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Hydrogeological assessment of non-linear underground enclosures

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Abstract

Excavations below the water table are usually undertaken by combining the protection of retaining walls with dewatering by pumping wells. Severe difficulties may arise if the retaining walls have defects. Therefore, their state must be determined and, if needed, the defects repaired or the dewatering system redesigned. The state of underground retaining walls can be evaluated using hydrogeological methods, but these methods are well-established only for linear excavations. The objective of this work is to propose a procedure to evaluate the state of non-linear underground enclosures by analyzing the groundwater response to pumping inside the enclosure. The proposed method, which is based on diagnostic plots (derivative of drawdown with respect to the logarithm of time), allows (1) determining if an underground non-linear enclosure has isolated openings or numerous defects and (2) computing its effective conductance or effective hydraulic conductivity. The methodology is tested with data collected during the excavation of a shaft required for the construction of the high speed train (HST) tunnel in Barcelona, Spain. The procedure can be applied using the wells drilled for dewatering. Although a test before the excavation is recommended to evaluate the underground retaining walls (Watertightness Assessment Test), the method can be applied using data collected at the beginning of the dewatering stage.

Keywords: Retaining walls, jet grouting, underground enclosure, excavation, shaft, pumping test

1. Introduction

Deep excavations are required to construct railway stations (Jurado et al., 2009) and/or shafts used during and after the construction of tunnels using Tunnel Boring Machines (TBM). These are commonly built below the water table, which could give rise to problems (El-Nahhas, 1999). The “cut and cover” method combined with dewatering wells (Forth, 2004) is generally employed to construct these excavations in urban areas. This procedure consists of excavating under the protection of an underground enclosure that can be made up of jet grouting piles (Flora et al., 2013), sheet piles, concrete piles, concrete panels (diaphragm walls) or others (Gulhati and Datta, 2005). The underground enclosure allows excavating under vertical walls (Xanthakos et al., 1994) limiting lateral groundwater inflow and reducing the outside impacts (drawdown and settlements). Pumping wells allow excavating in dry conditions and ensure stability at the bottom of the excavation by reducing water pressure (Pujades et al., 2012a). The procedure is relatively simple and safe. However, defects in underground enclosures are frequent (Bruce et al., 1989, Croce and Modoni, 2007). This study was motivated by faulty underground enclosures that occurred during the recent construction of underground infrastructures in Barcelona, such as the tunnels for the HST (Pujades et al., 2015, Culí et al., 2016) and the new subway line (L-9) (Jurado et al., 2011).

Complications caused by enclosure defects depend on their position. If they are located above the excavation depth, inflows may drag sediments, leading to the formation of sinkholes outside the excavation (Pujades et al., 2009). Moreover, inflows may flood the excavation and cause high drawdowns and settlements outside. When defects are located below the excavation depth, in addition to the outside drawdown and settlements, inflow through them increases the water pressure inside the underground

enclosure, which may lead to bottom raising or liquefaction, structure instability and subsidence related to soil migration (Xu et al., 2009).

Defects may be caused by several factors, and their nature depends on the construction technology (jet grouting piles, sheet piles or concrete piles and panels). Jet grouting piles may have defects caused by deviations and variations of column diameter (Croce and Modoni, 2007). The latter are common in high vertical heterogeneity soils (Modoni et al., 2006). In fact, a great concern is to anticipate the diameter of the jet grouting columns (Shen, et al., 2013a and 2013b). In addition, when jet grouting is used to reduce the hydraulic conductivity of permeable soils (Davis and Horswill, 2002, Wen, 2005, Wong and Poh, 2005, Nikbakhtan et al., 2010, Wang et al., 2013), coarse sediments may cause shadow effects, leading to openings (Vilarrasa et al., 2011). Enclosures made of concrete piles or panels should be less permeable than those made of jet grouting piles. However, their permeability may be relatively high because of construction defects (Wu et al., 2015a and 2015b). E.g. deviations during their construction lead to openings. These deviations may occur when 1) layers made of large boulders are drilled, 2) the drilled cavity collapses during the extraction of materials or 3) the set-up of the slurry wall excavator is not suitable. In either case, regardless of the construction technology, imperfect enclosures generally contain numerous defects because similar difficulties are faced for all piles and panels.

If underground enclosures have defects, they can be repaired or the dewatering system can be redesigned. For instance, defects can be repaired by injecting sealing substances. However, the reparation must be undertaken before the actual excavation stage because sealing substances may be dragged to the pumping wells if the dewatering has started. In the same way, if the dewatering system is redesigned, additional pumping wells should be drilled before excavation to minimize interference with the construction

work. Therefore, the state of underground enclosures must be assessed before the excavation stage.

Geophysical methods are commonly used to assess underground enclosures (Paikowsky and Chernauskas, 2003, Rausche, 2004). However, these methods do not allow the evaluation of the whole enclosure, and the results may be influenced by a number of factors (White et al., 2008). Additionally, access tubes may be damaged and unusable during the construction of the retaining walls (Pujades et al., 2012a). Instead, hydrogeological methods allow for determining the state of the whole enclosure (Vilarrasa et al., 2011, Pujades et al., 2012a). Ross and Beljin (1998) suggested that underground barriers can be hydraulically characterized from the groundwater head evolution. However, they do not provide solutions to determine the hydraulic conductivity of retaining walls and/or to locate defects. Effective hydraulic parameters of underground enclosures can be determined using numerical models (Knight et al., 1996, de Rienzo et al., 2008, Thierry et al., 2009, Vilarrasa et al., 2009). However, numerical models are time-consuming, and the results cannot be generalized to other sites.

Pujades et al., (2012a) proposed two methodologies to assess linear underground enclosures based on pumping and observations inside the retaining walls. Linear underground enclosures are those whose length is much larger than their width, such as enclosures used to excavate tunnels by the “cut and cover” method. Therefore, these procedures are not useful in the case of non-linear enclosures (i.e., circular or rectangular). Vilarrasa et al. (2011) proposed a procedure to determine the presence and location of one aperture in a circular underground enclosure. However, as discussed above, defective enclosures commonly have more than one defect, which limits the applicability of their method. Vilarrasa et al. (2011) also proposed a method to calculate

the effective parameters of retaining walls from the steady state hydraulic head. However, the time required to reach the steady state may be long.

