PREDICTION OF THE GROUND CONDITIONS AHEAD THE TBM FACE IN THE TUNNELS OF GUADARRAMA (SPAIN), USING GEOPHYSICAL METHODS AND IN SITU TESTING

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ABSTRACT: The tunnels of Guadarrama are new twin tunneles 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. In order to predict in detail the ground conditions ahead the TBM face, a review of the geological features has been done. This has consisted in detailed geological mapping with a precise photogeological study and systematic Electrical Resistivity Tomography (ERT) profiles along the axis of both tunnels. Also several geophysical investigation methods have been applied, in order to allow a good knowledge of the rock mass. In situ geotechnical tests have been also carried out, yielding ground geomechanical parameters. They can divide as follows:- Surface tests, carried out from the South Portal, previous to the TBM – Surface tests, carried out from the North Portal, previous to the TBM – La Umbría Fault, where various methods have been applied at the surface, in borehole, surface to borehole or borehole to borehole. This paper describes the field campaigns and shows the most significant results of the geophysical investigation in Guadarrama tunnel. In the main faults inclined boreholes were drilled in order to perform dilatometer and permeability in situ test. With all these data it was decided in advance if the double-shield was going to work in a single or double mode. A type of expert system have being used to interpret the data coming from TBM after crossing the expected faults, so allowing a feedback to the entire process.

1 INTRODUCTION

The Tunnels of Guadarrama are new twin tunnels crossing the “Sistema Central” (Central Range) of the Iberian Peninsula, between Madrid and Segovia, for the new High Speed Railway Link Madrid-Valladolid, to the NW of Spain.

Figure 1 shows the location of these tunnels.
The length of each tunnel is 28,3 km with a maximum overburden of 900 m.
The tunnels have been excavated using four double-shield TBMs; all of them with an excavation diameter of 9,5 m.

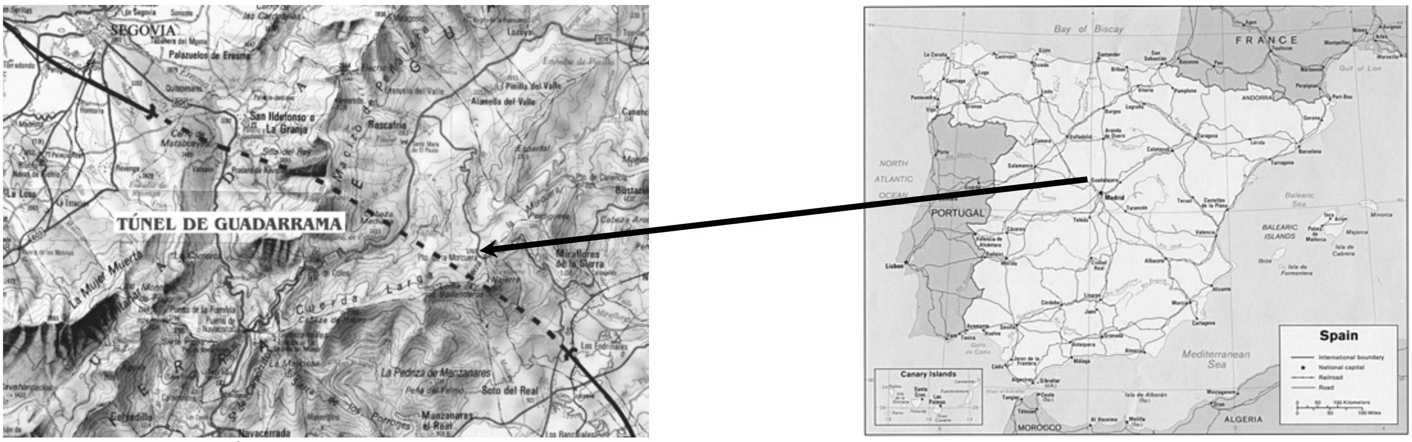

Figure 1.- Location of Guadarrama’s tunnels.

2 MAIN GEOLOGICAL FEATURES

The geological conditions consist of crystalline rocks, gneiss and granites crossed by several types of dykes. A main graben in the Lozoya valley where poor quality sedimentary rocks from the Cretaceous, including loose sands under water table, were crossed is the most problematic section of both tunnels. Nevertheless several faults and dykes have also been detected in the site characterization jobs, inside the crystalline bodies with different mylonites and water conditions.

