Engineering Geology 196 (2015) 238–250

Contents lists available at ScienceDirect

Engineering Geology

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

Assessment of the barrier effect caused by underground constructions on porous aquifers with low hydraulic gradient: A case study of the metro construction in Barcelona, Spain

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ARTICLE INFO

Article history:
Received 4 August 2014
Received in revised form 2 June 2015
Accepted 15 July 2015
Available online 17 July 2015

Keywords:
Tunnel
Barrier effect
Pumping test
TBM
Porous aquifer

ABSTRACT

Construction of tunnels can impact aquifers because of the changes produced in the natural groundwater behavior. The drain effect, which is one of the most important impacts, can be eliminated using a tunnel-boring machine (TBM) to drill a tunnel with an impervious lining. However, the use of impermeable linings results in aquifer obstruction, giving rise to the barrier effect, which may cause an increase and decrease of the hydraulic head upgradient and downgradient of the tunnel, respectively. This modification of the hydraulic head, which can be predicted analytically and is proportional to the natural hydraulic gradient of the aquifer perpendicular to the tunnel (i_N) (before it is constructed), is negligible for aquifers with values of i_N that are very small or null (approximately 0). In these cases, the analytical solutions are not useful to estimate the real impact because the head distribution is not largely affected.

This study proposes a methodology to evaluate the hydrogeological impact produced by the construction of underground impervious structures in aquifers, which have a small or null i_N. The method, which is based on the analysis of the groundwater response to pumping tests performed before and after construction, was tested in a stratified porous aquifer and was used along with numerical modeling to assess the barrier effect in an experimental site (Sant Cosme, El Prat de Llobregat, Barcelona). The impact on the head distribution was negligible. However, the reduction of the connectivity was considerable. Pumping tests can determine the changes in aquifer connectivity caused by the construction of an underground impervious structure. The behavior of the groundwater during the post-tunneling pumping changes with regard to the pre-tunneling tests. A delay in the response to the pumping and a decrease of the drawdown are observed in the piezometers located on the opposite side of the tunnel where the well is placed, whereas an increase of drawdown occurs in the piezometers situated on the same side of the well. The procedure explained in this paper reveals a useful tool for determining the impact caused by underground impermeable constructions in aquifers, where i_N is small or even 0.

1. Introduction

Most of the underground infrastructures constructed in the metropolitan area of Barcelona in the last decade have been excavated below the water table. The present study arose from a hydrogeological survey performed during the construction of the underground line L-9 in the Llobregat Delta (Fig. 1), which is located in the southern part of Barcelona (Spain). The tunnel, which was excavated with a Tunnel Boring Machine (TBM), cuts a large section of the Llobregat Delta Shallow Aquifer. The potential hydrogeological impacts caused by tunnel drainage, barrier effects or other sources should therefore be quantified.

The hydrogeological impacts caused by a tunnel depend on the properties of the lining, aside from the aquifer properties. If the lining is permeable, tunnel inflows could cause a piezometric drawdown (Goodman et al., 1965; Gargini et al., 2008; Kvaerner and Snilsberg, 2008; Yang et al., 2009; Raposo et al., 2010). If the tunnel has an impervious lining, this can create a barrier effect by partial or total reduction of the aquifer section (Marinos and Kavvadas, 1997; Vàzquez-Suñé et al., 2005; Carrera and Vàzquez-Suñé, 2009; Deveughele et al., 2010), decreasing 1) the effective transmissivity of the aquifer (the sum of the transmissivity of the different geological layers) in the site

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http://dx.doi.org/10.1016/j.enggeo.2015.07.006
0013-7952/

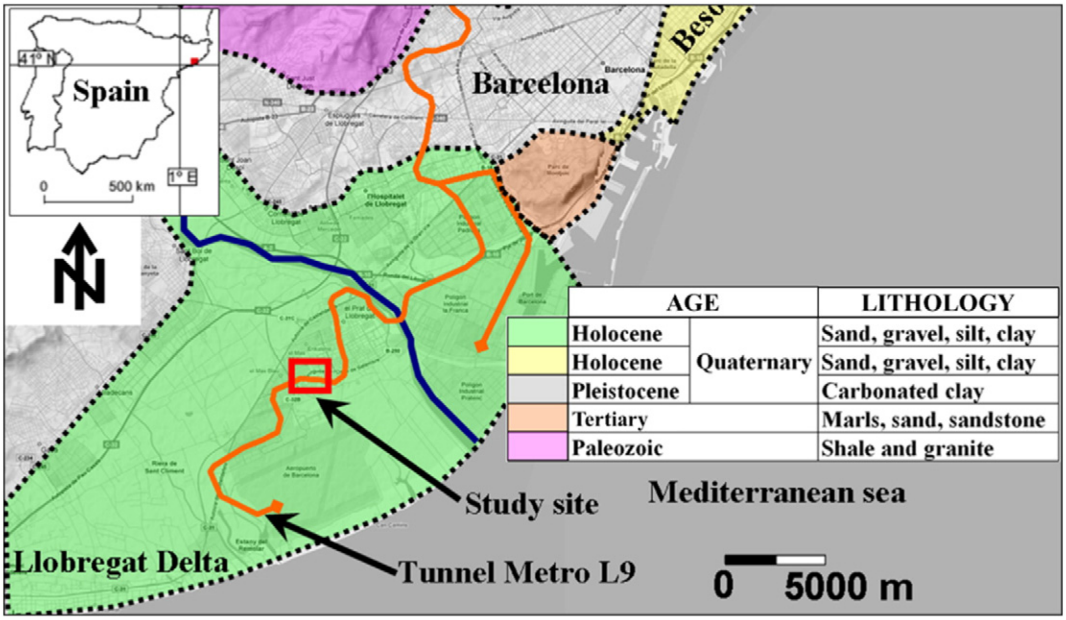

Fig. 1. Geographical and geological setting of the site area.

