Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society

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Challenges in assessing the hydrogeological impact of underground structures in urban renewal projects

Défis liés à l'évaluation de l'impact hydrogéologique des structures souterraines dans les projets de rénovation urbaine

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ABSTRACT: Lisbon's urban renewal projects have led to an increase in the construction of underground structures such as basements and tunnels. As riverfront areas are prone to flooding, since 2010 the City Council has made it mandatory to carry out hydrogeological impact studies for urban developments involving underground works in alluvial areas. The Laboratório Nacional de Engenharia Civil (LNEC) has been carrying out these studies for twelve years, facing increasing model complexity due to the spread of underground structures. This paper provides some guidelines for conducting hydrogeological impact studies, highlighting the difficulties and challenges met in developing these studies and the strategies used to overcome them.

RÉSUMÉ: Les projets de rénovation urbaine de Lisbonne ont entraîné une augmentation de la construction de structures souterraines telles que les sous-sols et les tunnels. Les zones riveraines étant sujettes aux inondations, le conseil municipal a rendu obligatoire, depuis 2010, la réalisation d'études d'impact hydrogéologique pour les aménagements urbains impliquant des travaux souterrains dans les zones alluviales. Le Laboratório Nacional de Engenharia Civil (LNEC) réalise ces études depuis douze ans et doit faire face à une complexité croissante des modèles en raison de l'extension des structures souterraines. Ce document fournit quelques lignes directrices pour la réalisation d'études d'impact hydrogéologique, en soulignant les difficultés et les défis rencontrés lors de l'élaboration de ces études, ainsi que les stratégies utilisées pour les surmonter.

Keywords: Hydrogeological impact; urban area; underground constructions; groundwater; numerical modelling.

1 INTRODUCTION

Urban renewal projects in the city of Lisbon (Portugal) have led to an increase in the construction of impervious underground structures such as basements and tunnels. These structures affect groundwater, mostly in terms of water level, water quality, flow direction and flow rate, due to the barrier effect caused by their presence.

Coastal urban areas as Lisbon are prone to flooding. Consequently, since at least 2010, Lisbon City Council has required specific studies for projects involving underground works in alluvial zones. These studies include the characterisation of hydrogeological conditions and the assessment of hydrogeological impacts, with the aim of predicting whether the design works will increase the risk of flooding.

An impermeable underground structure that crosses the direction of flow can raise water levels upstream and lower them downstream, increasing the risk of flooding around the structure (Ricci *et al.*, 2007).

LNEC has been carrying out hydrogeological impact studies in the Lisbon riverfront area for the last twelve years. Experience has shown that the development of this type of study is becoming increasingly complex, given the number of underground structures already built, under construction and planned.

Accordingly, based on LNEC's practice, some guidelines are given for carrying out hydrogeological impact studies, highlighting the difficulties and challenges identified during the development of these studies and the strategies to overcome them.

2 HYDROGEOLOGICAL IMPACT ASSESSMENT

In order to assess the hydrogeological impact of an underground structure, it is often necessary to simulate groundwater conditions by means of numerical modelling (Bonomi and Bellini, 2003; Ricci et al., 2007; Yang et al., 2009; Paris et al., 2010; Pujades et al., 2012).

Since 2012, LNEC has carried out around twenty hydrogeological impact studies related to the construction of buildings (with one to seven underground levels) in the Lisbon riverfront area, mainly located in the lower part of the Alcântara valley.

The studies were performed using Aquaveo's Groundwater Modelling System (GMS), which includes the computer code for solving the groundwater flow equation (Modflow) developed by McDonald and Harbaugh (1988).

