Barrier effect of underground structures on aquifers

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Abstract

Impervious structures below the water table modify the natural groundwater flow in aquifers. They act as barriers, causing heads to rise upgradient and to fall downgradient. We define the barrier effect as the increase in head loss across the barrier with respect to the natural conditions prior to construction. We distinguish between regional (the minimum head loss observed at long distances) and local (the maximum head loss observed close to the structure) barrier effects. We use numerical and analytical methods to derive semi-empirical equations to quantify the two barrier effects for semi-permeable, partially penetrating (or fully penetrating but finite in length), and barriers with a by-pass in confined aquifers. The resulting equations depend on the barrier geometry and on the natural head gradient in the aquifer and they are easy to apply. We test their validity at two construction sites, obtaining excellent agreement between the computed and observed barrier effects.

Keywords: Barrier effect, underground structure, tunnel, aquifer.

1. Introduction

Research has improved the construction of underground structures in cities (Tambara, *et al.*, 2003). They are successfully completed when rigorously and carefully planned (Jurado, *et al.*, 2011). However, it is essential to consider not only the construction stage but also the long term effects of these structures on the aquifer. When underground structures intersect aquifers, they may act as drains or barriers against the groundwater natural flow (Vázquez-Suñé, *et al.*, 2004), causing rise to environmental and economic impacts. A number of studies on underground constructions have focused on the evolution of pore pressure around the structure and on the characterization of the flow to its leaky parts, using analytical equations (Goodman, *et al.*, 1965; El Tani, 2003; Vilarrasa, *et al.*, 2011; Pujades, *et al.*, 2011) or numerical models (Font-Capó, *et al.*, 2011). However, few studies have dealt with the hydrogeological impacts of impervious structures (Deveughèle and Zokimila, 2010), which is the subject of this work.

Underground impervious structures modify the groundwater flow pattern because the structure reduces totally or partially the aquifer section. Thus, effective transmissivity is reduced, leading to a rise in the water table upgradient and a lowering downgradient (Ricci, *et al.*, (2007). These modifications of the water table can have negative consequences. Rising water levels may flood basements (Paris, *et al.*, 2010), promote soil salinization or affect flora by rotting the roots of plants (Tambara, *et al.*, 2003). Other impacts associated with the rise of heads include reduction of the bearing capacity of shallow foundations, expansion of heavily compacted fills under the foundation structures, settlements of poorly compacted fills upon wetting, increase in loads on retraining systems or basement walls of buildings, increase in the need for drainage in temporary excavations and propagation of contaminants contained in the partially saturated zone (Marinos and Kavvadas, 1997).

The lowering of heads on the downgradient side can cause seawater intrusion in coastal aquifers, ground subsidence, death of phreatophytes and the drying of wells and springs (Custodio and Carrera, 1989, Tambara, *et al.*, 2003). Moreover, the difference of water pressures between both sides of the underground structure leads to asymmetric loading for which building foundations have seldom been designed.

Corrective measures exist to decrease these variations in the water table. In essence, corrective measures consist in collecting groundwater upgradient and in discharging it downgradient (Kusumoto, *et al.*, 2003). These measures that allow the groundwater to pass through the structure can be termed “bypasses”.

Numerical models are used to quantify head variations and to design the solutions (Merrick and Jewell, 2003, Bonomi and Belleni, 2003, Paris, *et al.*, 2010 and Ricci, *et al.*, 2007). Building such models may be complicated because considerable detail is necessary close to the obstruction. Analytical solutions are therefore useful. Unfortunately, few analytical equations are available (Marinos and Kavvas, 1997, Deveughele and Zokimila 2010) and their validity is limited. In part, this reflects that the barrier effect problem has not been adequately formalized.

Thus, the objective of this study is to formalize the problem of the barrier effect and to obtain analytical solutions for different barrier types.