where the tunnel is located and 2) the hydraulic connectivity between both sides of the construction. High values of hydraulic connectivity between two points signify that changes performed at one of the points are easily transmitted to the other point. The main impact of the barrier effect consists of an increase in the hydraulic head on the upgradient side of the construction and a decrease on the downgradient side (Ricci et al., 2007). Under ideal conditions, the increase in the upgradient has the same magnitude as the decrease in the downgradient. The distribution on the impact varies depending on the boundary conditions of the aquifer (Pujades et al., 2012).

Drawdown caused by the drain effect or by the barrier effect (downgradient) could give rise to a number of problems, e.g., a) ground settlements caused by an increase in the effective stress (Zangerl et al., 2003, 2008a and b; Mokni et al., 2013; Carrera and Vàzquez-Suñé, 2009), b) drying of wells, springs (Gargini et al., 2008; Yang et al., 2009; Raposo et al., 2010) and wetlands (Kvaerner and Snilsberg, 2008), c) seawater intrusion into coastal aquifers and d) swelling as a result of gypsum precipitation in anhydrite rock massifs (Butscher et al., 2011).

Head increase on the upgradient side caused by the barrier effect could lead to a) floods in surface and ground structures, b) soil salinization (Vàzquez-Suñé et al., 2005; Carrera and Vàzquez-Suñé, 2009), c) soil contaminant lixiviation from piezometric cleaning (Navarro et al., 1992), and d) changes in the natural groundwater behavior that can mobilize contaminants (Chae et al., 2008; Epting et al., 2008).

It is possible to assess the impact caused by tunnel inflows on surface water (Gargini et al., 2008) and groundwater (Attanayake and Waterman, 2006). Analytical (Bear et al., 1968; Custodio, 1983) and numerical methods (Molinero et al., 2002; Epting et al., 2008; Yang et al., 2009; Raposo et al., 2010; Font-Capó et al., 2011) can be used for inflow quantification. The impact caused in the hydraulic head by the barrier effect can also be assessed numerically (Bonomi and Bellini, 2003; Merrick and Jewell, 2003; Tubau, 2004 and Ricci et al., 2007) and analytically (Marinos and Kavvadas, 1997; Deveughele et al., 2010 and Pujades et al., 2012).

The hydraulic head variation produced by the barrier effect can be expressed mathematically as the difference between the undisturbed hydraulic gradient and the hydraulic gradient once the underground structure is constructed (Pujades et al., 2012). The magnitude of this variation is proportional to the natural groundwater gradient perpendicular to the construction (i_N). A higher gradient increases head variation and vice versa. Therefore, at sites with small gradients, the impact in the hydraulic head caused by underground impervious structures is negligible. However, these constructions alter aquifers reducing their connectivity. Consequently, the assessment of the barrier effect, quantifying only the hydraulic head variation, is very limited including the corrective measures adopted to reduce it. In addition, because i_N is necessary to apply the analytical solutions, these may fail at sites with small i_N as a result of errors associated with the field measurements (inaccuracies in the altimetry of piezometers, in measurements, and in head fluctuations, a result of natural or anthropogenic causes). These errors, which may occur at other situations, are more important (regarding the magnitude of the barrier effect) at sites with small i_N.

During the construction of the tunnel for Line 9 of the metro in Barcelona, a small i_N was observed at some of the construction sites. Concretely, this fact was noticed at the neighborhood of Sant Cosme (El Prat de Llobregat, Barcelona). Given that it was necessary to predict the impact of the construction and that the analytical predictions were not believable (because of the small i_N), a procedure based on pumping tests was followed to assess the impact of the construction on the aquifer. The main conclusion is that the reduction in connectivity and effective transmissivity produced by the underground impervious structures in aquifers can be evaluated by comparing the drawdown evolution that occurred during pumping tests performed before and after the construction. This method does not depend on i_N.

This paper seeks to 1) quantify the impact of an impermeable tunnel constructed with a TBM on the steady state heads in a real site, and 2) propose a method to quantify the impact caused by an impervious tunnel on the connectivity of an aquifer by using pumping tests.

2. Problem statement (basic concepts)

2.1. General description of the barrier effect

Pujades et al. (2012) define the barrier effect (s_B) as the increase in head loss (or drop) along flow lines caused by the reduction in conductance associated with an underground construction. Therefore, the barrier effect (s_B) is defined mathematically as

$$s_B = \Delta h_B - \Delta h_N \quad (1)$$