The methodology defined and applied by LNEC in these studies over the last twelve years comprises the following steps:

a) 3D simulation of the reference phase, representative of the situation before the construction of the underground structure, duly calibrated with the results of a hydrogeological monitoring campaign;
b) 3D simulation of the final construction phase, representative of the situation after construction of the underground structure (predictive model number 1);
c) Impact assessment based on a comparison of the results of the two previous simulations;
d) Evaluation of potential remedial measures to minimise the hydrogeological impact (predictive model number 2 also in 3D);
e) Validation of the prediction model(s) based on the results of the hydrogeological monitoring to be carried out after the construction of the underground structure.

Figure 1 shows an example of a hydrogeological impact assessment for the construction of a four-level basement near a hospital, with a gravity drainage and pumping systems installed at the bottom of the building. In this case, although the water level upstream of the underground structure was expected to rise by up to 1m, the impact was considered small as the water levels were expected to remain negative.

3 DIFFICULTIES AND CHALLENGES IDENTIFIED

During the development of the hydrogeological impact studies, several difficulties and challenges had to be overcome in order to obtain reliable results. The following sections introduce and describe them.

3.1 Data type

The geological/lithological model is the basis for the assembly of the hydrogeological model. Firstly, the geological solid model is developed based on borehole data, and then the numerical model is created and fitted to the previous model, as shown in Figure 2.

In order to develop a hydrogeological model that accurately represents the conditions at the future construction site, it is therefore essential to have a set of information on the characteristics of the ground and the aquifers that will be intersected by the structures.

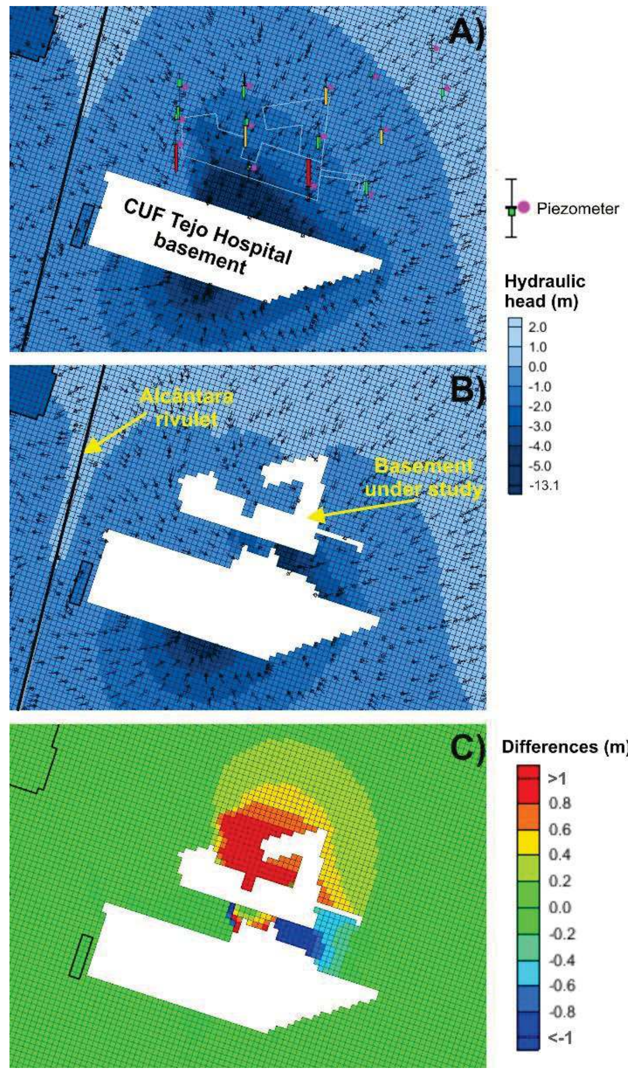

Figure 1. Example of hydrogeological impact assessment. A) Simulation of the reference phase (calibrated); B) Simulation of the final construction phase of the structure under study; C) Impact assessment.

