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Three-dimensional numerical soil-structure interaction analysis of deep excavations

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ABSTRACT: Appropriate modelling of deep excavations to predict wall deformations and related surface settlements is one of the most challenging tasks for geotechnical engineers. Its complexity arises from the necessity to consider geotechnical, structural engineering, and construction methodology simultaneously. The present article is a summary of our recently completed Ph.D. research project on the subject. A database of deformation monitoring results from nine deep excavations in Budapest was prepared. The assessment of the database provided empirical correlations between the deformations of the excavations and their technical characteristics, which can be used during the design of similar future projects. Based on this database, 56 calculation models were prepared to back-analyze ten monitored diaphragm wall sections of four deep excavations with depths between 9 and 18 meters. This series of analyses allowed us to assess the outcomes of different modelling techniques, ranging from Winkler-type models to 3D finite element techniques. In addition, specific recommendations could be made to determine geotechnical input parameters based on site test results for Budapest clay. Finally, two- and three-dimensional finite element models were prepared for three-, four-, and five-level deep excavations in the typical soil regime of Budapest city center. In the numerical parametric study, the widths of the ground anchor-supported diaphragm walls were varied within a realistic range to analyze the differences between 2D and 3D calculation results as a function of excavation geometry. The comparative evaluation of these calculations made it possible to assess the relevance and necessity of the rarely applied 3D models in this field of geotechnical engineering.

KEYWORDS: deep excavation, monitoring database, PLAXS 3D, back-analysis

1 INTRODUCTION

The majority of deep excavation projects in Hungary in recent decades have been carried out in the center of Budapest, where demand is not expected to decline. Many of these projects were executed under similar geotechnical conditions. The man-made ground, typically two to five meters thick, is underlain by finer and, at deeper levels, coarser-grained fluvial sediments of the Danube. The bedrock appearing at depths of eight to fifteen meters is most frequently the Oligocene clay, which has low permeability and favorable mechanical properties (Görög, 2008; Barsi et al., 2011), or the typically more heterogeneous Miocene clay, interbedded with more permeable granular layers (Kocsisné Bodnár, 2015).

The most typical retaining wall solution for such excavations is the diaphragm wall, embedded in the Tertiary clay layer with temporary supports (Szepesházi R. et al., 2009). For pit depths up to a maximum of fifteen to eighteen meters, temporary support of the diaphragm walls is feasible using ground anchors (see Figure 1) and, potentially, steel struts at the corners. In this way, the resulting displacements can be limited to an acceptable range. Deeper excavations can only be safely supported by steel props interconnecting the opposite sides of the excavation and/or by using top-down construction methods.

Many projects have been built using such technical solutions, but no comprehensive study has been published to summarize local design experience and deformation monitoring results, except for a few case studies (Deli et al., 2009; Szepesházi R. et al., 2009; Zsiros et al., 2018; Faragó et al., 2018; Szepesházi A., 2016). Local design offices only publish their experiences to a limited extent; therefore, design process development is not integrated.

Geotechnical finite element software products that allow the use of complex material models (Benz, 2008) and 3D geometry have been available for more than fifteen years. Despite promising research (Ou et al., 1996; Zdravkovic, 2009), these methods have not replaced the two-dimensional subgrade reaction (Winkler-type) models in routine engineering practice.

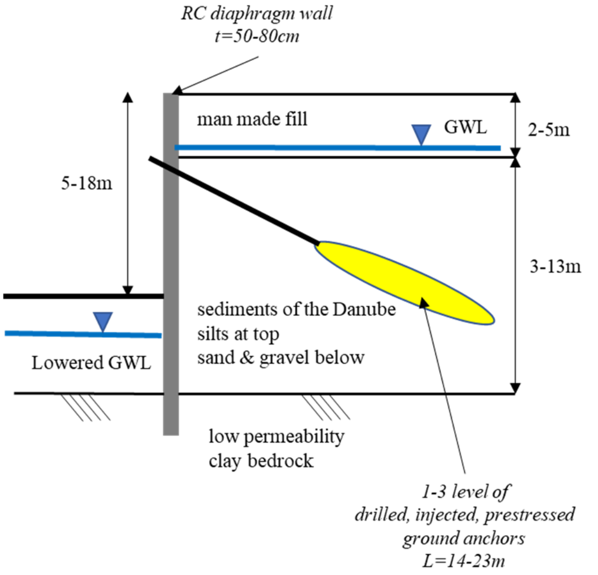

Figure 1. Typical geotechnical conditions and deep excavation solution in Budapest center

In the absence of comparable experience, the use of simple two-dimensional Winkler-type models raises numerous questions. In cases of different geotechnical conditions or more complex geometry, finite element procedures would theoretically provide more reliable solutions. These considerations motivated this research to analyze the experiences of many past projects built under the aforementioned conditions and to evaluate the applicability of modern modelling procedures.