2. Problem statement

2.1. Basic concepts and definitions

We define barrier effect (s_B) as the increase in head loss along flow lines caused by the reduction in conductance associated with an underground construction. Therefore

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

where Δh_B is the head drop across the barrier and Δh_N is the head drop between the same points under natural conditions, i.e. prior to construction (Figure 1).

In general, the magnitude of s_B depends on the location of the points across the barrier. The maximum head rise (or drop) commonly occurs close to the barrier and diminishes as distance is increased. In practice, therefore, it is important to distinguish between local (s_{BL}) and regional (s_{BR}) barrier effects

$$s_{BR} = \min \{s_B\} \quad (2)$$

$$s_{BL} = \max \{s_B\} \quad (3)$$

The regional barrier effect is measured at long distances from the barrier, where groundwater flow lines are unaffected by the barrier. This occurs at distances from the barrier larger than the longest length partially cut by the barrier (width or thickness), e.g. this distance would be the aquifer thickness in the case of a barrier that cuts partially the whole width of an aquifer.

The actual impact of the barrier effect depends on the boundary conditions of the aquifer. When head is prescribed downgradient, the barrier effect is concentrated on the upgradient side of the barrier, causing heads to rise (case b in Figure 1), and viceversa (case c in Figure 1). On the other hand, in the absence of a prescribed head, the head rises upgradient of the barrier and drops downgradient (case a in Figure 1).

To compute s_B , we will assume that the flow through the aquifer remains unchanged because the total flow is controlled by outside factors (i.e, recharge or pumping). Otherwise, the barrier may reduce the total flow rate across the aquifer.

2.2. Governing equations

The equation that governs the problem in steady state can be written as

$$k \nabla^2 h = 0 \quad (4)$$

where h is head and k is hydraulic conductivity, assumed constant. Commonly, aquifers are heterogeneous especially along the vertical direction (Velasco, *et al.*, 2011). Therefore, the vertical lengths to apply the analytical solutions need to be corrected using the anisotropic ratio (a) when the barrier forces a component of flow perpendicular to the stratification

$$k_h \left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} \right) + k_v \left(\frac{\partial^2 h}{\partial z^2} \right) = 0 \quad (5)$$

$$a = \sqrt{\frac{k_h}{k_v}} \quad (6) \quad \rightarrow \quad k_h \left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{1}{a^2} \frac{\partial^2 h}{\partial z^2} \right) = 0 \quad (7)$$

$$z' = az \quad (8) \quad \rightarrow \quad k_h \left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z'^2} \right) = 0 \quad (9)$$

where k_h and k_v are hydraulic conductivities, in the horizontal and vertical directions, respectively.

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2.3. Types of barrier

The following types of barriers can be distinguished: 1) semi-permeable barriers, 2) partial barriers, which do not completely obstruct one aquifer dimension, thickness or width (Figure 2a and b), 3) barriers that do not completely obstruct any aquifer dimension (barriers circumscribed in aquifers) (Figure 2c), and 4) barriers equipped with a system of bypasses (Figure 2d).

From a mathematical point of view, there is no difference between the two types of partial barrier.

Barriers circumscribed in aquifers are similar to partial barriers since we may ignore the thickness, which is not cut by the barrier, located above or/and below the structure.

Although bypass systems are designed to reduce the barrier effect, this is not totally removed. Bypass systems connect a water collection device upstream with a discharging device downstream through a pipe. These devices can be horizontal or vertical wells, possibly embedded in a gravel wall to improve their performance. The bypass studied in this paper consists in fully penetrating wells.

2.4. Dimensionless form

The problem may be written in dimensionless form by dividing the barrier effect over the head drop that occurs over the barrier length under natural conditions

$$s_{BD} = \frac{s_B}{h_C} = \frac{s_B}{i_N d_C} \quad (10)$$

Where s_{BD} is the dimensionless barrier effect, h_C is the characteristic head drop, i_N is the natural gradient and d_C a characteristic length that depends on the problem. Ideally, s_{BD} should only depend on the geometrical features of the barrier.