In the Figure 2 a longitudinal geological section of the tunnel is shown. It can be appreciated, the two main faults encountered that have been intensively investigated in advance using geophysical methods. There two faults corresponds to Valparaiso and to La Umbría fault areas.

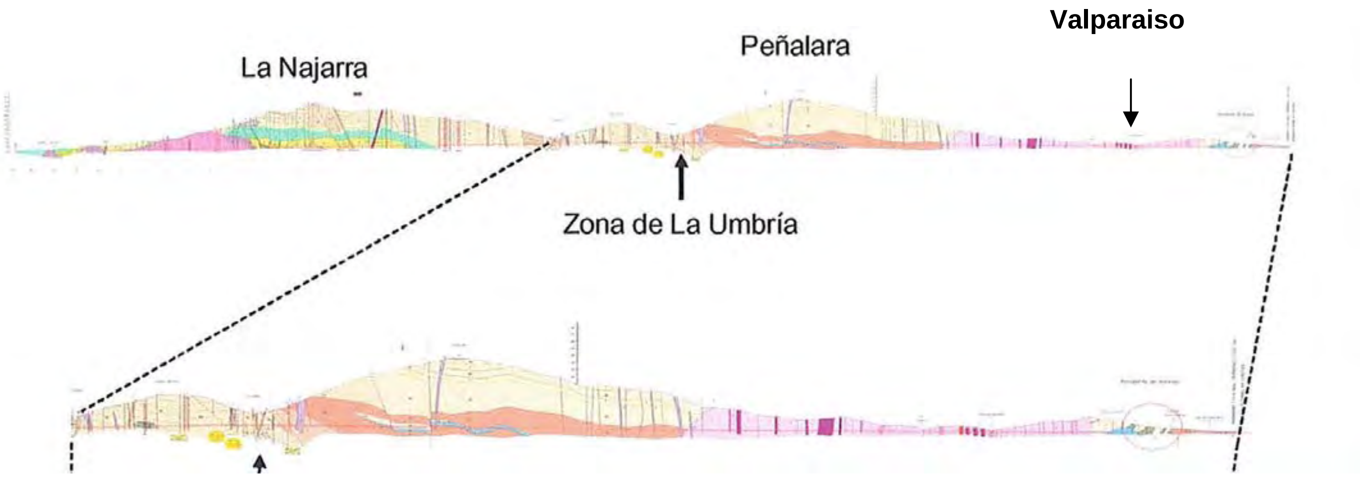

Figure 2.- Geological profile of the Tunnels of Guadarrama.

3 METHODOLOGY USED FOR THE PREDITION OF GROUND CONDITIONS AHEAD THE TBM FACE

Since the beginning of the excavation, the major importance of having a prediction of the ground conditions ahead the TBM face has been demonstrated, in order to take the decision to advance in a single or in a double-shield way or if it is necessary to make a ground improvement ahead the face of the tunnel.

For this purspuse a review of the main geological features has been done.

This review has consisted of a detailed (1:1000 scaled) geological mapping with a precise photogeological study.

Following this geological mapping an intensive geophysical survey of both tunnels was done. This survey has consists in the following works:

- Geophysical methods applied from surface.
- Geophysical methods applied between boreholes or between borehole and surface.

In Figure 3 it is shown a block-diagram showing the relationships between the different technologies used (Capote, 2005).

As a prediction tool a systematic Electrical Resistivity Tomography (ERT) profiling along the axis of both tunnels has been carried out.