The objective of this paper is to propose a generally applicable procedure to assess the state of non-linear underground enclosures below the water table. This work considers that non-linear underground enclosures are those whose length is comparable to their width. The method is based on the transient head response inside the enclosure to pumping inside, which facilitates taking advantage of wells and/or piezometers constructed to dewater and monitor the drainage.

2. Methods

2.1. Problem statement

The problem is formulated as shown in Figure 1. An excavation is undertaken below the water table using the “cut and cover” method in a confined homogeneous isotropic aquifer. The excavation is delimited by an underground enclosure. The construction technologies (jet grouting columns, sheet piles concrete piles or diaphragm walls) are not significant, and solutions must be suitable for all methods. From this point forward, elements that make up the underground enclosure are named “retaining walls”. Retaining walls penetrate down to the base of the aquifer and, in some simulations, are supposed to have construction defects (openings). It is assumed that retaining walls with low effective hydraulic conductivity (k'_{eff} lower than 10^{-5} m/d) do not present defects. Two types of retaining walls are considered:

- 1) “Homogeneous retaining walls” are modelled without discrete defects but with high values of k'_{eff} . These walls simulate enclosures with numerous defects that are more or less uniformly distributed.
- 2) “Heterogeneous retaining walls” are modelled by simulating discontinuities in the underground enclosure. The characteristics of the discontinuity (location

and size) are modified in different simulations. The hydraulic conductivity of the opening is the same as that of the aquifer, whereas the hydraulic conductivity of the retaining walls is low (10^{-5} m/d).

Fully penetrating wells and observation points are located inside the underground enclosure (Figure 1). Finally, the external aquifer boundaries are located 10000 m from the underground enclosure to avoid affecting the observation points during the early stages. The aquifer is circular to ensure that the influence radius of the pumping reaches all boundaries at the same time.

2.2. Basic concepts

2.2.1. Dimensionless process and diagnostic plots

Dimensionless analysis is a mathematical technique that simplifies problems by reducing the number of involved variables. The variables can be grouped in equations that define the problem depending on their relation with the fundamental units (mass, length, time). In addition, dimensionless analysis can 1) deduce the involved variables in the problem, and 2) homogenize the obtained results from similar scenarios (e.g., two scenarios where the enclosure radius is different). Dimensionless variables are written as:

$$\text{Dimensionless variable} = \frac{\text{Real variable}}{\text{Characteristic variable}}$$

where the “characteristic variable” is a parameter (or a group of parameters) based on fundamental variables that are common in all scenarios (e.g., the underground enclosure radius). The characteristic time and drawdown used to compare the computed numerical results and to obtain analytical solutions are defined above.

The diagnostic plots consist of calculating the drawdown derivative with respect to the logarithm of time and plotting it versus time. The drawdown logarithmic derivative (s') is highly sensitive to subtle variations in drawdown evolution. It allows

detecting behaviours that are difficult to identify only from the drawdown evolution curve (Renard et al., 2008). Diagnostic plots are used for pumping test interpretation in leaky aquifers by applying the inflection point method (Hantush, 1956). This method is based on identifying the time when the inflection occurs in the evolution of s' (t_{INF}). t_{INF} occurs when the value of s' is maximum (Trinchero et al., 2008). s' can be computed with respect to the decimal or the natural logarithm of time. In this paper, s' is computed with respect to the decimal logarithm.

2.3. Numerical model

The numerical model is built using the finite element code TRANSIN-IV (Medina and Carrera, 1996, Medina et al., 2000, Medina and Carrera, 2003), with the visual interface of VISUAL TRANSIN (UPC, 2003). Several simulations are undertaken by varying the aquifer parameters and the underground enclosure characteristics. The boundary conditions consist of prescribed flow at the pumping well and prescribed head at the external aquifer boundaries. The mesh is identical for all scenarios and consists of triangular elements whose size at the middle of the enclosure is refined (0.1 m) and increases towards the boundaries up to 300 m (Figure 2).

3. Mathematical formulation

3.1. Governing equations

Transient flow through a 2D confined aquifer is governed by the following equation (Bear, 1972):

$$S \frac{\partial h}{\partial t} = \nabla \cdot (T \nabla h) \quad (1)$$

where S is the aquifer storage coefficient, h is the hydraulic head, t is the time and T is the aquifer transmissivity. A zero initial value of head is adopted to work with

drawdown. The head is prescribed (Dirichlet boundary condition) at the outer boundaries:

$$r \rightarrow 10000 \text{ m}; h = 0 \text{ m},$$

and flow is prescribed in the pumping well:

$$Q_p = 2\pi T r_p \left. \frac{\partial h}{\partial r} \right|_{r=r_p} \quad (2)$$

where Q_p is the prescribed pumping rate, r is the radial distance from the pumping well and r_p is the pumping well radius.

3.2. Characteristic variables

The characteristic time (t_c) and drawdown (s_c) are needed to homogenize the computed numerical results. t_c is the time when s' is maximum (s'_{MX}), and s_c is the maximum drawdown. Assuming that pumping inside an underground enclosure does not produce a significant drawdown outside and applying the definition of S ,

$$S = \frac{V}{A\bar{s}} \quad (3)$$

where V is the pumped water volume, A is the area of the excavation and $\bar{s}$ is the average drawdown inside the underground enclosure. $\bar{s}$ is not known, but this is not important because we use logarithmic derivatives. From now on, s (drawdown) is used instead of $\bar{s}$. V and A are defined as:

$$V = Q_E t \quad (4), \text{ and}$$

$$A = \pi r_{EXC}^2 \quad (5),$$

where Q_E is the pumped flow-rate that comes only from inside the underground enclosure and r_{EXC} is the radius of the underground enclosure (distance from the centre

of the excavation to the half of the width of the retaining walls; Figures 1 and 2). Eq. 3 can be expressed as follows:

$$S = \frac{Q_E t}{\pi r_{EXC}^2 s} \quad (6)$$

The pumped flow-rate that passes through the retaining walls (Q_W) can be deduced by applying Darcy's law:

$$Q_W = 2\pi r_{EXC} b s C'_{eff} = 2\pi r_{EXC} b s \frac{k'_{eff}}{W_W} \quad (7),$$

