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A parametric study of the impact of deep excavation on existing buildings

Une étude paramétrique de l'impact d‘une excavation profonde sur des bâtiments existants

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ABSTRACT: Due to a growing urban density in big cities, nowadays, investors more often decide to buy plots, that they were not interested in before. These are the areas located in close proximity to the structures susceptible to settlements. The structure analysed in the paper is located in the city centre and is bounded on three sides by the existing historic tenement houses and on the fourth side by a subway line that runs in close proximity. In the paper an analysis of the diaphragm walls displacement and the subsidence of the nearby structures by means of FEM is presented, made both prior to the structure construction, during the design stage and also after construction, by using back analysis, taking into account the measurement results from the deformation survey of the structures near the excavation and inclinometer measurements of horizontal displacement of diaphragm walls. The FEM analysis that has been made allowed for verifying the need to and the scope of using ground reinforcement by using the jet-grouting method under the foundations of the historic tenement houses. The summary and discussion of the details on the theoretical and measured impact of the structure construction on the historic tenement houses is presented. The calibration of 2D model will allow for a later analysis of a 3D model and further inference.

RÉSUMÉ: La structure analysée dans ce papier est située dans le centre-ville et elle est délimitée sur trois côtés par des immeubles historiques, et sur le quatrième par une ligne de métro qui se trouve à proximité. Dans l’étude, une analyse du déplacement des parois moulées et du tassement des structures voisines par la méthode des éléments finis est présentée, pour les phases avant la construction de la structure, au stade de la conception et après la construction, en utilisant des retro-analyses, prennant en compte les résultats de déformation des structures proches de l'excavation et les mesures inclinométriques du déplacement horizontal des parois moulées. L'analyse par éléments finis a permis de vérifier la nécessité et la portée de l'utilisation du renforcement du sol par la méthode de jet-grouting sous les fondations des immeubles historiques. Un résumé et une discussion des détails concernant l'impact théorique et avéré de la construction de la structure sur les immeubles historiques sont présentés. La calibration du modèle 2D permettra une analyse ultérieure d'un modèle 3D et l‘établissement de conclusions complémentaires.

Keywords: deep excavation; displacements; influence zone; numerical analysis; FEM

1 INTRODUCTION

A growing urban density in big cities, forces investors to buy plots, that they were not interested in before. To a large extent, these are the areas with weak ground conditions (due to the presence of organic soils), the contaminated ones requiring soil replacement or remediation, or the areas located in close proximity to the structures susceptible to settlements. The limited space in cities causes also the increase of the usage of the underground space. More and more deep excavations are being designed to accommodate required parking and technical spaces. In such conditions, in dense urban area, the excavation design must also include a verification of the influence of the excavation on surrounding structures (Amorosi et al. 2014, Górska et al. 2013, Kadlicek et. al. 2016, Łukasik et al. 2014, Mitew-Czajewska 2015, Mitew-Czajewska 2018, Mitew-Czajewska 2019, Phien-wej et. al. 2012, Romani et. al. 2012, Superczyńska et al. 2016, Totsev 2012) as well as geotechnical risk analysis (Bogusz & Godlewski 2018 a, b), (Kolic 2018). This is made usually basing on finite element analysis, using profound numerical and geotechnical knowledge including e.g. the choice of proper material constitutive models.

The deep excavation analysed in the paper is located in the downtown area of Warsaw and is sourrounded on three sides by the existing historic tenement houses. On the fourth side, there is an existing metro line at a short distance from the excavation wall.

In the paper an analysis of the diaphragm walls displacement and the subsidence of the nearby structures by means of FEM is presented, made both prior to the structure construction, during the design stage and also after construction, comparing the measurement results from the deformation survey of the structures near the excavation and inclinometer measurements of horizontal displacement of diaphragm walls. The FEM analysis that has been made prior to construction allowed designing the jet-grouting reinforcement of the ground under the foundations of the historic tenement houses.

In the conlusions part the disscussion of the results of two stage numerical analysis is presented. The results of second stage analysis in form of vertical displacements of tenement houses are compared to the in-situ displacements measurements and summarized. Finally, conclusions on the selection of technologies were presented.

2 CASE DESCRIPTION

The 10.9 m deep excavation, with 3 underground storeys was located in a small yard between old tenement houses and a metro station on the forth side as presented in Figure 1.

The minimum distance between the excavation wall and the building was 0.47 m. The minimum distance to the metro station was approx. 2.5 m. The stability of the 0.6 m thick diaphragm walls was provided, in general, in temporary state, by two underground slabs (-1 and -2) with round opening in the middle.