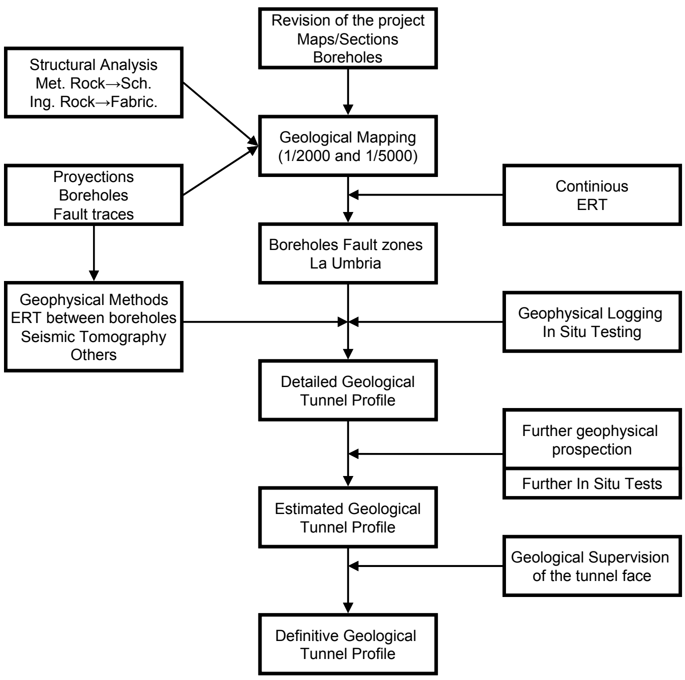

Figure 3.- Methodology used for the prediction of the ground conditions ahead the TBM face (modified from Capote, 2005).

In the main faults and accidents further inclined boreholes were drilled in order to perform dilatometer and permeability in situ tests, as well as to make some geophysical logging.

This methodology has proven to be effective and very precise down to an overburden around 150 m.

A special remark was done in relation with La Umbría Fault were several geophysical methods have been applied.

In this area most of the geophysical and in situ tests methodologies were used, to precise the structural position of the createaceous loose sands, as well as the position of the main gouge faults zones. It was encountered that the tectonized zones were located in the northern part of the valley.

3.1 *Electrical resistivity tomography (ERT)*

The use of Electrical Resistivity Tomography (ERT) for the detection of faults has already been used since faults usually give low values of resistivity because of the presence of day minerals and high water contents.

The method is based in the measurement of the potential drop between two electrodes (MN), obtaining the resistance of the ground to a current flow (AB).

The multi-electrods mode used has been an axial dipole-dipole, as this is the best mode for the detection of vertical resistivity anomalies.

After several trials a unit electrode spacing of 10,0 m has been used for low overburden, obtaining a constant depth of investigation of about 60 m.

Two parallel profiles along both axis of the tunnels have been done. With this geometry, a good correlation is assured in the strike and dip of the resistivity anomalies.

For the definition of the characteristic of the faults, a very detailed interpretation process has been used.

It has the following steps:

- The apparent resistivity pseudosection is measured.
- Secondly the resistivity is calculated from the resistance value.
- Thirdly, an iterative inversion process is done, minimizing the error between the measurement and the calculated values of resistivity. This accordance is given by the value of RMS error expressed as a percentage.

Finally, as is shown in the Figure 4, the model is corrected to allow for the real topography.

