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Groundwater-related aspects during the development of deep excavations below the water table: A short review

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Abstract

The expected growth of urban areas requires the construction of underground infrastructures, especially for improving transportation and mobility. These new infrastructures are commonly constructed below the water table because they must be deeper than previous underground structures. In addition, many urban areas are located near surface water bodies (i.e., seas, rivers and/or lakes) that induce a shallow water table. The "cut and cover" method combined with dewatering wells is a frequently used procedure under these conditions for the construction of underground infrastructures. The main concerns of this procedure are related to the stability of the excavation bottom, the behavior of the retaining walls and/or the impacts induced by the dewatering actions. These issues must be evaluated, and new solutions must be proposed to improve its weak points. This paper compiles the main publications focused on the construction of underground infrastructures below the water table and in urban areas by using the cut and cover method combined with pumping. This review reveals that, despite many published studies, more research is needed to address some relevant issues such as: (1) the mitigation of dewatering impacts by using artificial recharge, (2) the adaptation of methods for characterizing retaining walls to be used under heterogeneous conditions, (3) the improvement of the prediction of surface settlements produced by pumping, and (4) the consideration of non-Darcy flows in the design of dewatering systems.

Keywords: Dewatering; Excavation; Cut and cover; Retaining walls; Settlements

1 Introduction

Recent data from the United Nations show that half of the world's population lived in urban areas in 2014, and this proportion is projected to reach 66% by 2050 (UN, 2014). Cities around the world face the challenge of constructing new infrastructures to facilitate mobility, but they cannot be constructed on the surface due to space limitations. This situation leads to the vertical development of urban areas where new infrastructures must be deeper than the previous ones. Different construction methods and tools can be adopted depending on the characteristics of the infrastructure and the area in which the construction is developed. For example, tunnels can be drilled with tunnel boring machines (TBMs), excavated by the "cut and cover" method or constructed using traditional (Belgian, Madrid, German) or sequential (new Austrian) tunneling methods (Pulido, Darido, Munoz-Raskin, & Moody, 2018). Among the available techniques, the cut and cover method is one of the most commonly used to carry out excavations in urban areas (Konda, 2001). In fact, the cut and cover method is frequently adopted for the construction of stations in railway projects (Di, Zhou, Xiao, Gong, & Luo, 2016; Zhou, Wang, & Hu, 2013); the assembly, disassembly and maintenance shafts required when

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drilling tunnels by TBMs (Culí, Pujades, Vázquez-Suñé, & Jurado, 2016) or other kind of underground infrastructures such as parking lots (Pappa & Benardos, 2007). This method consists of excavating under the protection of vertical retaining walls (Gulhati & Datta, 2005) that can be constructed of steel, concrete, or jet-grouting piles or diaphragm walls, among other materials. The main advantage of this method is that the excavation walls are vertical, reducing the space occupied by the construction, which is meaningful in urban environments. The main steps of the cut and cover method are (1) to construct the retaining walls, (2) to excavate to the desired depth, (3) to construct the infrastructure, and (4) to fill the space between the top of the constructed structure and the surface (Gulhati & Datta, 2005; Mouratidis, 2008) (steps 1, 3, 4 and 5 in Fig. 1).

The construction of new urban underground infrastructures is usually performed below the water table because they must be deeper than existing underground structures. In addition, many cities are commonly located near rivers or in coastal areas where the water table is usually near the surface. The presence of groundwater and its interaction with the construction process must be properly considered to avoid accidents and difficulties (Pujades et al., 2012), especially during deep excavations. When excavating below the water table, the retaining walls are usually combined with dewatering wells (step 2 in Fig. 1). Retaining walls prevent lateral groundwater inflow, whereas dewatering wells allow excavating in dry and stable conditions. Pumping reduces the water table inside the enclosure and the water pressure in the bottom of the excavation, which prevents liquefaction and bottom uplift (Calin, Cristian, & Ioan, 2017). Liquefaction or bottom uplift occurs when the water pressure exceeds the soil weight. These phenomena have negative implications for the development of the excavation and the safety of nearby buildings and workers. For this reason, the dewatering wells and the retaining walls must be conscientiously designed to reach the required water pressure at the excavation bottom. Numerical models are a powerful tool to design dewatering systems and to ensure that water pressure does not exceed the desired threshold. However, although a dewatering system is properly designed, instability events may occur if the retaining walls have unidentified defects, which promote the water pressure to be higher than expected. Defects in the retaining walls are relatively common and can produce a wide range of negative consequences (flooding, sinkholes, bottom instability and large soil deformations) that depend on their relative location with respect to the excavation bottom. In addition, independent of the location of the defects, they contribute to propagate the effects of pumping outside the excavation enclosure. Thus, groundwater drawdown and its associated impacts, including surface settlements, increase when defects exist in the retaining walls. Dewatering impacts are of paramount importance, especially in urban areas, and they must be predicted in advance. The main impacts produced by dewatering are the drawdown of the water table and the surface settlements, which are very concerning since they can be large and damage urban structures (e.g., buildings) (Forth, 2004). Consequently, dewatering systems are designed to minimize them. The easiest way to mitigate surface settlements associated with the dewatering of deep excavations consists of elongating the retaining walls more than is structurally required until reaching deep impervious formations, which allows reducing or eliminating the pumping. However, this decision is controversial since the excessive elongation of the retaining walls may reduce the global efficiency of the construction. In addition, when pumping is eliminated by elongating the retaining walls, the safety exclusively depends on their watertightness capacity, and as has been reported by numerous authors, they commonly have defects (Bruce, DePaoli, Mascardi, & Mongilardi, 1989). Concurrently, some authors affirm that pumping settlements are smaller and less dangerous (i.e., no differential) than expected, especially when the soil is overconsolidated (Pujades, De Simone, Carrera, Vázquez-Suñé, & Jurado, 2017). Regardless, corrective measures to mitigate dewatering impacts already exist. These measures basically consist of returning the pumped groundwater to the aquifer by artificial recharge. Artificial recharge is commonly performed through deep wells located outside the excavation (Zeng, Zheng, Xue, & Mei, 2019). The efficiency of artificial recharge systems to

