Some Remarks on the Influence of Deep Excavations on Neighbouring Buildings

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SOME REMARKS ON THE INFLUENCE OF DEEP EXCAVATIONS ON NEIGHBOURING BUILDINGS

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ABSTRACT

Increasing density of urban areas leads to building high-rise buildings with deep foundations, enabling their basements for car parking and facilities. Increasing depth of the foundation of these buildings increases also the need for more rigid earth retaining systems. Thus, generally, due to the importance of the neighboring buildings, great care has to be taken in the design process of the retaining structure and the support system of deep excavation in densely built urban areas. The paper summarizes a parametric study on a geotechnical model of a deep excavation, proper to Bucharest subsoil, Romania. The analysis of the excavation was done on the basis of the finite element method. The constitutive soil model used for simulating the soil behavior took into account the fact that the specific phenomenon in the soil, during the excavation process, is based on unloading. The most important factors which affect the influence zone of the excavation (excavation depth, excavation width, distance to neighboring buildings, and the weight of the neighboring buildings) are shortly described and their importance on estimating the displacements of the retaining structure are discussed on the basis of the FE analysis results.

INTRODUCTION

The increasing density of urban areas has made tall buildings with deep foundations a necessity. In these conditions car parking and other facilities are located in their basements. The increase of the foundation depth of these buildings generates the need for larger and stiffer retaining works. This trend is also reinforced by the need to found on stiffer soils and the one of creating underground areas for locating the utility networks.

The present paper aims at analyzing the influence of parameters that controls the performance of deep excavations, from the point of view of the effects on the existing neighboring buildings. Bearing this in mind, the influence of the existing buildings upon the response of new excavations is analyzed. Since the relation between the excavation and the neighboring building is considered reciprocal, the effects of new excavations on the behavior of neighboring buildings are also taken into account. Furthermore, in the current paper it is also analyzed the influence of building's type on its admissible excavation–induced deformations, as well as the parameters variation for quantifying the performance of excavations with the building-excavation distance. Moving onwards, one can observe the relationship between the overburden load exerted by the neighboring building and the performance of excavations (expressed in terms of forces and lateral deformations of the retaining wall, as well as the prop forces).

The study is motivated by the problems regarding the performance of deep excavations in soft to medium soils such as the ones encountered in Bucharest, Romania. Thus, there is a need to perform good estimations regarding the soil displacements since this is a very important criterion for preventing the damage of neighboring constructions and utility networks. Using nonlinear finite element analysis represents a rational technique which is frequently used in current practice as it can integrate constitutive models for simulating soil real behavior and it also takes into account the complexity of the various construction stages. The above-mentioned arguments motivate the choice made, that is – use of nonlinear finite element analysis, which is also very useful in estimating the soil response for deep excavations and their reciprocal relation with the existing neighboring buildings.

SYSTEMIC ANALYSES OF EXCAVATIONS

This chapter presents the analysis of the system composed of excavations and their adjacent buildings, by considering the soil-structure interaction. Thus, there are analyzed the parameters influencing the behavior of excavations and their effects on the neighboring built environment. These parameters involve the width of the excavation, the bending stiffness of the retaining wall, the configuration and stiffness of the strutting system, the rigidity of the neighboring buildings and last but not least, the distance between the excavation and the adjacent buildings. Also, it will be analyzed the influence of different factors affecting the behavior of deep excavations in dense built areas.

The analysis was conducted by means of FEM, considering plane strain conditions. This method, unlike other calculation methods (such as limit equilibrium method or beam on elastic foundation method) allows for estimating the forces and the displacements of the retaining wall and also for the diagnosis of stress and strain state induced in the soil by the execution of deep excavations.

For establishing the factors that influence the performance of deep excavations, we have created a geotechnical model of an excavation. This was done by statistical analysis of a database for retaining walls and ground movements due to deep excavations. Before statistically analyzing the database compiled in 2001 (Long 2001), was extended by adding 27 new case studies on deep excavations (Căpraru, 2012).

Description of the Parametric Study

For understanding the effects of existing buildings on new excavations' performance, firstly it was necessary to determine a characteristic model for studying the influence parameters. The parametric study aims at identifying possible effects of neighboring buildings on new excavations. Thus, the parameters of the characteristic model refer to the following: excavation depth, retaining wall type, its depth and bending stiffness, strutting system configuration and axial stiffness, the height regime of neighboring buildings (which also affects their rigidity) and the excavation-neighboring building distance. All these features of the model, together with the soil layers and geotechnical parameters were determined based on the technical literature review (Căpraru, 2012).

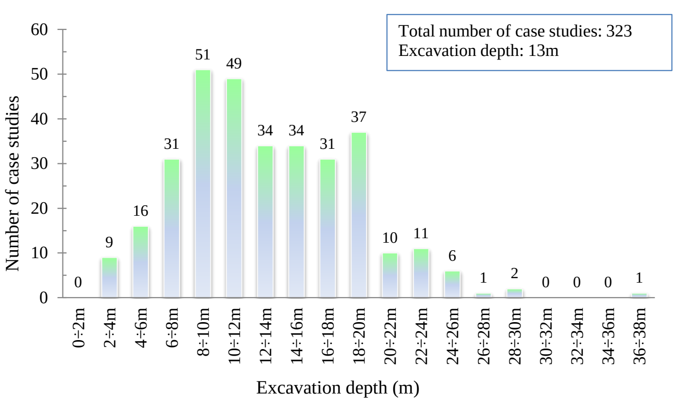

Fig. 1. Distribution of the case studies based on their excavation depth.