2.5. Semi-permeable barrier case

The above concepts are illustrated by the semi-permeable (fully-penetrating) barrier case, which can be regarded as paradigmatic. Consider a structure that completely obstructs the aquifer and causes a reduction of the effective hydraulic conductivity over the constructed volume, but the flow rate continues crossing this area. Assuming that the flow rate across the aquifer is unaffected by the construction we can write

$$q_X = k b i_N = k_B b \frac{\Delta h_B}{L_B} \quad (11)$$

165 where b is the aquifer thickness, q_X is the flow that cross the aquifer, k_B is the hydraulic
 166 conductivity of the barrier and L_B is the width of the barrier. Ignoring the head loss across the
 167 barrier area (i.e. $i_N L_B \ll \Delta h_B$), we obtain

$$168 \quad s_B = \frac{k}{k_B} i_N L_B \quad (12)$$

169 The barrier length L_B is the characteristic length. Combining equations (12) and (10), yields

$$170 \quad s_{BD} = \frac{s_B}{i_N L_B} = \frac{k}{k_B} \quad (13)$$

171 If the natural head gradient in the barrier area is not neglected, then

$$172 \quad s_B (\text{in barrier area}) = \Delta h_B (\text{in barrier area}) - \Delta h_N (\text{in barrier area}) \quad (14)$$

173 and

$$174 \quad \Delta h_N (\text{in barrier area}) = i_N L_B \quad (15)$$

175 Therefore

$$176 \quad s_{BD} = \frac{s_B - i_N L_B}{i_N L_B} = \frac{k}{k_B} - 1 \quad (16)$$

177 Notice that the actual s_B depends on the barrier thickness. It is possible to characterize the
 178 barrier with a leakage coefficient (α_B)

$$179 \quad \alpha_B = \frac{q_X}{s_B} = \frac{k b i_N}{s_B} = \frac{k b}{s_{BD} L_B} \quad (17)$$

180 The latter expression is general, i.e. given s_{BD} and k (or the aquifer transmissivity,
 181 T), it is possible to use Eq. (17) to derive the leakage factor α_B . This can be used in some
 182 codes (Hsieh et al, 1993) to characterize barriers. Alternatively, the net effect of the barrier
 183 can be represented in models by assigning an effective transmissivity to the barrier $T_B = \alpha_B L_B$
 184 over a band of width L_B . In the semi-permeable barrier case, this leads to $T_B = k_B b$, which is
 185 trivial.

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3. Methodology

Except for the semi-permeable barrier, which was discussed above, the solutions to the other types of barrier are obtained using the following steps:

1. Study of the conceptual model setting and equations that govern flow behaviour.
2. Statement of the problem in dimensionless form and identification of the characteristic variables that govern the solution.
3. Preparation of a numerical model to compute s_B for different values of the characteristic variables. We used the finite element code TRANSIN-IV (Medina and Carrera, 2003), with visual interface of VISUAL TRANSIN (UPC, 2003).
4. Performance of a conceptual and/or analytical study of the problem to predict the form of the terms in the analytical solution.
5. Fitting of the analytical terms to the numerical solution by multiple regression analysis. These analysis provide different functions of the variables that explain the behaviour of the system and allow us to calculate s_B . Each function has one regression coefficient (R^2) and the function with the regression coefficient closest to one is selected. The routine of IMSL DRBEST is used for the multiple regression analysis. This routine uses the Furnival and Wilson algorithm (1974).

4. Analytical expressions for s_{BD} .

4.1. Partial barriers

As discussed in section 2, this type of barrier completely cuts only one aquifer dimension, i.e. either thickness or width (Figures 2a and b). Therefore, two types of partial barriers might be distinguished depending on the dimension cut. However, the two are equivalent from a mathematical point of view and share the same solution. In fact, differences

between these two partial barriers are restricted to the meaning of the variables. For instance, we choose b as a characteristic length, which is half the width of the aquifer in the fully penetrating finite barrier case (Figure 2b) or the aquifer thickness in the partially penetrating infinite case (Figure 2a). Assuming that the flow rate that cross the aquifer remains unchanged, the problem is fully defined in terms of the open fraction b_a/b of the aquifer, where b_a is the length of the aperture.