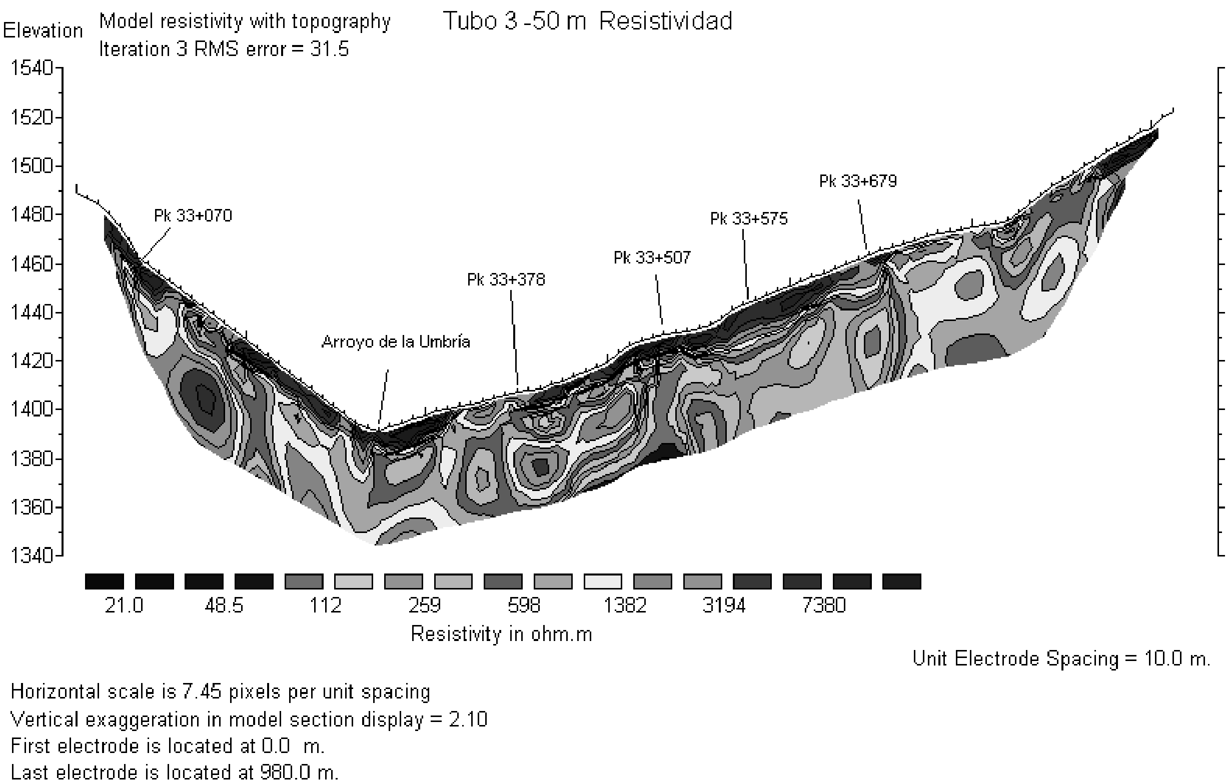

Figure 4.-Final section with real topography.

For the final interpretation it is very significative to analyze the chargeability section. This analysis has provided data for the prediction of water inflow into the tunnel.
Since the beginning of the excavation from the North Portal of the tunnels, more than 1.1980 ml of ERT profiles have been done, while the excavated length is 13.500 m for each tunnel (Tunnels 3 and 4).
The prediction system has proven to give satisfactory results. Figure 5 shows the correlation between the geological and the resistivity sections in one of the main faults encountered.

