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Hydraulic characterization of diaphragm walls for cut and cover tunnelling

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ABSTRACT

Underground linear excavations often encounter problems when crossing aquifers. A viable option for shallow tunnels is the “cut and cover method”. Still, when enclosing diaphragm walls display open joints, even this method risks flooding, which affects construction operations, and soil dragging, which may lead to subsidence and affect nearby buildings outside the enclosure. Characterizing the state of the enclosure prior to excavation would be desirable. We propose in doing so by analysing the response to groundwater pumping during dewatering. We use numerical modelling and analytical methods. The steady state heads along the enclosure and the variations in the flow behaviour during pumping depend on the state of the diaphragm walls. Monitoring of the heads is therefore proposed during drainage of the enclosure to characterize the diaphragm walls. An analytical solution in steady state and two transient state methodologies are presented. These methodologies are implemented to evaluate the state of the diaphragm walls used in the construction of a High Speed tunnel at Bellvitge near Barcelona, where large openings caused significant sediment drag, which provoked sinkholes outside the enclosure.

1. Introduction

Tunnel construction through an aquifer under the water table can be complex. A number of methods can be adopted (Forth, 2004). A frequent choice for shallow tunnels is the “cut and cover method” combined with drainage wells. The “cut and cover method” consists in excavating under the protection of diaphragm walls (Gulhati and Datta, 2005). Diaphragm walls ensure that the excavation walls are stable and prevent lateral groundwater from entering the excavation. The main steps of this method are as follows (Figure 1):

1. Construction of diaphragm walls.
2. Drainage of the space between diaphragm walls using pumping wells.
3. Excavation of the space between diaphragm walls until the desired level.
4. Construction of tunnel vault and floor.
5. Filling of the gap between the vault and the ground surface.

Drainage must be continuous from steps 2 through 4 in order to ensure dry conditions and the stability of the soil. Excavation with the “cut and cover method” is not complicated, but unforeseen events during excavation can lead to serious problems (Rienzo et al., 2008). Openings are relatively frequent in the construction of diaphragm walls (Bruce et al., 1989). If the openings are located above the excavation level, inflows may drag sediments, leading to the formation of sink holes outside the enclosure, which results in damage to nearby buildings (Pujades et al., 2009). If the openings are located below the excavation level, inflow through them may cause a reduction in shear strength of the soil between diaphragm walls, leading to structure instability, bottom raising, bottom liquefaction and settlements (Xu et al., 2009). These situations not only endanger the lives of workers but also pose a threat to the works and, in urban areas, to adjacent buildings. Defects in the diaphragm walls detected before the excavation stage are relatively easy to repair by injecting sealing substances. However, defects spotted after excavation (step 3) are much more difficult and costly to repair because pumping cannot be interrupted to ensure the stability of the bottom of the excavation. Thus, groundwater flowing through the openings tends to drag the injected sealing substances. The question is whether it is possible to detect defects in the diaphragm walls before excavating.

Geophysical and hydrogeological methods can be used to spot openings. A typical geophysical method is crosshole sonic logging, which essentially consists in measuring the transit time of a sonic signal across the concrete (Paikowsky and Chernauskas, 2003; Rausche, 2004). High velocity indicates continuous concrete whereas slow velocity suggests a defect. The transmitter and receptor are introduced into two tubes separated by a given distance and set inside the diaphragm wall during its construction (Hollema and Olson, 2003). However,

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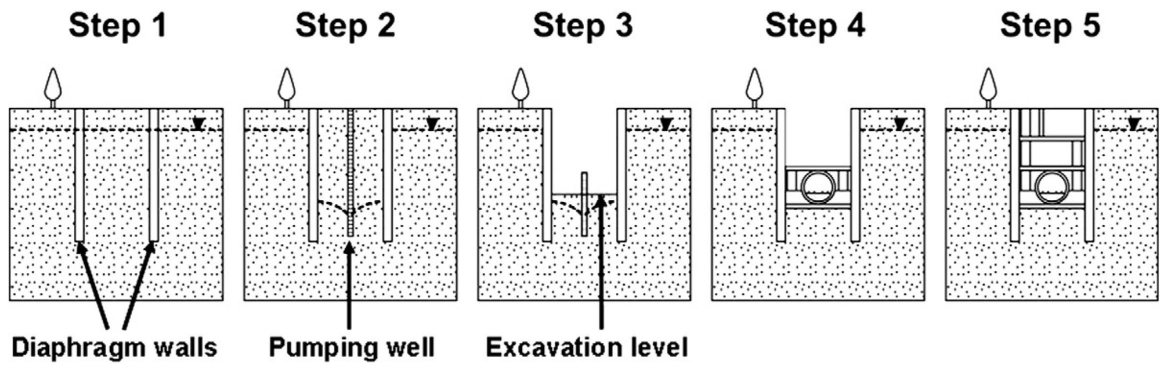

Fig. 1. Cut and cover method steps.

only the concrete between the access tubes can be assessed and the results may be influenced by a number of factors (White et al., 2008). Given that the access tubes must be cast during the construction of the diaphragm walls, they may break, fill up with concrete or become displaced, which makes them unusable. As an example, only five tests, out of the sixteen planned, could be performed in an excavation during the construction of high speed tunnel in Barcelona.