As the design of underground works in alluvial areas generally involves the construction of diaphragm walls down to the bedrock, regardless of the number of basement levels to be constructed, both the alluvial deposits and the bedrock formations should be characterised

Therefore, prior to modelling, a site investigation and monitoring programme must be designed and carried out to provide the following data:

- Geological characteristics of the alluvial deposits (composition, thickness and spatial distribution) and the bedrock formations (nature, structure and stratigraphic sequence) based on borehole data and sampling. Boreholes should preferably be located outside and on all sides of the building area. The lithological information is also of paramount importance in the analysis of the solution obtained in the numerical groundwater flow model during the calibration process. It can often justify hydraulic potentials that may appear erroneous at first sight.
- Hydraulic conductivity of alluvial deposits and rock formations determined by water permeability tests in boreholes and/or pumping tests. It should be emphasised that in these studies the use of high-water pressures on the bedrock chambers does not add any value to the determination of hydraulic conductivity, since the works to be carried out do not impose any additional hydraulic loads;
- Water pressure distribution and flow direction in the aquifers crossed by the works, through monitoring campaigns carried out in at least three non-collinear piezometers installed in each aquifer;
- Evaluation of the influence of tides (in coastal areas) based on the interpretation of a continuous monitoring campaign of the water levels during at least one tidal cycle (one high and one low tide) under spring tide conditions. The behaviour of the records (water level variation curves) can also be used as a check on the consistency of the permeability test results.

By analysing the water levels measured in piezometers with more than one water pressure chamber installed in different formations, it is possible to understand whether there are water levels under pressure, *i.e.* confined aquifers. It is also possible to determine if water levels are affected by anthropogenic activities such as water extractions (permanent or temporary).

3.2 Reliable data

Site investigation programmes designed by non-geotechnical professionals usually fail to provide reliable hydrogeological data because piezometers are installed with a single water pressure chamber across multiple and different aquifer formations. This makes it impossible to determine the water levels and flow direction in each aquifer affected by the works. To avoid this situation, it is important to check the specifications already drawn up and propose the appropriate number of water pressure chambers depending on the number of aquifer formations to be intersected by the structures. If there is more than one aquifer formation, the water pressure chambers should be properly isolated so that they are independent.