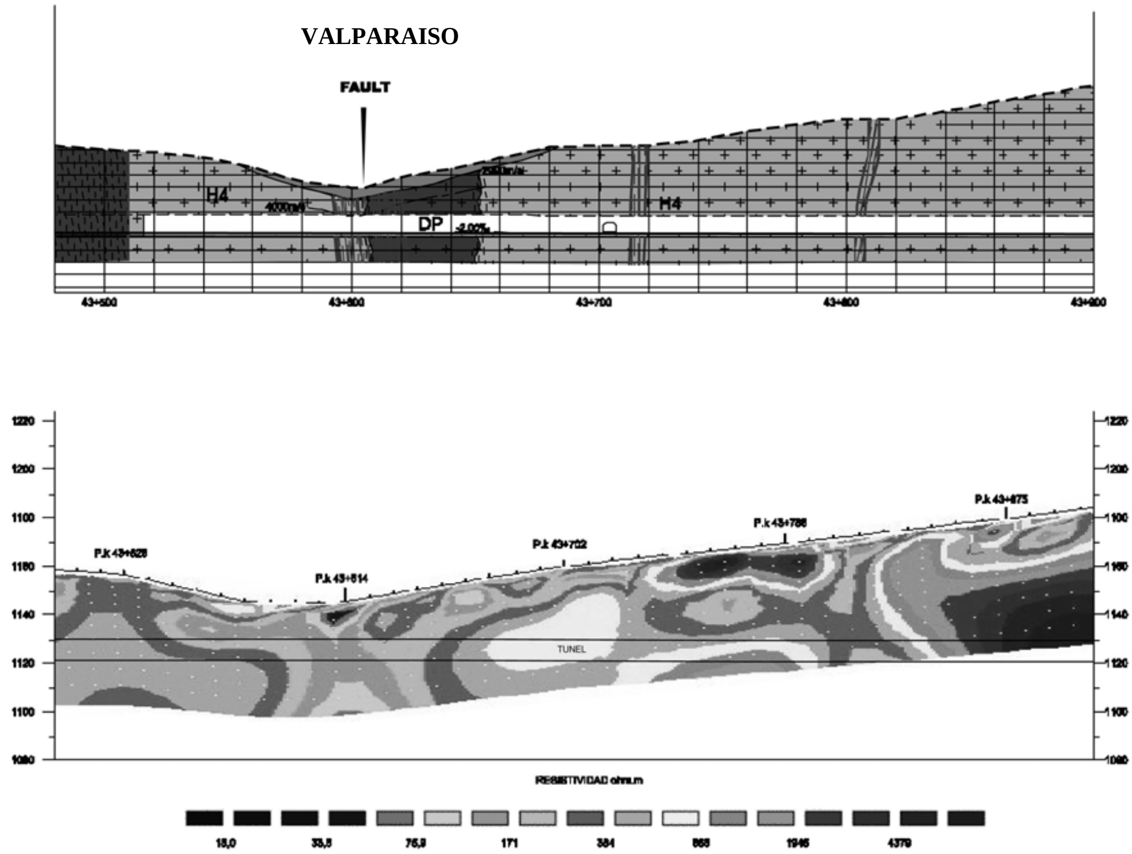

Figure 5.- Example of the correlation between the resistivity and the geological profiles. (Valparaiso Fault).

3.2 *3D Interpretation of ERT*

In La Umbría fault 4.600 m of ERT profiles from surfaces were done, as well as 5 electrical tomography borehole-borehole and 6 ERT borehole-surface. This has allow to make a complicate 3D interpretation of the fault.
Figure 6 shows a tridimensional section of Tunnel 3, in which the two low resistivity main faults can be appreciated.
As it has been said, these two zones are located in the northern part of the valley.

3.3 *Seismic Crosshole Tomography*

The seismic tomography is based on the elastic waves propagation to obtain a spacial distribution of the velocities inside a volume of rock mass.

Once the data acquisition is done, it is calculated the velocities between all the nots of the mesh.
In La Umbria Fault it was done a seismic survey between boreholes.
Considering:

- The distance between boreholes: As bigger this distance is lesser is the accuracy.
- The distance between geophones an shot points.
- The accuracy in the knowledge of the position of emissor and receptors.

Figure 7 shows the raypath, of one of the sections measured. While Figure 8 show the results of the interpretation carried out.