where W_W and C'_{eff} are the width and the effective hydraulic conductance of the retaining walls, respectively, and b is the thickness of the aquifer. s' increases continuously at the beginning of the pumping when $Q_p = Q_E$ and $Q_W \approx 0$. Conversely, s' is minimum and constant after a long pumping period when $Q_p = Q_W$ and $Q_E \approx 0$. During intermediate times, $Q_p = Q_E + Q_W$ and the behaviour of s' depends on the percentages of Q_E and Q_W . When $Q_E > Q_W$ the increment of s' is positive, while if $Q_W > Q_E$ the increment of s' is negative. As a result, s' increases until $Q_E = Q_W$. Therefore, s'_{MX} is reached when $Q_E = Q_W$. Consequently, t_C is determined by comparing Eq. 6 and Eq. 7,

$$t = t_C = \frac{S r_{EXC}}{2 C'_{eff} b} = \frac{S W_W r_{EXC}}{2 k'_{eff} b} \quad (8)$$

s_C can be computed from Eq. 7 by replacing Q_W with the total pumping rate (Q_p). Thus,

$$s = s_C = \frac{Q_p}{2\pi r_{EXC} C'_{eff} b} = \frac{Q_p W_W}{2\pi r_{EXC} k'_{eff} b} \quad (9)$$

4. Results

4.1. Numerical results

4.1.1. Groundwater flow evolution

Groundwater behaviour is briefly explained using numerical results. T and S of the modelled scenario are, respectively, 100 m²/d and 0.001. The pumping well, whose pumping rate (Q_p) is 100 m³/d, is located at the centre of a 10 m radius excavation. The retaining walls are homogeneous, and their k'_{eff} and W_w are, respectively, 0.5 m/d and 1 ($C'_{eff}=1$ d⁻¹). Figure 3 shows the drawdown (s) (left) and s' (right) evolutions in the log-log (up) and semi-log (down) scales. The figures on the bottom represent the first three stages of the groundwater behaviour. Drawdown is computed in the pumping well. Results without retaining walls (dotted line) and considering retaining walls without defects (double line) are included in Figure 3. Four stages can be differentiated depending on the flow behaviour.

Stage 1

During the early stage of pumping, flow behaves radially until the retaining walls affect the pumping well and the flow behaviour changes from radial to linear. This change starts at time $0.1t_l$, and the flow behaviour is completely linear at time t_l . t_l (Eq. 10) is a characteristic time taken as characteristic distance r_{exc} :

$$t_l = \frac{S2r_{exc}^2}{T} \quad (10)$$

t_l is different if the pumping well is not centred. However, this difference can be neglected because t_l is a very short time. The $0.1t_l$ can be identified in the log-log plots of Figure 3. It occurs when the dotted line (without underground enclosure) separates from the continuous and double lines (with underground enclosure).

Stage 2

The flow behaviour is linear during Stage 2 because the excavation is drained linearly. As a result, the drawdown evolution is a straight line defined by Eq. 6. The

value of s' during Stage 2 is 2.3 times the value of s . This fact can be mathematically demonstrated by taking decimal logarithms in Eq. 6

$$\log s = \log \frac{Q_p}{\pi r_{EXC}^2 S} + \log t \quad (11)$$

Q_E is replaced by Q_p in Eq. 6 because during Stage 2, most of the pumped water comes from inside the underground enclosure. Deriving Eq. 11 with respect to $\log_{10} t$

$$\frac{d \log s}{d \log t} = \frac{1}{\ln 10} \frac{d \ln s}{d \ln t} = \frac{1}{s \ln 10} \frac{ds}{d \ln t} = \frac{s'}{s \ln 10} = 1 \quad (12)$$

Therefore,

$$s' = s \ln 10 = 2.3 \frac{Q_p t}{\pi r_{EXC}^2 S} \quad (13)$$

If s' is computed with respect to the natural logarithm of time, Eq. 13 can be written as

$$s' = s = \frac{Q_w t}{\pi r_{EXC}^2 S} \quad (14)$$

The slope of s and s' during Stage 2 can be derived analytically. The evolution of s' during stage 2 is defined by Eq. 15, which is obtained by taking logarithms in Eq. 13

$$\log s' = \log \frac{2.3 Q_w}{\pi r_{EXC}^2 S} + \log t \quad (15)$$

This equation has a slope of 1 in the log-log plots, which can be verified in Figure 3. If the drawdown derivative is calculated with respect to the natural logarithm, the equation of s' is as follows:

$$\log s' = \log \frac{Q_w}{\pi r_{EXC}^2 S} + \log t \quad (16)$$

Stage 2 finishes when Q_w cannot be neglected. Its duration is shorter if C'_{eff} is high and vice versa.

First half of the transition between Stages 2 and 3 (T2-3(1))

The percentage of Q_w increases during the transition between Stages 2 and 3, However, Q_E is higher than Q_w during the first interval of the transition. As a result, s and s' increase, but the rate of increment decreases with time (Figure 3, right). The first half of the transition finishes when $Q_w = Q_E$ and s'_{MX} is reached.

Second half of the transition between Stages 2 and 3 (T2-3(2))

Q_w is higher than Q_E during the second interval of the transition between stages 2 and 3. Therefore, s' decreases. The transition finishes when $Q_E \approx 0 \text{ m}^3/\text{d}$.

Stage 3

All of the pumped water passes through the retaining walls during Stage 3 ($Q_p = Q_w$) and the flow behaves radially. s and s' are controlled by the aquifer parameters. The slope of s is the same as for the scenario without underground enclosure, where the flow is always radial (semi-log plot of drawdown). The computed s' , considering homogeneous retaining walls, matches the calculated s' without considering the underground enclosure. The value of s' during Stage 3 can be deduced from the Cooper and Jacob solution (1946) (Eq. 17)

$$s = \frac{Q_p}{4\pi T} \ln \frac{2.25Tt}{r^2 S} \quad (17)$$

If s' is computed using Eq. 17,

$$s' = \frac{2.3Q_p}{4\pi T} = 0.183 \frac{Q_p}{T} \quad (18)$$

Q and T are $100 \text{ m}^3/\text{d}$ and $100 \text{ m}^2/\text{d}$, respectively, in the modelled problems. As a result, s' must be 0.183 m , which agrees with the numerical results (Figure 3). If s' is computed with respect to the natural logarithm of t ,

$$s' = \frac{Q_p}{4\pi T} \quad (19)$$

Stage 4

Finally, the external boundaries affect the pumping well. Given that a Dirichlet boundary condition is adopted, s becomes constant and, therefore, s' is 0. The time to reach Stage 4 depends on the aquifer and the underground enclosure properties. Stage 4 is reached later if C'_{eff} and T are small and S is high.