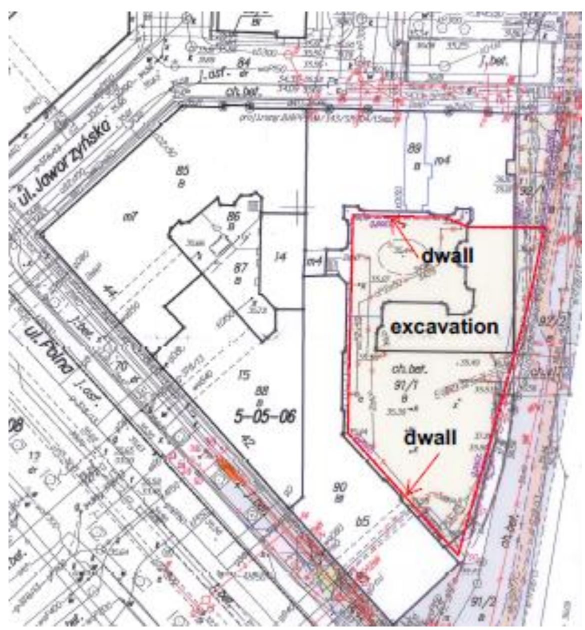

Figure 1. The location of the excavation

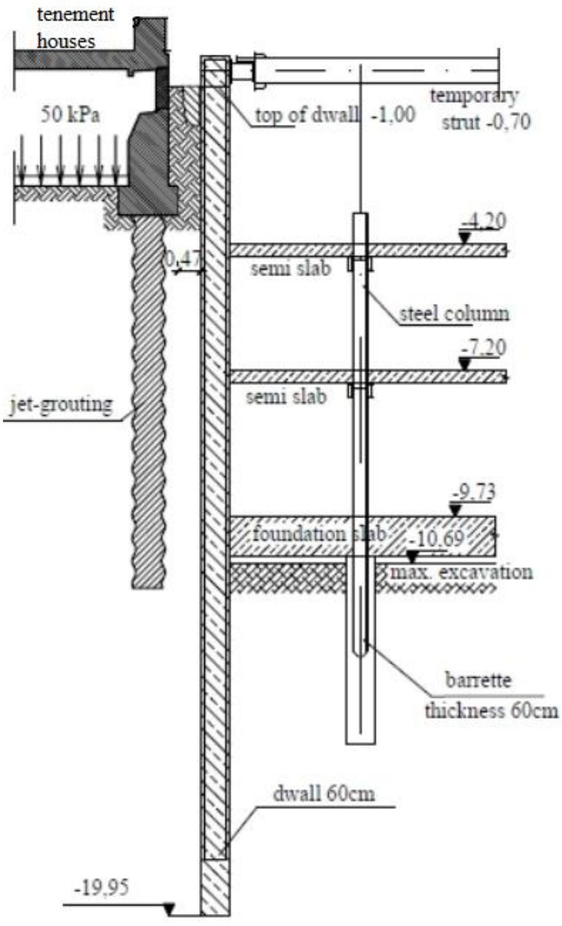

Figure 2. The cross-section of the excavation

An exception was made along the significant part of the excavation wall adjacent to the tenement house, in which the wall was supported by three levels of steel tubular struts due to the unfortunate location of the entry ramp for cars.

The typical cross-section of the underground part of the case is shown in Figure 2 including the foundation of the wall of the old tenement houses closest to the excavation.

2.1 Description of geotechnical conditions

The analyzed excavation is situated in Warsaw on the left bank of the Vistula river within the area of glacial plateau.

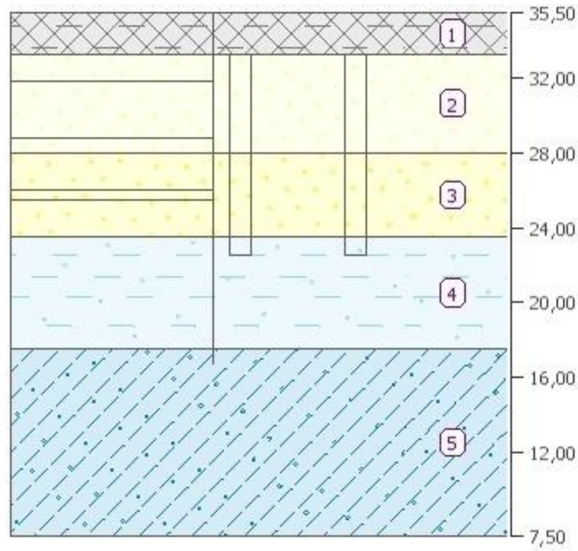

Figure 3. Geotechnical conditions

According to the geological report following geotechnical layers were found in the excavation area (Figure 3):

- 2.2 m thick anthropogenic soils (Layer 1 - Fill).
- approx. 10 m thick sandy formations - in form of medium dense and dense fine fluvioglacial sands (divided into two layers distinguishing different parameters: Layer 2 and Layer 3),
- approx. 6 m thick stiff Neogene-Pliocene clay deposits (Layer 4),
- down to exploration depth, stiff to very stiff sandy clays (Layer 5).