Note that the barrier effect can be divided into two terms (Figure 3b): the barrier effect between the aquifer boundary and the barrier (s_{BO} ; s_{BRO} or s_{BLO}) and the barrier effect below the structure (s_{BI}). These two effects must be added to obtain the total barrier effect. The barrier effect resulting from the flux below the structure is given by the semipermeable barrier solution

$$s_{BI(L,L+L_B)} = \frac{q_X L_B}{k b_a} - \frac{q_X L_B}{k b} = i_N L_B \left(\frac{b}{b_a} - 1 \right) \quad (18)$$

$$s_{BID(L,L+L_B)} = \frac{s_{BI}}{i_N L_B} = \frac{b}{b_a} - 1 \quad (19)$$

where s_{BID} is the dimensionless barrier effect below the barrier. This value, which could be negligible when $b \gg L_B$, must be added to the barrier effect resulting from flow concentration towards the opening. This is discussed below.

4.1.1. Dimensionless regional barrier effect (s_{BROD})

Several numerical results of the barrier effect have been obtained from the numerical model (Figure 3c) by varying b_a . For each run, the regional barrier effect is defined as the head rise at the outer boundary, where flux is prescribed. As shown in Figure 3c, flow in depth towards the opening is radial. Therefore we expect that the solution contains terms

233 similar to Thiem equation. That are $\ln(b_{aD})$ and $\ln(b_{bD})$, where b_{aD} and b_{bD} are the
 234 dimensionless lengths of the aquifer cut and uncut by the barrier respectively ($b_{aD} = b_a/b$ and
 235 $b_{bD} = b_b/b$). Polynomial terms are also included similarly to the general hydrological
 236 equations to solve radial flow. We obtain an equation that is similar to that of Thiem, except
 237 for very large openings ($b_{bD} < 0.1$), when the regional barrier effect can be neglected

$$238 \quad s_{BROD} = \frac{s_{BRO}}{i_N b} = \begin{cases} 0 & \text{if } b_{bD} \leq 0.1 \\ \frac{2}{3\pi} \ln \left(\frac{1}{5\pi b_{bD} (1-b_{bD})^6} \right) & \text{if } b_{bD} > 0.1 \end{cases} \quad (20) \text{ and } R^2 = 1.00$$

239 Figure 5a displays the relationship between s_{BROD} and b_{aD} . Note that numerical results
 240 (dots) match perfectly those obtained with Equation (20) (line). Note also that the barrier
 241 effect increases logarithmically when the opening is reduced. This increase is diminished
 242 when the aperture exceeds 30% of the aquifer thickness (vertical barrier) or width (horizontal
 243 barrier).

244

245 4.1.2. Dimensionless local barrier effect (s_{BLOD})

246 The solution is obtained following the same steps adopted in the case of the regional
 247 barrier effect but evaluating the head variation at the local observation point O_L (Figure 3c).
 248 Two situations must be distinguished. On the one hand, when the opening is small
 249 ($b_{bD} > 0.28$), flow towards the opening is essentially radial with the result that the equation
 250 of the barrier effect is similar to that of Thiem. On the other hand, when the opening is large
 251 ($b_{bD} > 0.28$), flow is linear and the head drop between O_L (Figure 3) and the edge of the
 252 opening is equivalent to that of the natural gradient ($\Delta h = i_N b_b$). This value has to be
 253 multiplied by 2 to account for head loss on the downgradient side. The value 0.28 has no

specific meaning, but simply results from the fitting procedures, which leads to the following equation:

$$s_{BLOD} = \frac{s_{BLO}}{i_N b} = \begin{cases} 2b_{bD} & \text{if } b_{bD} < 0.28 \\ \sqrt{\frac{3}{8}} \ln \left(\frac{2b_{bD}^{0.29}}{b_{aD}^2} \right) & \text{if } b_{bD} \geq 0.28 \end{cases} \quad (21) \quad \text{and } R^2 = 1.00$$