The described drawdown evolution is similar to those caused by large diameter pumping wells (Papadopoulos, 1967, Papadopoulos and Cooper, 1967). The only difference occurs at the beginning because the flow behaves linearly from the start in the case of a large diameter well.

4.1.2. Influence of the location of pumping and observation points

The position of the wells and observation points is crucial to apply the proposed methods by Vilarrasa et al. (2011) and Pujades et al. (2012a). The changes produced on s and s' when the location of the pumping and observation points is modified are analysed in this section. Four simulations are conducted by modifying the location of the pumping and observation points and considering both types of retaining walls (heterogeneous and homogeneous). The results from the four simulations are compared in Figure 4. The location of the pumping and observation points in these simulations is selected to ensure that the measured drawdowns are different. T , S and Q_p are the same in the four scenarios ($T=100$ m/d, $S=0.001$ and $Q_p=100$ m³/d). Firstly, s and s' from Sce1 and Sce2, where heterogeneous retaining walls are considered, are compared (Figure 4a). There is one opening located at O1. The pumping well is located at P5 for Sce1 and at P1 for Sce2. Drawdown is computed at P1 and P5 in both scenarios. The well losses are not considered when drawdown is computed at the pumping well. The location of the opening, the pumping well and the observation points can be observed in Figure 1 or in the sketches included in Figure 4. Secondly, s and s' of Sce3 and Sce4, where homogeneous retaining walls are considered, are also compared (Figure 4b). The

k'_{eff} of the retaining walls is 0.1 m/d ($C'_{eff}=0.1 \text{ d}^{-1}$). Regarding the location of the pumping well and the observations points, the former is located at P5 for Sce3 and at P1 for Sce4. The latter are placed at P1 and P5 in both simulations (Figure 1 and Figure 4).

The absolute values of s and s' are different for Sce1 and Sce2 because (1) the pumping well is moved and (2) the drawdown around an isolated opening is different than in other locations. However, the flow behaviour evolution at all observation points is the same because s and s' evolve in the same manner. As a result, s'_{MX} is reached at the same instant, and t_{INF} is the same for Sce1 and Sce2. However, the value of s'_{MX} depends on the location of the pumping well and observation points. The evolution of s and s' does not depend on their position if homogeneous retaining walls are considered (Sce3 and Sce4). Therefore, s'_{MX} is also reached at the same time (t_{INF}). However, contrary to the heterogeneous scenarios, the value of s'_{MX} is not affected by the position of the pumping and observation points. Nevertheless, differences can be observed if the C'_{eff} of the homogeneous retaining walls is increased. Figure 5 displays s' versus time considering two new scenarios (Sce5 in Figure 5a and Sce6 in Figure 5b) that assume homogeneous retaining walls. k'_{eff} is 10 m/d ($C'_{eff}=10 \text{ d}^{-1}$), and the pumping well is located at P5 in Sce5 (centre) and at P1 in Sce6 (Figure 1). The rest of the parameters and characteristics are the same as for the previous scenarios. Drawdown is computed at P3, P4 and P5 (Figure 1). t_{INF} does not vary, but s' depends on the location of the pumping and observation points. If the pumping well is located in the centre (Sce5), s' is the same in P3 and P4 (placed at the same distance from the pumping well), which is helpful to differentiate between homogeneous and heterogeneous retaining walls. The differences in s' at two observation points located at different distances from the pumping well and considering homogeneous retaining walls are observed when $k'_{eff} \geq 0.01k$, where k is the hydraulic conductivity of the aquifer.

The flow behaviour also depends on the location of the pumping and observation points during early times, from the start of the pumping until the underground enclosure affects the observation point (Stage 1). However, this time is too short to be noticed when the global flow evolution is considered. As a result, it can be neglected. Subsequent simulations are performed by placing the pumping well in the centre (P5 in Figure 1) and computing the drawdown in P4 (Figure 1).

4.1.3. Influence of the aquifer parameters, underground enclosure characteristics and analytical solution based on t_{INF}

Figure 6 displays the computed s' vs. logarithmic time for several scenarios, which assume homogeneous walls. The aquifer parameters and underground enclosure characteristics are varied to determine their influence on the groundwater flow behaviour. The results computed considering different scenarios are compared with those calculated from a reference scenario (SceR). The properties of SceR are as follows: T is 100 m²/d, S is 0.001, r_{EXC} is 10 m, W_w is 1 m, k'_{eff} is 0.01 ($C'_{eff}=0.01d^{-1}$) and $Q_p=100$ m³/d. For the other scenarios, only one variable is modified with regards to SceR. Firstly, the influence of the aquifer parameters and the pumping rate are assessed (Figure 6a). T is reduced to 10 m²/d for Sce6, S is increased to 0.01 for Sce7 and the pumping rate is increased five times for Sce8. Then, the influence of the underground enclosure characteristics are evaluated (Figure 6b). r_{EXC} is increased to 15 m in Sce9, W_w is increased to 2 m in Sce10 and k'_{eff} is 0.1 m/d in Sce11. The results considering impervious retaining walls ($k'_{eff}=0.00001$ m/d) and without underground enclosure are also computed and displayed. T and Q_p do not affect t_{INF} , which agrees with the fact that they are not included in the derived characteristic time equation (Eq. 8). T and Q only affect the value of s' during Stage 3 of the drawdown evolution. s' is calculated by

setting Eq. 18 equal to 1.83 for Sce6 and 0.915 m for Sce8. In the other scenarios, Eq. 18 is 0.183 m because T and Q do not vary.

