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Comparisons between design estimations and measurements on several design sections of a deep excavation in Bucharest

Comparaisons entre les estimations de conception et les mesures sur plusieurs sections de calcul d'une excavation profonde à Bucarest

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ABSTRACT: The paper briefly presents the ground investigation, monitoring program and field measurements of a large-surfaced deep excavation in Bucharest, retained mostly by self-supporting diaphragm walls and on several sections by diaphragm walls supported through steel struts. The detailed investigation program for the ground investigation report is presented (boreholes, CPTs, sCPTs, Downhole test, pumping tests), for assigning the ground model and the design estimation results. Then, the emphasis is on the comparisons made between the measured displacements and the displacements estimated by design and the high variability of these differences for seven design sections of the deep excavation. The values of the measurements are resulted mainly from thirteen inclinometer devices installed in the retaining walls, as well as from topographical measurements of the 3D displacements of the diaphragm walls on displacement marks installed on the capping beam and also from settlement measurements of the neighbouring structures by topographical methods and of the foundation ground by extensometers. The monitoring stages were assigned in accordance to the construction physical stages of the excavation. This whole logical connection between the geotechnical activities (investigation, design, monitoring) together with experimental works and readjusting the models and parameters through back-analysis leads to higher quality construction works and to improved future results based on similar works. However, special attention should be given to model assumptions since the parameters influencing the design estimations are numerous and complex and in can be observed from the comparisons presented that in different situations the results might be quite variable.

RÉSUMÉ: Le document présente brièvement l'investigation de terrain, le programme de surveillance et les mesures sur le terrain d'une vaste excavation profonde recouverte à Bucarest, retenue principalement par des parois moulées autoportantes et sur plusieurs sections par des parois moulées étayés par des entretoises en acier. Le programme d'investigation de terrain détaillé est présenté (forages, CPT, sCPT, test Downhole, tests de pompage), permettant de créer le modèle de sol et les résultats de l'estimation du calcul. Ensuite, l'accent est mis sur

les comparaisons effectuées entre les déplacements mesurés et les déplacements estimés par calcul et la grande variabilité de ces différences pour sept sections de calcul de l'excavation profonde. Les valeurs des mesures résultent principalement de treize dispositifs d'inclinomètre installés dans les parois de soutènement, ainsi que de mesures topographiques des déplacements 3D des parois moulées sur des marques de déplacement installées sur la poutre de couronnement ainsi que de mesures de tassement des structures voisines par méthodes topographiques et du sol de fondation par des extensomètres. Les étapes de surveillance ont été attribuées en fonction des étapes physiques de la construction de l'excavation. Toute cette connexion logique entre les activités géotechniques (investigation, calcul, surveillance) et les travaux expérimentaux et le réajustement des modèles et des paramètres par «back-analysis» conduit à des travaux de construction de meilleure qualité et à de meilleurs résultats futurs basés sur des travaux similaires. Cependant, une attention particulière doit être accordée aux hypothèses de modèle car les paramètres influençant les estimations de calcul sont nombreux et complexes et les comparaisons présentées permettent d'observer que les résultats peuvent être assez variables.

Keywords: Deep excavation; Site investigations; Monitoring; Inclinometer; Numerical methods

1 INTRODUCTION

1.1 Aim of the paper

Deep excavations in urban areas are associated with several risks related to their behaviour and influence on the neighbouring buildings. These risks can be reduced when there is a proper knowledge and checking of the design assumptions both prior to execution, through site investigation and during construction, through measurements and records. Moreover, one of the design assumptions according to current Eurocode 7 is that "adequate continuity and communication exist between the personnel involved in data-collection, design and construction" (SR EN 1997-1:2004). This is especially needed, in almost real-time, when Observational Method is considered or resulted as necessary.

Another important aim of following all the project data with enough confidence and clarity is to perform back-calculations to improve further models which lead to more efficient design.

In the present paper, we present a project where the working geotechnical team conducted a complete approach of the deep excavation works which imply site investigations, calculation and design, monitoring and interpretation (Ene et. al., 2016).

1.2 Brief description of the project

The project presented in this paper refers to three office buildings with 2B+SB+10F+Tech. The site of the development is about 20 000 sqm, while the excavation was performed on about 12 000 sqm surface, common for all the three buildings (Figure 1).