The results of this approximation together with those of the numerical solution are shown in Figure 5b. Again, the fit is visually perfect (errors are smaller than 0.02 for $b_{aD} > 0.005$).

4.2. Barrier with bypass

Bypasses can be used as a corrective measure to reduce s_B . They may be of several types (Kusumoto, *et al.*, 2003, Lopez, *et al.*, 2009). We analyze a bypass consisting of deep wells connected by a pipe through the underground construction (Figure 2d).

The system can be simplified for computational purposes as shown in Figure 4. Because of symmetry, the model domain is the rectangle bounded by the flow line along the wells and the axis perpendicular to the barrier located halfway between two adjacent wells. The intersection of this axis with the barrier is the point with highest head rise (point O_L in Figure 4), where the local barrier effect is computed. The system is modelled by imposing a prescribed head at the well radius and the natural flux at the inflow boundary. All other boundaries are assumed to be impervious. The barrier effect is calculated as twice the difference between computed and natural heads at the inflow boundary (regional barrier effect) and at point O_L (local barrier effect).

4.2.1. Dimensionless regional barrier effect (s_{BRD})

The problem can be solved analytically by means of the image theory or by using the solution for a drain in a long confined aquifer (Schneebeili, 1966, cited by Custodio and

Llomas, 1983). The latter is simpler, but also requires the use of the image theory to accommodate the no flow boundary at the barrier. We consider two wells at $x = \pm d$, where d is the distance between well and barrier. These two wells are equivalent to a single well of radius $\sqrt{2r_w d}$ when $d \ll A$, where A is the distance between wells and r_w is the radius of the bypass well (Figure 4). Subtracting the natural head drop $i_N L$, where L is the length to the furthest inflow boundary from the drawdown at the well, and dividing by $i_N A$ (A is the characteristic length) we obtain

$$s_{BRD} = \frac{s_{BR}}{i_N A} = \frac{1}{\pi} \ln \frac{A^2}{8\pi^2 r_w d} - \frac{2d - L_B}{A} \quad (22)$$

Figure 5c displays s_{BRD} versus d_D for two values of r_{wD} (dimensionless well radius) using Equation (22) (lines) and the numerical model (dots) that overlap. The regional barrier effect can be considerably reduced by increasing the well radius, e.g. constructing the well inside a gravel trench. The greater the distance (d) from the well to the barrier, the greater the efficiency of the bypass. However, it is possible that the improvement obtained by placing the well further away from the barrier does not offset the increase in the difficulty of constructing the connecting pipe.

4.2.2. Dimensionless local barrier effect (s_{BLD})

The solution of Schneebeli (1966 cited by Custodio and Llomas, 1983) can also be used to obtain the local barrier effect, using the same steps as above, which yields

$$s_{BLD} = \frac{s_{BL}}{i_N A} = \frac{1}{\pi} \ln \frac{A^2}{2\pi^2 r_w d} - \frac{2d - L_B}{A} + \frac{\pi d^2}{A^2} \quad (23)$$

Figure 5d displays the influence of d and r_{WD} on s_{BLD} . As in the case of s_{BRD} , the increase in d and r_{WD} diminishes the local barrier effect although the reduction is smaller than in the regional barrier effect.

5. Application

5.1 Introduction

We tested the validity of the above equations by applying them to the barrier effects at two underground construction sites: the tunnel for the High Velocity Train (HVT) in Barcelona (Spain) and a Railway Station (RS) at El Prat de Llobregat (Spain) (Figure 6). Only the local barrier effect was measured at both sites because the piezometers were close to the structures, which is not infrequent at most construction sites. Moreover, to achieve the steady-state barrier effect for long distances is time consuming.