The computed s' in all scenarios (SceR and Sce6 to Sce11) are plotted versus the logarithm of t_D (Figures 7a and 7b). s'_{MX} always occurs at the same dimensionless time (t_D). The dimensionless inflection time (t_{INF}) is 1 in all scenarios. Therefore, an equation to calculate k'_{eff} (and C'_{eff}) is derived from Eq. 8 and taking into account the definition of a dimensionless variable:

$$t_{INF} = 1 = \frac{t_{INF}}{t_C} = \frac{t_{INF}}{SW_W r_{EXC} / 2k'_{eff} b} \Rightarrow k'_{eff} = \frac{SW_W r_{EXC}}{2t_{inf} b} \quad (20)$$

Two additional scenarios (Sce12 and Sce13) considering heterogeneous retaining walls are modelled to evaluate Eq. 20. With the exception of the size of the opening in the retaining walls, the characteristics of both scenarios are the same: T is 100 m²/d, S is 0.001, r_{EXC} is 10 m, W_W is 1 m and $Q_p=100$ m³/d. The opening, whose size is 0.5 m in Sce12 and 1 m in Sce13, is located at O1 (Figure 1) in both simulations. The rest of the walls have low hydraulic conductivity (0.00001 m/d). k'_{eff} is calculated analytically for Sce12 and Sce13 by simulating pumping, identifying t_{INF} (Figure 8) and applying Eq. 20. The calculated k'_{eff} values are 0.3 m/d for Sce12 and 0.44 m/d for Sce13. The analytical k'_{eff} is then compared with the numerical value. This numerical k'_{eff} is computed by considering two equivalent scenarios (Sce12' and Sce13') that assume homogeneous retaining walls. k'_{eff} is computed numerically as follows: (1) a drawdown is prescribed in the pumping well of Sce12 and Sce13 (heterogeneous retaining walls), and the steady state pumping rate is determined, (2) the heterogeneous retaining walls (Sce12 and Sce13) are replaced by homogeneous walls (Sce12' and Sce13'), and (3), prescribing the same drawdown in the pumping well, k'_{eff} of the

homogeneous retaining walls is modified until the steady state pumping rate of the equivalent scenarios (Sce12' and Sce13') is equal to those determined from Sce12 and Sce13. The computed k'_{eff} is 0.32 m/d for Sce12' and 0.45 m/d for Sce13'. The analytical k'_{eff} agrees with that computed numerically from the equivalent scenarios. Error is caused because t_{INF} is not exactly known because s'_{MX} occurs between two simulated times.

4.1.4. Analytical solution based on s'_{MX}

Subsequently, the computed s' from scenarios SceR and Sce6 to Sce11 is written in the dimensionless form (s'_D) and plotted versus t_D (Figure 9a and 9b). s'_D is calculated from the dimensionless drawdown (s_D). The maximum s'_D (s'_{MXD}) is the same in all scenarios ($s'_{MXD}=0.81=\ln 2.25$). Therefore, a solution to calculate k'_{eff} (and C'_{eff}) from s'_{MX} is derived using Eq. 9 and taking into account the definition of a dimensionless variable:

$$s'_{MXD} = \ln 2.25 = \frac{s'_{MX}}{s_C} = \frac{s'_{MX}}{Q_P W_W / 2\pi r_{EXC} b k'_{eff}}$$

$$\Downarrow$$

$$C'_{eff} = \frac{Q_P}{2\pi r_{EXC} b s'_{MX}} \ln 2.25 \Rightarrow k'_{eff} = \frac{Q_P W_W}{2\pi r_{EXC} b s'_{MX}} \ln 2.25$$

This equation must not be applied if the retaining walls are heterogeneous or homogeneous with a high hydraulic conductivity ($k'_{eff} \geq 0.01k$). Given that the state of the underground enclosure is initially unknown, it would be advisable to use this analytical solution only to verify the results from Eq. 20 when the following conditions are satisfied. First, the pumping well is located in the centre, and s'_{MX} is the same, at least, at two observation points located at different distances from the well (one of the observation points could theoretically be the pumping well).

4.2. Application procedure

4.2.1 Assessing underground enclosures

The methodology to assess the state of an underground enclosure consists of the following steps:

- 1) Determination of the aquifer parameters by pumping tests before constructing the enclosure.
- 2) Performing a Watertightness Assessment Test (WTAT) (Pujades et al., 2014a) before starting the excavation (the measured drawdown at the beginning of the dewatering stage can also be used). The pumping well and piezometers (or other wells where the drawdown is measured) must be located inside the underground enclosure. At least one observation point is needed, which could theoretically be the pumping well. However, the more observation points that are measured, the more reliable the results. The pumping rate, which must be precisely known (Pujades et al., 2008), should be as constant as possible.
- 3) Compute s' from the measured drawdown and plot it versus time.
- 4) Identify s'_{MX} and t_{INF} . Different interpretations can be undertaken depending on the location of the pumping and observation points, the number of observation points and the observed response.
  - a) Compute k'_{eff} (or C'_{eff}) using t_{INF} : k'_{eff} can always be determined using the value of t_{INF} and applying Eq. 20. The location of the well and the observation points is not important. Only one observation point is needed. If there is more than one observation point, k'_{eff} should be computed considering all data, and the results have to be compared.

- b) Assess the retaining walls using s'_{MX} from the pumping and observation points that are not specifically distributed (e.g., if those drilled to perform the dewatering are used). More than one observation point located inside is needed to evaluate the walls with s'_{MX} . The interpretation depends on the location of pumping and observation points.
- i) The pumping well is not located in the centre or it is in the centre but the observation points are at different distances from the well: if s'_{MX} is the same at all observation points, the retaining walls behave homogeneously and their k'_{eff} can be computed by Eq. 21. Different values of s'_{MX} indicate that the enclosure is heterogeneous or the enclosure is homogeneous but $k'_{eff} \geq 0.01k$. In these cases, k'_{eff} can only be computed from t_{INF} .
- ii) The pumping well is placed in the centre and the observation points are located at the same distance from the well: if s'_{MX} is different in the observation points, the retaining walls behave heterogeneously, and k'_{eff} must be computed from t_{INF} (Eq. 20). When s'_{MX} is the same at all of the observation points, the enclosure is homogeneous. However, k'_{eff} can only be computed from s'_{MX} (Eq. 21) if $k'_{eff} < 0.01k$. Therefore, another observation point located at a different distance from the pumping well is needed (data from the pumping well could theoretically be used). If the calculated s'_{MX} from this new observation point matches those calculated from the previous ones, $k'_{eff} < 0.01k$ and k'_{eff} can be computed from s'_{MX} (Eq. 21). If the calculated s'_{MX} from this new observation point is different, $k'_{eff} \geq 0.01k$. As a result, k'_{eff} cannot be computed from s'_{MX} .

c) Assess the retaining walls using s'_{MX} from the strategically distributed pumping and observation points (e.g., if a WTAT is specifically undertaken to characterize the underground enclosure). In this case, it is recommended to drill the pumping well in the centre of the underground enclosure and to use at least three piezometers. Two of the piezometers must be located at the same distance from the pumping well and the other at a different distance. The latter could theoretically be replaced by the pumping well.