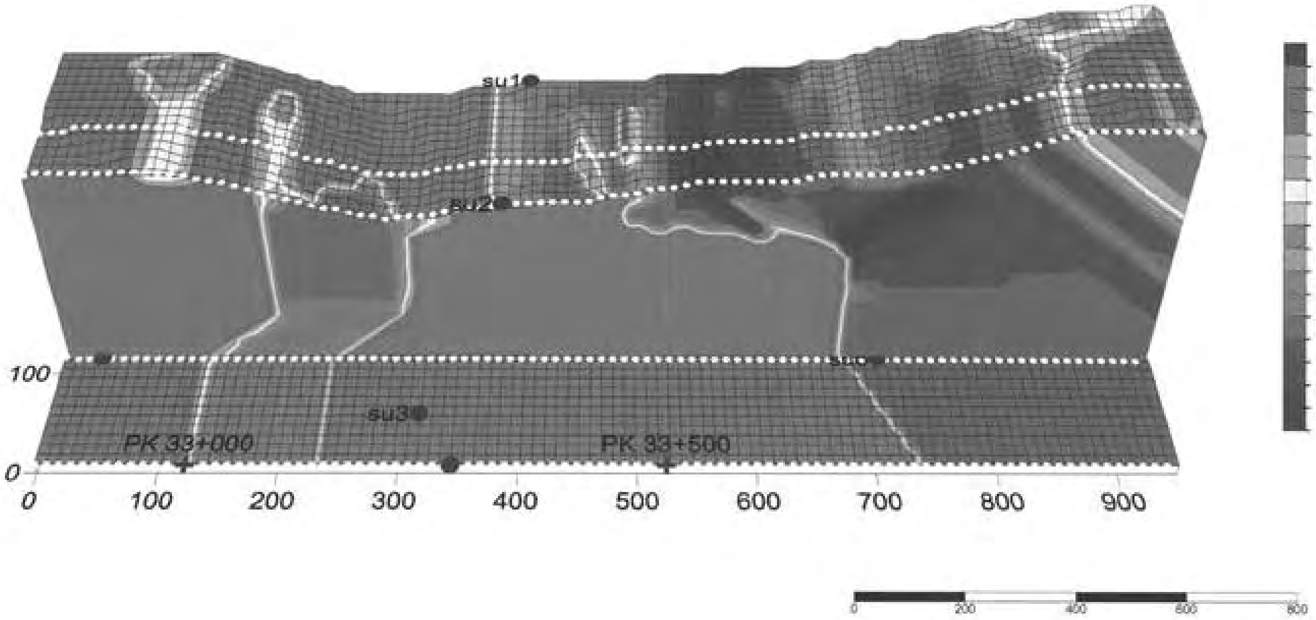

Figura 6.- Resistivity 3D model of La Umbria Fault zone. (In the horizontal plane, both tunnel axis have been marked).

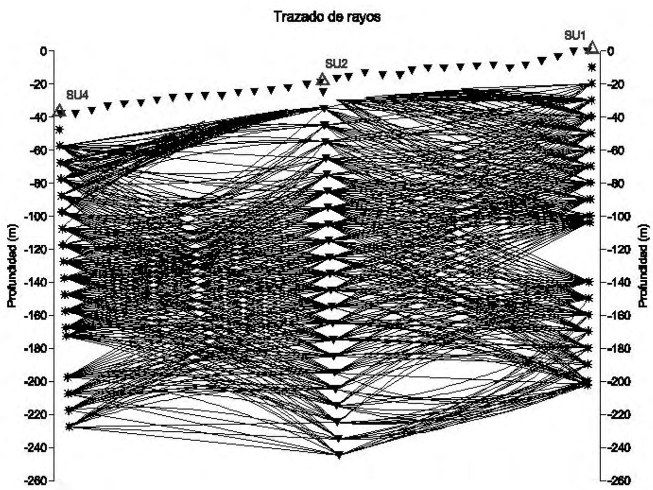

Figura 7.- The raypaths of one of the sections measured with seismic tomography in La Umbria Fault zone.

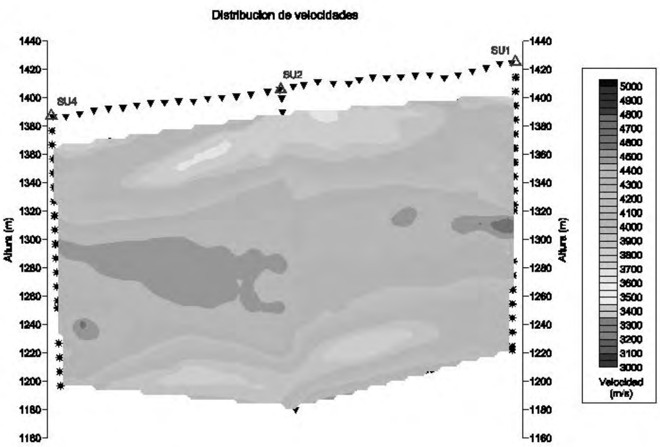

Figura 8.- Results of the interpretation, of seismic tomography in La Umbria Fault zone.

3.4 *In Situ Testing*

The following techniques have been used:

- Geophysical logging (see Table 5.1).
- Hidrofract tests (see Figure 9).
- Dilatometer Tests.

These tests have been very useful for geotechnical site characterisation of La Umbria fault, as well as for other tectonical features.

The geophysical logging and in situ test carried out inside the drilled boreholes, have provided a very valuable information concerning:

- structural data
- natural stress field (with a high ratio k_0, between horizontal and vertical stresses).
- rock mass deformability, specially in the sedimentary rocks of the Cretaceous, including loose sands.

Table 5.1.- Geophysical logging used in boreholes.

EQUIPMENT	LOG
SCHLUMBERGER	HALS-PEX-Laterolog-Plataform Express Logs
	HNGS - Espectometría Gamma Nuclear
	FMI-Fullbore Fm. Microimager
	DSI-Dipolo Shear Imager
	GR-Gamma Ray
MOUNT SOPRIS	Caliper
	Acoustic Televiewer
	Full wave sonic
	Temperature
	Gamma Ray