The HVT in Barcelona was built using a Tunnel Boring Machine (TBM), which decreases the aquifer thickness. Thus, this may be regarded as a partially penetrating infinite barrier. Moreover, vertical hydraulic conductivity is smaller than the horizontal one. Therefore, this case illustrates the application of the anisotropy correction factor. At the RS at El Prat de Llobregat, the full thickness of the aquifer (but not its width) is cut by the diaphragm walls. This case may therefore be regarded as a fully penetrating finite barrier.

5.2 HVT tunnel in Barcelona:

The HVT tunnel crosses all the city of Barcelona penetrating the geological formation of the Barcelona plain. The length of the tunnel is 5.1 km. Permeable units under Barcelona include Tertiary (Pliocene) and Quaternary deposits. The Pliocene materials are the most affected by the tunnel, but it also cuts Quaternary deposits at some places (Figure 7a).

The Quaternary materials are made up of sequences of sand/gravel with clay matrix and silts with calcareous nodules. They contain levels of calcrete, which belongs to periods of no sedimentation. Sand/gravel layers with clay matrix are deposits from alluvial fans and the silt materials are eolian deposits. The percentage of clay varies, which can predominate at some layers. At the bottom, the Tertiary materials consist of very low permeability marls that contain high permeability sand strata (Figure 7b).

The Barcelona plain can be considered as an aquifer with high vertical heterogeneity, because it is formed by the alternation of different strata, but heads of the different layers are related. The effective transmissivity of the aquifer is 100-200 m²/d. The Quaternary clays and the Pliocene marls display low hydraulic conductivity, ranging from 0.001 to 0.01 m/d. On the other hand, the hydraulic conductivity of the Quaternary sands and gravels ranges from 0.1 to 10 m/d, similar to Pliocene sands.

Two piezometers located in the middle of the tunnel route (Figure 7c) were monitored before and after tunnel construction. At this section, the tunnel is somewhat shallow and cuts through the top portion of the aquifer. One piezometer was located upgradient and the other downgradient. Both piezometers were screened on the upper side of the aquifer (Figure 7b), where the maximum s_{BL} was measured. Although the piezometer was broken during the construction of the tunnel, its data were used to obtain i_N and Δh_N . Figure 7d displays the head evolution at both piezometers. It is observed a small step where the head rises at the upgradient side and drops symmetrically at the downgradient side at the beginning of May 2011. Later, the downgradient piezometer was broken, and then the head rise on the upgradient side is assumed to be equal (symmetrical) to the drop on the downgradient side. Therefore, the observed local barrier effect (s_{BL}^{obs}) is given by

$$s_{BL}^{obs} = \Delta h_N - \Delta h_B = 8 \text{ m}$$

Figure 7d shows that s_{BL} is produced when the TBM crosses the site. In this case, the barrier effects between the barrier and the aquifer boundary (s_{BLO}) and below the barrier (s_{BI}) are calculated and added. Given that $b_{bD} > 0.28$ and applying Equation (21), we obtain

$$s_{BLOD} = \sqrt{\frac{3}{8}} \ln \left(\frac{2b_{bD}^{0.29}}{b_{aD}^2} \right) = 0.97$$

And applying Equation (19), we obtain

$$s_{BID} = \frac{b}{b_a} - 1 = 0.76$$

The characteristic length of the vertical barrier effect is the aquifer thickness (b), which must be corrected for anisotropy. Computing the anisotropy ratio (a) (Equation 6) requires knowledge of the hydraulic conductivity distribution. k_V and k_H were calculated using the data of a pumping test, as the harmonic and arithmetic averages, respectively, of the hydraulic conductivities of the layers. i.e.

