MODELLING AND QUANTIFYING THE HYDROGEOLOGICAL EFFECTS IN THE ADVANCE OF A TUNNEL EXCAVATION BY TBM

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ABSTRACT
During the construction of a new metro line in Barcelona with Tunnel Boring Machine (TBM), it is necessary to find a method for predicting where the water inflows will be larger. For this objective, a numeric model is done which calibrates the hydraulic parameters with theoretical water inflows using the inverse method. It calibrates the transient state for the 500 meters of a sector of the metro tunnel close to the Besos River, in Barcelona (Spain).

RESUME
Pendant la construction de la nouvelle ligne de metro a Barcelona, il est necessaire de trouver un methode pour faire la prediction de l’apport le plus important au niveau de le front d’excavation. Pour porvenir a cet objectif nous avons calibre un modele numerique de l’apports les plus importants en eau utilisant la methode inverse. Le modele a ete calibre a partir des etats transitoires dans les 500 metres d’un secteur de tunel, situe pres de la Riviere Besós a Barcelone (Espagne).

1. INTRODUCTION
During the construction of the new line of the Barcelona Metro (Line 9), 40 Km of tunnels have been drilled in the Barcelona Plain and between the deltas of Besos and Llobregat rivers.

Tunnel perforation is made by means of a 12 m diameter TBM (Tunnel Boring Machine). This machine forms a shield for rock with the possibility of working in closed mode like an Earth Pressure Balance (EPB). In this area the geology is very complex, so the TBM operation is very sensitive to unexpected changes on geological, geotechnical and hydrogeological settings. Therefore, there are a great amount of geologic, geotechnical and hydrogeological data obtained from previous projects and during the actual construction. This information give us the opportunity to study the potential impacts during the tunnel construction on both the hydrogeological setting and the tunnel advance.

The objective of this work is define a methodology that allows, through groundwater modelling, to preview and quantify possible groundwater inflows to the projected tunnel until it has been drilled, especially those more significative. For this evaluation we have selected a pilot area located near Barcelona, at East part the of the Besos River (Figure 1).

In that area geology is characterized by granites crossed by complex fracture network and porphyric dykes. They show several degrees of weathering. Furthermore, in some areas quaternary alluvials are deposited. It is necessary to improve the geological description in order to make a more accurate hydrogeological conceptual model definition.

There are several examples where groundwater inflow to the tunnel is quantified by groundwater modeling (Kavvadas, 1997; Vázquez-Suñé, 1998; Vázquez_Suñé et al 1999; UPC, 2000; Molinero et al 2002; Martinez-Landa, 2005. Here we use the “mixed model” approach (Martínez-Landa, 2004). This approximation consists basically of identifying the dominating discontinuities (fractures, dykes, etc.) and including them explicitly, while the matrix is treated as a porous equivalent medium that accounts for the effect of minor fracturing too.

To simulate the tunnelling advance and the tunnel drainage effects, we applied the Cauchy boundary condition, so that water extraction is proportional to the difference between groundwater heads (h) and the water pressures (H) in the drainage point (we assume the tunnel bottom).

2. METHODOLOGY

2.1. Geological characterization

The Tunnel Boring Machine (TMB) is one of the main drilling methods used nowadays, particularly in homogeneous media where displays its best performance. The changes in lithologies and surface
contact between the weathered layer and non-weathered rock disrupt the drilling work, especially when hydraulic conductive fracture zones are located in the tunnel course. The presence of groundwater can cause the collapse of the soft ground or unstable rocks into the tunnel. For this reason, the detailed characterization of the physical properties and the geometry of the rock bodies allow improving the soil resistance, by means of chemical, cementations grout, or other methods, before the TMB goes through the non-consolidated area.

Figure 1. Geographical situation of the study area.