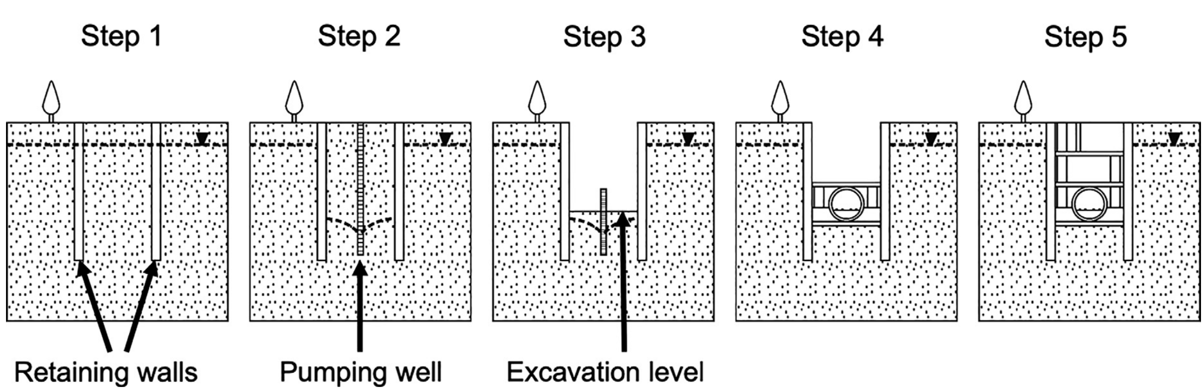

Fig. 1. Cut and cover method steps for the construction of an infrastructure below the water table (modified from Pujades et al., 2012).

eliminate surface settlements depends on the spatial distribution of the recharge wells and the methods used to solve clogging-related issues. Finally, another concern during deep excavations is the deflection of the retaining walls, which also produces soil deformations. Most published studies barely consider the influence of the groundwater fluctuations on the displacements of the retaining walls. Only some authors have probed whether dewatering tasks may produce important retaining wall deflections.

Studies focused on investigating groundwater-related aspects during deep excavations have been published beginning many years ago. Science related to this topic has been developed and has evolved over time through numerous publications. The objective of this publication is to show the most recent innovative progress in the field. For this reason, the main findings over the last five years are compiled in this paper. Investigations regarding the stability of the excavation bottom, the behavior of the retaining walls, the impacts induced by the dewatering and corrective measures to avoid them are considered and discussed.

2 Methodology and considered literature

This review includes published studies during the last five years focused on excavations developed in urban areas. In total, Tens of studies are considered. Most of them are focused on underground constructions developed in China but also in Spain, Italy and Singapore. Table 1 summarizes the main characteristics of the constructions. This manuscript is structured considering relevant issues related to deep excavations in urban areas (state and behavior of the retaining walls, design of dewatering systems, impact mitigation). Studies containing information about more than one issue are cited and discussed in different sections.

3 State and behavior of the retaining walls

3.1 Watertightness and defects

One of the roles of the retaining walls used in deep excavations is to prevent groundwater lateral inflow, which facilitates dewatering, and for this reason, they must have a very low hydraulic conductivity. However, retaining walls commonly have defects (Bruce et al., 1989) that increase their effective hydraulic conductivity and allow the groundwater to flow through them. Defects produce different kinds of difficulties depending on their nature and relative location with respect to the excavation bottom. If defects are located above the excavation depth, groundwater inflows may drag sediments from behind the retaining walls, which leads to the formation of sinkholes outside the excavation (Pujades et al., 2012; Vilarrasa, Carrera, Jurado, Pujades, & Vázquez-Suné, 2011). If defects are located below the excavation bottom, the water pressure at the bottom is higher than expected, leading to liquefaction or bottom uplift phenomena, which can produce, among others, structural instability and subsidence related to soil migration (Xu et al., 2014). Defects also increase the hydraulic connection between the inside and outside of the excavation enclosure. Consequently, the excavation may be flooded, and the effects of the dewatering (i.e., drawdown and settlements) are more easily propagated outside. Defects are relatively easy to repair by injection grouting, but the repair must be undertaken before the excavation stage. If the repair is carried out during the excavation stage, all injected grout flows toward the dewatering wells. As a result, defects remain open, and the dewatering wells are damaged. If defects are abundant and they cannot be repaired, the alternative option is to redesign the dewatering system, considering the existence of the defects and assuming a high value of hydraulic conductivity for the retaining walls. In both situations, isolated or numerous defects, it is always mandatory to characterize the retaining walls before the excavation stage.