The main objectives of the research were to:

- Build and evaluate a deformation monitoring database of deep excavations in Budapest and find empirical correlations between horizontal wall deformations and the related surface settlements as a function of pit geometry.

- Assess the reliability of the widely used two-dimensional Winkler-type modelling procedures by comparing their results with monitored deformations.
- Back-analyze deep excavations using two-dimensional finite element models, considering the small-strain stiffness of the soil.
- Build complex three-dimensional models to back-analyze deep excavations and evaluate their practical applicability.

The PhD research (Szepesházi 2023) was divided into three main chapters:

- Compilation of a database containing inclinometer data from 20 wall sections of 9 different deep excavations in Budapest, along with the associated deformation monitoring results of adjacent buildings (see Table 1). Key conclusions and design recommendations were presented based on the evaluation of this database.
- Findings of the two- and three-dimensional back-analysis of 10 wall sections from 4 different deep excavations with ground-anchored diaphragm walls, where inclinometer data were available (see Table 1).
- A numerical parametric study of typical three, four, and five level underground garage structures supported by ground-anchored diaphragm walls in the typical geotechnical conditions of Budapest. The varied parameters included the relevant geometrical characteristics of the excavation pits. The numerical analyses were conducted using two- and three-dimensional finite element models.

2 MONITORING DATABASE OF DEEP EXCAVATIONS IN BUDAPEST

The deformation monitoring results of 9 deep excavation projects (Table 1) were compiled, including horizontal wall displacements monitored by inclinometers and settlements of surrounding buildings measured by geodetic surveys. During the evaluation, the database was divided into two groups: five of the case studies involved diaphragm walls supported by temporary ground anchors, while the other four used diaphragm walls constructed with the top-down method, referred to as “rigidly supported” excavations. A detailed evaluation report is available in Szepesházi (2023) and Szepesházi & Móczár (2022).

The following relationships were identified:

- Figure 2 shows the correlation between horizontal wall displacement and excavation depth. It can be observed that the horizontal deformation of rigidly supported diaphragm walls does not exceed 1‰ of the excavation depth. In the case of ground anchor-supported diaphragm walls, the recorded horizontal movements increase with depth but do not exceed 3‰ of it.
- Figure 3illustrates the relationship between excavation depth and horizontal wall movement for anchor-supported excavations, along with their linear correlation as expressed in Equation (1), with a coefficient of determination of R = 0.41:

$$u_{x,max}[mm] = 1,92 * H_{full}[m] - 1,75 \qquad (1)$$

- Figure 4 indicates that the settlement of buildings adjacent to ground anchor-supported deep excavations does not exceed 2‰ of the excavation depth. Settlements exceeding 1‰ are only observed on structural elements located directly next to the diaphragm wall.
- Figure 5 shows that the maximum settlement of buildings adjacent to rigidly supported diaphragm walls does not exceed 0.7‰ of the excavation depth.
- Surface settlements induced by deep excavations typically extend laterally up to three times the excavation depth. However, settlements exceeding the order of ±1–2 mm, which is the typical accuracy range of geodetic measurements, develop within two times the excavation depth from the excavation wall (Figure 4 & Figure 5).

Table 1. Overview of monitoring database

Project	Depth [m]	Support type	No. of inclino-meters	No. of. settlement monitoring points
Office building at Bajcsy-Zsilinszky road	16.2	2 anchor rows	1	-
Office building at the corner of Váci road and Róbert K. road	13.4	1 anchor row	4	-
Mixed-use building at Szervita Square	17.8	3 anchor rows	3	41
Mixed-use building at Pozsonyi road	8.7	1 anchor row	2	-
Hotel building at Fiumei road	7.4	2 anchor rows	1	67
Szent Gellért Sqaure Metro4	36.1	top-down	5	21
II. János Pál Pápa Sqaure Metro4	24.9	top-down	4	10
Móricz Zsigmond Square Metro4	27	top-down	-	27
Fővám Square Metro4	37.1	top-down	-	24

