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Three-dimensional numerical back-analysis of a monitored deep excavation retained by strutted diaphragm walls

Mohamed Nabil Houhou[a,*], Fabrice Emeriault[b], Abderahim Belounar[a]

[a] Department of Civil Engineering, Mohamed Khider University, LMN2I2S Lab, Biskra 07000, Algeria
[b] Grenoble-INP, UJF-Grenoble 1, CNRS UMR 5521, 3SR Lab, Grenoble F-38041, France

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ABSTRACT

The urban development often requires the use of the underground space and the number of deep excavation pits in city centers is increasing every year. To minimize the effects of excavations on adjacent structures, it is becoming increasingly important to estimate not only the lateral displacement of retaining walls but also the movement of the retained soil. Empirical methods have been developed on the basis of experimental data as to define the displacements field induced by excavation in greenfield hypothesis. However, numerical analyses can be used when more complex situations have to be analyzed. A case study of interaction between a monitored deep excavation and existing buildings is presented in this paper. The Saint-Agne subway station of Toulouse (France) new line B has been realized with a diaphragm wall supported by up to three levels of steel struts and has been built in an overconsolidated molassic geological context. The set of measurements obtained with different monitoring devices have been compared with the 3D numerical analysis using a finite difference code in which the dewatering is taken into account through an uncoupled flow-mechanical calculation. A good agreement is observed between the numerical results and the monitoring data. The model also gives an insight on the 3D behaviour of the excavation and its impact on nearby structures. Short remarks regarding the prediction of the excavation behavior by means of 2D compared to 3D numerical analysis results are briefly issued.

1. Introduction

In recent years, an increasing number of excavation works have come close to adjacent structures. Controlling ground surface deformations (both horizontal and vertical) around the excavation zone is an essential task in the design of a deep excavation. The range of these deformations is related to a complex phenomenon which depends primarily on the geological conditions, structural characteristics, construction sequences and the excavation geometry. In urban areas, excessive ground settlements frequently damage the surrounding structures (Wang et al., 2010, Ou et al., 2000).

The estimation of the ground surface displacements induced by deep excavation has been the topic of continuous research effort. One can refer to the work of Briaud et al. (2000), Clough and O'Rourke (1990), Long (2001), Moormann (2004), Ou et al. (1993), or Peck (1969). The analysis is generally based on a large number of case histories which give the relationship between the above- mentioned factors and wall deformation or ground surface settlement in greenfield conditions. This is clearly an overestimation of damage because the structure stiffness modifies the behavior of ground movements (Hong et al., 2015, Capraru and Adam, 2014, Caudron, 2007, Son and Cording, 2005). However in congested sites, soil-structure interaction phenomena occurring between the retaining wall and the existing buildings have not received much attention.

Despite the numerous developments of specific numerical codes and their encouraging results, discrepancies are still observed during comparison of numerical simulation of such structures with monitored sites (Ghareh and Saidi, 2011, Schweiger, 2008, Shao and Macari, 2008). On the other side, very limited field data are found for the response of adjacent buildings.

In this context, this research focuses on the 3D numerical modeling of an irregularly-shaped monitored deep excavation consisting of a diaphragm wall supported by several rows of steel struts. The Saint-Agne station is located on the Toulouse (France) subway line B and has been built in an overconsolidated molassic geological context with in particular a high value of K_0. The limitation of the impact of the excavation on existing buildings is a key issue because in most cases the stations are close to old buildings.

The partners of the research project METROTOUL have been given the opportunity to install on this station a complete set of measuring

* Corresponding author at: Department of Civil Engineering, Mohamed Khider University, BP 145 RP, Biskra 07000, Algeria.
E-mail address: nabil.houhou@univ-biskra.dz (M.N. Houhou).

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devices. Two particular sections have been studied in further details to improve the understanding of ground response and the soil-structure interaction phenomena induced by deep excavation close to existing buildings and to collect precise data for validating numerical models. The basement was completed using semi top-down construction. The whole construction activities include staged dewatering, excavation and strutting.

The aim of the present paper is to performed a full numerical back-analysis of the behaviour of the excavation in terms of lateral displacements of diaphragm walls, ground surface movements, and internal forces in struts, as well as the impact on the existing buildings and to shed some light on the 3D nature of the movements induced by the excavation.

The FLAC^{3D} software (Itasca, 2012) is used to model the various phases of the work. All the parameters come either from standard laboratory tests or from previous back-analysis in similar location and on similar underground works. The only "adjusted" parameter concerns the effective stiffness of the steel struts that is back-calculated from measured strut loads and associated wall deformation (that implicitly account for the installation conditions). The results of this 3D model are validated by comparing them to the in-situ measurements. The pertinence of the 3D model is also judged by comparison with the 2D plane strain model, implemented in the FLAC^{2D} code.