i) If s'_{MX} is the same at the three observation points, the retaining walls behave homogeneously and its $k'_{eff} < 0.01k$. As a result, k'_{eff} can be computed from s'_{MX} (Eq. 21).

ii) If s'_{MX} is the same in the observation points located at the same distance from the pumping well but different from that calculated at the other observation point, the retaining walls behave homogeneously and $k'_{eff} \geq 0.01k$. Thus, k'_{eff} cannot be computed from s'_{MX} .

iii) If s'_{MX} is different at the observation points located at the same distance from the pumping well, the retaining walls are heterogeneous. As a result, k'_{eff} cannot be computed from s'_{MX} . If a defect is equidistant to the two observation points located at the same distance from the pumping well, s'_{MX} is the same at both observation points. In this case, another observation point at the same distance from the pumping well is needed to discern between homogeneous or heterogeneous retaining walls.

4.2.2 Data treatment

Computing s' from field data is usually complicated due to measurement errors and groundwater head oscillations caused by external actions (e.g., pumping). The

drawdown slope evolution between consecutive measures changes considerably. As a result, if s' is directly calculated from the field data, the obtained plot consists of consecutive increments and decrements of s' . Therefore, data must be treated to soften the drawdown evolution. It is suggested to use a code that can obtain a tendency curve (and its equation) from values of s and t . With this tendency curve, s is recalculated for different times (s^* is the recalculated drawdown). Finally, s' can be computed without abrupt changes from s^* . In the application section, the data from WTAT are treated following this procedure. Microsoft Excel 2013 software is used to calculate s^* .

4.2.3 Square enclosures

All of the simulations undertaken above consider circular underground enclosures. However, the results are also applicable to underground enclosures that have other shapes, such as square or rectangular geometry. The stored volume of water inside the underground enclosure controls the transition between linear and radial flow behaviour, and therefore, the s' evolution. Thus, the radius used in Eq. 20 and Eq. 21 (r_{EXC}) must be replaced by an equivalent radius (r_{EQ}) if the underground enclosure is not circular. r_{EQ} is computed as follows:

$$r_{EQ} = \sqrt{\frac{A_{EXC}}{\pi}} \quad (22),$$

where A_{EXC} is the area of the non-circular excavation. The computed r_{EQ} (from Eq. 22) is not suitable in the case of too elongated rectangular enclosures. These enclosures should be characterized by methods for linear excavations (Pujades et al., 2012a). A pumping ($Q_P=100 \text{ m}^3/\text{d}$) inside a square shaped underground enclosure is simulated. The C'_{eff} of the retaining walls is assessed from the computed drawdown to test the proposed solutions. Each side of the excavation measures 15 m (Figure 10a). T and S

are 100 m²/d and 0.001. k'_{eff} and W_w are 0.005 m/d and 1 m, and b is 10 m. The retaining walls penetrate down to the base of the aquifer. The pumping well is located at the centre of the underground enclosure, and drawdown is computed at PZ4 (Figure 10a). Figure 10b displays s' versus time. r_{EQ} , which is calculated by Eq. 22, is 16.92 m. C'_{eff} is computed from t_{INF} (Eq. 20) and s'_{MX} because the retaining walls are homogeneous.

$$C'_{eff} = \frac{Sr}{2t_{inf}b} = 0.0046 \text{ m/d}$$

$$C_{eff} = \frac{Q_c}{2\pi r b s'_{MX}} \ln 2.25 = 0.0057 \text{ m/d}$$

The calculated C'_{eff} agrees with the modelled value.

5. Application

5.1. Case study

Data collected during the construction of the circular Padilla shaft (19.7 m diameter) are used to validate the proposed methods. The k'_{eff} of the underground enclosure used to excavate the shaft is calculated analytically and compared with the numerical results. The Padilla shaft was required during the construction of the high speed train (HST) tunnel in Barcelona (Spain) (Pujades et al., 2015). The tunnel crosses Barcelona and was drilled with a TBM. Some shafts were excavated to undertake maintenance operations of the TBM during the tunnel construction and to be used as emergency exits (Figure 11a). Figure 12 displays a schematic geological cross-section and the plan view of the Padilla shaft. Geologically, the tunnel penetrates the geological formation of the Barcelona plain (Pujades et al., 2012b), which is formed by Quaternary and Tertiary sediments (Figure 11b). The Quaternary sediments can be divided into the Pleistocene and Holocene. The former is composed of deposits of gravels with a clay

matrix, deposits of brown-yellow silts and calcareous nodules and calcrete stratum. The latter consists of clay-silt layers and sand-gravel layers with a clay matrix. Tertiary materials (Pliocene) contain clays and grey marls (marine deposits) and sequences of fine-medium sands with variable percentages of silty matrix. Hydrogeologically, the Quaternary and Tertiary are divided into several strata of different textural and lithological properties that can be considered as a single aquifer with considerable vertical heterogeneity. The effective transmissivity (T_{eff}) is 100–200 m²/d. The hydraulic conductivity of the clay layers ranges from 0.001 to 0.01 m/d, and that of the sand and gravel layers varies from 0.1 to 10 m/d (Pujades et al., 2014a).

The Padilla shaft was constructed by the “cut and cover” method. The enclosure consists of 46.5 m deep diaphragm walls and jet grouting piles from 42.5 to 61.5 m depths. Initially, excavation was planned using only diaphragm walls. However, the enclosure was elongated to reduce the dewatering impact (i.e. settlement). The jet grouting piles were lengthened as far as a low permeability layer ($k=0.0009$ m/d) and overlapped the diaphragm walls by 4 m, ensuring the sealing of the enclosure (Figure 12b).

5.2. Hydrogeological characterization

A pumping test was conducted at the Padilla site to characterize the aquifer hydraulic properties before constructing the underground enclosure. Figure 12a displays the location of the pumping well (W1) and the piezometers (PZ1, PZ2 and PZ3). These piezometers were screened at different depths to measure the hydraulic responses in several layers (Figure 12b). The hydraulic head was measured manually and automatically by pressure sensors. The average pumping rate was 4.5 l/s. The pumping test lasted four days: two for pumping and two for recovery. Given the importance of S in the proposed methods, the test is reinterpreted using an axisymmetric numerical

model built with the code TRANSIN IV (Medina et al., 2000, Medina and Carrera, 2003). Appendix 1 shows the fitted curves of the piezometers PZ1, PZ2 and PZ3 (Figure A1) and the hydraulic parameters of each layer obtained after automatic calibration (Table A1). The computed T_{eff} is $\sim 200 \text{ m}^2/\text{d}$, and S is 0.17. T_{eff} agrees with that obtained analytically by applying Jacob's method (Pujades et al., 2014b).

