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Parametric study of the impact of deep excavation on an existing metro station

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ABSTRACT: In the paper, a parametric study (back analysis), concerning the estimation of 13 m deep excavation influence on an existing metro station is described. FEM model of the excavation, surrounding soil body and existing metro station was built in order to estimate the range of the impact zone as well as to calculate values of vertical and horizontal displacements of excavation walls and adjacent structures. The displacements of the diaphragm wall as well as displacements of the existing metro station obtained from the analysis were compared to the measurements performed during construction. A significant difference was observed, especially in terms of vertical displacements of the metro station. In order to obtain more accurate results, further calculation series were made with the modification of material model of the soil body (MC, MMC, DP), modulus of elasticity of soils and the ranges of the FEM model.

1 DISPLACEMENTS AROUND DEEP EXCAVATION

Displacements of the soil body and terrain around the excavation depend on several factors, such as: the type of casing, excavation dimensions, soil parameters, levels of groundwater, methods of construction, etc. as for example can be seen in: (Popa et al. 2006), Schweiger (2001, 2003), Mitew-Czajewska (2015), (Superczyńska et al. 2016). There are different methods to evaluate the range of the impact zone and displacements within this zone:

- Empirical methods—displacement is determined on the basis of data from similar sites executed in similar geotechnical conditions,
- Semi-empirical methods—the nomograms are developed for typical cases and are further applied for the estimation of displacements,
- Numerical methods—in most of the cases finite element method is used for modeling of the excavation and adjacent soil body.

In Poland, a semi-empirical method evaluated by the Building Research Institute (ITB) and published in the ITB Instruction no 376/2002, Kotlicki & Wysockiński (2002) and (Łukasik et al. 2014) is very often used as a first estimate of the range of the influence zone and a rough estimate of values of terrain settlements. When a more detailed analysis is necessary, e.g. in order to assure the safety of surrounding structures, Finite Element Method (FEM) is used.

In the paper, a case study including parametric back analysis concerning the estimation of 13 m deep excavation construction influence on existing

metro station is presented. Recommendations on the choice of soil model and values of the elasticity modulus for Finite Element Method (FEM) analysis of deep excavations are given.

2 DESCRIPTION OF THE CASE

2.1 General information

Figure 1 shows the location of the investment (divided into two stages – 1 and 2) in relation to the existing metro station. The case study concerns analysis of the influence of the construction of the underground part of building 1 on the existing metro station.

The minimum distance between the entrance to the metro station and the boundary of the new structure was 7.7 m (Fig. 2).

The minimum distance to the main building of the metro station was ~17.0 m.



Figure 1. Location of analysed building in relation to the existing metro station.

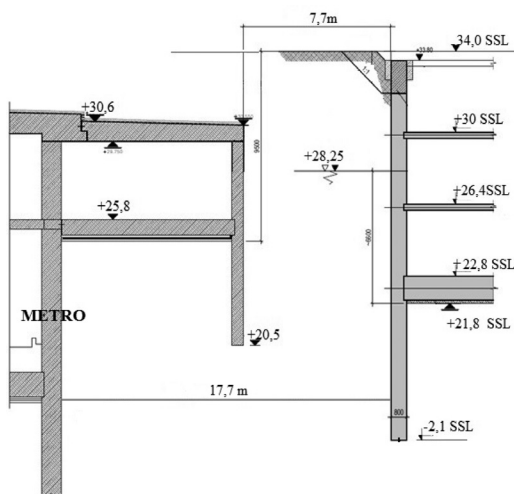


Figure 2. Schematic cross-section of the analysed structure and the nearby metro station (SSL-standard surface level, in Warsaw corresponding to "0" level of Vistula river).

Cut and cover method was used for the construction of the underground part of the new building; the stability of diaphragm walls during excavation was ensured by 2 levels of underground slabs. Maximum excavation depth was over 13 m in the central part and 12.2 m close to the diaphragm wall. The width of the excavation in the direction perpendicular to the metro station was 90 m.

2.2 Geotechnical conditions

In Warsaw, in the area of the excavation concerned, the subsoil is composed of Tertiary deposits on great depths covered with a complex of Quaternary formations from Pleistocene and Holocene periods. In the analysed case, up to the investigated depth, there are mostly glacial clays and fluvioglacial sands.