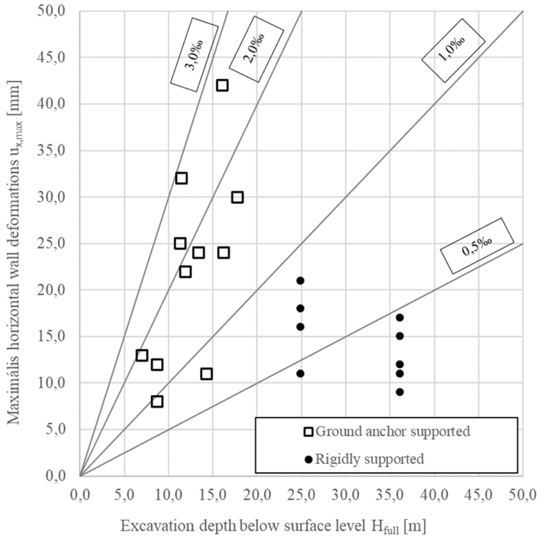

Figure 2. Maximum horizontal deformation of diaphragm walls in function of excavation depth

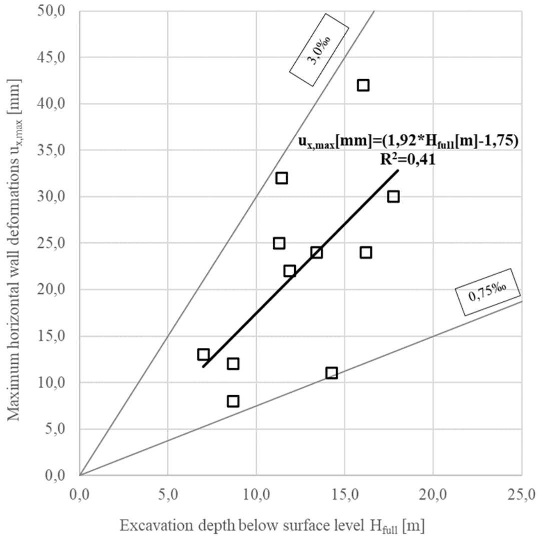

Figure 3. Maximum horizontal deformation of ground anchor supported diaphragm in function of excavation depth

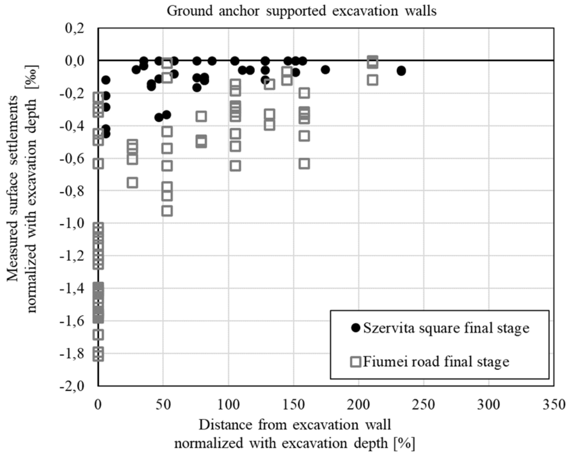

Figure 4. Surface settlements around ground anchor supported deep excavations in function of distance from the diaphragm wall

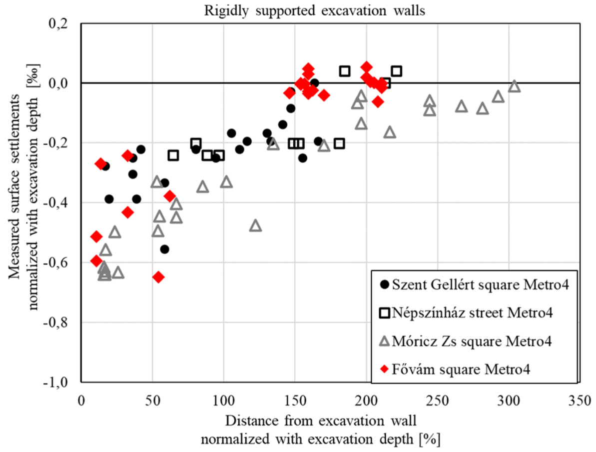

Figure 5. Surface settlements around rigidly supported deep excavations in function of distance from the diaphragm wall

3 NUMERICAL BACK-ANALYSIS

Four ground anchor-supported diaphragm walls from the monitoring database were selected for detailed back-analyses. The excavations, ranging in depth from nine to eighteen meters, had a minimum width of at least 2.5 times their depth, which effectively ensured plane strain conditions in the vicinity of the inclinometer sections. The numerical back-analyses were conducted on 10 monitored wall sections at the final excavation stage.