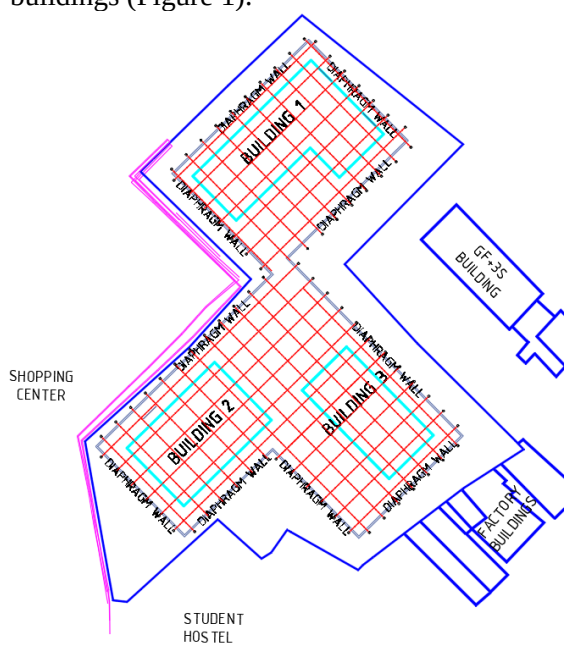

Figure 1. Site and project layout

Because prior to starting the execution works, there were several remaining of older buildings, it was necessary to perform preliminary excavation works of 3 to 4 m depth in order to extract these remaining and perform the diaphragm wall from a lower level.

2 GROUND INVESTIGATION

In order to determine the parameters of the foundation ground and to create typical geotechnical profiles, field and laboratory investigations were carried out, defined by a Scope of Works developed by the designer, as seen in Figure 2: 10 geotechnical boreholes with depths ranging from 25 m to 50 m (with disturbed and undisturbed soil samples and SPT tests), 2 additional drillings of 10 m and 15 m depth (equipped as satellite wells for pumping tests), 7 CPT tests (+2 additional), 5 sCPT tests, 2 pumping tests, 1 Downhole test, 8 pits for exposing the foundations of the dead-wall neighbouring buildings and the existing heating channel, seismic micro-zoning study, equipping the boreholes as piezometric wells for 18 months of groundwater monitoring.

Due to the height and function of the buildings, the loads transmitted to the foundation ground, the location of the site in a seismic area, and considering the presence of groundwater near the surface, the project was classified into the geotechnical category two (GK 2), corresponding to the degree of medium difficulty, according to European and Romanian regulations (SR EN 1997-1:2004, SR EN 1997-2:2007, NP 074-2014). This involves carrying out routine investigations and using routine design methods. However, taking into account the scale of the project, the fact that special laboratory and field tests have been carried out which have been carefully processed and correlated and that the excavation works were to be carried out on a considerable depth through a non-homogeneous filling layer, we recommended that the design method to be complex by advanced calculation, which may not be part of the technical regulations in force, corresponding to the geotechnical category 3.

Figure 2. Layout of the ground investigations

Based on the laboratory tests, following statistical analysis and based on experience in similar works, characteristic values of geotechnical parameters were proposed for the computation of the retaining structures, as shown in Table 1.

Table 1. Stratigraphy and main geotechnical parameters (characteristic values) for the design model

Layer	Characteristic values				
	γ_{nat} (kN/m^3)	E_{oed} (kN/m^2)	c (kPa)	Φ (°)	G_0 (kN/m^2)
Filling	19.0	5	15	10	60
Silty clay	19.5	7	30	17	-
Sand with gravel	21.0	35	0	33	130
Clay to sandy clay	20.0	16	42	21	200
Clayey sand	20.0	23	0	33	250
Clay	19.9	21	62	16	350
Fine sand	19.1	28	0	33	450