	Conductivity
	Resistivity
	SP

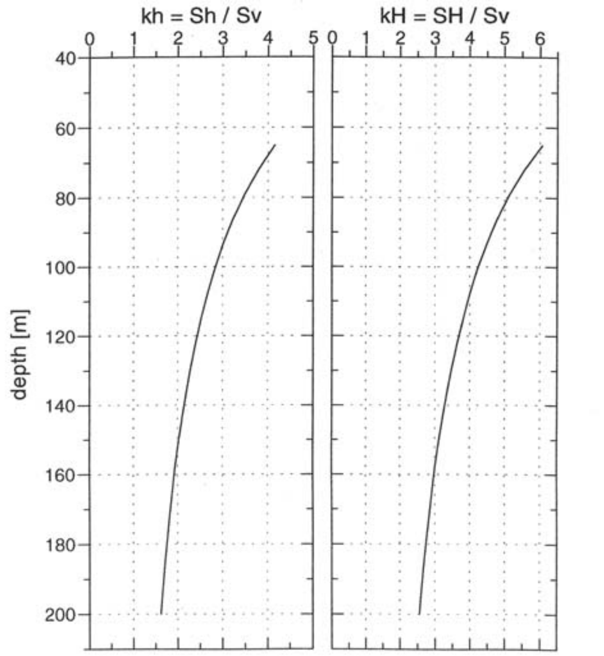

Figura 9.- Result of the Hidrofract tests carried out in one borehole, showing high horizontal stresses.

4 DISCUSSION AND CONCLUSIONS

The geophysical surveys and in situ tests carried out, have contribute to define the geological and geomechanical profile of Guadarrama tunnels.
This methodology has allow to predict in advance, the constructive difficulties of the rock mass to be excavated by the 4 TBMs.
The figures of these measurements are the following:
- 3.501 ml seismic profiles.
- 24.870 ml surface ERT.
- 3.860 ml of VLF.
- 11.019 ml of geophysical logging.
- 5 ut. ERT borehole-borehole.
- 6 ut. ERT borehole surface.
- 18 ut. Seismic Tomography borehole-borehole.
- 25 ut. Dilatometric tests.

The ERT has proven to be an efficient system for the prediction of faults and dykes ahead the TBM face in the gneiss and granites of Guadarrama Tunnels.
The use of the chargeability profiles is very interesting for the prediction of water inflow conditions.
The interpretation is very difficult when the strike of the resistivity anomaly is parallel to the axis of the tunnel.
Using the resistivity profile it has been decided in advance, if the TBM has to work in a single or in a double shield way.
For an overburden higher than 250 m, Najarra and Peñalara massifs, no geophysical survey has been used, as all the tests done didn’t give enough reliability and accuracy in the interpretation.
For the Umbria Fault, the electrical and seismic tomographies, have contribute to define the position of cretaceous loose sands.
The in situ tests have contributed, in conjuction with the geotechnical logging of the drilled boreholes and the last test to the mechanical characterization of the rock mass.

5 BIBLIOGRAPHY

- Capote, R (2005). La geología del proyecto del túnel de Guadarrama. In: Túnel de Guadarrama. ADIF. Ed. Entorno Gráfico: 67-93.
- Galera, J.M.; Peral F.; y Rodríguez, A (2004). Prediction of the ground conditions ahead the TBM face in the tunnels of Guadarrama (Spain), using Electrical Resistivity Tomography (ERT). In Proc. 2nd Int. Conf. on Site Characterization. Ed. Millpress: 1443-1447.
- Galera, J.M.; Pescador, S; Rodriguez, A y Torres, M. (2005). Empleo de las técnicas geofísicas y de los ensayos in situ en los túneles de Guadarrama. In: Túnel de Guadarrama. ADIF. Ed. Entorno Gráfico: 97-115.
- Loke, M. H. & Barker, R. D. 1996. Practical techniques for 3D resistivity surveys and data inversion. *Geophysical Prospecting, 44, 1996:* 499-523.
- López, F. (2005). Perfil geológico del túnel de Guadarrama. Estudios de caracterización de fallas: La Umbría: In: Túnel de Guadarrama. ADIF. Ed. Entorno Gráfico: 149-187.
- Oteo, C (2005). Geotecnia, auscultación y modelos geomecánicos en los túneles ferroviarios de Guadarrama: In: Túnel de Guadarrama. ADIF. Ed. Entorno Gráfico: 191-220.
- Sasaki, Y. 1994. 3-D resistivity inversion using the finite element method. *Geophysics, vol. 59, no. 11, December 1994:* 1839-1848.