Two-dimensional Winkler-type models were developed using the PARIS design software by Soletanche Bachy, while both two- and three-dimensional finite element models were created in PLAXIS using the Hardening Soil Small-Strain (HSS) model (Figure 6). Soil stiffness parameters were refined step by step to achieve the best possible agreement between measured and calculated deformations. The stiffness of the clay bedrock was primarily adjusted, assuming drained behavior, and the following principles were consistently applied across all case studies: the widely accepted relationship $E_{oed} = E_{50} = E_{ur}/3$ was considered valid in every model. Small-strain stiffness parameters were estimated using the correlations recommended by Kramer (1996) and Benz (2008). The same soil parameters were applied within a given project, assuming homogeneity across the site. Finally, undrained behavior for the clay was also analyzed. Further details of the study can be found in Szepesházi & Móczár (2023).

The assessment of the outcomes focused primarily on wall deformations; however, bending moments and anchor forces calculated by the different modeling approaches were also analyzed. A typical diagram of wall displacements is presented in Figure 7.

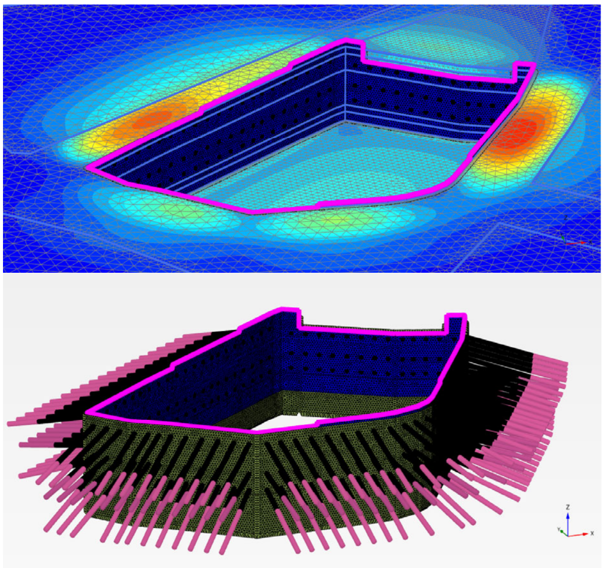

Figure 6. Three-dimensional model of one of the excavations

The following conclusions were drawn for excavations designed in the typical geotechnical conditions of Budapest:

- for Winkler-type calculation models the subgrade reaction modulus of the clay bedrock in the passive zone of ground anchor supported diaphragm walls can be estimated from CPTu test results using equation (2).

$$k \left[\frac{MPa}{m}\right] = 2.5 \div 3 \cdot q_{c.avg}[MPa] \qquad (2)$$

- for geotechnical FEM calculation models the unloading-reloading stiffness modulus of the clay bedrock in the embedded passive zone of ground anchored supported diaphragm walls can be estimated from CPTu test results using equation (3)

$$E_{ur}\,[\mathrm{MPa}] = 2.5 \div 3 \cdot q_{c.avg}[\mathrm{MPa}] \qquad (3)$$

Both equations are considered valid in the range of $q_{c.avg}$=3÷20 MPa.

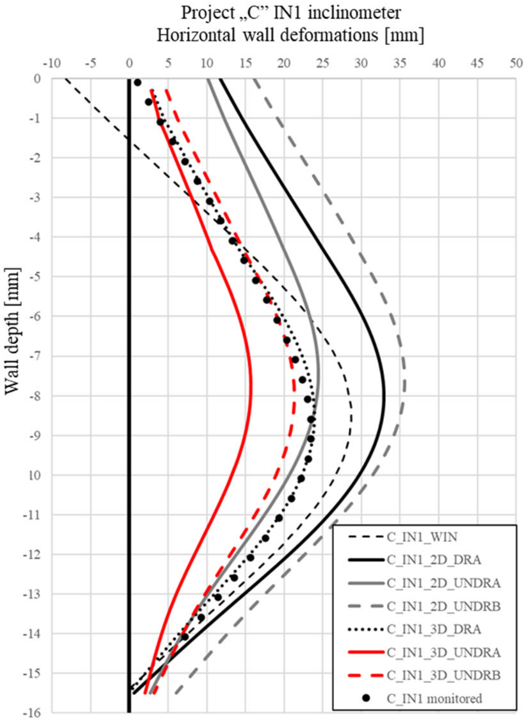

Figure 7. Back-analysis wall results of Project "C" at IN1 section – Wall deformation vs. depth

