Engineering Geology 121 (2011) 46–54

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Groundwater inflow prediction in urban tunneling with a tunnel boring machine (TBM)

Jordi Font-Capó [a,b,*], Enric Vázquez-Suñé [a], Jesús Carrera [a], David Martí [c], Ramon Carbonell [c], Andrés Pérez-Estaun [c]

[a] GHS, Institute of Environmental Assessment & Water Research (IDAEA), CSIC, Jordi Girona 18, 08034 Barcelona, Spain
[b] GHS, Dept Geotechnical Engineering and Geosciences, Universitat Politecnica de Catalunya, UPCBarcelonaTech, Jordi Girona 1-3, 08034 Barcelona, Spain
[c] Institute of Earth Sciences Jaume Almera (ICTJA/CSIC) Lluís Solé i Sabarís s/n 08028 Barcelona, Spain

ARTICLE INFO

Article history:
Received 28 October 2010
Received in revised form 3 April 2011
Accepted 15 April 2011
Available online 22 April 2011

Keywords:
Inflow
Tunnel
TBM
Groundwater
Modeling

ABSTRACT

Tunneling in urban areas demands an accurate characterization of the shallow subsurface to minimize risks during excavation. Unexpected high water inflows constitute a major problem because they may result in the collapse of the tunnel face and affect surface structures. Such collapses interrupted boring tasks and led to costly delays during the construction of the Santa Coloma Sector of L9 (Line 9) of the Barcelona Subway. A method for predicting groundwater inflows at tunnel face scale was implemented. A detailed 3D geological and geophysical characterization of the area was performed and a quasi-3D numerical model with a moving tunnel face boundary condition was built to simulate tunnel aquifer interaction. The model correctly predicts groundwater head variations and the magnitude of tunnel inflows concentrated at the crossing of faults and some dikes. Adaptation of the model scale to that of the tunnel and proper accounting for connectivity with the rest of the rock massif were crucial for quantifying the inflows. This method enables us to locate the hazardous areas where dewatering could be implemented.

1. Introduction

The unexpected encounter of high water inflows and soft ground is a major concern in tunnel excavation. Water inflows may drag large amounts of material and cause face instabilities, collapses, chimney formations and surface subsidence. When using tunnel boring machines (TBM) the problems caused by these inflows are often ascribed to the presence of hydraulically conductive fractures or faults (Deva et al., 1994; Tseng et al., 2001; Shang et al., 2004; Dalgic, 2003). The simultaneous occurrence of soft geological formations and high water inflows can create a “snow ball effect” (Barton, 2000), i.e. high inflows drag soft materials that increase permeability and connectivity with the rest of the aquifer, producing further water inflows and sediment drag in a process that grows in intensity. These scenarios lead to stoppages requiring corrective measures, and higher construction costs, not to mention the risk to life and damage to property (Cesano et al., 2000; Day, 2004; Schwarz et al., 2006; Varol and Dalgic, 2006).

This study was prompted by the difficulties encountered during the construction of the Barcelona Subway L9 (Line 9). Forty kilometers of tunnels are currently being excavated in the metropolitan area of Barcelona (Figure 1a). The first tunnel sector was drilled under the town of Santa Coloma (Figure 1b). A dual Tunnel Boring Machine (TBM) with a capacity to work in open mode when excavating hard rocks or closed mode when crossing unstable materials was used. The combination of unexpected weathered granite and water inflows in a small area of the Santa Coloma sector (Fondo zone) caused tunnel face instability and machine stoppage. Similar conditions had been forecasted when crossing another area of the Santa Coloma sector (B-20 zone) (Figure 1b). Both areas shared difficulties due to mixed face conditions (hard rock bottom-half section and weak rock top-half section) since each type of rock requires different excavation modes that are hard to handle simultaneously (Barton, 2000; Babendererde et al., 2004). Tunneling had been uneventful in the B-20 zone, because it had been well characterized (Font-Capo et al., submitted for publication). This enabled us to modify the tunnel trajectory and to implement a groundwater pumping that lowered heads and reduced water inflows into the tunnel. The problems encountered in the Fondo zone were attributed to the lack of adequate forecasting. Geological data, which were mainly derived from surface mapping, were insufficient to provide a detailed characterization. Although surface research can detect most fractures and possible inflow areas, it cannot precisely locate and determine the volume of tunnel inflows (Banks et al., 1994; Mabee, 1999, Cesano et al., 2000, 2003; Mabee et al., 2002; Lipponen, 2007). In contrast to the Fondo zone, a prediction was carried out in the B-20 zone, and this required accurate characterization, including deep borehole drilling, and the assessment of inflow rates. Given that the problem of the Fondo zone had not been