Accidents such as those reported by Feng and Lu (2015) and Tan and Lu (2017) may occur if defects are not identified before the excavation stage. Both studies reported accidents during excavations associated with the presence of defects in the retaining walls. Feng and Lu (2015) presented the case of a failure during the construction of a subway station in Nanchang, China. The main consequences of the faulty retaining walls were leaks, bottom liquefaction and sinkholes outside the enclosure. Tan and Lu (2017) reported groundwater inflow, dragged sediments, increased settlements, sinkholes outside the excavation and cracks affecting nearby buildings.

Given the potential risks associated with faulty retaining walls, some authors have proposed methods to assess their state before the excavation stage by means of the interpretation of pumping tests. The pumping tests, which are undertaken after the construction of the retaining wall, are called "watertightness assessment tests" (WTATs). Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al. (2014) and Pujades, Vázquez-Suñé, Carrera, and Jurado (2014) showed the results of three WTATs performed before the excavation of three TBM maintenance shafts required for the construction of the high speed train (HST) tunnel in Barcelona. The shafts were located near the Sagrada Familia Basilica at the sites of Padilla (Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al., 2014), Bruc (Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al., 2014) and Trinxant (Pujades, Vázquez-Suñé, Carrera, & Jurado, 2014). Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al. (2014) performed two WTATs. The retaining walls of one of the excavations were made up of the combination of diaphragm walls and jet-grouting piles (shaft of Padilla), while only diaphragm walls were used for the enclosure of the second shaft (Bruc shaft). As expected, the WTAT performed in the Padilla shaft revealed that the hydraulic conductivity of the jet-grouting enclosure was relatively high (0.6 m/d), and groundwater could inflow easily inside the excavation enclosure. The dewatering system was redesigned considering the hydraulic conductivity of the

Table 1
Main characteristics of the considered studies. The column "Topic" refers to the addressed issue(s) and it is also related with the section(s) of this paper in which each study is classified. D is retaining walls deflections (Section 3.2); I is dewatering impacts (Section 4.2); F is faulty retaining walls (Section 3.1); SF is design of dewatering systems and stability of the excavation bottom (Section 4.1); R is impact mitigation by artificial recharge (Section 5).

Reference	Location	Topic	Max. deflection (mm)	Max. settlement (mm)	Depth (m)			
					Excavation	Pumping wells (screen)	Recharge wells (screen)	Walls
Feng and Lu (2015)	Nanchang, China	F/D	20	≈12	15.5–17.8	19.5–21.8		20.5
Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al. (2014) and Pujades et al. (2016)	Barcelona, Spain (Padilla shaft)	F/SF/I		<5	41	61.5		61.5
	Barcelona, Spain (Bruc shaft)	F/SF/I		2.4	40	60		60
Pujades, Vázquez-Suñé, Carrera and Jurado (2014)	Barcelona, Spain (Trinxant shaft)	F/SF/I		2	33	55		50
Russo et al. (2016)	Napoli, Italy (San Pasquale station)	D	40	24	27	—		50
Serrano-Juan et al. (2016)	Barcelona, Spain (Sagrera station)	D	6		20	35		35
Shen et al. (2017)	Shanghai, China (East Nanjing Road)	I			24.24–26	52		46–55
Tan and Lu (2017)	Shanghai, China (Central business district)	F/D	40	100	31.4–33.1	53 (26.5–30, 40–52)		55
Wang et al. (2016)	Shanghai, China (Qilianshan South Road)	SF/I			17.4–19.5			30.8–34.2
	Shanghai, China (Xinzang South Road)	SF			23–25			38–40
	Shanghai, China (Hanzhong Road)	SF			30.8–32.3			59–62
Wang et al. (2017)	Hangzhou, China (Qianjiang Century City)	SF			26	58 (37–41/49–58); 45–49 (37–41; 37–43)		52
Wang et al. (2018)	Shanghai, China (Yishan Road)	I						
Wu, Shen, Xu et al. (2015) and Wu, Shen, Yin, et al. (2015)	Hangzhou, China	F/SF/I		<5	24	43–50		43–54
Xing et al. (2016)	Shanghai, China	D	<10	<10	16.3	—		33.5
You et al. (2018)	Nanjing, China	SF/R		<95	9.5–27	51 (6–22, 28–50)		40–52
Zeng et al. (2018)	Tianjin, China (Beizhan station)	D	10	<5	17.6–23	2–20.6		33
Zeng et al. (2019)	Tianjin, China (Test 1)	R		< 50	21	28–31.5	46 (26,29,38–44)	37.9
	Tianjin, China (Test 2)	R				28–31.5	51 (40–50)	
Zhang, Li, et al. (2017) and Zhang, Wang, et al. (2017)	Shanghai, China (Hanzhong Road)	R		<17	33.1	73 (63–72)	77 (63–75) / 80 (63–78)	59–62
Zhang et al. (2018)	Singapore (Cashew station)	D	≈15	≈120	20	—		29
Zheng et al. (2014)	Tianjin, China (Beizhan station)	D	10		17.6–23	2–20.6		33–42
Zheng et al. (2018)	Tianjin, China	R		<1.8	21	28–31.5	51 (40–50)	37.9
Zhu et al. (2014)	Shanghai, China (Yishan Road)	I		30	30.6	59/61		48–62

jet-grouting. Conversely, no defects were observed during the WTAT in the Bruc shaft. Pujades, Vázquez-Suñé, Carrera and Jurado (2014) also showed the results of a WTAT performed before the excavation of the Trinxant shaft. In this case, discrepancies between expected and observed drawdown indicated that the retaining walls had defects. Wu, Shen, Xu, and Yin (2015) showed the results of a WTAT that was performed to characterize the retaining walls of a deep excavation in Hangzhou, China. The excavation was required for the construction of an interchange subway station. The results indicated the existence of a leak through a defect. The authors associated the location of the faulty zone with difficulties that occurred during the construction of the retaining walls through a gravel layer. Afterwards, Wu, Shen, Yin, and Xu (2015) developed a numerical model to simulate the WTAT. They varied the hydraulic conductivity at different areas of the retaining walls to simulate the faulty zone. Finally, Pujades, Jurado, Carrera, Vázquez-Suñé, and Dassargues (2016) proposed a method for the characterization of circular enclosures. This method is based on the interpretation of a WTAT by using diagnostic plots and allows determining the general state of the retaining walls and locating defects. The method was tested with data from the WTAT performed at the Padilla shaft (Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al., 2014).