- The 2D Winkler-type models and the 2D and 3D finite element models can be adequately precise for practical purposes. However, horizontal wall deformations derived from 3D finite element models are consistently lower than those obtained from 2D finite element models using the same soil parameters. Moreover, 3D models consistently provided results that better approximated the measured deformations.
- The behavior of ground anchor support in diaphragm wall models was represented more realistically by 2D Winkler-type models than by 2D FEM models. The latter showed greater axial anchor deformations than those observed in monitoring results, while defining the fixed end of the ground anchor at the midpoint of its grouted section in Winkler-type models resulted in more realistic axial stiffness and deformation.

4 PARAMETRIC NUMERICAL STUDY

In the final stage of the research project, two-dimensional and three-dimensional models of typical deep excavations were developed, considering the typical geotechnical conditions of Budapest. The excavation models, with depths of H_{full} = 10 m, 13 m, and 16 m, represent typical three-, four-, and five-level deep underground garages. The excavations were retained by 60 cm and 80 cm thick diaphragm walls, supported by pre-stressed temporary ground anchors arranged in one, two, and four rows (see Figure 8). The small-strain behaviour of the soil was also taken into account in the models. The 3D models were built with a rectangular layout and varied lengths of L = H_{full} = 25 m, 50 m, 75 m, and 100 m.

A comparison between the 2D and 3D model results was made by analyzing the plane strain ratio (PSR), as defined by Ou et al. (1996). The definition of PSR is presented in Equation (4) and illustrated in Figure 9.

$$PSR = \frac{\text{max wall deform. in a section of the 3D model}}{\text{max wall deform. in a section of the 2D model}} \qquad (4)$$