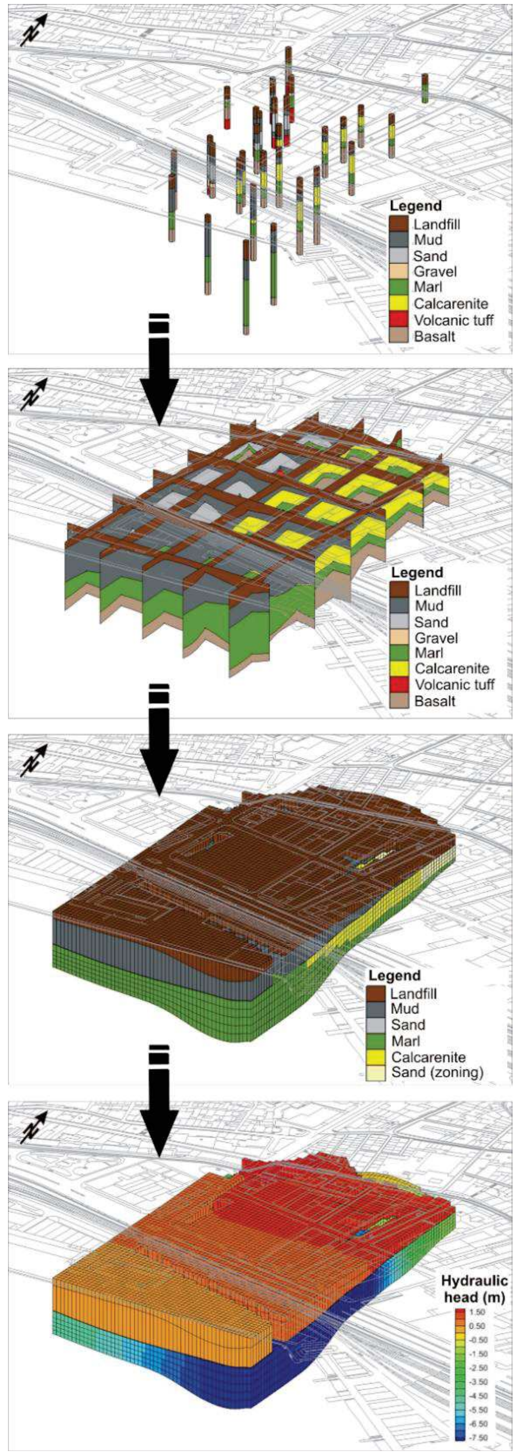

Figure 2. General stages in the creation of groundwater flow models.

Figure 3 shows the distribution of the borehole locations selected for the installation of piezometers where the construction of buildings with basements was planned. After analysis of the existing information in the study area, it was determined that the data from previous site investigations works did not provided all the data needed to perform the study. Therefore, given the constraints identified in the study area, namely the density of buildings and the occurrence of infrastructures, a set of 7 borehole locations, shown in Figure 3, were defined for the installation of piezometers. Piezometers with double and triple water pressure chambers have been defined, depending on the number of aquifer formations that will be crossed by the building structure at each site.

During the drilling works, it is also necessary to check whether products that may affect the permeability of materials (such as bentonite) are used mainly in alluvial sands. The use of this type of product compromises the data obtained and prevents water permeability tests as well as the installation of piezometers.

As groundwater flows preferentially through permeable zones, it is important to determine the permeability of these layers associated with specific lithologies, such as sands and fractured rocks. These lithologies should therefore be selected for testing during or after drilling.