3.2 Deflections

Some authors have focused their attention on the deflection of retaining walls associated with groundwater variations and its relation with soil settlements. Deflections occur when the balance of the forces affecting the walls is modified because of excavation or dewatering. There are different types of deflections, as well as, associated surface settlements (Fig. 2).

In this review, only studies in which groundwater behavior plays a special role have been included. Wall deflections are commonly measured by using inclinometers embedded inside the retaining walls (Zhang et al., 2018). However, some authors have proposed alternative methods to improve the measurements. Specifically, Serrano-Juan et al. (2016) observed wall deflections by using a ground-based synthetic aperture radar (Gb-SAR) during a pre-excavation dewatering (PED) test for the construction of an intermodal station (railway, bus, subway, HST) in Barcelona, Spain. The Gb-SAR sensor was located on one side of the excavation, and the maximum measured displacement was approximately 6 mm (Table 1). The advantage of using a Gb-SAR sensor is that it allows observation of the behavior of all the retaining walls located inside its field of vision, while inclinometers only provide punctual information. Zheng, Zeng, Diao, and Xue (2014) observed and modeled the retaining wall deflection that occurred during a PED test for the construction of a subway station in Tianjin, China. The numerical model was used to study the mechanism that produced the deflections. Zheng et al. (2014) did not pay attention to outside settlements; in contrast, they only considered the soil deformations occurring inside the excavation, which reflected the influence of the soil-wall friction. Xing, Xiong, and Wu (2016) developed a similar investigation as they observed and modeled the wall deflections and the surface settlements that occurred during the construction of a station in Shanghai, China. The main difficulty in this construction was that the new station was constructed below a pre-existing subway station. Consequently, it was of paramount importance to minimize the retaining wall deflections and, in general, soil deformations. Xing et al. (2016) used a numerical model to compute them under different scenarios. The numerical results allowed proposing an alternative construction method for mitigating deformations. This method consisted of reinforcing the retaining walls by using a square box formed by jet grouting soil piles. The adopted method proved to be useful, and the maximum observed retaining wall deflections and surface settlements were less than 10 mm (Table 1). The importance of predicting and monitoring the retaining wall deflections was highlighted by Russo, Nicotera, and Autuori (2016), who focused their investigation on the horizontal displacements of the retaining walls that occurred during the construction of the San Pasquale Station in Napoli, Italy. This station was located near historical buildings, which could be damaged by excessive soil displacements. In this context, Russo et al. (2016) monitored and modeled the horizontal displacements that occurred during the construction. The maximum displacements, which were measured with inclinometers, reached up to 40 mm (Table 1). Similarly, Zeng, Xue, Zheng, Xue, and Mei (2018) studied the retaining wall deflections induced by PED tasks and their relationship with soil vertical deformations (i.e., settlements) that occurred outside the excavation. This study was focused on the construction of a subway station in Tianjin, China. Initially, they developed a numerical model for computing the retaining wall deflections, which was validated with real measurements (maximum retaining wall deflection reached 10 mm). They also predicted the surface settlements assuming that they were consequence of ground loss behind the wall due to wall deflection and using the empirical solution proposed by Hsieh and Ou

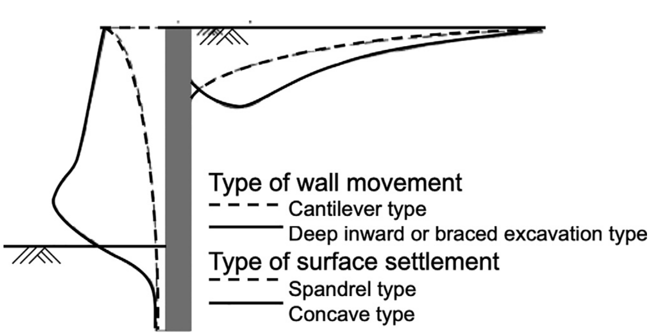

Fig. 2. Different types of deflections and surface settlements (Chheng & Likitlersuang, 2018).

(1998). They also assessed the role of the soil hydraulic conductivity on the retaining wall deflections and surface settlements. The system behavior was also analyzed by considering the presence of intercalated aquitards between aquifers. The main findings were that (1) the PED can induce centimetric wall deflections and surface settlements, and (2) the wall displacements and soil settlements occur during PED increase when the hydraulic conductivity of the soil is high. Consequently, in the case of a multilayered aquifer system, wall deflections and surface settlements increase as more aquifers are affected by pumping.

