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Integration of groundwater by-pass facilities in the bottom slab design for large underground structures

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A B S T R A C T

The impacts induced by the interaction between underground constructions and groundwater should be minimised by implementing corrective measures. These impacts are twofold, which means that underground constructions affect groundwater, and vice versa. Two common situations resulting from this interaction are the barrier effect (impact of an underground construction on groundwater) and groundwater pressure on the bottom slab (impact of groundwater on an underground construction). In the literature, there are examples and designs of mitigation measures to minimise both impacts. However, to the best of the authors' knowledge, there are not any designs that combine corrective measures to minimise these simultaneously. This paper proposes an innovative groundwater by-pass design to mitigate the barrier effect and to alleviate the groundwater pressure on the bottom slab. The proposed integrated design was applied to the largest underground infrastructure in Barcelona: the Sagrera railway station. The design was tested and compared numerically with a solution initially designed (not integrated). The numerical comparison was undertaken with three different hydrogeological scenarios. The proposed integrated design mitigated the barrier effect and optimised the bottom slab. It considerably reduced costs and increased safety during the construction phase.

1. Introduction

The competition for space in urban areas due to an exponential population growth has resulted in underground engineering playing a crucial role in the development of cities (Li and Yuan, 2012). As a result, underground infrastructures are more frequently required. These infrastructures must be efficient, which needs to be kept in mind during all phases of a project: (I) design, (II) construction, and (III) implementation. Thus, a wide range of variables (cost, duration, safety, management, maintenance, and environmental issues, amongst others) must be considered. Groundwater plays an important role in the efficiency of underground construction as it is related to environmental, safety, and maintenance issues (Cesano et al., 2000). Consequently, studies focused on the interaction between groundwater and underground construction are of paramount importance. Most previous studies proposed procedures to avoid the difficulties resulting from groundwater (Angel et al., 2015), or to minimise the impact on aquifers (Kusumoto et al., 2003). However, none of them considered both problems together, or combined procedures to increase the efficiency of the system.

The interaction between underground construction and groundwater is twofold, i.e. groundwater impacts an underground construction and vice versa (Attard et al., 2016; Wu et al., 2016). This interaction must be assessed during the initial stages of the project (phases I and II), when it is easier, cheaper, and more efficient to adopt mitigation measures.

During the construction phase of an underground structure below the water table, groundwater is usually pumped in order to work in dry conditions, and to avoid bottom instabilities. These instabilities could lead to bottom uplift or liquefaction (Preene, 2001; Wu et al., 2015a,b). After the construction phase, pumping is stopped and the water table returns to its original level. As a result, groundwater pressure on the bottom slab of the structure increases. At this stage, it is of paramount importance to both distribute the groundwater pressure homogeneously on the bottom slab and to limit the overpressure to avoid breaking the bottom slab. The most common techniques to control the groundwater pressure on the bottom slab are a gravel layer under the structure or an oversized bottom slab. The gravel layer allows the water to flow without constraints, and thus, the groundwater pressure is evenly

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distributed. An oversized bottom slab ensures structural integrity when the pressure increases. However, this technique is not able to decrease the groundwater pressure by itself. Therefore, if the maximum designed-for groundwater pressure is exceeded, slab breaking becomes a possibility. To avoid this risk, artesian wells are commonly drilled through the bottom slab, allowing the groundwater pressure to be relieved by maintaining the groundwater at a desired level.