The parameters of soil layers described above are given in Table 1.

The main groundwater level with free and locally slightly confined water table stabilizes ~4.15 m below the ground surface (bgs).

Table 1. Geotechnical parameters.

Layer	**γ** [kN/m^3]	**ϕ’** [°]	**c’** [kPa]	**E** [MPa]	**Eur** [MPa]
1	18,0	25	1	25	25
2	19,0	30,9	0	50	150
3	20,0	31,4	0	60	180
4	20,0	18	12	25	75
5	21,0	30	10	80	240

2.2 Construction stages

Following construction stages were designed, and considered in the numerical analysis made prior to the construction (first and second stage of analysis – without and with soil strengthening below strip foundations, respectively):

Stage 1 – Initial stage including existing structures in the proximity of the excavation

Stage 2 – Construction of the diaphragm wall (in the second stage analysis in this stage also the strengthening of the soil below two strip foundations closest to the diaphragm wall by means of jet-grouting were considered)

Stage 3 – Installation of steel struts in the level of the 0 slab,

Stage 4 – Excavation below the first underground slab (-1 slab), i.e. 3.7 m bgs,

Stage 5 – Installation of steel struts in the level of the -1 slab,

Stage 6 - Excavation below the second underground slab (-2 slab), i.e. 6.7 m bgs,

Stage 7 - Installation of steel struts in the level of the -2 slab,

Stage 8 – Final excavation to the level 25,50 m above Vistula river level, i.e. 10-10.9 m bgs.

The diaphragm walls on the whole periphery of the excavation were embedded into the impermeable clay layer, therefore the water table was lowered only within the excavation and no impact of dewatering on surrounding area was expected.

3 NUMERICAL ANALYSIS

3.1 General assumptions for numerical analysis

The plain strain analysis was made in 2D space, using GEO5 FEM software, (Fine 2018). The elastic-perfectly plastic constitutive soil model was used with the Coulomb-Mohr plasticity criterion for modelling the soil body.

For concrete structures, i.e. diaphragm walls, underground slabs and foundations of the neighboring buildings, a linear-elastic isotropic model was used.

The mesh was made of isoparametric, six-node triangular elements and interface-type contact elements.

3.2 The results of numerical analysis

The results of finite element analysis were obtained in all calculation stages including: displacements and stresses in the soil body, displacements of the diaphragm wall and settlements of foundations of tenement houses in the nearest vicinity.

In the first stage of analysis, without strengthening of the soil under foundations of tenement houses, significant settlements of two rows of foundations closest to the excavation wall were obtained. The map of vertical displacements in the last excavation stage (Stage 8) is shown in Figure 4. The maximum settlement below the most loaded foundation (second row from the excavation) obtained in the analysis was 14.6 mm. While the settlement of the last foundation (furthest from the excavation) was only 1.2 mm. It was stated that both the maximum settlement and also the differenttial settlement exceed the alowable values for such fragile, old, brick stuctures. The decision was made to strengthen the soil below two closest rows of foundations by means of jet-grouting.

Second stage numerical analysis was made again, considering soil strengthening. Below, in Figure 5, the map of vertical displacements of the model in the last excavation stage (Stage 8) after consideration of the soil strengthening is shown. The maximum calculated settlement of the two foundations closest to the excavation are up to 6 mm, and the settlment of the furthest foundation is 1.9 mm. It was decided that this settlement is acceptable for the structure and the decision of strengthening of the soil by jet-grouting below two strip foundations closest to the excavation was taken.