$$k_V = b \sum \frac{k_i}{b_i} = 0.008 \frac{m}{d} \quad \text{and} \quad K_H = \frac{\sum k_i b_i}{b} = 0.87 \frac{m}{d}$$

where k_i is the hydraulic conductivity of each layer and b_i is its thickness. Then,

$$a = \sqrt{\frac{k_h}{k_v}} = 10.21$$

Thus

$$b_C = b \cdot a = 22 \text{ m} \cdot 10.21 = 224.6 \text{ m}$$

where b_C is the corrected thickness of the aquifer. Using $i_N = 0.035$, which was obtained with the head observations measured at both piezometers before the tunnel construction

$$s_{BLO} = s_{BLOD} i_N b_C = 7.6 \text{ m}$$

Similarly, s_{BI} is obtained from s_{BID} as

$$s_{BI} = s_{BID} i_N L_B = 0.32 \text{ m}$$

and

$$s_{BL} = s_{BLO} + s_{BI} = 7.9 \text{ m}$$

This value is close to that of s_{BL}^{obs} observed as a result of the tunnel construction (Figure 7d).

5.3 El Prat de Llobregat Railway Station

The El Prat de Llobregat RS is located in the middle of the Llobregat River Delta (Figure 8a). The Delta is delimited by the Garraf mountain range at the west, the sea at the south and east and the city of Barcelona at the north (Figure 6). This Delta have a complex structure as consequence of the sea level variations during the Quaternary (Tubau, 2004), but basically, contains two aquifers separated by a silt formation. The station was built using the “cut and cover” method. Diaphragm walls were used to perform the enclosure. Their depth was 29 m and they cut completely the shallow aquifer.

Both aquifers and the silt formation are quaternary deposits. At the top of the shallow aquifer, above the groundwater table, there are thin strata of flood plain clays, deposited during periods of overflowing of the river. In the bottom of the Delta, below the depth aquifer, there are Pliocene marls (Figure 8b). Aquifers are formed by sand and gravel deposits, and the silt formation is consequence of a marine transgression. Their thickness ranges from 12 to 20 m for the upper aquifer and from 4 to 12 m for the lower aquifer (Tubau, 2004).

Aquifer transmissivities range from 200 to 500 m²/d for the upper aquifer and from 1000 to 5000 m²/d for the lower aquifer. The silt layer can be considered as bottom boundary for the upper aquifer. Both aquifers constitute a valuable reservoir of water to the city of

Barcelona. Therefore, they must be preserved and the underground constructions should not modify them.

As in the case of the HVT in Barcelona, s_B was measured near the structure (Figure 8c) so that only s_{BL} was measured. Head evolution (Figure 8d) was measured at two piezometers located on the upgradient and downgradient sides of the station. Both piezometers were screened at the shallow aquifer. Δh_N was measured before the construction works start. Heads fluctuated a lot during construction, reflecting the diaphragm walls construction and the dewatering used during the excavation stage. After the end of construction, head rose upgradient and dropped downgradient. The difference between both is constant during 6 months. At this period Δh_B is measured. Given Δh_N and Δh_B , the observed local barrier effect can be obtained as:

$$s_{BL}^{obs} = \Delta h_N - \Delta h_B = 1.2 \text{ m}$$

Applying the equations proposed in this paper and using the geometry of the Delta and the station (Figure 8a), s_{BL} can be estimated. The methodology is similar to the case of the HVT except that no anisotropy correction is required. The RS constitutes a fully penetrating finite barrier, because the aquifer thickness is completely cut but not its width. Then, the length b (5750m) is the distance between the middle of the RS and the Garraf mountain range. The length b_a (4850m) is the distance between the edge of the RS and the Garraf mountain range. Finally, b_b (900m) is the length of the half of the RS. In this case $b_{bD} = b_b/b = 0.16$. Therefore, using Equation (21), we obtain

$$s_{BLOD} = 2b_{bD} = 0.31$$

In this case, the barrier thickness is negligible because the gradient is much smaller than in the previous case with the result that $s_{BLO} \approx s_{BL}$. We calculate the natural gradient i_N

as $\Delta h_N / L_P$, where L_P is the distance between the piezometers. This yields $i_N = 0.00066$, which is consistent with the piezometric surface (not shown). Therefore s_{BL} yields

$$s_{BL} = s_{BLOD} i_N b = 1.19 \text{ m}$$

This value is again similar to s_{BL}^{obs} when the construction was completed.