Soil conditions at the construction site and around metro station are as follows:

- directly under the surface, 2 m thick anthropogenic soils (so called artificial fills, fills) are found,
- below the layer of fills there is a 4 m thick layer of glacial clays,
- then, up to great depths fluvioglacial formations are found in the form of medium to coarse sands. In the model, this layer is divided into 2 layers taking into account the change in its parameters with depth.

The main groundwater table is located at 28.25 m above the "0" level of the Vistula River (~6.0 m below the surface of the ground).

Table 1. Basic geotechnical parameters.

Soil layer	γ kN/m ³	ϕ °	c kPa	E MPa
Fill	19	20	0	25
Clay	22	28	5	40
Sand 1	20	33	0	150
Sand 2	20	33	0	200

Basic geotechnical soil parameters of all soil layers specified above and considered in numerical analysis are compiled in Table 1.

2.3 Construction stages

The Station was built using cut and cover and top down method. The following construction stages were distinguished and modelled in the numerical FEM analysis:

- Stage 1 – Greenfield (including the structure of existing metro station);
- Stage 2 – Construction of the peripheral diaphragm walls;
- Stage 3 – Excavation to the level of 29.85 m above "0" level of Vistula river (i.e. ~4.15 m below ground surface);
- Stage 4 – Construction of the first underground slab (30.00 m above "0" level of Vistula river);
- Stage 5 – Excavation to the level of 26.40 m above "0" level of Vistula river (i.e. ~7.6 m below ground surface); lowering of the water table within the excavation 1 m below the excavation (i.e. ~8.6 m below ground surface);
- Stage 6 – Construction of the second underground slab (26.40 m above "0" level of Vistula river);
- Stage 7 – Final excavation to the level 21.80 m above "0" level of Vistula river close to the diaphragm wall (i.e. ~12.2 m below ground surface); lowering of the water table within the excavation 1 m below the final excavation level (i.e. ~14 m below ground surface);

Further construction stages including construction of foundation plate and the "0" slab (around ground surface level) and loading by the final structure load were also modelled, but not discussed further in the paper. The author decided to neglect it as the results obtained in these stages were realistic; the loading cases are effectively modelled by geotechnical FEM software.

Groundwater table was lowered successively during excavation only within the excavation boundary. Its flow from outside was cut by diaphragm walls embedded in a very thin layer of silty clays (not considered in the numerical model). Lowering of the water table within the excavation was modelled accordingly in the numerical model.

2.4 Monitoring results

During the construction of the building, regular measurements of displacements caused by construction, in accordance to construction stages, were made.

Following values were measured (Figs. 3–5):

- horizontal displacements of the diaphragm wall;
- vertical displacements of the top of the foundation plate in the metro station;
- vertical displacements of the entrance building;

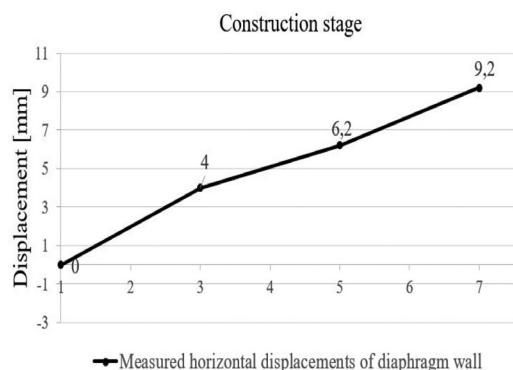


Figure 3. Horizontal displacements of diaphragm wall.

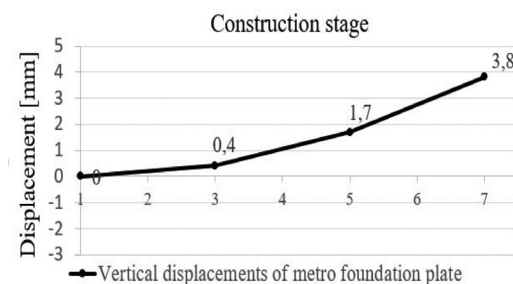


Figure 4. Vertical displacements of metro foundation plate.

