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Probabilistic assessment of groundwater leakage in diaphragm wall joints for deep excavations

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ABSTRACT

A probabilistic method is proposed for conducting groundwater-related hazard assessments that are useful for the risk management of deep excavations in saturated soils in urban areas. The design of deep excavations, construction procedures and execution methods aimed at realizing underground infrastructure are characterized by major uncertainties related to soil properties, construction imperfections and hydrogeological site conditions. During the construction stages, geometrical imperfections and ineffective technologies to control wall seepage can strongly affect the level of risk to the adjacent built environment, leading to severe damages. The aim of this study is to provide an assessment of the leakage probability in reinforced concrete (RC) retaining walls. We model the main geo-structural factors that influence trench stability and the key geometric and technological parameters that affect construction imperfections as relevant random variables. Moreover, through Bayesian updating, useful recommendations are provided regarding the effectiveness and influence of the monitoring phase on reducing the failure probability.

1. Introduction

Empty spaces in urban areas are extremely rare nowadays, and the growth of urban activities is increasingly leading to the use of underground spaces for urban services, transportation infrastructure, parking and other types of engineering works. These require the design of deep excavations (Abd El-Razek, 1999; Lee et al., 1999; Li et al., 2014) near existing buildings in densely populated districts or areas characterized by the presence of historical buildings and cultural heritage sites. Excavations generally induce significant changes in the stress and strain fields of the soil around them and, therefore, the displacements to adjacent structures and infrastructure (Leung and Ng, 2007; Long, 2001; Moormann, 2004; Pakbaz et al., 2013). In this context, in order to reduce risks induced by underground works, it is fundamental to characterize the geo-mechanical properties of the underlying soil or rock layers at increasing depths by means of appropriate tests (i.e., in situ and in laboratory) (Hansen et al., 2015; Clerici, 1992; Sciotti, 1990; Zhou et al., 2014) as well as to assess the leakage risks related to the physical and geochemical processes which occur in geological systems such as in shallow aquifers (Dai et al., 2014; Little and Jackson, 2010). In terms of the displacement-induced damages caused to existing structures located around the excavation area or tunnels, the estimation of these effects is characterized by statistical uncertainty. In literature, many different approaches to estimate excavation-induced vertical and horizontal displacements have been proposed, classified in two classes: empirical methods (Clough and O'Rourke, 1990; Kung et al., 2007; Peck, 1969) and numerical methods (Finno and Calvello, 2005; Hashash et al., 2006; Pane and Tamagnini, 1997; Poulos and Chen, 1997). This uncertainty has led more and more to the use of reliability-based design methodologies in recent times. In fact, a number of new methodologies have been proposed to estimate this kind of structural damage. These methodologies use theoretical or empirical data on settlements, and introduce new potential damage criteria using a probabilistic approach (Camós et al., 2016; Castaldo et al., 2013, 2014; Hsiao et al., 2007, 2008; Schuster et al., 2008, 2010; Song et al., 2016; Palazzo et al., 2011). Other works (Castaldo and De Iuliis, 2014; Mo and Hwang, 1996) have analyzed the increase in the seismic vulnerability of existing buildings due to deep excavation-induced effects. Therefore, in an urban area, the risk to existing buildings is strongly linked to the risk to the underground infrastructure during both the construction stages and the service life.

It is only in the last few years that a probabilistic risk assessment (PRA) framework aimed at quantifying risks to the safety of underground constructions caused by groundwater has been proposed by

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Tartakovsky (2007), Bolster et al. (2009), De Barros et al. (2011) and Jurado et al. (2012). Very few research efforts are focused on the risk to underground infrastructure during the construction stages. In fact, the construction of diaphragm walls, even when based on advances in "slurry wall" techniques, is always accompanied by a lot of uncertainty with regard to, for example, estimating the deformation of the trench sides in order to design and determine the density and other specifications of the bentonite to be employed. During the process of excavation below the water table, many complications can arise. These may lead to leakages or discontinuities in concreting (Anagnostou and Kovari, 1994; Abdelhadi et al., 1996; Filz et al., 2004; Hannink and Thumann, 2013; Lee et al., 1999), causing very severe damages (e.g., piping phenomena with an inrush of groundwater and ground material and water incoming into the underground station). In fact, during recent deep excavations of underground structures built below the water table, many soil-related failures have occurred, such as: the Naples subway (Italy, 2013), in Cologne (Germany, 2009) (Haack, 2009; Rowson, 2009), in Barcelona (Spain, 2008) (Pujades et al., 2011), in Taipei (Taiwan, 2003) (Chien-chung et al., 2011), the Seoul (South Korea) subway tunnel (Shin et al., 2006), and in Shanghai (China) (Ishihara and Lee, 2008).