6. Conclusions

Underground constructions may cause head variations when intersecting an aquifer. Heads tend to rise upgradient at the obstruction and to fall downgradient. To quantify these variations, the barrier effect is defined as the increase in head drop along a streamline interrupted by a structure (Equation 1).

This increase is, in general, larger close to the obstruction (local barrier effect) than at long distances (regional barrier effect). But both barrier effects must be evaluated when assessing the impact of a tunnel.

We developed semi-empirical equations to quantify the regional and local barrier effects for several geometries of an obstruction. The equations are easy to apply. They only depend on the geometry of the barrier, which is known, and on the natural gradient prior to the construction, which can be easily obtained from the piezometric surface.

The resulting barrier effect can be used directly to assess acceptability or to derive the conductance of the barrier as input in numerical models to study alternative flow scenarios. In all cases, the barrier effect can be mitigated by the construction of bypass structures. The efficacy of bypasses can also be assessed using the equations proposed.

The validity of the equations proposed was tested at two construction sites. At both sites, the application of these equations was straightforward and yielded results that were close to the observations.

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Figure captions

Figure 1. Cross section of an ideal aquifer whose transmissivity is reduced to an effective T_B with respect to its natural initial T over L_B . The head distribution before and after the barrier construction is displayed. Head variations depend on the boundary conditions, a) No prescribed heads, b) prescribed head on the downgradient side and c) prescribed head on the upgradient side. The type of boundary does not modify the value of s_B , which is the same in all cases. h_B and h_N are the head distributions with and without barrier.

Figure 2. Cross sections (left) and plan views (right) of different types of barrier. s_{BL} and s_{BR} are shown in all cases. a) Partially penetrating infinite barrier. b) Completely penetrating finite barrier. c) Barrier included in aquifer. Section C-C' shows that the free area below the barrier is negligible. d) Barrier with bypass.

Figure 3. a) Schematic description of the barrier effect of a partially penetrating barrier with a long section of aquifer with a reduced thickness under the construction. b) The barrier effect consists of two terms: head loss below the construction and head loss by convergence into the opening. The computation grid is also shown (c). s_{BRO} is the barrier effect between the aquifer boundary and the barrier, s_{BRI} across the barrier and Δh_{NI} the natural head through the barrier.

Figure 4. a) Schematic description of the barrier effect for barriers with a system of bypass. b) The problem can be studied as a pumping well surrounded by no flow boundaries. c) The barrier effect results from the flow convergence into the well. The computation grid is also shown (d).

Figure 5. Dimensionless barrier effect, regional and local, versus some variables. Above-left a) s_{BROD} vs. b_{aD} . Above-right b) s_{BLOD} vs. b_{aD} . Below-left c) s_{BRD} vs. d_D for two well dimensionless radius (0.0005 and 0.0015). Below-right d) s_{BLD} vs. d_D also for two well radius.

Figure 6. Study sites.

Figure 7. a) Tunnel section above Barcelona. b) Detailed geological section of the study site. c) Plan view of the study site. d) Head evolution at the piezometers.

Figure 8. a) General plan view of the study site. b) Schematic profile of the aquifers distribution in the Llobregat Delta River. c) Detailed plan view. The piezometers were located close to the underground station. d) Head evolution at the piezometers.

a) No prescribed head

b) Prescribed head downgradient

c) Prescribed head upgradient

— — — h_N — · — · h_B

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8