Zhang et al. (2018) developed a numerical model to compute the retaining wall deflections and settlements during the construction of an underground station in Singapore. The numerical model was validated with real measurements and used to predict the behavior of the system. The maximum retaining wall deflection and surface settlement during the excavation were 15 and 120 mm (Table 1), respectively. The authors also assessed the influence of groundwater drawdown outside the excavation. They showed that the deflection of the retaining walls increases and settlements decrease as the groundwater drawdown outside the excavation is reduced. In addition, they observed that (1) the depth at which the maximum wall deflection occurs does not depend on the groundwater drawdown and (2) the magnitudes of the retaining wall deflection and surface settlements are not only linearly proportional to the drawdown but also depending on the thickness of compressible layers.

Finally, it is interesting to note the cases reported by Feng and Lu (2015) and Tan and Lu (2017). They observed wall deflections and surface settlements during deep excavations in which failures occurred. Feng and Lu (2015) observed wall deflections up to 20 mm (Table 1). The maximum retaining wall deflection occurred during the failure. However, given that the maximum displacement was less than the critical action value, retaining wall displacements were attributed to the normal behavior of the excavation. Surface settlements, which were nearly constant, increased up to 10 mm after the failure. The maximum wall deflection and surface settlement observed by Tan and Lu (2017) reached 40 and 100 mm (Table 1), respectively. The retaining wall deflections were lower than the maximum critical value, and the failure did not promote their increase. In fact, the measured retaining wall displacements were similar at observation points located at different distances from the failure. In contrast, surface settlements increased abruptly near the failure (up to 50 mm at some observation points).

4 Design of dewatering systems

4.1 (Hydraulic) stability of the excavation bottom

Excavations beneath the water table can suffer from potential problems caused by groundwater, including fluidization and bottom uplift (Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al., 2014). Fluidization might take place when the excavation is undertaken in unconfined aquifers, and bottom uplift might occur when the excavation bottom is located above a confined aquifer (Cashman & Preene, 2001). An excavation can be performed safely as long as the vertical total stress in the ground (σ_V) exceeds the pore water pressure (P_W). This gives rise to a "safety factor" (SF),

$$SF = \frac{\sigma_V}{P_W}, \tag{1}$$

which defines the excavation to be safe if $SF = 1$, but it is common to require safety factors greater than 1 (i.e., Pujades, Vázquez-Suñé, Carrera, & Jurado, 2014; Wu et al., 2015) to account for the insufficient characterization of the system. In practice, positive effective stresses are essential at all stages of the construction process to work in safe conditions. The vertical effective stress (σ'_V) can be calculated using Terzaghi's equation in the vertical direction (Terzaghi & Peck, 1948) as follows:

$$\sigma'_V = \sigma_V - P_W. \tag{2}$$

The total σ_V is given by the following:

$$\sigma_V = z\gamma_S, \tag{3}$$

and the water pressure as:

$$P_W = h\gamma_W, \tag{4}$$

where z is the depth of the observation point, γ_S is the specific weight of the soil, h is the piezometric head at the observation point, and γ_W is the specific weight of the water.

Some authors have shown how to compute the SF to ensure the hydraulic stability of the excavation bottom. Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al. (2014) analyzed different dewatering schemes for the excavation of two TBM shafts in Barcelona, Spain. The authors considered three different scenarios: (1) short retaining walls that were constructed at the minimum depth required structurally, (2) long retaining walls that were deeper than the minimum depth required structurally, and (3) an enclosure made up by the combination of diaphragm walls and jet-grouting piles. In the last scenario, the depth of the diaphragm walls was the minimum required structurally, while jet-grouting piles were used to increase the depth of the enclosure up to an impervious layer. In all the scenarios, the minimum imposed SF was $\not<$ 1.2, and it was computed for each meter below the bottom of the excavation because the soil was heterogeneous and the drop of pressure was different in each geological layer. Similarly, Pujades, Vázquez-Suñé, Carrera and Jurado (2014) proposed a methodology to improve the construction of deep excavations in urban areas. This methodology was applied to the Trinxant shaft of the HST tunnel in Barcelona, and the SF was calculated at different depths for four different scenarios. The retaining walls (50 m depth) and the dewatering well (55 m depth) have the same characteristics in all the scenarios. The difference between them was the imposed drawdown in the dewatering well, which was 25, 30, 35 and 40 m for scenarios 1 to 4, respectively. Stable conditions ($SF \nless 1.2$) were achieved with 40 m of drawdown in the dewatering well, which allowed for draining materials with low values of hydraulic conductivity (alternating layers of clay-silt and sands). Similarly, Wu, Shen, Xu, et al. (2015) and Wu, Shen, Yin, et al. (2015) evaluated the SF for the construction of a metro station in Hangzhou, China. The station was excavated in a gravel aquifer between retaining walls, and the maximum excavation depth was 24 m (below the ground surface). Several pumping tests were conducted to determine whether the original depth of the retaining walls (43 m) was sufficient to maintain safety at the base of the excavation. Finally, the retaining walls were elongated to a depth of 54 m to effectively protect the base of the excavation from the upward seepage and to satisfy a $SF \nless 1.1$ set up by the Chinese Design Code guidelines. The same SF was considered by Wang et al. (2016), who aimed to understand the interaction between the retaining walls and dewatering wells and their effect on the subsidence associated with intensive dewatering of station foundation pits in the subway system in Shanghai (China). Finally, You, Yan, Xu, Liu, and Che (2018) proposed different dewatering schemes for the construction of a deep foundation pit in Nanjing, China near the Yangtze River. The foundation pit consisted of three ramps (A, B and C) and a main road connecting a cross-river tunnel. The shape of the foundation pit was irregular, and the depth was not uniform. The maximum depth of the foundation pit was 27 m. To guarantee the safety of the pit excavation ($SF \nless 1.1$) and ensure the stability of the Yangtze River levee, different dewatering requirements were proposed. To conclude, it is necessary to mention the study developed by Wang et al., 2017. This study considered the effects of non-Darcy flow caused by the combination of dewatering wells and retaining walls. They analyzed the area affected by non-Darcy flow under different scenarios in which the geometry of the dewatering wells and the retaining walls was modified. The objective was to improve the efficiency of dewatering systems taking into consideration that drawdown under Darcy conditions is smaller than that produced under non-Darcy flow. Consequently, if the area affected by non-Darcy flow is increased, a lower pumping rate is required to produce the same drawdown. From this study, it is possible to conclude that the drawdown necessary to reach a required SF is overestimated when non-Darcy flow is not considered.