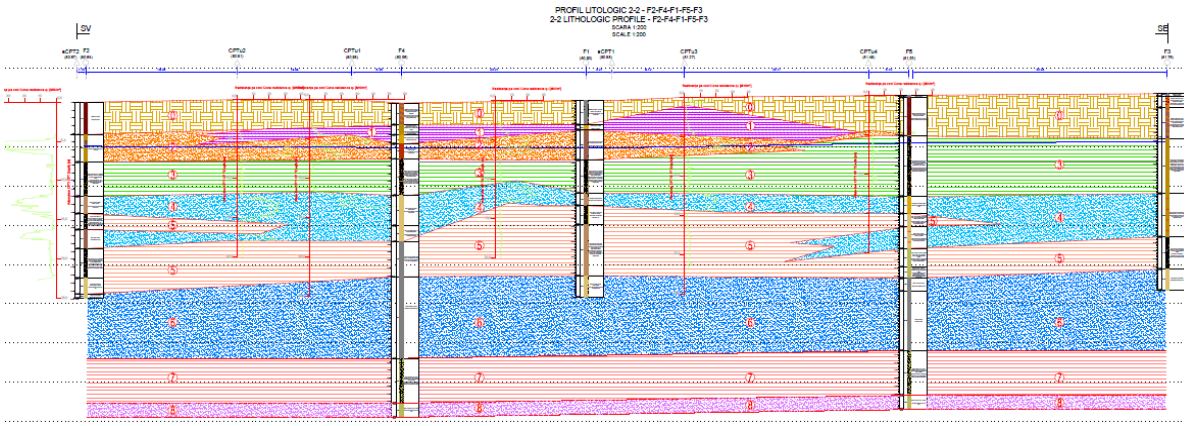

Figure 3. Lithologic section with part of the geotechnical investigations carried out for the Ground Investigation Report

The parameters in Table 1 are:
γ_{nat} – unit weight at natural moisture content;
E_{oed} – oedometer modulus referred to the mean geologic load of the layer;
c – cohesion in effective stresses;
Φ – internal friction angle in effective stresses;
G_0 – shear modulus for small strain domain.

3 DESIGN ASSESSMENT

The excavation retaining system was dimensioned using a 2D Finite Element model for plane strain state in Plaxis software, considering an elasto-plastic constitutive law with small strain hardening for the ground. The soil-structure interface was modelled using Mohr-Coulomb law, associated with the soil strength parameters reduced by R_{inter} factor considered 0.7.

The retaining system consisted of 60 cm thick diaphragm walls either self-standing or supported by one row of inclined struts with different lengths resulted from calculations or for water tightness conditions.

Due to the variability of the geotechnical conditions on the site including the groundwater, adjacent constructions and geometry, solution for preliminary excavation and the excavation depth, seven design sections were considered in the design as presented in Table 2.

Table 2. Characteristics of the design sections

Section	Wall length, m	Excavation depth, m	Preliminary excavation
Diaphragm wall supported by one row of inclined struts			
S1	20	13.35	4m - 1:1.15 slope
S3	18	12.55	-
Unsupported diaphragm wall			
S2	18	11.00	4.3 m - 1:2 slope and Berliner system
S4	19	12.55	4.3 m - 1:2 slope and Berliner system
S5	19	12.55	3 m - 1:2 slope
S6	19	12.55	2m - 1:2 slope
S7	19	11.40	-

Examples of the design characteristic sections representations are given in Figure 4 for the diaphragm wall supported by struts and in Figure 5 for the self-supporting diaphragm wall.

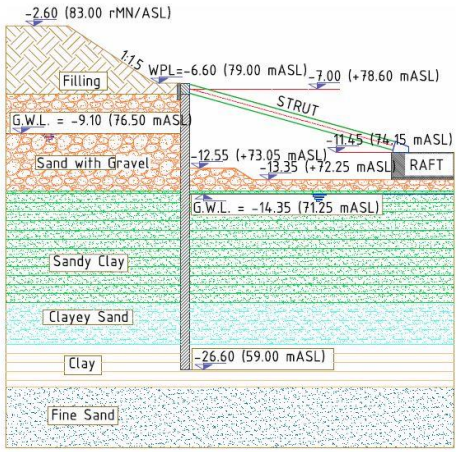

Figure 4. Section 1 of the excavation pit - diaphragm wall supported by struts

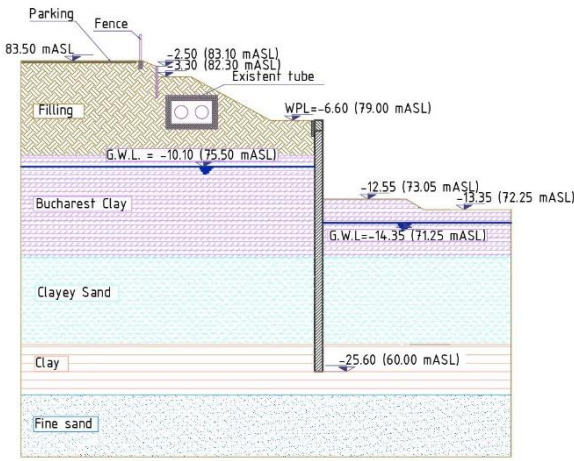

Figure 5. Section 4 of the excavation pit - self-supporting diaphragm wall

4 FIELD MEASUREMENTS

4.1 Monitoring Program

The monitoring works and measurements given in the design of the excavation and implemented during construction were as follows:

-Neighbouring buildings – cracks and vertical displacements on 51 settlement markers;

-Retaining walls at the property limit - 3D displacements on 12 topographic markers and tilt on 5 tilt steel plates measured with tiltmeter;

-Groundwater level in 16 piezometric wells both inside and outside the excavation pit, equipped in the lower and upper aquifer;

-Vertical displacements of the foundation ground, in 5 extensometers 50 m deep each;

-Horizontal displacements of the diaphragm wall in 13 inclinometer columns 25 m deep (installed with the base below the diaphragm walls) and on 50 displacement markers on the capping beam.

Also, for the new buildings, topographical measurements of the vertical displacements on 46 settlement markers were provided.

The measurements were performed before starting the construction works and then at each excavation stage and also at a maximum interval of two weeks during the execution of the infrastructure.

4.2 Groundwater level measurements

In short time after completing the diaphragm walls closing the excavation pit, it was observed through piezometric measurements that the water level raised on the North area and lowered on the South area because the precinct created a barrier for the groundwater (Figure 6).

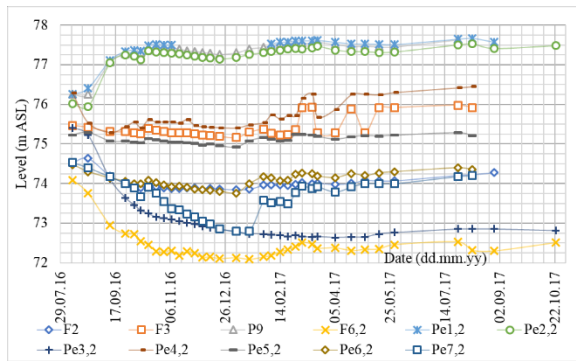

Figure 6. Time variation of the upper aquifer level measured in exterior piezometric wells

Though this phenomenon is justified by groundwater flow towards Dambovita River located about 500 m South and was intuited from the site investigations, the effect was greater than expected and re-calculations were performed to check the retaining system.

4.3 Diaphragm wall displacement

In Table 3 are presented the maximum values measured in each inclinometer column and on the corresponding topographical marks in comparison with the calculated values at SLS, using characteristic values of the geotechnical parameters.

Table 3. Horizontal displacements resulted from calculations versus measured displacements

Section	**Displacement (mm)**			
	Calculated	Measured		
		Inclinometer		Topo.
S1	35	*I1*	12	15
		I2	9	11
		I12	8	6
		I13	16	14
S2	27	*I3*	7	5
S3	21	*I11*	10	4
S4	43	*I4*	18	10
		I5	29	27
S5	48	*I6*	14	13
S6	32	*I7*	10	9
		I8	18	13
		I9	18	6
S7	15	*I10*	4	6

In most of the cases, the topographical measurements are in good correspondence with the inclinometric measurements – within the measuring accuracy – and no corrections were needed.

The results of calculations at SLS in terms of maximum horizontal displacement (after struts removal, where the case) and the corresponding measured values in the inclinometric columns are presented in Figure 7 and in Figure 8.

It must be noted that all measurements were performed by the same personnel, using the same equipment throughout the project and significant repeatability was obtained due to the frequency provided. In Figure 10 and Figure 9 it can be seen that confirmation and stabilization were obtained for the same execution stage during the works. So, it can be considered that all the data obtained offer enough trust and the scatter might be due to different site conditions.

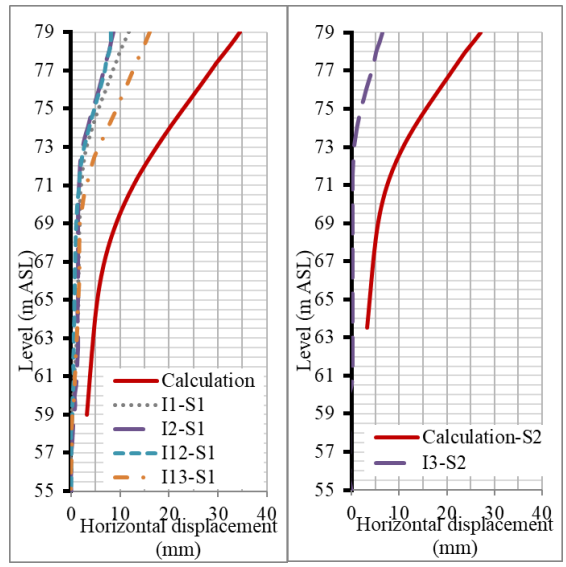

Figure 7. Horizontal displacements of the diaphragm wall for Section 1 and Section 2