* Corresponding author. Tel.: +34934006100.
E-mail address: fontjordi@hotmail.com (J. Font-Capó).

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doi:10.1016/j.enggeo.2011.04.012

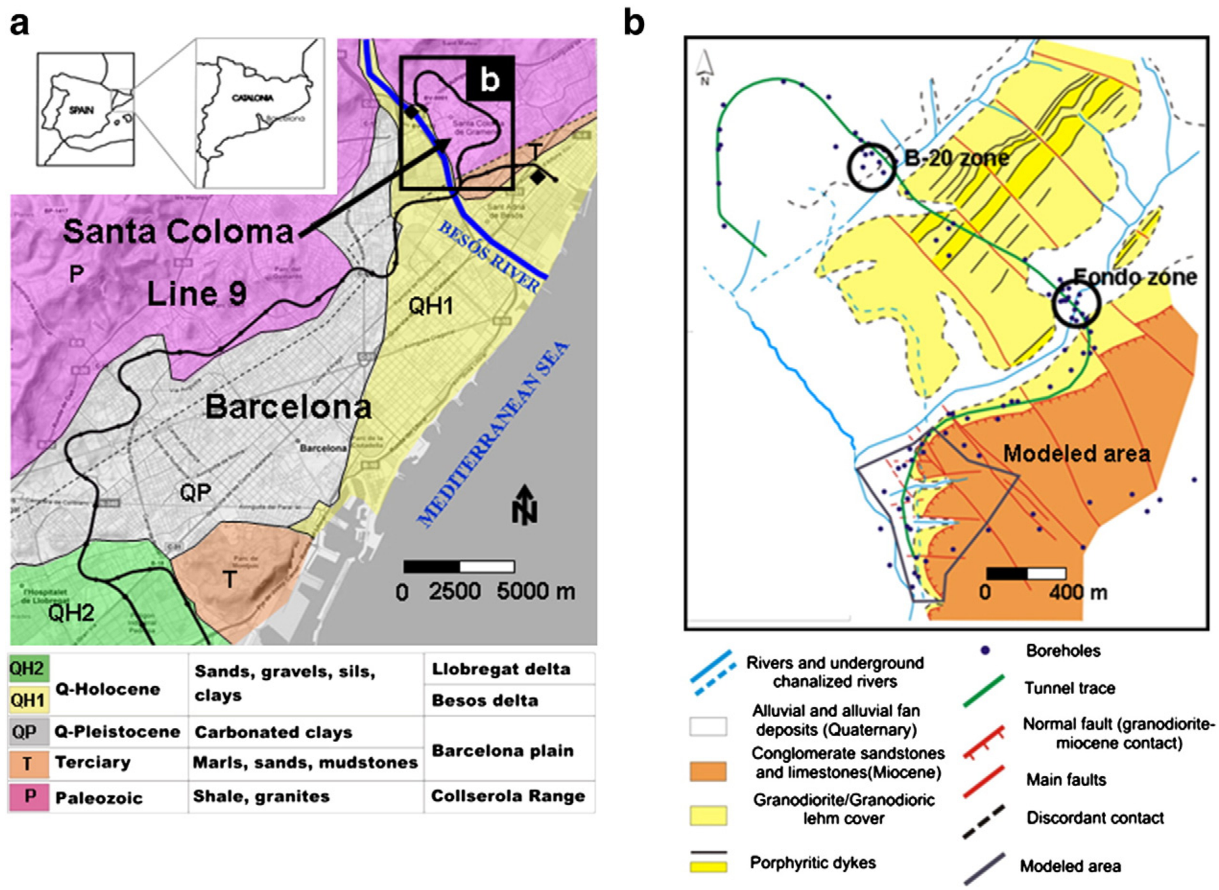

Fig. 1. (a) Map of Barcelona conurbation and Line 9 subway, (b) geological map of the Santa Coloma sector of Line 9 subway, B20 and Fondo zones.

anticipated, it became apparent that more effective solutions were needed to assess potentially problematic areas, characterize them and compute tunnel inflows.

Inflows can be calculated by means of numerical or analytical solutions. A number of analytical formulas have been developed to predict tunnel inflows under different hydraulic conditions. Most of these assume homogeneous media and either steady state (Goodman et al., 1965; Chisyaki, 1984; Lei, 1999; El Tani, 2003; Kolymbas and Wagner, 2007; Park et al., 2008) or transient conditions (Maréchal and Perrochet, 2003; Perrochet, 2005a, 2005b; Renard, 2005). Some analytical solutions have also been developed for heterogeneous formations (Perrochet and Dematteis, 2007; Yang and Yeh, 2007). These solutions are suitable for systems with layers that are perpendicular to the tunnel so that flow is generally radial. Moreover, they can only be used when the system is relatively unaffected by inflows. Therefore, they cannot be used for assessing large inflows to relatively shallow tunnels because the boundary conditions evolve with time and flow takes place primarily in the aquifer plane rather than radially in the vertical plane perpendicular to the tunnel. Moreover, since the Santa Coloma tunnel is lined, the radial flow toward the tunnel is very small, and most inflows appear at the tunnel face (or in machine-rock contact). The presence of high conductivity fractures that are well connected with permeable boundaries further hinders the use of analytical formulae to compute water inflows. Numerical modeling is required under these conditions.