4.2 Impacts

Impacts associated with dewatering of deep excavations are a relevant issue that is regarded in most studies. The two most meaningful impacts produced by dewatering actions are groundwater drawdown (Fig. 3) and soil deformations (i.e., surface settlements), both of which occur outside the excavation (You et al., 2018).

Surface settlements are truly concerning because they can damage nearby structures (Forth, 2004) (i.e., buildings or other infrastructures), while groundwater drawdown affects the available water resources, which is especially relevant in arid and semiarid regions. Both impacts are related since surface settlements are consequence of groundwater drawdown. In fact, surface settlements are proportional to groundwater drawdown (Bear & Corapcioglu, 1981a, 1981b; Cashman & Preene, 2001), except in the vicinity of dewatering wells (Pujades et al., 2017). Assuming only vertical deformations, settlement at the surface can be computed as follows:

$$\rho = \gamma_W s D \alpha, \tag{5}$$

where ρ is the surface settlement, s is the head drop, D is the aquifer thickness and α is the soil compressibility. α can be easily derived from the storage coefficient (S) if the aquifer is overconsolidated and behaves elastically. Considering the equation proposed by Jacob (1950) and cited by Ferris, Knowles, Brown, and Stallman (1962),

$$S = \gamma_W \theta D \left(\beta + \frac{\alpha}{\theta}\right), \tag{6}$$

where θ is the porosity and β is the water compressibility, it is possible to assume that $S_S = \alpha$ since β is very small compared with α, where S_S is the specific storage coefficient, which can be obtained from pumping tests.

The design of the dewatering system (i.e., retaining walls and dewatering wells) plays a special role in mitigating the potential impacts, and it must be conscientiously chosen. This section is focused on studies that report dewatering impacts and assess different designs of dewatering systems to mitigate them. Note that surface settlements can also be produced by the deflection of retaining walls, but literature focused on this kind of settlement is included in Section 3.2.

Zhu, Huang, Tan, and Chen (2014) analyzed the soil displacements induced by the dewatering undertaken for the construction of the Yishan Road station of the Shangai Metro Line 9, which is a four-story underground station. The maximum measured surface settlements reached 30 mm (Table 1). Zhu et al. (2014) monitored the settlements at different depths by using a high-precision multiple-position extensometer. Measurements revealed that settlements in some geological layers were higher than those observed at the surface. This fact would indicate that some layers expanded during the dewatering, which mitigated the surface settlements. This behavior was subsequently corroborated by Wang et al. (2018) by using a physical model test and a numerical model. Similarly, Xu, Shen, Ma, Sun, and Yin (2014) studied the influence of the depth of the retaining walls on outside drawdown. This study arose from experiences during underground constructions in Shanghai, China. They undertook laboratory tests and developed numerical models to analyze the blocking effect of retaining walls and how the outside groundwater drawdown decreases when the depth of the

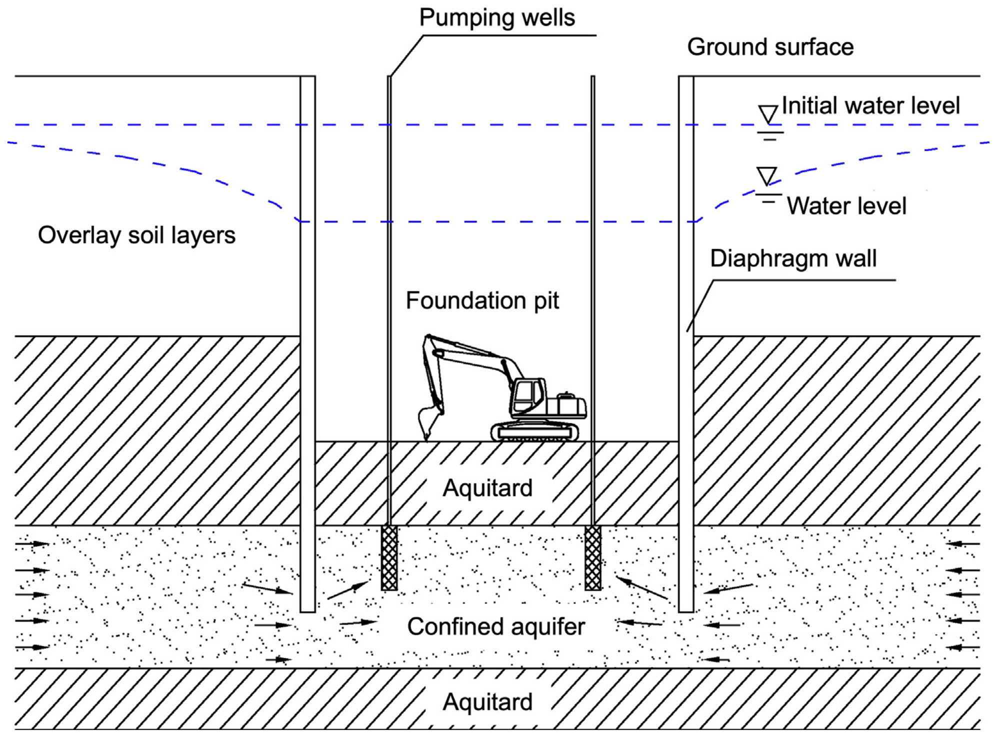

Fig. 3. Example of drawdown produced by the dewatering of a confined aquifer (Wang et al., 2017).

