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Hydrogeological impact assessment by tunnelling at sites of high sensitivity

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ABSTRACT

A tunnel for the High Speed Train (HST) was constructed in Barcelona with an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). The tunnel crosses Barcelona and passes under some famous landmarks such as the Sagrada Familia and the Casa Milà. Both monuments are UNESCO world heritage sites and a committee appointed by the UNESCO acted as external observers during the construction. Concerns about soil settlements and the hydrogeological impacts of the construction were raised. These concerns were addressed during the design stage to forestall any unexpected events. The methodology consisted of 1) characterising the geology in detail, 2) predicting the impacts caused in the aquifer, 3) predicting the soil displacements due to water table oscillations produced by the construction, and 4) monitoring the evolution of groundwater and soil settlements. The main estimated impact on groundwater was a moderate barrier effect. The barrier effect, the magnitude of which matched the predictions, was detected during construction. The monitoring of soil settlements revealed short and long term movements. The latter movements matched the analytical predictions of soil displacements caused by the groundwater oscillations.

This paper proposes a realistic procedure to estimate impacts on groundwater during tunnel construction with an EPB. Our methodology will considerably improve the construction of tunnels in urban areas.

1. Introduction

The High Speed Train (HST) "Madrid–Barcelona–France frontier" crosses Barcelona in a Southwest–Northeast direction (Fig. 1). The stretch of the tunnel in Barcelona was dug using an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). Although the tunnel does not pass under any building, it passes by the front of the Sagrada Familia Basilica (declared UNESCO World Heritage Site in 2005) and Casa Milà (declared UNESCO World Heritage Site in 1984; Fig. 1). The construction of the Basilica commenced in 1882 and is ongoing. It was designed by the Modernist architect Antonio Gaudi and is the maximum tourist attraction of Barcelona, drawing thousands of sightseers every year. The proximity of the tunnel to the Sagrada Familia Basilica led to much controversy among politicians and citizens, who feared for its safety during the construction of the tunnel.

These fears were enhanced by accidents and/or incidents that occurred during the construction of the HST tunnel in Barcelona. In 2005, a tunnel to extend the underground line 5 collapsed during the construction stage, affecting numerous residents of the El Carmel neighbourhood (Cia and Blanchar, 2005; Melis, 2005). Fortunately, there were no victims. The tunnel collapsed mainly (in addition to other factors associated with the construction) because of the presence of an undetected fault zone (Jimenez and Senent, 2012). Subsequently, problems arose during the construction of other stretches of the HST line "Madrid–Barcelona–France frontier", e.g. in the Bellvitge neighbourhood in the South of Barcelona. The tunnel was constructed by the cut and cover method and numerous sink-holes appeared during the excavation. These were caused by defects in the diaphragm walls and could have affected adjacent buildings (Pujades et al., 2012a). During the drilling of the HST tunnel in Barcelona other high profile incidents occurred in other parts of the world, deepening the concern about the construction. One well-known incident was the collapse of the underground tunnel in Cologne in 2009 (Van Baars, 2011).

Because of these setbacks, representatives of the Basilica, neighbourhood associations and some politicians launched a campaign against the construction. As a result, the construction specifications were made stricter than usual in order to avoid accidents and minimise the impact of the construction around the Sagrada Familia. The impacts were anticipated, the initial project was modified to mitigate them and additional safety measures were adopted.

It was initially planned to construct the tunnel by the cut and cover method. This option was not considered because the impact on the groundwater would have been excessive since the diaphragm walls obstructed a large portion of the aquifer. The hydraulic head would have been altered by more than 3 m, which would have affected the capacity of the soil to support loads and would have caused soil movements (heave on the upgradient side of the tunnel and subsidence downgradient). In addition, the cut and cover method causes considerable disruption to the normal life of cities. The tunnel was therefore

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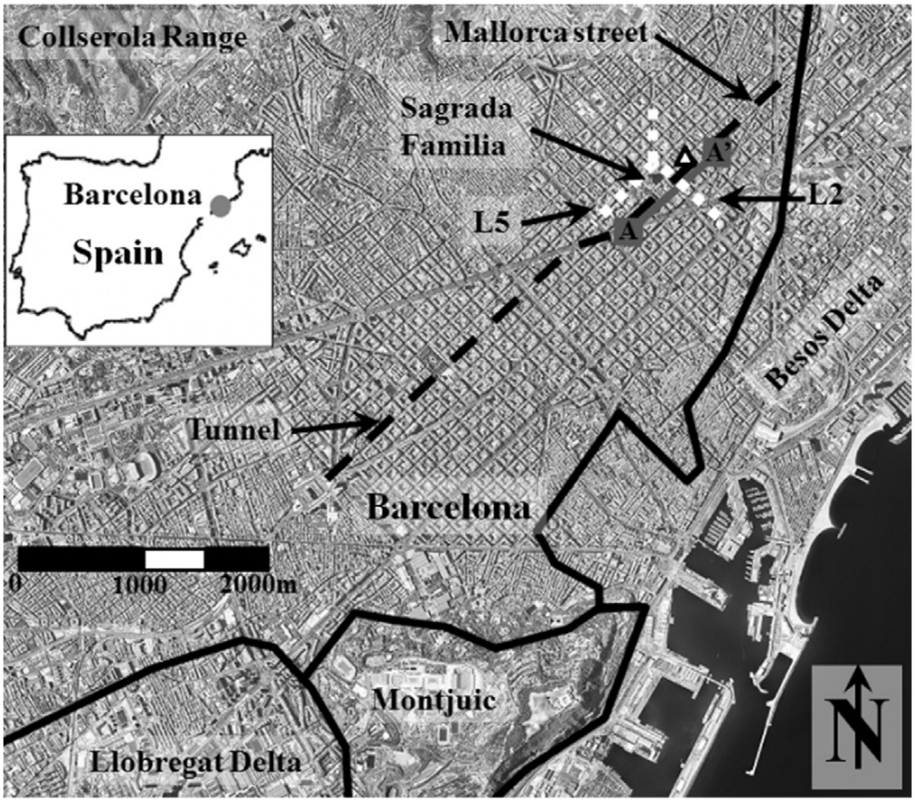