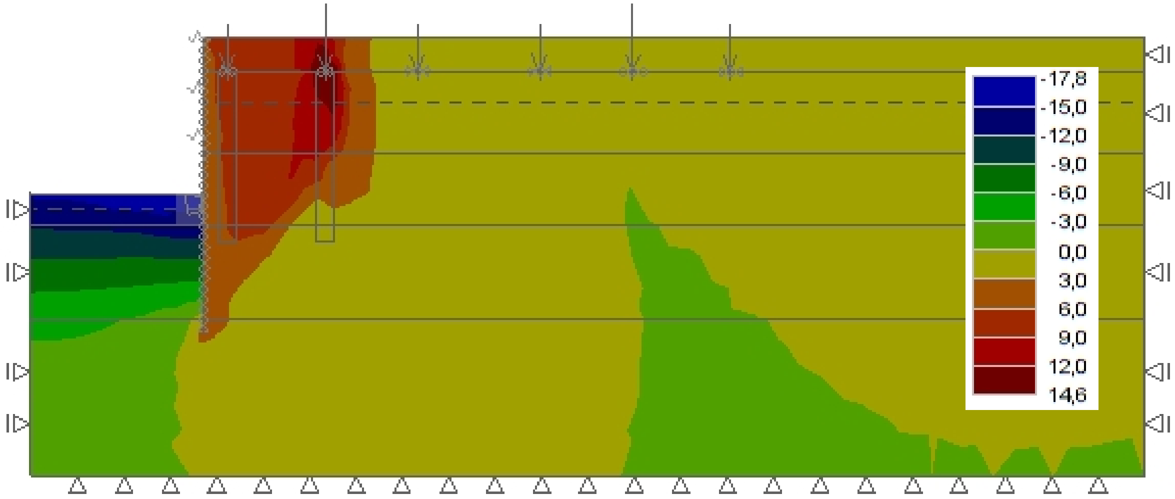

Figure 4. Vertical displacements of the model without strengthening of the foundation soil

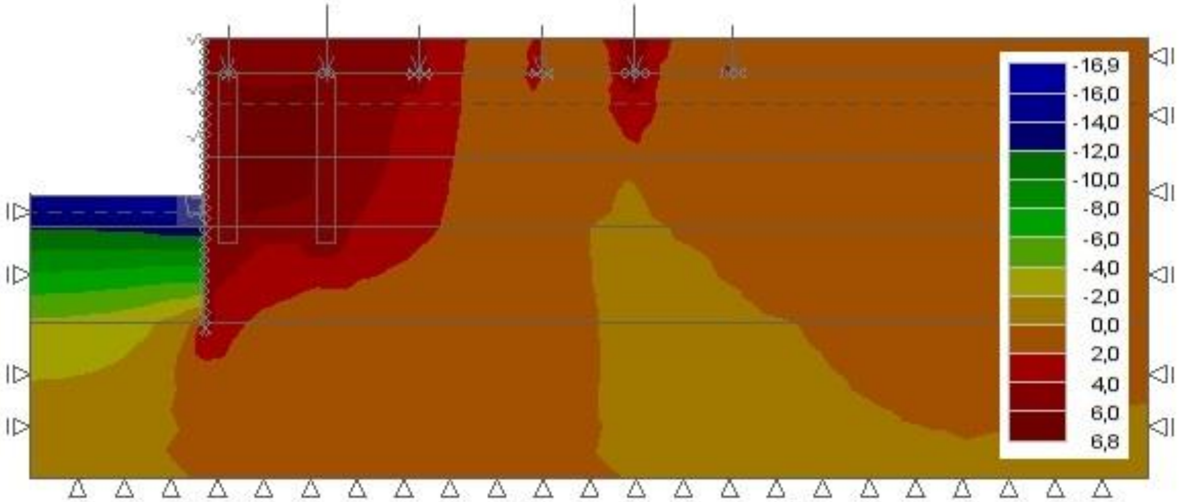

Figure 5. Vertical displacements of the model considering jet-grouting strengthening of foundations

4 THE RESULTS OF DISPLACEMENTS MEASUREMENTS ON SITE

Detailed, continuous monitoring was made during construction. Horizontal displacements of excavation walls, vertical displacements of old tenement houses as well as vertical displacements of the track bed in the metro station were measured. Average measured values are shown and compared to the respective analysis results, as discussed and presented further in this chapter.

The monitoring of the neighboring tenement buildings began a few months prior to the start of excavation works. The first and significant vertical displacements were noted during the jet-grouting strengthening of foundations and the excavation of the diaphragm walls. The maximum settlement of the foundation closest to the excavation related to these works amounted to 7.9 mm. In the same time (construction stage) the most distant wall moved slightly upwards up to + 0.3 mm. The resulting differential settlement was 8.3 mm. The results of vertical displacements measurements in relation to construction stages, taken on several benchmarks located on the tenement houses, on the wall closest to the excavation are presented in Figure 6. The average value of these results is further compared to the appropriate numerical analysis results in consequent construction stages (Figure 7).