The detailed characterization of the shallow subsurface is mandatory for any hydrogeological model of the area. In the study area (Figure 2), the planned tunnel basically goes through a granite massif characterized by an unconsolidated weathered layer (lehm cover) of variable thickness and geometry. Several major and minor faults and porphyric dykes control the water flow pattern. Even thermal water circulation was observed in some parts of the drilled tunnel. There is a fault zone mapped at surface that is also a significant geological feature. This fault divides the granite domain located at the NE, from Miocene age clayed gravels domain at SE (ATM, 2000; IJA-UPC, 2006; Martí et al., 2006).

A revised geology map was obtained from integration of the surface geology review, old aerial photographs interpretation, core interpretations and the application of the geophysical methodologies in the several complex areas along the projected tunnel trace.

Figure 2. Geology of studied area.

The seismic experiments carried out in this project tried to apply different geometry acquisition configurations to resolve the subsurface structures within a densely populated city. 2D seismic profiles were acquired when the tunnel trace coincide at surface with an accessible street (convenient for reception of receivers and sources). Crossing seismic profiles were used to obtain oriented structures and volumetric features of the rock massif. A 3D tomographic experiment was also designed to image the rock volume located below a building, in this case a football stadium. The results show that the seismic tomography is a powerful tool to characterize the shallow surface, even in very noisy areas (such as a city, Martí et al., 2006).

The integrated information derived from the geological mapping review (Figure 3) and the geophysical experiments constrain, in detail, the subsurface structural architecture of the study area, defining the geometry of the faults and the location and extension of the porphyric dykes. These structures control the geometry of the surface weathered layer. This layer features very low seismic velocities and it is present in all the study area. Furthermore, it is presumably very heterogeneous as it contains all the city services (sewage, gas, electricity, water supply, etc.). At tunnel depth, the study has been able to identify the contact between the non-cohesive (lehm) and cohesive granite (Figure 4). This contact surface is clearly differentiated by the seismic velocities, featuring a very high velocity gradient.
2.2. Hydrogeology and conceptual model

From the new geological description mentioned above and hydrogeological data collection (heads, pumping tests, etc.), it has been possible to define a more accurate hydrogeological conceptual model.

General groundwater flow from granite and Miocene age clayed gravels is discharging in the Besos alluvial aquifer. It has been also possible to identify the main fractures and porphyric dykes. These fractures and dykes control principal flow paths into the granite and the Miocene materials.

Permeability values were inferred from geotechnical or hydrogeological tests, and also from the lithological and geomechanical characteristics of the rocks. For non-fractured and unweathered granite, permeability is very low, local test values of $10^{-9}$ m/d are the norm in this context. But, for hydraulic tests in this area the effective parameters are quite higher 0.1 m/d or even more. The effective permeability is controlled by a minor fault network and weathering processes. Geographically, in the north there is fresh granite and in the south there is weathered granite. Results of some hydraulic tests in the area give values of effective transmissivity between 20 to 100 m$^2$/day. Furthermore, hydraulic tests conditioned by major faults have an effective transmissivity of more than 100 m$^2$/d. Very low values of permeability have been measured for Miocene age clayed gravels.

2.3. Modelling

The first step in the modeling process is to define the boundary conditions. The west limit is the contact with the alluvial aquifer, where a Cauchy boundary condition is imposed. The eastern limit is a Newman boundary condition because it is located in a watershed. (Figure 5)

Hydrogeological zonification is conditioned by geology, geometry and the estimated hydraulic parameters (Figure 6).
With the aim of reducing the hydraulic pressure near the projected tunnel, a long term drainage pumping in two boreholes was performed. Response observed in several pizometers allow the computation parameters. These include the hydraulic parameters of the weathered granite, porphyric dykes and faults that were near the pumping site (Figure 7). These parameters are considered as previous information parameters for the model calibration. A first steady state model is obtained by fitting measured and computed heads (Figure 8).

From this steady state it is possible to include the tunnel advance, calibrating the tunneling parameters (leakage) and quantifying the groundwater drainage.