retaining walls is increased. They proposed a concept called "effective depth ratio" that relates the aquifer thickness and the depth of the retaining walls. The "effective depth ratio" allows estimating the magnitude of the groundwater drawdown occurring outside the excavation enclosure during the dewatering. Pujades, Vázquez-Suñé, Carrera, Vilarrasa, et al. (2014) and Pujades, Vázquez-Suñé, Carrera and Jurado (2014) showed the procedure to design three dewatering systems for excavating maintenance shafts required for the construction of the HST tunnel in Barcelona, Spain. They used numerical models to compute groundwater drawdown and surface settlements under different scenarios in which the depth of the retaining walls was modified. The optimum dewatering system was proposed considering the groundwater drawdown, the surface settlements and the *SF* in the excavation bottom. The most relevant information is related to the monitored surface settlements during the excavation of the three shafts. Measurements indicated that the soil was overconsolidated because it behaved elastically before groundwater drawdown. The maximum measured surface settlement was lower than 5 mm (Table 1), which is a relatively low magnitude considering that groundwater drawdown inside the excavation was approximately 50 m. Measurements also showed that surface settlements were produced not only by dewatering tasks but also by other actions, namely, the construction of the retaining walls, which produced surface settlements even higher than those induced by pumping. Similarly, Wu, Shen, Xu et al. (2015) analyzed the influence of the depth of the retaining walls on groundwater drawdown and surface settlements that occurred outside the excavation enclosure during the construction of a subway station in Hangzhou, China. They monitored the groundwater and soil behaviors during two pumping tests. The first test was performed with a 43 m retaining wall depth, while the retaining wall reached a 53 m depth during the second test. Observations corroborated that groundwater drawdown outside the excavation enclosure decreased when the retaining walls were elongated. As a result, a reduction in the surface settlements was also expected. However, monitoring data indicated that the surface settlements during the two tests were similar. In addition, no pattern relating the evolution of the surface settlements and the pumping tests was observed, which would indicate that the surface settlements were influenced by other factors or activities. Anyway, the magnitude of the measured surface settlements during both pumping tests was very low (≅3 mm), which would indicate that the soil was overconsolidated. Wu, Shen, Yin, et al. (2015) developed a numerical model considering the measured data during these two pumping tests. The numerical model was used to analyze the blocking effect of the retaining walls. Groundwater drawdown and surface settlements during a dewatering period of 180 days were estimated considering the two depths for the retaining walls (43 and 53 m). The results showed that the volume of pumped groundwater, the groundwater drawdown and the surface settlements that occurred outside the excavation increased dramatically when the depth of the retaining walls was reduced. Wang et al. (2016) investigated the influence of the depth of the retaining walls and dewatering wells on the impacts that occurred outside the excavation. They developed research in the context of the construction of the Shanghai rail transit lines and used a standard geometry of a railway station as a reference. The results showed how surface settlements vary considerably depending on the configuration of the dewatering system (i.e., the depth of the retaining walls and the dewatering wells). An ideal distance between the bottom of the pumping wells and the retaining walls was proposed to minimize the surface settlements in an efficient manner. Most of the existing studies are based on the modeling of real sites and the prediction of the system behavior under different circumstances. For this reason, the study presented by Shen, Wu, and Misra (2017) is especially relevant. Contrary to previous studies, Shen et al. (2017) proposed an analytical equation to compute the groundwater drawdown difference between the inside and outside of the excavation enclosure. This equation is useful during the design stage of dewatering systems because it allows easy prediction of the expected drawdown outside the excavation and, therefore, of the surface settlements. The proposed solution was validated by comparing its results with numerical and real data.

5 Adopted measures for impact mitigation

Artificial recharge outside the excavation is sometimes considered to reintroduce the pumped water into the aquifer and mitigate impacts (i.e., settlements and groundwater drawdown) induced by the dewatering tasks. The artificial recharge system usually consists of wells located outside of the excavation enclosure (Fig. 4).

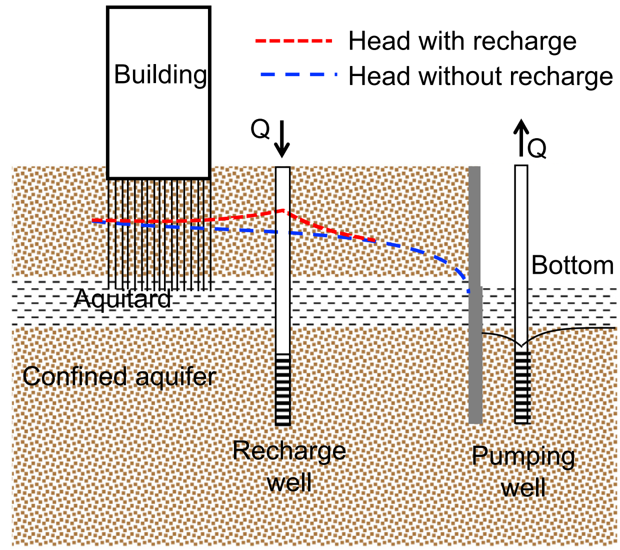

Fig. 4. Example of artificial recharge by recharge wells (modified from Zhang, Li, et al., 2017).