On the other hand, underground construction may have an impact on groundwater. The barrier effect (s_B) between them is the main concern when underground structures are poorly conductive (Vázquez-Suñé et al., 2004). The underground construction acts as a flow barrier, reducing the effective transmissivity of the aquifer, leading to a rise in the water table upgradient and a lowering downgradient (Xu et al., 2013, 2014; Ma et al., 2014). This modification of the water table may have negative consequences (Deveughèle et al., 2010). Rising water levels may promote flooding of basements, soil salinisation, rotting the roots of plants, reduction of the bearing capacity of shallow foundations, expansion of heavily compacted fills under the foundation structures, settlement of poorly compacted fills upon wetting, increment in loads on restraining systems or basement walls of buildings, increasing the need for drainage in temporary excavations, and/or propagation of contaminants contained in the partially saturated zone (Marinos and Kavvadas, 1997; Tambara et al., 2003; Ricci et al., 2007; Paris et al., 2010). Reducing the piezometric head on the downgradient side could result in seawater intrusion in coastal aquifers, ground subsidence, death of phreatophytes, and/or the drying up of wells and springs (Custodio and Carrera, 1989; Tambara et al., 2003; Xu et al., 2012). In addition, the difference in groundwater pressure between the sides of an underground structure leads to asymmetric loading, which could induce shear stresses. These could damage the underground structure if they had not been planned for. Although the s_B has negative consequences, it can be mitigated by employing by-pass systems. Their main objective is to increase the effective transmissivity of the area occupied by the underground structure (Hamate et al., 2003; Ribera, 2008; Nishigaki, 2010). Fig. 1 shows some designs for by-pass systems proposed by authors, and used at different underground constructions (Akagi, 2004). During the construction of the Kyoto subway (Japan), semi-pervious walls were used to intake and recharge groundwater (Fig. 1(1)) (Hashimoto et al., 2001). In the construction of a highway in Nerima (Japan), the upper parts of the cut-off walls were removed to allow the water to cross the structure through a set of siphon pipes below it (Fig. 1(2)) (Ueda, 1999). For the construction of a subway tunnel in Barcelona (Spain), some sections of the cut-off walls, and the space above the tunnel, were filled with gravel (Malavia et al., 2008). A by-pass system was also used in the construction of the high speed train tunnel in Barcelona. In this particular case, hydrochemistry aspects were considered, and two sets of intake and recharge pipes, located at different depths, were used. The objective of this design was to avoid the mixing of water with different chemical compositions. This increased the useful life of the system, as clogging and/or corrosion were reduced (López, 2009). There are certain aspects that need to be considered when designing by-pass systems, in order to improve their efficiency. These aspects are related to the design of facilities used for collecting and recharging groundwater. The use of bentonites during the construction of retaining walls leads to a reduction of the local transmissivity, reducing the capacity to collect, by-pass, and release water when prefabricated permeable walls are installed (Fig. 1(1)), or when the retaining walls are removed (Fig. 1(2)). Additionally, prefabricated permeable walls compromise the safety of a facility due to the large volume of water and high hydraulic loads in the wall. Thus, the use of vertical wells appears to be a better alternative (Fig. 1(3)); however, their effectiveness is limited in thin aquifers as it depends on their length. In these cases (i.e. thin aquifers), horizontal drains (Fig. 1(4)) would be a better alternative as their effectiveness increases with their length. Horizontal drains can be arranged radially if the machinery used is unable to drill sufficiently long drains, and this improves their functionality (Santamaría et al., 2008).

Groundwater pressure on the bottom slab and s_B are usually solved for independently. This is surprising as the groundwater level is the key variable in both cases. The best way to deal with different problems sharing common variables is to design integrated solutions. This improves the efficiency of the system while reducing costs. In this particular case, distributing and limiting the groundwater pressure, and the by-pass system, should be integrated into a single design. To the best of the authors' knowledge, there have been no literature studies in this regard.

This paper presents an innovative design for a by-pass system that also provides a homogenous distribution of the groundwater pressure on the bottom slab. This new, integrated design, which meets its objectives, led to a considerable reduction. The integrated design was applied to the largest underground infrastructure in Barcelona (Spain), the Sagrera railway station, whose location is shown in Fig. 2. This station is located in the metropolitan area of Barcelona, and aims to become the city's major intermodal-transit hub. It is expected that this station will process more than 100-million passengers per year from high-speed trains, short- and medium-distance trains, four metro lines, and buses (ADIF, 2015). Construction began in 2010, and is planned for completion by 2020. As of today, excavation almost complete, and the bottom slab construction is the next stage.

2. Materials and methods

2.1. Geographical, geological and hydrogeological description

The metropolitan area of Barcelona is located on the Mediterranean coast, in northeastern Spain (Fig. 2). Geologically, this area is formed by a coastal plain (the Barcelona Coastal Plain) (Vázquez-Suñé et al., 2016), bounded by two Quaternary deltaic formations corresponding to

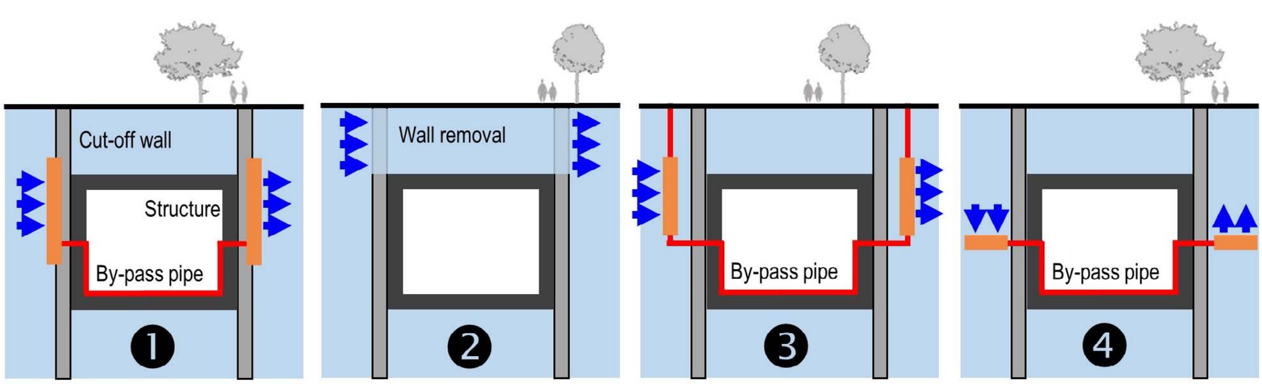

Fig. 1. Groundwater by-pass designs. (1) Removal of cut-off wall, (2) intake and recharge pipes installed in drilled hole, (3) intake and recharge through permeable cut-off walls, and (4) intake and recharge wells. Modified from Akagi, 2004. Not to scale.