For the calibration of the steady state induced by the construction of the tunnel, the tunnel has been divided in 36 zones of 18.5 meters of length (10 rings of support) that is slightly longer than the length of the TBM. In these zones it has been applied a boundary condition of prescribed head (bottom of the tunnel) and Cauchy condition, activated with the function time of the TBM. When the machine arrives to one of this locations, the leakage is fully activated (100%), and while it goes trough, the function of leakage decreases to descent to arrive at 0.01 % in 10 days. This value simulates the lining rings used to waterproof the tunnel, since it was impossible to know the real waterproof of every ring and calibrate the real remanent leakages.

In the sector corresponding to the drainage pumping (piezometers ZPA-22, ZPA-23 and ZPA-24) the addition of a continuum pumping (with not always very good detail) and the effect of a near stopping of the machine (with not clear knowledge of water inflow) difficult the calibration of the tunnel water inflow. In the other pizometers (except the ZPA-12) some pumping drainages were activated in the vicinity only when the tunnel boring machine was near. This pumpings have unknown time functions, because bad drilling practices, and of pumping and the effects of tunnel advance yuxtapose (Figure 9). In general terms, with the exception of noise of pumpings, adjustments are not too bad.

It is necessary to remember that one of the main objectives of this model is to know the water inflow in the face of the tunnel. In the figure 10 it is possible to observe the water inflows with the advance of the TBM, which can reach up 1000 m$^3$. Before arriving at

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Figure 6. Hydrogeological zonification

Figure 7. Hydrograms of the different pizometers during the drainage pumping; points are the measured values and grey line the estimated values.

Figure 8. Steady state heads.

3. RESULTS

With the transient state of the TBM advance the model is recalibrated (figure 8). In table 1, it is possible to observe the hydraulic parameters of the simulated zones. The values are very similar to the calibrated values in the drainage pumping.

### Table 1. Hydraulic parameters calibrated.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Transmissivity (m$^2$/d)</th>
<th>Specific storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>fresh granite</td>
<td>14</td>
<td>0.14</td>
</tr>
<tr>
<td>weathered granite</td>
<td>0.35</td>
<td>0.001</td>
</tr>
<tr>
<td>aluvial formation</td>
<td>4500</td>
<td>0.25</td>
</tr>
<tr>
<td>Miocene formation</td>
<td>0.03-0.3</td>
<td>0.0001</td>
</tr>
<tr>
<td>porphyric dykes</td>
<td>0.8-2.1</td>
<td>0.01</td>
</tr>
<tr>
<td>fractures</td>
<td>190-350</td>
<td>0.005</td>
</tr>
</tbody>
</table>

In the sector corresponding to the drainage pumping (piezometers ZPA-22, ZPA-23 and ZPA-24) the addition of a continuum pumping (with not always very good detail) and the effect of a near stopping of the machine (with not clear knowledge of water inflow) difficult the calibration of the tunnel water inflow. In the other pizometers (except the ZPA-12) some pumping drainages were activated in the vicinity only when the tunnel boring machine was near. This pumpings have unknown time functions, because bad drilling practices, and of pumping and the effects of tunnel advance yuxtapose (Figure 9). In general terms, with the exception of noise of pumpings, adjustments are not too bad.
Figure 9. Map of the transient state of the TBM in some stages during the simulation.

Figure 9. Hydrograms of the different piezometers during the pass of the TBM. The points are the measured values and grey line the estimated values.
Figure 10. Water inflow in the tunnel.

Kilometric point 1600, the maximum levels observed are in fault zones. Later this does not happen, there are some pumping drainages that extract water. These values of inflow were confirmed for the people of the constructing company, they did not quantify the amount of water but they were agree on terms of qualitative information.

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References


IJA-UPC, INSTITUT JAUME ALMERA, CSIC-UNIVERSITAT POLITECNICA DE CATALUNYA (2005). Caracterización sísmica para la construcción de la futura l-9 de metro (Santa Coloma de Gramenet. Inédito)


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