On March 4, 2013 at approximately 10:00 am, a portion of the building at Naples Riviera di Chiaia 72, located in the immediate vicinity of the Arco Mirelli Metro Line 6 Station, which was being excavated, collapsed. Judicial investigations (Augenti and Grazioso, 2013) have shown that when the excavator removed the clod of earth adjacent to two diaphragms, a flaw was discovered at the joint between them, through which came copious amounts of water and land that were hard to lock; Figs. 1(a) and (b). The sudden escape of water from the flaw, which corresponded to a more than 15m lowering of the piezometric and the imposition of land transport within the station site, resulted in a loss of support for the building foundations and a significant reduction in the degree of subsoil density in a large area along the Riviera di Chiaia, where many buildings suffered major relative displacements; Figs. 1(c) and (e). Expert judicial reports (Augenti and Grazioso, 2013) revealed that the opening of that flaw *"was caused by an imperfect implementation of the joint between two concrete panels of the retaining wall… also due to an insufficient overlap in secant diaphragms procedures"*. Like a hole in a ship's hull, this was a serious danger to the adjacent built environment. More particularly, and with reference to the design phase, the experts also clearly highlighted that *"… neither … the planning stage nor …the executive had …expected the described eventuality"*, *"… it is quite clear at this point the fact that the recordings made by instruments on board the hydromill, about the verticality of the excavations, did not correspond to the actual position of the diaphragm, so there is no doubt about the fact that the equipment was faulty"*.

A risk assessment of the event associated with problems of waterproofing involved in such site conditions would have led to fundamentally changed design, execution and monitoring decisions. Failure cases show that, in the urban context, it is very important to adopt a general risk management methodology in order to meet appropriate safety standards and to control monitoring for the piping hazards arising from the retaining walls, not only during a structure's life-time, but also during the construction phase.

In this context, it is also important to meet safety standards in terms of the instability of the retaining walls, again not only during their lifetime, but also during the construction stage.

This study carries out an assessment of the leakage probability of underground infrastructure systems, with the aim being to evaluate the probability of a leak in a generic joint between two adjacent diaphragms along a reinforced concrete (RC) retaining wall. A probabilistic approach is then proposed to assess the failure probability of slurry-supported trench walls. The main geo-structural factors, which influence stability (i.e., the mechanical parameters of both the bentonite slurry mix and the soil), and the key geometric and technology parameters, which affect the construction imperfections during the construction process (i.e., height of the slurry level, verticality of the trench walls), are modelled as relevant random variables characterized by appropriate probability density functions (PDFs). The evaluation of the leakage probability is based on the combination of two independent events: "Event 1" – related to the construction process; and "Event 2" – regarding the trench wall stability. Monte Carlo simulations are used to assess the leakage probability in a joint between two adjacent diaphragms along a RC retaining wall at different depths, ranging from free field (0m) to the maximum excavation depth H (herein equal to 50m) in saturated sandy soil. In particular, an extensive parametric study is carried out for different values of the main geometric and construction parameters, such as the overlapping length between two adjacent diaphragms, the number of diaphragms along the retaining wall and the definition of the threshold area beyond which a leakage may occur.

Finally, through Bayesian updating, useful recommendations are made regarding the effectiveness and influence of the monitoring phase on the reduction of failure probabilities. The results related to the monitoring stage are also discussed by considering different values of the number of joints monitored at different depths and the uncertainty characterizing the precision of the monitoring process (i.e., false alarm probabilities).

Accordingly, the proposed risk assessment procedure allows us to evaluate the leakage probability in a generic joint between two adjacent diaphragms along a RC retaining wall at different excavation depths, taking into account both the construction and the monitoring phases.

2. Diaphragm wall construction-stage description

Diaphragm wall construction, as described by Abdelhadi et al. (1996), is mainly based on the use of bentonite slurry, and its success is strongly related to the development of excavation machines and bentonite processing plants. This is because building these walls is always accompanied with difficulties and problems that are mainly due to estimating the deformation of the trench sides in order to be able to design and determine the density and other specifications of the bentonite to be employed. Prior to starting the excavation, a central bentonite slurry plant must be prepared for mixing and providing bentonite to the trench or panels under excavation through a net of steel pipes. This pipe system is spread along the areas of work to facilitate the provision of fresh bentonite and the removal of used bentonite for recycling by separating the rock fragments and soil fractions mixed with the bentonite during the excavation process.

The excavation of soil layers, especially hard strata, is usually performed with a cutter (milling machine) in several stages. Several design and construction precautions have to be considered at this point, such as defining a cutting rate of the trench that is sufficient for the bentonite to form what is called a "filter cake" membrane on the wall sides/bentonite surface, as also discussed in Anagnostou and Kovari (1994), and Filz et al. (2004). It is also recommended by Abdelhadi et al. (1996), Anagnostou and Kovari (1994), Filz et al. (2004), and Hannink and Thumann (2013) that bentonite density just before concreting should not exceed a particular limit value. Moreover, its viscosity must be low enough to ensure both the cleansing of steel bars during concreting and the flow of the bentonite.

As a first step in the excavation procedure of any diaphragm wall, guide walls must be constructed to prevent the collapse of soil from the top of the wall and to facilitate the implementation of the pipes that will provide the trench with bentonite during the excavation process. In fact, as described by Bruce et al. (1989), the milling machine, equipped with contra-rotating milling wheels, is lowered progressively into the trench and excavates and crushes the soil or rock. This debris is simultaneously mixed with the bentonite slurry and is brought to the surface by a large reverse circulation mud pump located above the cutting wheels. Clean and fresh bentonite slurry is fed back into the top of the trench to maintain the slurry level and ensure trench stability.