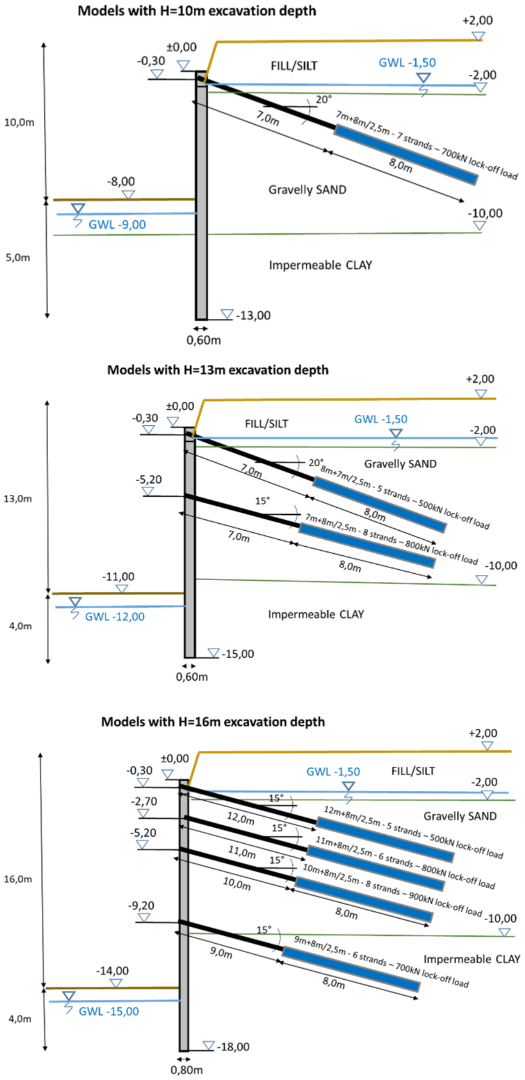

Figure 8. Sections of the 3, 4 and 5 level deep excavation

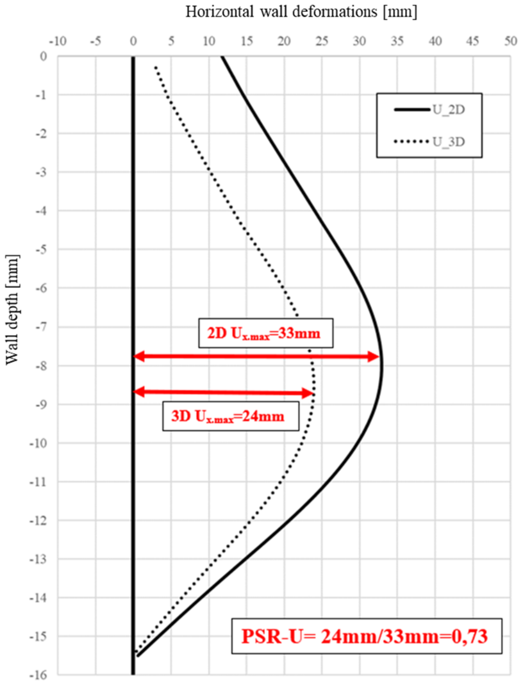

Figure 9. Definition of PSR-ratio – example

The variation of the plane strain ratio (PSR) was analyzed as a function of the distance d from the corner of the excavation pit, as well as its normalized value with respect to the total width L of the pit. Figure 10 presents a typical output diagram comparing wall displacements from the different calculation models. Additional models were also developed to assess the impact of the following factors on wall deformation:

- the relevance of the horizontal stiffness of the diaphragm wall in 3D FEM models which is practically neglected in 2D models,
- the influence of steel props at the excavation corners,
- the influence of the variability of the soil mechanical parameters.

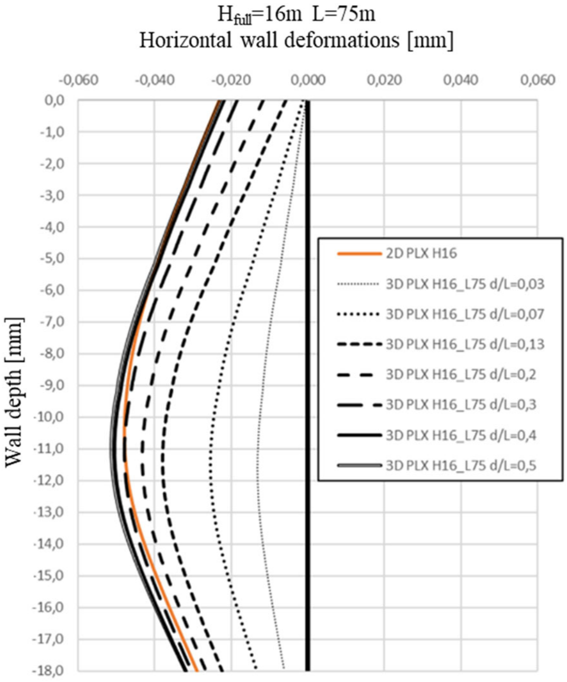

Figure 10. Comparison of wall deformation results of 2D and 3D models for excavation with Hfull=16m, L=75m

The following conclusions were found:

- The PSR of horizontal deformations is highly influenced by the variability of geotechnical parameters. The lower the strength and stiffness parameters of the soil, the smaller the PSR, as shown in Figure 11. (It should be noted that in some cases, PSR values between 1.1 and 1.2 were found. This anomaly is likely due to relatively low deformation magnitudes and calculation errors caused by differences in mesh refinement between the 2D and 3D models.)
- The deeper and narrower a deep excavation is, the smaller the plane strain ratio becomes (when measured halfway between the corners), and the wider the zone around the pit corners where the arching effect reduces deformations, as illustrated in Figure 12.
- The maximum plane strain ratio (PSR) of horizontal deformations—typically measured halfway between the excavation corners—can be estimated using the following formula:

$$\text{PSR U}_{\max}\ [-] = 1.28 * e^{-1.30*\left(\frac{H_{full}}{L}\right)} \qquad (5)$$

- It was concluded that the normalized plane strain ratio of maximum horizontal wall deformations depends more on the excavation length than on its depth, as demonstrated by the series of diagrams in Figure 13.