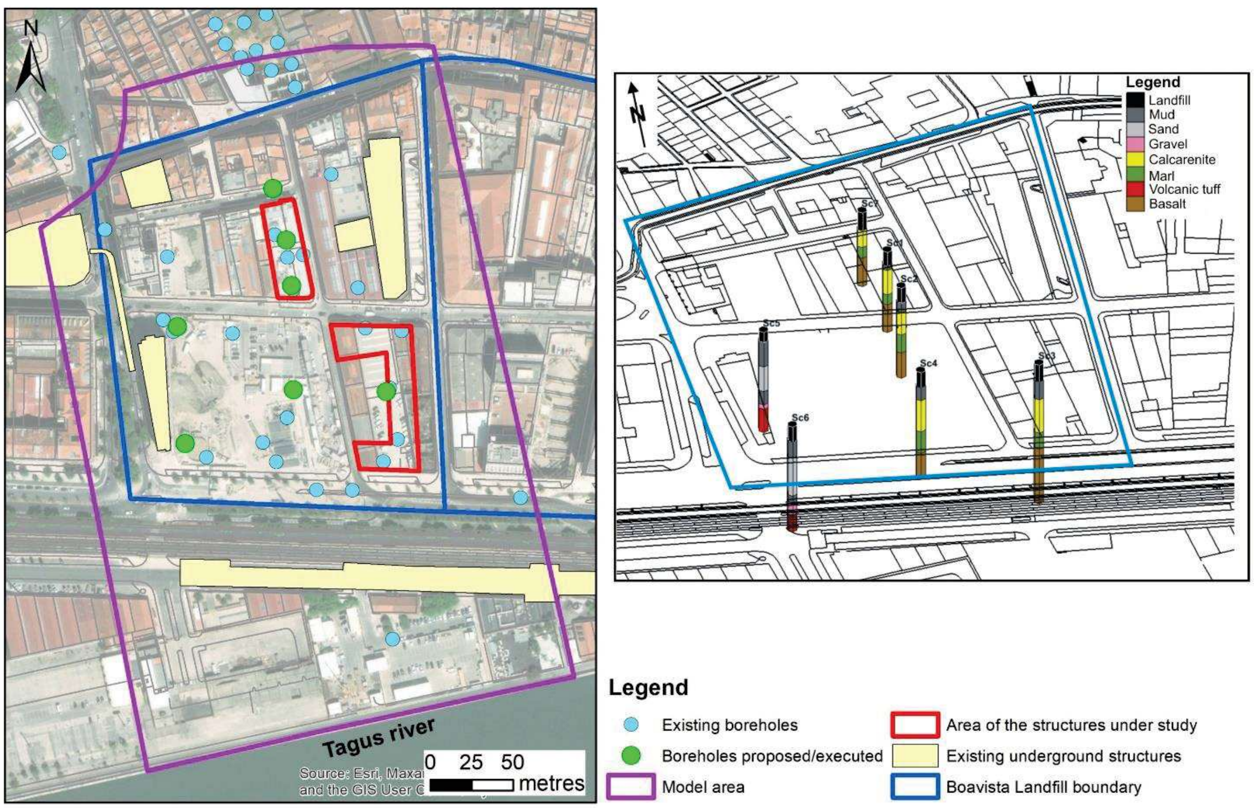

Figure 3. Distribution of the sites selected for the installation of piezometers in the Boavista landfill (Lisbon).

3.3 Model scale (dimensions)

However, such a study requires information on a very large area in order for the model to be representative of existing conditions and to take into account physical hydraulic boundaries and existing underground structures.

Hydrogeological impact studies are usually requested/contracted to consider only the construction area. However, such a study requires information on a wider area in order for the model to be representative of current conditions and to take into account physical geological and hydraulic boundaries and existing underground structures. Therefore, the geological and hydrogeological data should cover as much of the model area as possible.

3.4 Model complexity and calibration

The main challenge of the hydrogeological impact studies was undoubtedly the creation of highly complex numerical models and the respective calibration. The dimensions of the model to represent the physical geological and hydraulic boundaries the characteristics of the underground structures, as well as the interventions in the ground during the studies, all contributed in different ways to the complexity of the model.

The studies carried out in Lisbon's riverfront area focus on two important sites: the Alcântara valley and the Boavista landfill. Both areas are under constant development, with numerous building and tunnel projects in planning and construction phase.

An example of a model created for the Alcântara valley is shown in Figure 4. It is a very complex and extended model, covering an area of 1.3 km^2. This model includes several buildings with one to four basement levels, some of which have drainage and pumping systems installed at the bottom.

In areas affected by tides, the model should be run in a transient state, which increases the complexity of the modelling, especially during the calibration process.

In addition, in some cases water level behaviour can only be explained by water withdrawals whose location and characteristics are unknown.