5.3. Watertightness Assessment Test (WTAT) and jet grouting numerical characterization

A WTAT was conducted to evaluate the hydraulic properties of the jet grouting underground enclosure. A pumping well (W2), which was screened along the aquifer thickness, was located inside the underground enclosure. Drawdown was measured inside (PZ5) and outside (PZ4) (Figure 12). Both piezometers were drilled after the construction of the retaining walls with the objective of characterizing the jet grouting and monitoring the dewatering stage. PZ5 was screened along the whole aquifer thickness and PZ4 in the most transmissive layer cut by the jet grouting piles (Figure 12b). The average pumping rate during the WTAT was 5 l/s, and it lasted four days: two for pumping and two for recovery. The test was calibrated numerically using a multilayer model because the pumping well was not located in the centre of the enclosure. The computed hydraulic conductivity of the jet grouting was 0.6 m/d.

5.4. Jet grouting analytical characterization

Jet grouting characterization is performed using the drawdown data from W2 and PZ5 measured during the WTAT (Figure 13). The steps are as follows:

Step 1. Evaluation of the drawdown without noise (s^*): before applying the proposed methodology, the data must be treated to handle the noise. The drawdown evolution is adjusted using polynomial trend lines:

$$\text{PZ5: } s = 11.683t^3 - 40.147t^2 + 45.665t \quad (23)$$

$$\text{W2: } s = -40.974t^2 + 52.724t + 2.1226 \quad (24)$$

s^* is computed using Eq. 23 at PZ5 and Eq. 24 at W2 (Figure 13).

Step 2. Identification of t_{INF} and s'_{MX} : the logarithm derivative of the drawdown (s') is computed and plotted versus time (Figure 13). s'_{MX} and t_{INF} are 19.5 m and 0.33 days at W2 and 17.7 m and 0.38 days at PZ5.

Step 3. Determination of the behaviour of the walls: the values of s'_{MX} are different at the observation points. Consequently, the underground enclosure behaves heterogeneously or homogeneously with $k'_{eff} \geq 0.01k$ (the pumping well is not located in the centre). k'_{eff} must be calculated using t_{INF} .

Step 4. Evaluation of k'_{eff} : jet grouting k'_{eff} is calculated using Eq. 20 with the data from both observation points. k'_{eff} is 0.56 m/d at W2 and 0.49 m/d at PZ5. These values are similar, and their difference (0.07 m/d) might be due to the drawdown being fit to the trend lines. The results agree with those obtained numerically.

6. Summary and conclusions

Defects in retaining walls may lead to several difficulties. A method based on the drawdown evolution during a pumping is proposed to assess the state of underground enclosures.

- The method allows determining the (1) effective conductance (C'_{eff}) or hydraulic conductivity (k'_{eff}) of underground non-linear enclosures and (2) its behaviour (heterogeneous or homogeneous). The procedure is based on diagnostic plots from the drawdown measured inside the underground enclosure. The construction of pumping wells or piezometers is not required because those drilled to undertake

the dewatering can be used. At least one observation point located inside is needed, which can theoretically be the pumping well.

- Four different stages can be differentiated in the drawdown evolution inside an underground enclosure. The first three stages depend on the flow behaviour changes (radial or linear), and the fourth is reached when the external boundaries affect the observation point. Transition between Stages 2 and 3 is the most important for assessing underground enclosures. The time when 50% of the pumped water passes through the retaining walls (t_{INF}) is used to evaluate the state of the underground enclosures. t_{INF} is easily identified from s' because s'_{MX} , which is also essential to evaluate the retaining walls, occurs at t_{INF} .
- The positions of the well and observation points do not influence t_{INF} , which only depends on the parameters included in the derived characteristic time (t_C) (Eq. 8). Although T and Q_p are not included in t_C , T affects t_{INF} because it controls the duration of Stage 1. However, this stage is very short and can be neglected. If Stage 1 is too long, its duration is subtracted from t_{INF} to characterize the retaining walls.
- k'_{eff} (C'_{eff}) of underground enclosures can be quantified from t_{INF} . The proposed solution is easy to apply and depends neither on the behaviour of the retaining walls nor on the locations of the well and observation points.
- s'_{MX} can be also used to determine the behaviour of the retaining walls and, in some cases, to determine k'_{eff} (C'_{eff}):
  - If s'_{MX} depends on the distance from the observation point to the well (this can be verified if the pumping well is centred), the enclosure behaves homogeneously and its $k'_{eff} > 0.01k$.

- If s'_{MX} is different at observation points located at the same distance from the well, the enclosure behaves heterogeneously.
  - If s'_{MX} is the same at all observation points independently of their location and the position of the pumping well, the retaining walls behave homogeneously and its $k'_{eff} < 0.01k$. Only in this case, k'_{eff} can be calculated from s'_{MX} (Eq. 21).
  - The proposed characterization method is tested with the data measured during the construction of the Padilla shaft (Barcelona, Spain). The k'_{eff} of a jet grouting enclosure, which was assessed numerically resulting in 0.6 m/d, is evaluated. Results show that the underground enclosure behaved heterogeneously or homogeneously with high value of k'_{eff} . The calculated k'_{eff} is 0.49-0.56 m/d that agrees with that obtained numerically.
- The procedure proposed allows assessing the state of underground enclosures. This method is easy and fast to apply and does not interfere with the excavation works. Its application prevents serious accidents produced by unexpected groundwater inflows that occur in faulty underground enclosures.