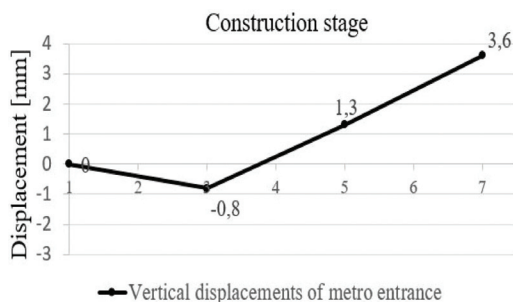


Figure 5. Vertical displacements of the entrance to the metro.

3 NUMERICAL MODELLING

3.1 Assumptions

Finite element plain strain analysis were carried out using GEO5 FEM software, Fine Ltd (2016). One, typical geotechnical and structure geometry cross section was modeled, closest to the metro entrance.

The following basic assumptions were adopted:

- Final excavation depth – 12.2 m,
- Diaphragm wall height – 36.1 m,
- Diaphragm wall thickness – 0.8 m,
- 2 slabs supporting the diaphragm wall; thickness of both slabs 0.3 m,
- Distance to the entrance to the metro building – 7.7 m, distance to the main metro building 17.1 m,
- Construction stages as specified in Section 2.3,
- Geotechnical conditions and soil parameters as specified in Section 2.2.

Model dimensions were 50×190 m. Finite element mesh and model are shown at Figure 6. For the basic (further called Original) model elastic perfectly plastic constitutive material model Coulomb-Mohr was chosen. FEM model mesh, generated automatically, was built of 13287 nodes, 8306 elements (4606 15-nodes triangle surface elements, 925 beam elements and 2775 contact elements).

3.2 Parametric study

The analysis was performed using the first—Original model. The displacements of the diaphragm wall as well as displacements of the existing metro station obtained from the analysis were compared to the measurements performed during construction (Figs. 7–9).

A significant difference was observed, especially in terms of vertical displacements of the metro station.

The observation showed clearly that all terrain (including metro building) around the excavation went up slightly during excavation, while in the numerical analysis settlements were obtained. Author observed similar discrepancies analyzing other cases in Warsaw, Siemińska-Lewandowska & Mitew-Czajewska (2009). Finite element geotechnical models handle with difficulties cases concerning unloading caused by excavation. First possible cause of this falsity is the lack in the applied software of proper constitutive models differing soil parameters in loading and unloading. Several other factors may influence the result as well, such as underestimated values of soil parameters (especially the modulus of elasticity), ranges of the model, mesh density.

In order to obtain more accurate results parametric back analysis was made. In further calculation

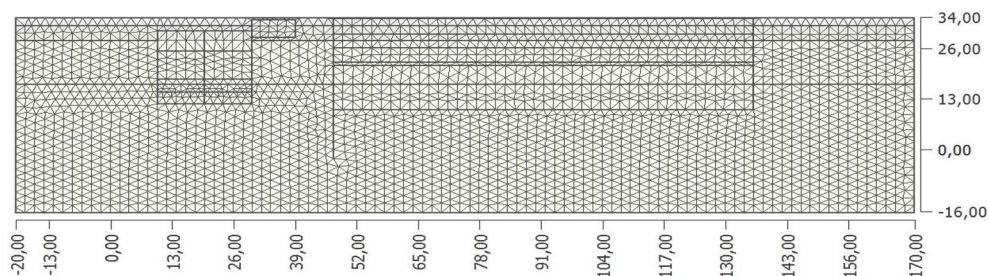


Figure 6. Numerical model—finite element mesh.

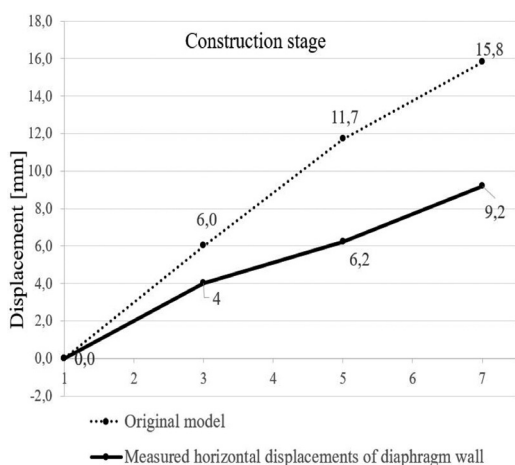


Figure 7. Original model—horizontal displacements of diaphragm wall.