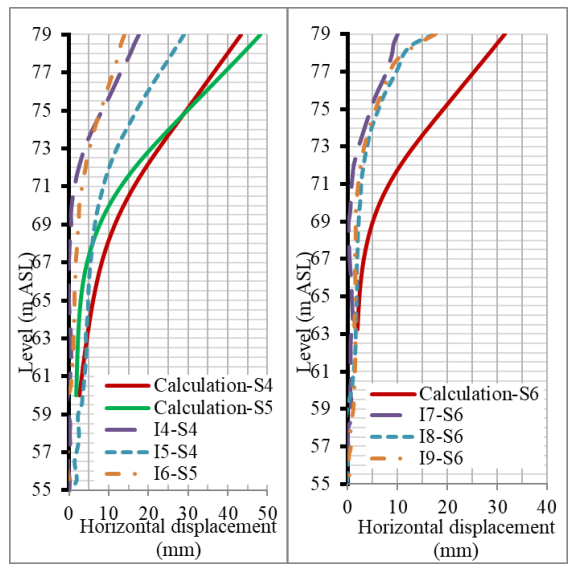

Figure 8. Horizontal displacements of the diaphragm wall for Section 4, Section 5 and Section 6

For Section 1, a horizontal displacement of 34 mm was estimated by design, while measurements revealed 8 to 16 mm. While this difference can be justified by cautious estimations, the difference between the measurements obtained in the inclinometric columns is important: simple to double and greater than the measuring precision.

For Section 2, 3, 5, 6 and 7, the difference between the design and the measurements is around 25% to 35%.

On the area of Section 4, with greater uncertainties regarding the geometry and ground due to the works outside the excavation, the design model also gave less favourable results and Observational Method was implemented from the start. This implied that intervention measures were drafted in the design. The limit imposed was set to 30 mm displacement, as a best estimate value, following that when this value was reached intervention measures were prepared.

For Section 4, the measurements were closer to the estimations, the difference resulting between 40% in I4 and 67% in I5.

In the case of Section 6, a closer correspondence was obtained between the measurements in different inclinometric columns.

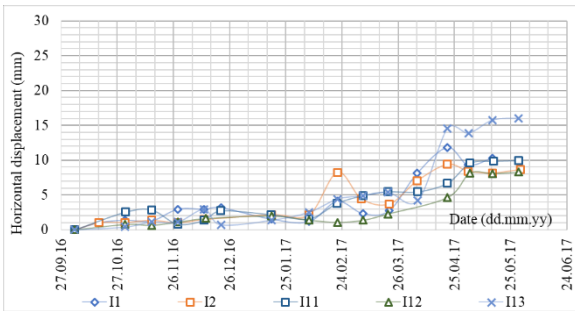

Figure 9. Time variation of the displacements in inclinometers on the areas of diaphragm wall supported by struts

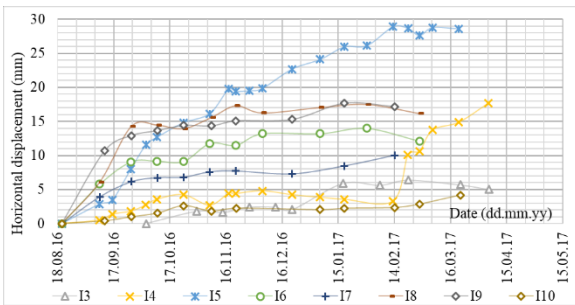

Figure 10. Time variation of the displacements in inclinometers on the areas of unsupported diaphragm wall

4.4 Ground vertical displacement

Vertical displacements of the ground in depth were measured through extensometers and it was possible to record both heave due to the excavation and settlement during construction of the new buildings, especially before the topographical marks could be installed and measured.

The results of calculations at SLS in terms of maximum heave (after excavation) and the corresponding measured values in the extensometers are presented in Figure 11 and the history of the vertical displacements (heave and settlement) during construction are given in Figure 13.