Careful modeling of flow through fractured formations requires separating the less permeable areas from the dominant fractures, which carry most of the water. This may be accomplished by hybrid models, which combine the main features of equivalent porous media models (EPM) and discrete fracture networks (DFN), i.e. hydraulically dominant fractures are modeled explicitly by means of 1 or 2D elements that are embedded in a 3D continuum model representing minor fractures. The approach is appropriate since it explains scale effects in hydraulic conductivity (Martinez-Landa and Carrera, 2005, 2006). Numerical models have been used to calculate the groundwater flow around the tunnels. In fact, inflows are often used to calibrate the numerical model (Stanfors et al., 1999; Kitterod et al., 2000; Molinero et al., 2002) or find the inflows in a large scale (Yang et al., 2009). By contrast, numerical models have rarely, if ever, been used for forecasting inflows during tunnel excavation (Molinero et al., 2002; Wittke et al., 2007).

The present paper presents a methodology for predicting the location and magnitude of tunnel inflows using a numerical groundwater flow model. The method was applied to the last 700 m of the Santa Coloma sector of L9 of the Barcelona Subway. To this end, a geological conceptual model and a hydrogeological parameterization were carried out, and a quasi-3D numerical model was constructed. After calibrating this model, the groundwater transient state caused by the TBM was simulated and tunnel water inflows were obtained.

2. Geological and geophysical conceptual model

Geological characterization in linear works is commonly restricted to the tunnel course, which creates two sets of problems: a) a 3D picture cannot be obtained because information is restricted to a vertical plane, and b) the connectivity with the most relevant geological features must be obtained beyond the tunnel trace because water may flow laterally toward the tunnel.

Geological studies to gain a better understanding of the geology of the Santa Coloma sector of L9 were extended beyond the tunnel trace to include (1) a detailed study of the limited outcrops available in city