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 808

List of notations:

- 809
- 810
- 811 A : area of the excavation [L^2].
- 812 A_{EXC} : area of the non-circular excavation [L^2].
- 813 b : thickness of the aquifer
- 814 C'_{eff} : effective hydraulic conductance of the retaining walls [T^{-1}].
- 815 h : hydraulic head [L].
- 816 k : hydraulic conductivity of the aquifer [LT^{-1}].
- 817 k'_{eff} : effective hydraulic conductivity of the retaining walls [LT^{-1}].
- 818 O_i : opening.
- 819 P_i : observation / pumping well.
- 820 Q_E : pumped flow-rate that comes only from inside the underground enclosure [L^3T^{-1}].
- 821 Q_p : pumping rate [L^3T^{-1}].
- 822 Q_w : pumped flow-rate that passes through the retaining walls [L^3T^{-1}].
- 823 r : radial distance from the pumping well [L].
- 824 r_{EQ} : equivalent radius [L].
- 825 r_{EXC} : radius of the underground enclosure/excavation [L].
- 826 r_p : pumping well radius [L].
- 827 S : aquifer storage coefficient [-].
- 828 s : drawdown [L].
- 829 s' : drawdown logarithmic derivative [L].
- 830 $\bar{s}$: average drawdown inside the underground enclosure [L].
- 831 s^* : recalculated drawdown avoiding abrupt changes [L].
- 832 s_C : characteristic drawdown [L].
- 833 S_{cei} : scenario.
- 834 s'_D : dimensionless drawdown logarithmic derivative [-].
- 835 s'_{MX} : maximum value of the drawdown logarithmic derivative [L].
- 836 s'_{MXD} : maximum value of the dimensionless drawdown logarithmic derivative [-].
- 837 T : aquifer transmissivity [L^2T^{-1}].

- 838 t : time [T].
- 839 t_c : characteristic time [T].
- 840 t_D : dimensionless time [-].
- 841 t_{INF} : inflection time of the drawdown logarithmic derivative [T].
- 842 $t_{INF D}$: dimensionless inflection time [-]
- 843 V : pumped water volume [L³].
- 844 W_w : width of the retaining walls [L].
- 845

Figure captions:

Figure 1. Plan view (top) and cross-section (bottom) of the problem. A detailed plan view of the excavation is also displayed (top-right). W_w is the width of the retaining walls, r_{exc} is the radius of the underground enclosure and b is the thickness of the aquifer. O1 indicates the position of the opening while P1 to P5 show the location of the pumping well and/or observation points (depending on the simulation).

Figure 2. General (left) and detailed (right) plan views of the numerical model.

Figure 3. Evolution of the drawdown (s) and its logarithmic derivative (s'). s and s' are plotted versus time and the logarithm of time. It is possible to differentiate three stages depending on the flow behaviour. The fourth Stage is achieved when the pumping well reaches the boundaries. The flow behaviour during Stages 1, 2 and 3 is shown in the sketch located on the bottom.

Figure 4. s and s' in four different simulations. The results of Sce1 (top-left), Sce2 (top-right), Sce3 (bottom-left) and Sce4 (bottom-right) are compared. A sketch of the enclosure is added to each plot to locate the pumping well (circle with X), the piezometers (grey circle) and the opening (O1).

Figure 5. Numerical results of Sce5 (Figure 5a) and Sce6 (Figure 5b). s' is plotted versus time. Differences in s' depending on the position of the pumping and observation points are considered. t_{INF} is always the same. A sketch of the enclosure is added in each plot to show the location of the pumping well (circle with X) and the piezometers (grey circle).

Figure 6. s' versus time for scenarios SceR, Sce6, Sce7, Sce8, Sce9, Sce10 and Sce11. SceR is compared with the results of Sce6 to Sce8 (left) and Sce9 to Sce11 (right).

Figure 7. s' versus t_D . s' at SceR is compared with Sce6, Sce7 and Sce8 (left) and with Sce9, Sce10 and Sce11 (right). s'_{MX} occurs at the same dimensionless time ($t_{INF} = 1$).

Figure 8. s' versus t_D at scenarios Sce12 and Sce13. t_{INF} is identified to compute k'_{eff} of both scenarios. The retaining walls behave heterogeneously.

Figure 9. s'_D versus t_D . The maximum value of s'_D (s'_{MXD}) is the same in all scenarios ($s'_{MXD} = \ln 2.25$) and occurs at $t_D = 1$.

Figure 10. Plan view of the synthetic model simulated (left). The enclosure is square, the pumping well is located in the centre and the drawdown is measured in P4. s' versus time is displayed on the right. t_{INF} and s'_{MX} are identified to compute k'_{eff} .

Figure 11. Plan view of the high speed train tunnel through Barcelona (Spain). The tunnel crosses the city from SW to NE. Constructed shafts are displayed with white circles. Modified from Pujades et al. (2012b).

Figure 12. (a) On the top, plan view of the Padilla shaft. Piezometers and pumping wells used during the two pumping tests. The observation points used to characterize the soil are displayed as triangles, whereas those used during the WTAT are shown as circles. The excavation was undertaken near buildings; therefore, it was necessary to avoid accidents. (b) On the bottom, schematic cross-section of the Padilla shaft. The excavation crossed Quaternary and Tertiary materials. The symbol of the piezometers is located at the place where they were screened. PZ5 was used during the WTAT and was screened from the top to the bottom of the aquifer. Jet grouting piles overlap the diaphragm walls and penetrate in a low hydraulic conductivity layer located at the bottom of the aquifer. Modified from Pujades et al. (2014a).

Figure 13. s measured during the WTAT, s^* and the logarithmic derivative of s^* versus time. The results at both observation points located inside the enclosure during the WTAT are shown. t_{INF} and s'_{MX} are identified to compute k'_{eff} .

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Appendix 1

Figure A1. Drawdown fitted curves of the piezometers located at Padilla (PZ1, PZ2 and PZ3). The curves are obtained from the numerical calibration of the pumping test.

Lithology	Top (depth)	Bottom (depth)	<i>k</i> (m/d)
Sandy silt	13.5	13.8	0.15
Silty calys with sand	13.8	14.7	0.05
Fine - medium sands	14.7	16.4	1.6
Silty clays	16.4	16.8	0.07
Fine - medium sands with silt	16.8	18.6	2.6
Sandy silt with sand layers	18.6	23.4	0.2
Sands with some of clays	23.4	27.6	6.7
Silty clays with some sand layers	27.6	38.1	0.14
Fine - medium sands	38.1	42.6	29.9
Marl	42.6	51	0.0032
Medium sands	51	60.65	3.2
Marl	60.65	70.65	0.0009

Table A1. Description of the layers of Padilla and the hydraulic conductivity values obtained from the pumping test. Only the layers located in the saturated part of the soil are included.