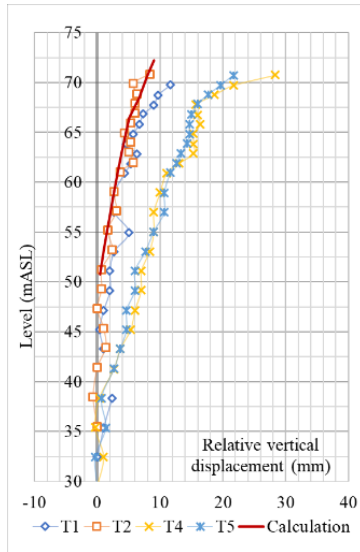

Figure 11. Vertical displacements of the foundation ground

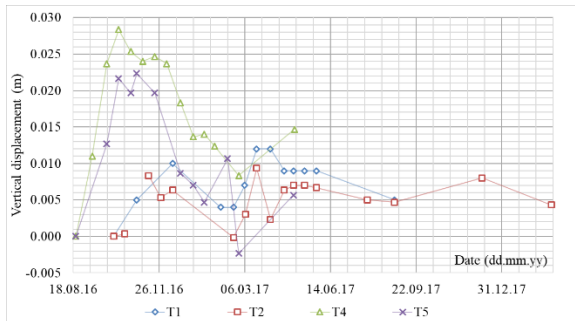

Figure 12. Time variation of the displacements measured in extensometers T1, T2, T4 and T5

The results obtained by calculation expected about 9 mm heave, while the results obtained through measurements showed about 25 mm.

4.5 Vertical displacements of the neighbouring buildings

In Figure 13 it can be observed that, though the values are very small for the safety and stability of the neighbouring buildings (between 2 mm settlement and 4 mm heave), the entire execution history was well correlated with the building vertical displacement: small settlement during the execution of the diaphragm walls, heave during excavation and again settlement during construction of the new buildings.

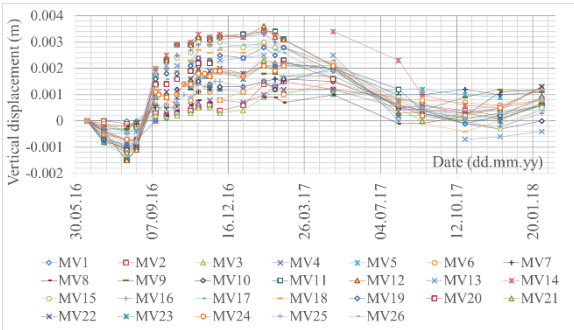

Figure 13. Time variation of the vertical displacements measured on the settlement marks mounted on one of the neighbouring buildings

In usual excavation MEF models, the vertical displacements due to the slurry wall execution process are not intercepted and neither the heave following the excavation is not well correlated.

5 CONCLUSIONS

High variability of the measured data was obtained in some cases, with enough confidence of the results, on sections considered as similar within the design, based on comprehensive site investigation. This observation leads to the obvious conclusion that special care should be given when performing back-calculation and for generalization based on limited results.

As observed in several cases, it is again confirmed that current MEF models do not correlate well vertical and horizontal displacements of the ground. A good calibration of one of these parameters would not suite the other, as previously attempted (Popa et. al., 2018).

What is more, though experienced from the design stage, the need to implement the Observational Method resulted as more obvious during the construction works based on the monitoring results.

The complete interaction between the site investigations, design and measurements allowed fast reaction and implementation of changes where necessary leading to a good control of the risks. Needless to say, more powerful tools such as BIM in geotechnical engineering is a must for such complete approach in the current century, due to the clearer views it can offer, fast processing and decision making.

6 REFERENCES

Ene A., Marcu D., Popa H., 2016. Complete approach of the deep excavation works. *Proceedings of Two seminars of TC207 ISSMGE in Edinburgh and Pune in 2015*, (Eds: Lisyuk, M., Ulitsky, V. & Choudhury, D.), 19-24. Georeconstruction Engineering Co., Russia.

SR EN 1997-1:2004. *Eurocode 7: Geotechnical design. Part 1: General Rules.*

SR EN 1997-2:2007. *Eurocode 7: Geotechnical design. Part 2: Ground investigation and testing.*

NP 074:2014. *Norm regarding the geotechnical documentations for construction works.*

Popa H., Ene A., Miritoiu R., Ionescu I., Marcu D., 2018. Back analysis of an embedded retaining wall for a deep excavation in Bucharest. *Proceedings of XVI Danube - European Conference on Geotechnical Engineering*, (Eds: Jovanovski, M., Jankulovski, N., Moslavac, D. & Papic, J. Br.), 743-748. Wiley Ernst & Sohn, Skopje, Macedonia.