Hydrogeological methods consist in observing the response of groundwater to pumping (Knight et al., 1996; Ross and Beljin, 1998; Vilarrasa et al., 2011). If water levels drop as expected, it may be concluded that the enclosing system is satisfactory. Otherwise, repairs may be needed. This approach is advantageous because pumping and observation wells are essential to the construction (step 2) with the result that the only extra cost is that of data interpretation. Despite the potential interest in hydrogeological methods, there are few studies in the literature. Most research concentrates on methods to calculate water inflows to tunnels constructed below the water table (Meiri, 1985; El Tani, 1999, 2003; Lei, 1999; Hwang and Lu, 2006; Kolymbas and Wagner, 2007; Park et al., 2007; Li et al., 2009; Font-Capo et al., 2011). But little research focuses on the detection of hydraulic defects.

The only specific publications are those of Ross and Beljin (1998), Knight et al. (1996) and Vilarrasa et al. (2011). Ross and Beljin (1998) proposed a solution for evaluating the efficiency of the system. This solution consists in observing the spatial distribution and temporal evolution of water levels inside and outside the enclosed area. These authors did not seek specifically to calculate the effective transmissivity of the diaphragm walls or the location of the openings. Knight et al. (1996) analysed a case of drainage on a large square closed perimeter in the United Kingdom. They used the ERNA (Electrical Resistance Network Analogue Model) to calculate steady state drawdown versus hydraulic conductivity of the diaphragm walls. The resulting graph allowed the evaluation of the hydraulic conductivity of the diaphragm walls using drawdown recorded in the area after a long pumping period. These authors observed that small defects in diaphragm walls can significantly alter their effective hydraulic conductivity. They sought to measure the drawdown outside the enclosure, but this is not practical for linear enclosures (e.g. highway or railway tunnel) given the need for a large number of observation points. Moreover, steady state may take a very long time to reach in some situations. Although the ultimate objective of the aforementioned works is essentially similar to what is proposed in the present paper, these works cannot be implemented in other scenarios. Vilarrasa et al. (2011) developed a methodology to characterize the walls of a circular enclosure. The methodology, which is based on type curves to fit the observed time evolution of drawdowns, may be applied in different scenarios. However, in order to apply this methodology, drawdown must be measured outside the enclosure, which as stated above is not practical in linear excavations. Moreover, the methodology by Vilarrasa et al. (2011) is useful in circular enclosures but not for characterizing the diaphragm walls of linear excavations. Therefore, the question remains as to whether it is possible to characterize the diaphragm walls of linear enclosures using a methodology that is straightforward and generally applicable. The present paper seeks to analyse the groundwater behaviour under different diaphragm wall conditions in an attempt to obtain a suitable methodology.

2. Methods

2.1. Problem statement

The problem is formulated as shown in Fig. 2. A tunnel is excavated below the water table using the “cut and cover method” in a uniform confined aquifer. The diaphragm walls or similar supporting methods penetrate down to the base of the aquifer. It is assumed that the diaphragm walls are open at both ends of the underground construction. A pumping well is located in the centre of the excavation. The aquifer has sufficient extension to ensure that the pumping cone does not reach the boundaries. Two types of problems are considered:

1. Homogeneous diaphragm walls are modelled with several values of effective conductance. Actually, diaphragm walls are heterogeneous bodies with very high conductivity contrasts between sections of

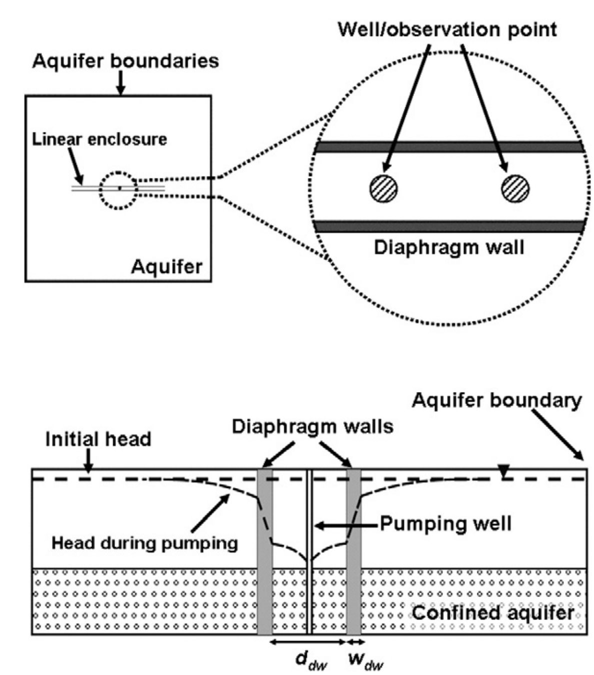

Fig. 2. Problem statement. Above, plan view of the enclosure (general and detail of the middle). Below, schematic cross section where the diaphragm walls and the pumping well are shown.