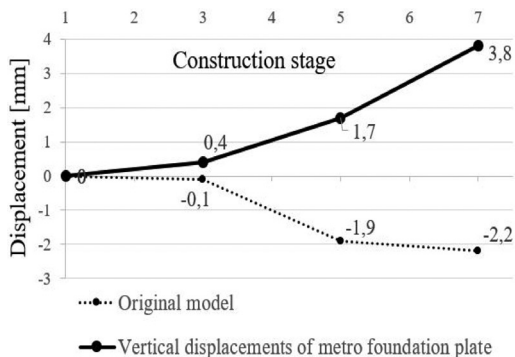


Figure 8. Original model—vertical displacements of metro foundation plate.

series following model parameters were modified: material model of the soil body (MC, MMC, DP), modulus of elasticity of soils, the depth and ranges of the FEM model. Detailed information on these studies will be presented further except changing

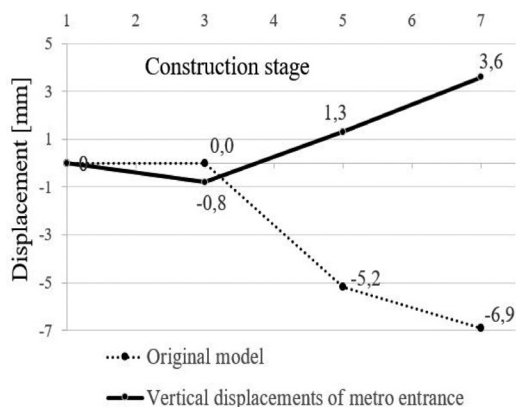


Figure 9. Original model—vertical displacements of the entrance to the metro.

the ranges of the model which proved to have little influence on the final result.

3.2.1 Parametric study—modification of material model

In the first back analysis series the change of the material model of soil mass was studied. Two additional models, chosen from models available in the software, were applied—Modified Mohr-Coulomb (MMC) and Drucker Prager (DP). It was decided that other available models (Modified Cam Clay and Hypoplastic Clay) are not applicable in this case, because of domination of non-cohesive soils in the model. Comparison of results is shown on Figures 10–12. Analysis performed with the use of Modified Mohr-Coulomb model showed best results in terms of both diaphragm wall and metro displacements.

3.2.2 Parametric study—modification of the value of the modulus of elasticity of soil layers

In the second back analysis series, modulus of elasticity of soils was changed. In usual practice, values of modulus of elasticity are obtained by

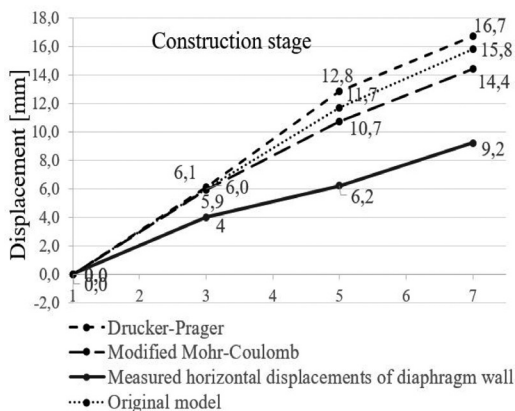


Figure 10. Horizontal displacements of diaphragm wall—variation of material models.

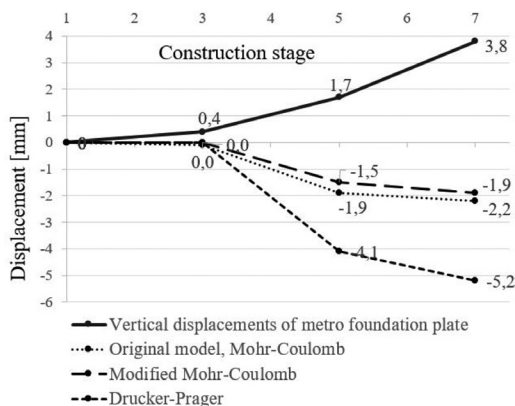


Figure 11. Vertical displacements of metro foundation plate—variation of material models.