Some studies reporting and studying numerically the efficiency of artificial recharge systems have been published in recent years. For instance, Zhang, Li, Wang, Chen, and Zhu (2017) monitored and modeled a pumping-recharge test before the construction of the Hanzhong Road station of subway line 13 at the Jing'an District in Shanghai, China. The planned excavation was surrounded by multiple structures, including four roads, four high-rise buildings, one subway station and the Suzhou River, which has a flood control wall. The objective was to ascertain the effects of future dewatering on the buildings and on the flood control wall. The results showed that artificial recharge was useful to mitigate dewatering settlements. In fact, settlements were eliminated on the side where the recharge wells were installed since recharged water produced the vertical expansion of the aquifer. In the same way, artificial recharge also mitigated horizontal displacements induced by pumping. Later, Zhang, Wang, Chen, and Li (2017) developed a deeper study focused on artificial recharge at the same location. The authors studied the system behavior during a more realistic test and the excavation phase. In the preliminary test, whose results were analogous to those obtained in the previous study (i.e., Zhang, Li, et al., 2017), the pumping rate was increased to simulate real conditions. Measurements during the excavation phase, which agreed with the results obtained in the previous test, were also analyzed. In these two studies (Zhang, Li, et al., 2017; Zhang, Wang, et al., 2017), artificial recharge proved to be a useful method to mitigate dewatering impacts. Similarly, Zheng, Cao, Cheng, Ha, and Wang (2018) proposed a numerical study to estimate the effects of artificial recharge by deep wells prior to the construction of a subway station in Tianjin, China. In this study, some tests were performed near the excavation site before the construction of the walls. Zheng et al. (2018) undertook and modeled three types of tests: single-well tests (pumping or recharge), multiwell tests (pumping and recharge using different wells) and combined-recharge tests from two nearby wells. The single-well tests showed how the soil responded to pumping or recharge events, whereas the results of the multiwell tests probed whether artificial recharge was a useful method to control dewatering settlements. The objective of the combined-recharge tests was to ascertain whether settlements induced during redevelopment phases (to eliminate clogging) could be mitigated by recharging water at nearby wells. The results showed that redevelopment settlements can be controlled. You et al. (2018) also showed the usefulness of recharge wells to mitigate surface settlements produced by dewatering tasks. They controlled surface settlements by installing 27 recharge wells. Finally, Zeng et al. (2019) reported a case in which artificial recharge was used to minimize pumping settlements during a deep excavation near a religious building. Five recharge wells located between the excavation and the building were used to mitigate settlements during the excavation phase. Measurements showed that settlements were stabilized when the recharge wells were started. However, settlements increased during seven redevelopment periods, which were undertaken to avoid clogging effects. This observation motivated a test performed in similar materials, whose objective was to ascertain if it was possible to mitigate redevelopment settlements. The test, which was modeled, showed that redevelopment settlements can be eliminated by recharging from a nearby well during the redevelopment phases.

6 Discussion and conclusions

Numerous studies in the literature have focused on topics related to underground excavations below the water table. Most of these studies are based on real construction projects developed in Asia, especially in China, which would be related to the increase in population in this area and therefore to the need to construct new underground infrastructures. However, this fact also indicates the increasing economic conditions in Asia that allow for investments in new infrastructures.

Defects in retaining walls are relatively common and may affect the safety of construction and nearby structures. In addition to the studies that report cases of faulty retaining walls, some authors proposed methods to characterize them. However, these methods were developed by assuming homogenous media. It would be interesting to go further and adapt the existing methods to heterogeneous media.

Most of the literature focused on the deflections of retaining walls does not consider the influence of groundwater. However, the studies collected in this review show that groundwater plays an important role. In fact, important deflections can be produced only by dewatering tasks (e.g., during pre-excavation dewatering or WTAT). Future research must be devoted to clarify the real influence of groundwater.

The topic to which authors pay more attention is the impacts produced by dewatering tasks, among which dewatering settlements stand out. This fact is understandable since some authors have attributed large soil deformations to dewatering. However, recent studies have demonstrated that surface dewatering settlements could be smaller than expected. This fact may be related to processes not considered by commonly used analytical equations, such as the vertical expansion of layers or the nonproportionality between drawdown and surface settlements. This issue requires more numerical and analytical investigation.

Methods adopted by most researchers to design dewatering systems, in which the stability of the excavation bottom is guaranteed, are similar. It would be interesting to pay more attention to the influence of non-Darcy flows, as suggested by Wang et al. (2017), which might be relevant for improving the efficiency of dewatering systems.

Artificial recharge as a tool for mitigating dewatering impacts is a relatively new investigation field, which is reflected in the low number of scientific studies published to date. Consequently, more investigation is needed. Specifically, it would be interesting to propose analytical solutions to design artificial recharge systems in an easy way as a previous step to numerical modeling. In the same manner, more research is needed to better establish the system behavior during the redevelopment of recharge wells.

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Declaration of Competing Interest

No potential conflict of interest is reported by the authors.

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