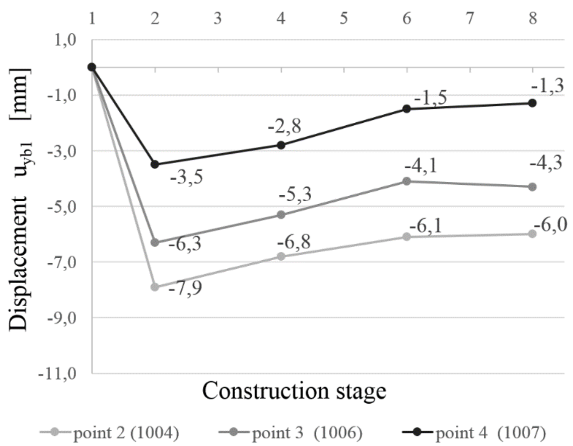

Figure 6. Vertical displacements of the building

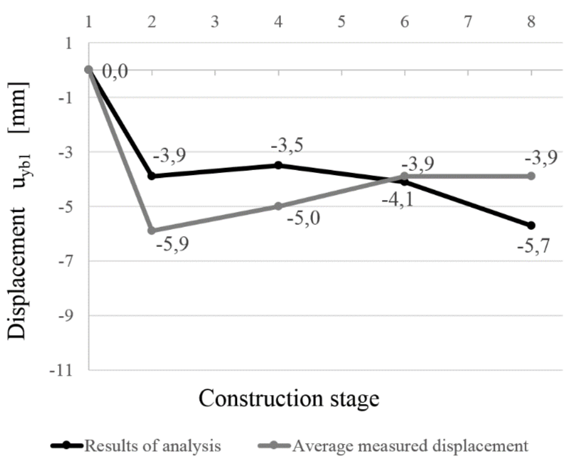

Figure 7. Vertical displacements of the building

The difference between the average measured and calculated values of vertical displacements in all construction stages is up to 2 mm.

Mesurements taken at other benchamrks in different locations on the building further from the excavation showed minimal, gradual, upwards movement up to 1.0 – 2.0 mm. The authors decided not to discuss these values due to it insignificance.

The diaphragm wall displacements were measured by inclinometers, to have a complete overview of the results obtained for each construction stage. The maximum displacement of 4.9 mm occurred during the final excavation stage (Stage 8) and was 3.6 mm smaller than the resulting displacement obtained in the numerical analysis, as shown in Figure 8. The shape of the wall displacement was similar for the measurements and the analysis.

5 CONCLUSIONS

The finite element analysis made prior to the construction, on the design stage, showed too large theoretical settlements as well as unacceptable differential settlements for the delicate structure of old tenement houses. Basing on this result it was decided that the soil below two strip foundations closest to the excavation should be strengthened and the jet-grouting method was chosen.

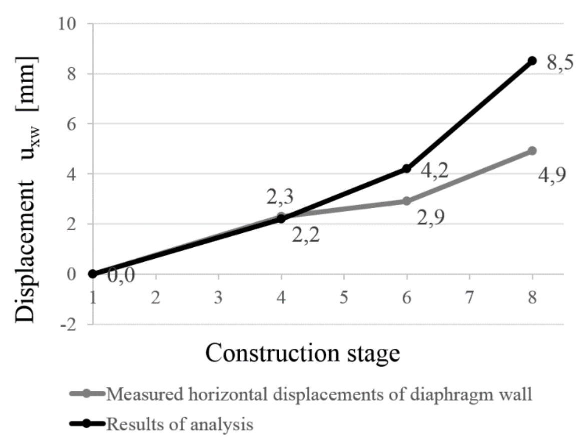

Figure 8. Vertical displacements of the building

The second stage numerical analysis proved that this solution should be appropriate.

The results of the analysis considering the jet-grouting columns were verified by comparing horizontal displacements of the diaphragm wall and settlements of foundations measured on site with appropriate theoretical values. The differences in the maximum calculated displacement values didn't exceed 3.6 mm for the horizontal displacement of the wall in the last excavation stage, being in a very good accordance in intermediate calculation stages and 2,0 mm for the vertical displacement of the closest wall of tenement houses.

It can be stated that technologies chosen (additional strengthening of the soil below two strip foundations by means of jet-grouting as well as the type of excavation wall and the method of excavation wall support) basing on the two stage numerical finite element analysis made prior to construction were suitable for execution of the excavation in such close vicinity to the existing old tenement houses. Numerical analysis proved to be very precise and adequate.

The maximum measured settlement of the tenement house wall closest to the excavation was 7.9 mm. It occurred actually before the excavation, during the construction of the diaphragm wall and strengthening of foundation soil. In the same time (stage) the most distant wall moved slightly upwards up to + 0.3 mm. The resulting differential settlement was 8.2 mm. This proved to be acceptable for the old structure of historical houses.

The precise calibration of 2D model will allow for a later analysis of a 3D model and further inference.

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