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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 analysing 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.

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 (TBMs). 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, 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, 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

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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, 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 Fig. 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 that 10^{-5} m/d) do not present defects. Two types of retaining walls are considered:

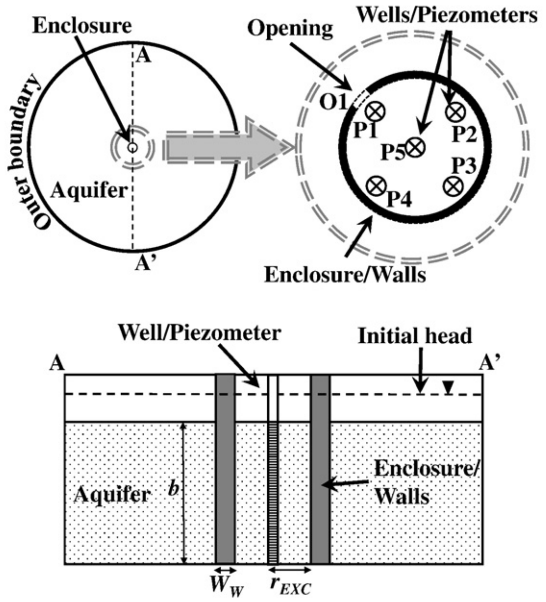

Fig. 1. Plan view (top) and cross-section (bottom) of the problem. A detailed plan view of the excavation is also displayed (top–right). W_W is the width of the retaining walls, r_{EXC} is the radius of the underground enclosure and b is the thickness of the aquifer. O1 indicates the position of the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

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 (Fig. 1). Finally, the external aquifer boundaries are located 10,000 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.