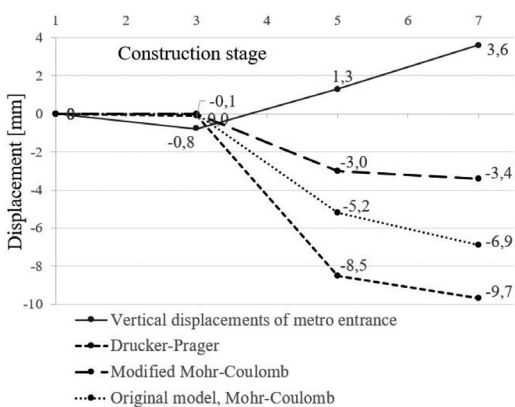


Figure 12. Vertical displacements of the entrance to the metro—variation of material models.

means of conventional soil testing for large strain ranges. These shouldn't be applicable for retaining walls and deep excavation analysis. Often, it is not possible to obtain values of modulus of elasticity of soils for the small strain ranges. A wide range of different testing methods available for obtaining modules in small strain ranges, Godlewski & Szczepański (2015), (Kuszyk et al. 2012), are still not popular due to its high costs. During this analysis series the modulus of elasticity of all layers was multiplied twice, three times and four times comparing to the original value (conventional testing—large strain range) in order to simulate small strain modules. It was observed (Figs. 13–15) that in terms of diaphragm wall displacements the

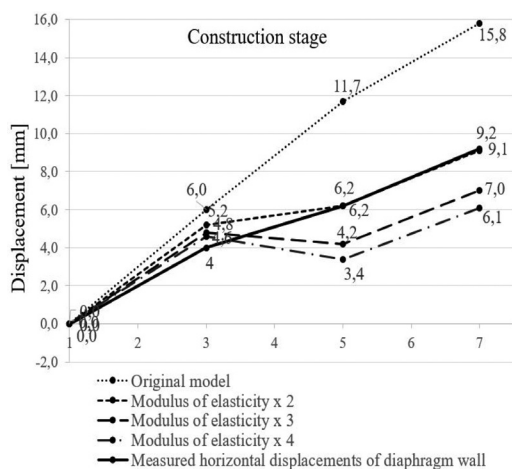


Figure 13. Horizontal displacements of diaphragm wall—variation of values of modulus of elasticity of soil layers.

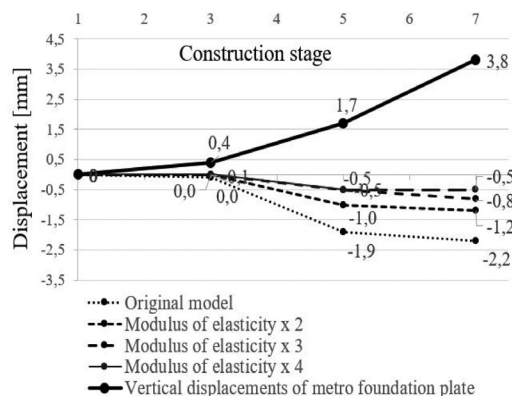


Figure 14. Vertical displacements of metro foundation plate—variation of values of modulus of elasticity of soil layers.

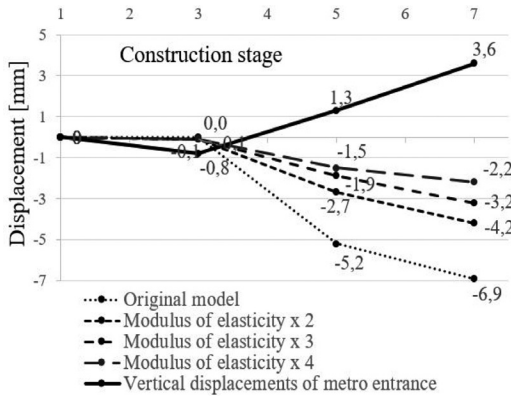


Figure 15. Vertical displacements of the entrance to the metro—variation of values of modulus of elasticity of soil layers.