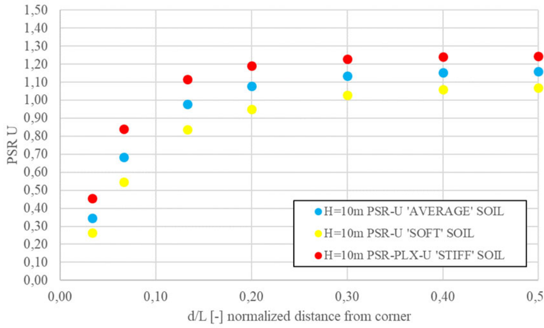

Figure 11. PSR of horizontal wall deformations of H_{full}=10m deep excavation models with different soil characteristics

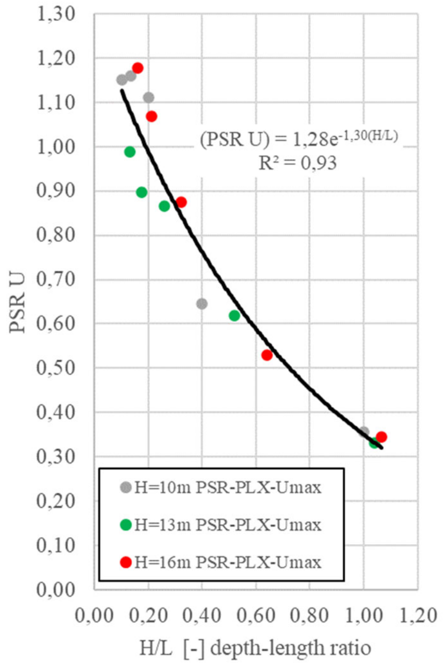

Figure 12. PSR of horizontal wall deformation in function of H_{full}/L ration for 10-13-16 m deep excavations

5 CONCLUSIONS

The presented PhD research project is the first detailed synthesis of deep excavation project experiences in Budapest. The correlations derived from the monitoring result dataset provide an opportunity to predict deformations or to verify the calculation results of diaphragm walls for future deep excavations in the city center of Budapest or in similar geotechnical conditions. Moreover, the compiled dataset could be extended with future projects to further refine the presented mathematical correlations. The proposed empirical relationships allow for the determination of stiffness parameters or the subgrade reaction modulus of Budapest clay bedrock from CPT test results for use in FEM or Winkler-type models. The results of the numerical parametric analysis with the 3D model series can support decision-making during the design phase by forecasting the relevance of 3D modelling based on excavation geometry.

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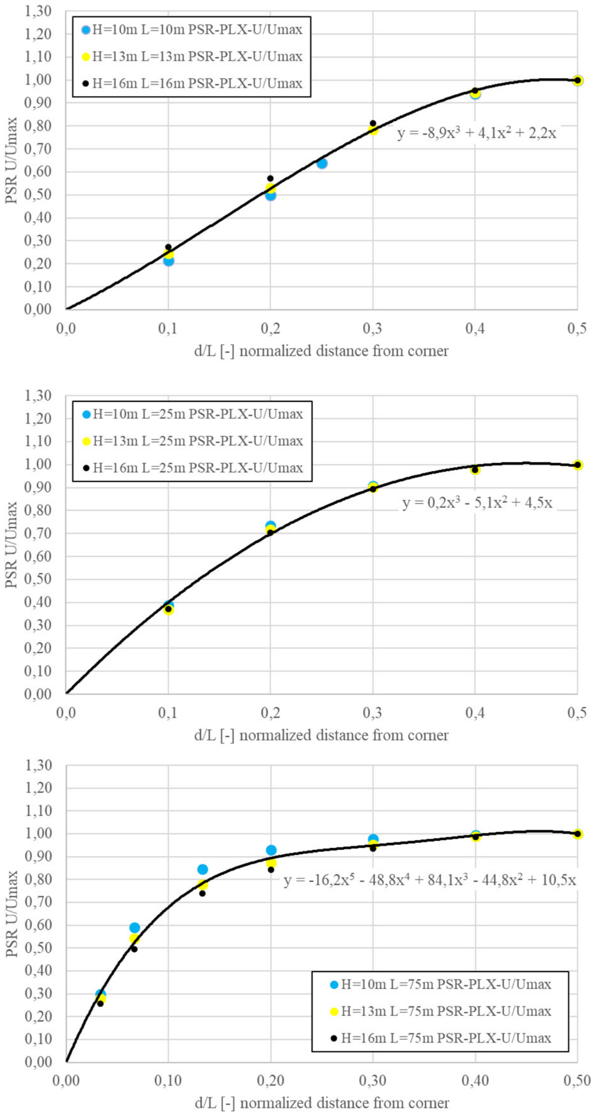

