration index (I_p)

$$I_p = \frac{F_c\ (kN)}{p} \tag{2}$$

that proportionates the thrust per cutter to penetrate 1 mm per revolution.

- Specific energy of excavation (E_s)

$$E_s\ (kJ/m_3) = \frac{F}{A} + \frac{2\pi \cdot N \cdot T}{A \cdot ARA}\ \text{(Teale, 1965)} \tag{3}$$

where E_s = specific energy of excavation (kJ/m^3), F = total cutterhead thrust (kN), A = excavated face area (m^2), 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.

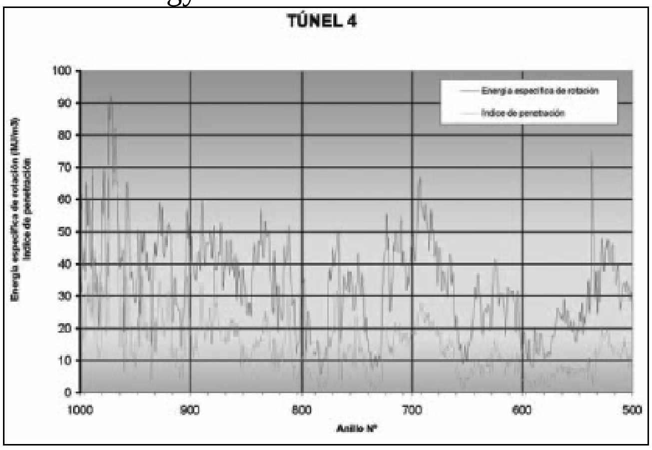


Figure 13. Relationship between I_p and E_{sr} for 500 segments rings.

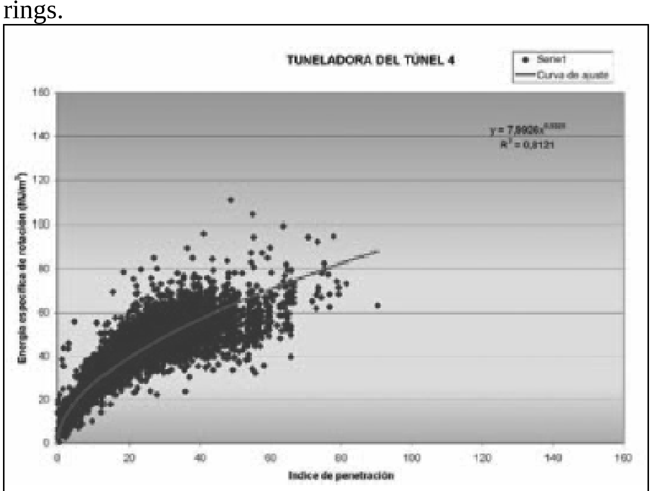


Figure 14. Correlation between E_{sr} and I_p ($E_{sr} = 8 \cdot I_p^{0.52}$).

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-naturritenskapllige 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).

ROCK MASS CLASSIFICATION	DISCONTINUITIES SPACING (cm)
0	Massive
0-I	160
I	80
I-II	40
II	20
III	10
IV	5

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.

Rock Mass Type	Spacing (cm)	Joints/m	I_p	E_{sr} (kJ/m^3)	Debris
I	>40	4	20-30	40-60	chips
II	20	4-8	10-15	20-30	chips and occasional blocks
III	10	8-15	4-7	10-15	cm and dm blocks
IV	5	15-30	1	5	heterometrical blocks (dm, cm, fines)
V	<5	>30	>0	<5	sand and fines

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.

LITHOLOGY	Density (gr/cm^3)	UCS (N/mm^2)	Is50	σ_t (N/mm^2)	V_p (m/s)	Qz (%)	Quartz equi-valent (%)	DRI	CLI	Cerchar
Ortogneiss	2.703	89.6	8.30	9.5	5100	33	53	46	13.0	3.4
Adamellite	2.625	85.9	7.50	7.6	5095	33	55	55	11.7	3.1
Leucocratic Granite	2.591	95.1	7.71	9.0	4737	33	57	42	9.7	3.2
Episienite	2.582	75.6	4.50	5.6	4686	3	34	55	18.6	2.4
Granitic Porphyr	2.598	125.0	9.18	13.0	5530	22	47	37	12.3	3.0
Diorite	2.723	152.1	10.34	-	5577	1	32	38	27.7	2.5
Paragneiss	2.759	-	9.00	10.1	-	-	-	-	-	-
Marble	2.711	-	5.30	7.3	-	0	9	71	64	1.4
Skarn	2.726	-	8.10	9.9	-	3	20	-	-	-
Pegmatite	2.756	110.3	-	9.7	-	47	-	-	-	-
Quartz	2.657	76.0	6.84	-	5805	99	99	47	5.3	3.1

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