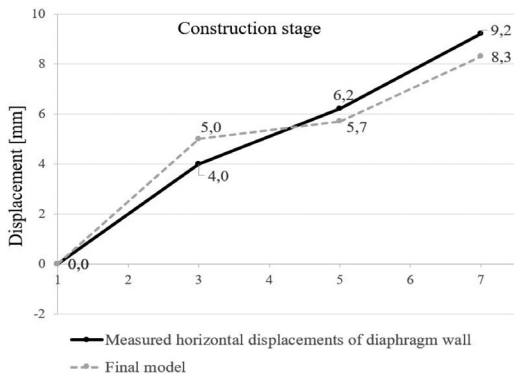


Figure 16. Horizontal displacements of diaphragm wall—final model.

best consistency in the results was obtained when the elasticity modules were multiplied twice.

Analyzing vertical displacements of the metro building, the results are improving with strengthening of the soil body, but most significant improvement could be observed for the case of doubled modulus. Unfortunately changing the value of modulus decreased the difference in the result only (measured displacement versus original analysis). In each case settlement was obtained instead of uplift.

3.2.3 Parametric study—final model

Taking into consideration all results of parametric study analysis two final verification models were calculated, both using Modified Mohr-Coulomb model. In the first model, values of modulus of elasticity of soil layers were multiplied twice in the second three times (comparing to original values). Best consistency in the results was obtained by

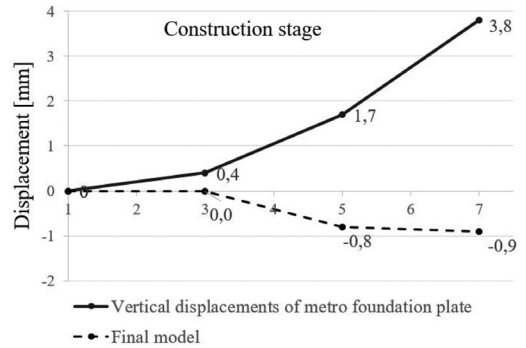


Figure 17. Vertical displacements of metro foundation plate—final model.

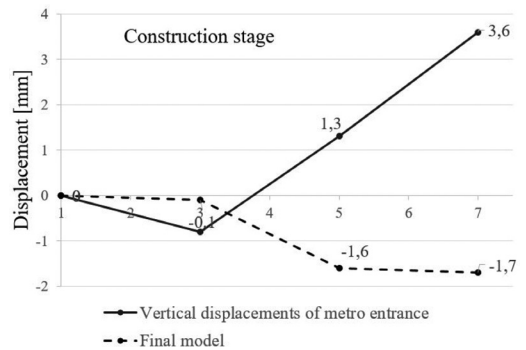


Figure 18. Vertical displacements of the entrance to the metro—final model.

double multiplication of modules, both in terms of wall and metro displacements (Figs. 16–18).

4 CONCLUSIONS

A great number of numerical FE back analysis of a deep excavation influence on the existing nearby metro station were performed in order to obtain the best fitting result to displacement measurements performed during construction. Typical modelling with the use of most popular Mohr-Coulomb soil model and values of modulus of elasticity of soil layers obtained from conventional soil testing for large strains ranges led to huge discrepancies in displacements values. Unfortunately, it is a very common practice that large scale soil investigations are not being performed and data concerning soil parameters for the design purpose is very limited. Back analysis performed for the described case aimed to give practical recommendations on how to deal with projects with limited geotechnical data issues.

After several series of analysis it was found that the best consistency in the values of displacements (comparing theoretical and measurement values) both in terms of horizontal displacements of walls of the excavation as well as vertical displacements of structures in the vicinity of the excavation is obtained when using Modified Mohr-Coulomb model together with doubled values of elasticity modulus of soil layers (twice the value obtained for large strain ranges in standard testing).

It must be also underlined that well-fitting result for the vertical displacements of structures located outside the excavation walls could not be obtained due to limited material models availability in the software. All available models (excluding these not fitting for analyzed soil conditions) are not suitable for proper modeling of unloading caused by excavation. The results are in the acceptable range and on the safe side from the engineering practice point of view. Further analysis should be made using different soil models in order to obtain more accurate results.

For the design of excavation protection walls the combination of parameters given above (Modified Mohr-Coulomb model together with doubled values of elasticity modulus of soil layers) may be used.

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