Fig. 1. Geographical location of the study site. The path of the HST tunnel and of the subway lines (L2 and L5) are displayed together with the location of the Padilla shaft (triangle). The section where the geological profile was made is also displayed in this figure (A–A′).

constructed by using an EPB. Two protection measures were adopted in the areas adjacent to the Sagrada Familia in order to mitigate the impact and risks of the construction. First, a wall of non-secant piles (BPW) was built to reduce the tunnelling settlements under the Sagrada Familia (Rodríguez and Blanco, 2012). Second, a shaft was excavated near the Basilica (Pujades et al., 2014a). The aim of this shaft was to service the EPB in order to excavate the tunnel under the Sagrada Familia with the EPB under optimal conditions. All the potential impacts were considered and are described below.

The most significant hydrogeological impacts potentially caused by the construction of a tunnel in an aquifer are the barrier effect (s_B) and the drain effect (Vázquez-Suñe et al., 2005). The barrier effect is caused by underground impervious structures located below the water table. These structures reduce the effective transmissivity of the aquifer, leading to a rise in the water table upgradient and to a drop downgradient (Ricci et al., 2007; Deveughèle and Zokimila, 2010). The barrier effect may entail geotechnical and/or environmental consequences and may affect pre-existing infrastructures (Custodio and Carrera, 1989; Marinos and Kavvadas, 1997; Tambara et al., 2003; Paris et al., 2010). The drain effect is caused by drainage tunnels which are designed to extract groundwater so as to avoid water loads. These tunnels cause a head drop that may have far-reaching environmental and geotechnical consequences (Li and Kagami, 1997; Chae et al., 2008; Vicenzi et al., 2009; Butscher, 2012). Both effects can be determined accurately prior to the construction numerically and analytically (Goodman et al., 1965; Meiri, 1985; El Tani, 1999, 2003; Kolymbas and Wagner, 2007; Pujades et al., 2012b). If the predictions show that these impacts are not acceptable, the construction must be modified or corrective measures must be adopted, e.g. Kusumoto et al. (2003) proposes solutions to minimise the barrier effect.

Other impacts when tunnelling with an EPB include those related to the excavation of shafts, which are used as maintenance, emergency and/or ventilation exits (Ni and Cheng, 2011). The dewatering needed to excavate deep shafts causes a drop in the head and modifies the groundwater behaviour and the water pressure distribution around the shaft. The impacts of the head drop are similar to those of the drain effect (settlements are the most feared impact). However, the head drop (and associated settlements) is punctual. Moreover, accidents such as siphoning or base heave events may cause large soil movements outside the enclosure, posing a risk to adjacent buildings (The German Society for Geotechnics, DGGT, 2012).

Finally, the most perceptible impacts when tunnelling with an EPB are the soil movements during the tunnel excavation. Movements can be divided into short and long term movements. Short term movements are caused mainly by 1) ground loss during the excavation, which redistributes the stress in the soil and results in a stress relief (Ercelebi et al., 2011), 2) injection of grout and 3) pushes of the TBM over the soil to advance. Long term movements are observed after the excavation process and are associated with creep, stress redistribution, consolidation of the soil after drainage, and perhaps with soil consolidation resulting from groundwater changes due to the interaction between the tunnel and the aquifer (Ercelebi et al., 2011; barrier effect or drain effect).

The methodology to assess all the potential impacts summarised above consisted in:

1) Characterising the soil geologically and hydrogeologically.
2) Predicting numerically and analytically the magnitude of the potential impacts caused by the construction: water levels and long term settlements associated only with groundwater evolution.
3) Monitoring the evolution of groundwater and soil movements at different monitoring points.
4) Comparing the groundwater and the soil movements measured with the predictions in order to validate the procedure. The efficiency of the BPW (to reduce soil movements) was also assessed by analysing the data obtained during the construction.