Figure 13. Normalized ratios of PSR-U/PSR-Umax of Hfull=10-13-16m excavation depth and L=25-50-75-100m excavation length in function of normalized distance from excavation corner (d/L)

7 REFERENCES

Barsi, I., Görög, P., Török, Á, 2011. A 4-es metró budai nyomvonala menti kiscelli agyag előfordulások statisztikai és mérnökgeológiai értékelése. In: Török, Á., Vásárhelyi, B. (eds.): *Engineering Geology-Rock Mechanics 2011*. Budapest, Hungary. Hantken Kiadó,

Benz, T. 2007. Small Strain Stiffness of Soils and its Numerical Consequences. PhD Thesis. Stuttgart, Germany. Universitaet Stuttgart.

Deli, Á., Kaltenbacher, T., Havas, P., 2009. Role of monitoring in execution of deep excavations. In: Mahler, A., Nagy, L. (eds.) *Deep Excavations and Retaining Structures*, Budapest, Hungary. ISSMGE Hungarian National Committee.

Görög P., 2008. *Engineering geological assessment of Eocene and Oligocene clayey rocks of Buda.* PhD Thesis. Budapest, Hungary. Budapest University of Technology and Economics.

Faragó, T., Szendefy, J., Szepesházi, A., Karner, B. 2018. Back analysis of a shoring system at the excavation site of M4 subway, Budapest. *XVI DECGE 2018 Proceedings of the 16th Danube - European Conference on Geotechnical Engineering*. Berlin, Germany, Ernst und Sohn.

Kocsisné Bodnár; N., 2015. *Engineering geological reinterpretation of Danube crossing part, Kálvin Square and Rákóczi Square area of metro line no. 4.* PhD Thesis. Budapest, Hungary. Budapest University of Technology and Economics.

Kramer, S.L., 1996. *Geotechnical Earthquake Engineering*. Prentice Wall, Upple Saddle River, New Jersey.

Ou, C.Y., Chiou, D.C., Wu T.S. 1996. Three-dimensional finite element analysis of deep excavations. *Journal of Geotechnical Engineering.* 1996(122). 337-345.

Szepesházi, A. 2016. Back-analysis of a deep excavation in Budapest. In: Ernest, O., Sanda, M. (eds.). *Proceedings of the 25th European Young Engineers Conference*. Bucharest, Romania, Editura Conspress.

Szepesházi, A., 2019. Comparison of 2D and 3D finite element modelling results of deep excavations. In: Huszák, T. (ed.): *Proceedings of the 5th Kézdi Conference*. Pécs, Hungary. Hungarian Geotechnical Society.

Szepesházi, A., Móczár, B., 2022. Deep excavation works in Budapest - Evaluation of deformation monitoring results. *Concrete Structures - Journal of Hungarian Group of fib.* 2022(1), 40-51.

Szepesházi, A., Móczár, B., 2023. Two- and three-dimensional numerical back-analysis of deep excavation case studies from Budapest, Hungary. *Periodica Polytechnica Civil Engineering*. 67(3), 659-670.

Szepesházi A., 2023. *Three-dimensional numerical soil-structure interaction analysis of deep excavations.* PhD Thesis. Budapest, Hungary. Budapest University of Technology and Economics.

Szepesházi, R., Meszlényi, Zs., Radványi, L., 2009. Hungarian practice for retaining structure design according to Eurocode 7. In: Mahler, A., Nagy, L. (eds.) *Deep Excavations and Retaining Structures*. Budapest, Hungary. ISSMGE Hungarian National Committee.

Zdravkovic L. 2009. Modelling deep excavations in 3D analysis. In: Mahler, A., Nagy, L. (eds.) *Deep Excavations and Retaining Structures*, Budapest, Hungary. ISSMGE Hungarian National Committee.

Zsiros, N., Móczár, B., Szepesházi, A. 2018. Back analysis of Budapest Rákóczi square metro4 station deep excavation. *XVI DECGE 2018 Proceedings of the 16th Danube - European Conference on Geotechnical Engineering*. Berlin, Germany, Ernst und Sohn.