2. Case study of a deep excavation

2.1. General description of the project

The Saint-Agne station is located on the new line B of Toulouse subway. This station is a 55.2 m × 17.15 m rectangular deep excavation (Fig. 1). The retaining structure consists of a cast in situ diaphragm wall with a thickness of 1.0 m. The depth of the diaphragm wall was set to about 20.65 m as presented in Fig. 2. During the excavation to a depth of 17.2 m, the retaining walls were supported at the top by partial slabs and diagonal beams and in depth by means of three levels of temporary steel struts 0.61 or 0.66 m in diameter and 10 or 12.5 mm thick as depicted in Figs. 2 and 3. A typical plan view of the wall strutting is shown in Fig. 4. This station is surrounded on the south side by residential houses R + 1, and on the North side by a building R + 0 (noted building A) which will be of particular interest afterwards and of a building R + 2 (noted building B) as presented in Fig. 1.

2.2. Construction sequences

The method of strutted diaphragm walls is one of the most commonly used methods of deep excavation support. Preexcavation of about 1.9 m depth was required for the implementation at the top of the wall of partial slabs and diagonal beams (West side).

The whole construction activities included staged dewatering, excavation and strutting. At each stage, dewatering is first performed to lower the ground water table down to 1 m below the bottom of the subsequent stage of excavation, then the soil is removed and followed by the installation of all the struts at 0.4–0.5 m above the bottom of the excavation. Step by step, the subsequent staged dewatering, excavation and strutting phases can follow each other until the final bottom of excavation is reached. Table 1 summarizes the different excavation phases and schedule.

2.3. Geological and geotechnical context

The regional geological substratum is constituted by molassic formations dating from the Tertiary. These grounds have been overtopped by a minimum of 200 m of Stampien and Miocene which have been eroded before the deposition of the quaternary alluviums. In fact, the Toulouse molasses exhibit a very high overconsolidated behavior with in particular a high value of the at rest earth pressure coefficient K_0.

For the preliminary geological survey, several boreholes were drilled within the station area. It can be noted that the site shows a very heterogeneous lithological structure. The molasse is either clayey or sandy, the layers alternate in depth. Over the whole height of the excavation, there are mainly compact clayey sandy molasses with some thin interbedded sandy layers. The molasse is overlain by 1.2 m of fill and alluvial sandy silt and the water table is approximately 2 m below the ground level. A preliminary hydrogeological study has highlighted the risk of raising the water table due to its partial cut by the diaphragm walls. As a result, the retaining wall was designed with a reduced embedded length.

In order to determine deformation moduli in the range of the stresses which reign in the soil mass, high pressure CD triaxial tests (300 kPa to 3 MPa) were carried out on different soil samples (Serratrice 2005). A clear dependence of the moduli with the confining stress is observed. Given all the tests carried out and the dispersion of Young's modulus values, a linear increase of this module with depth z is proposed (it does not take into account the lithologic distinction between clayey molasses and sandy molasses but considers the molassic substratum as homogeneous in terms of deformability):

$$E(MPa) = E_0 + \beta.\ z = 66 + 9,9.\ z(m) \quad (1)$$

This linear variation is also based on the numerical back-analysis of the excavation of a 8.0 m in diameter tunnel in the vicinity of the project (Houhou et al., 2016) and of the Jeanne d'Arc deep excavation, a similar work whose characteristics are substantially equivalent and realized in the same geological context (Houhou et al., 2010).

High pressure K_0 oedometer tests (Serratrice, 2005) revealed that the molasses are overconsolidated and have a transition to a normally consolidated behaviour for stresses of about 2 MPa. Preconsolidation stress is therefore estimated close to 2 MPa (in agreement with the geological analysis mentioned above). These tests have also shown that the overconsolidated molasses is subject in-situ to very high horizontal initial stress (K_0 is estimated equal to 1.6). The main geotechnical characteristics of molasses deduced from laboratory tests are presented in Table 2.

2.4. Description of the monitoring sections

Two fully equipped monitoring sections have been installed on the Saint-Agne excavation site (Fig. 1): Section 2 corresponds to Greenfield conditions whereas Section 1 includes a 9 m × 27 m old brick building perpendicular to the excavation with a minimum distance to the diaphragm wall equal to 2 m. Each section includes one inclinometer in the diaphragm wall, 4 vibrating wire strain gauges (Type SC-5 E Telemac) installed at mid-span on each of the three strut levels with automatic data acquisition and precise levelling. Horizontal extension of the brick building is measured on several intervals with Distomatic invar thread as well as crack opening with Demec strain gauges.

The data collected during all the construction phases (excavation, strut installation, slab concreting and strut removing) are further presented and analysed. The comparison of the results obtained for Sections 1 and 2 gives an insight on the soil-structure interaction phenomena induced by deep excavation close to existing buildings.

2.5. Analysis of monitoring results

2.5.1. Deflection of the diaphragm wall

The diaphragm wall deflections are measured by the two inclinometers I_1 and I_2. Measurements are performed in both transverse and longitudinal directions. Thus, the movements of the diaphragm wall may be obtained in both directions at each phase of work. The movements in the transverse direction (perpendicular to the long side) are greater than in the longitudinal direction. The measurements show that the deformed inclinometer tubes 1 and 2 resulting in the longitudinal direction, remain within the range of measurement accuracy