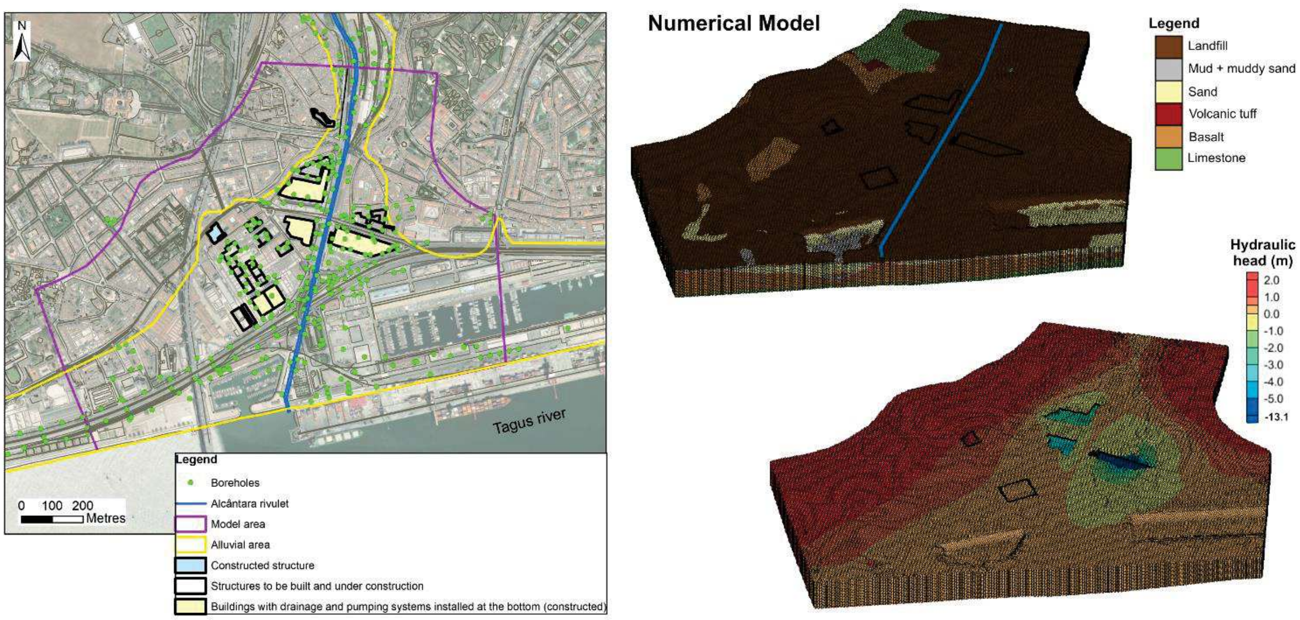

Figure 4. Dimensions, underground structures and characteristics of a numerical model developed for the Alcântara valley (Lisbon)

3.5 Study submission phase

According to the Lisbon City Council's administrative regulations, hydrogeological impact studies must be submitted at the earliest stage of the process, i.e. when the architectural project is being analysed.

This poses a problem because for the impact analysis it is necessary to include the geotechnical solutions in the model, namely the elevation of the bottom of the excavation and the base of the retaining walls, for which there is usually no concept or design at this stage.

As it is not possible to conduct the study without this information, part of the geotechnical concept and design must be developed before the architectural project is approved or alternatively, the worst-case scenario can be analysed, i.e. retaining walls that extend down to the bedrock. However, the best solution would be to require the study to be submitted with the geotechnical design.

3.6 Model validation

Numerical modelling is a representation of reality. It is then important to validate the results of the hydrogeological impact prediction models with field observations collected in piezometers during and after the construction of an underground structure. With this in mind, the data for the model must come from an area larger than the construction site, and the water levels must be monitored during the various phases of the work by means of piezometers installed outside the perimeter of the retaining walls.

3.7 Model reuse

Each study requires the creation of a groundwater flow model in sufficient detail to take into account the geological information of the site and the existing underground structures.

Since the studies and works are not carried out simultaneously and each new study provides data to update the knowledge of the geological and hydrogeological conditions, a new model must always be developed.

4 CONCLUSIONS

This paper provides a comprehensive overview of hydrogeological impact studies in the context of urban redevelopment projects involving the construction of underground structures. These studies aim to support sustainable urban development by mitigating flood risks.

It also outlines a methodology for the studies, which involves numerical modelling to simulate groundwater conditions before and after construction. These simulations are used to assess the impact of the construction of underground structures on groundwater flow and to evaluate potential mitigation measures.

Based on LNEC's experience, several difficulties and challenges have been identified in the development of hydrogeological impact studies over the past twelve years, including obtaining reliable data, modelling at an appropriate scale, managing model complexity and validating model results.

Accurate groundwater modelling depends on comprehensive data on geological and hydrogeological characteristics obtained through site investigation and monitoring programmes. However, the main challenge is the development and calibration of complex numerical models that have to represent both the geological conditions and the underground structures. Finally, it should be emphasised that validation of the models with water levels measured in piezometers is a crucial task to ensure the accuracy of the predictions.

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