Excavation's depth. Figure 1 presents the statistical distribution of case studies based on the excavation depth. To find the optimum distribution of case studies based on their excavation depth, the data was grouped in consecutive series of 2m step. From the analysis of this figure, one can easily observe that for most of the case studies (approx. 83% - meaning 267 case studies) the excavation depth is comprised in the range 6÷20m. Moreover, the medium excavation depth is about 13m. Thus, the excavation depth of the characteristic model was chosen to be H_e=13m.

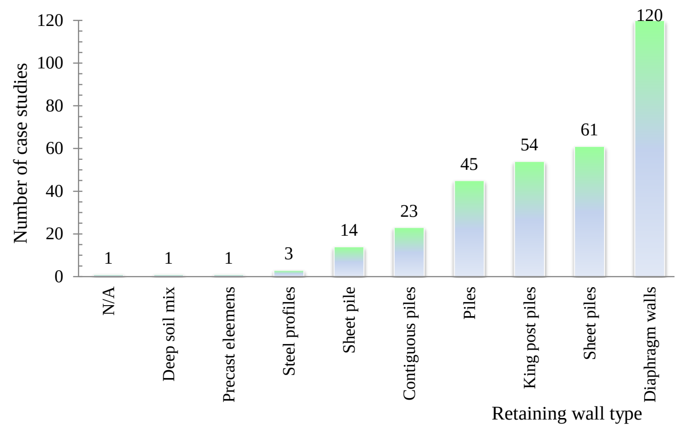

Fig. 2. Distribution of the case studies based on the retaining wall type.

Retaining wall type and its bending stiffness. Figure 2 presents the statistical distribution of case studies based on retaining wall type. From this figure one can easily see that, among all the case studies in the extended database, the predominant type is the diaphragm wall (120 case studies meaning approximately 37%). This high percentage can be explained by the large stiffness of this type of wall compared to other conventional retaining wall types.

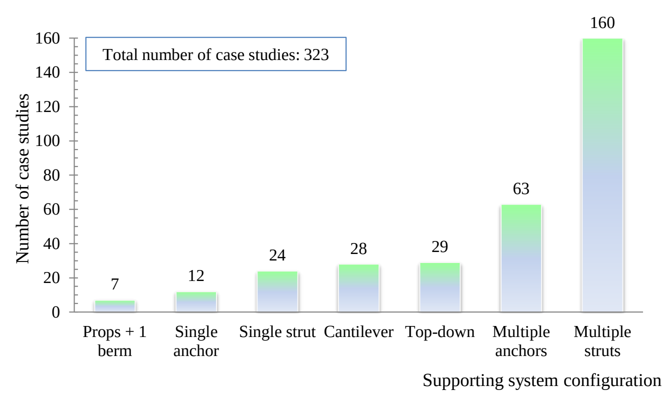

Fig. 3. Distribution of case studies based on the supporting system configuration.

Following statistically analysis of the extended database, the bending stiffness of the excavation's retaining wall resulted in the value $EI=1.75\times10^6 kNm^2/m$. According to the recommendations provided by Saidel *et al.* (2010), wall depth was set at $H_p \approx 23.5m$.

Configuration of The Strutting System and Distance Between Strutting Levels. Figure 3 illustrates the statistical distribution of case studies based on the configuration of the strutting system. Among the types of excavations' support systems included in the extended database, most common are multiple levels of struts (about 50% - meaning 160 case studies), followed by multiple level of ground anchors (about 20% - meaning 63 case studies). The high in-use of multiple levels of props among recorded case studies, might be attributed to the ease of their installation and the fact that this type of support system allows for a greater ease in the technological sequence of operations that occur in the excavation pits. However, unlike some of the supporting types listed in Fig. 3, the struts could add a substantial stiffness contribution to the supporting system of an excavation, even for placement at "large" in-plane distances.
From the facts presented above, for the characteristic geotechnical model it has been considered appropriate the choice of a supporting system consisting of multiple levels of struts, placed at a vertical distance of approximately $h_s=4m$. This is also motivated by the common use of such a propping type in Romanian current practice. As the depth of excavation, previously established is 13m, there were considered 3 levels of struts placed at a vertical distance of 4m (i.e. EL-2m, EL-6m, EL-10m).

Table 1. Neighboring building parameters

Building type	No. of stories	Total load	Bending rigidity
[-]	[-]	[kN/m^2]	[kNm^2/m]
A	1	37.5	2.03×10^7
B	2	56.3	3.04×10^8
C	3	75.0	1.42×10^9
D	4	93.8	4.25×10^9
E	8	168.8	4.15×10^{10}

Neighboring Buildings. For conducting the parametric study, five types of buildings (with a height regimen of 1÷8 stories – typical for Bucharest) were considered. The buildings' characteristics are presented in Table 1. For each story of the building a height of 3m and a dead load of 15kPa were considered in the calculations within the parametric study.
The simulation of building behavior was achieved by modeling it as a surface beam (taking into account both the bending stiffness and the axial stiffness of the building). In calculation of the bending stiffness as well as the axial stiffness of the surface beam, only the reinforced concrete slabs' rigidity were considered (ignoring the stiffness of vertical structural elements). The model was proposed by Potts and Addenbrooke (1997). To study the influence of the stiffness of a building located at the ground surface on constructing bored tunnels, they used a surface beam model. The beam used to simulate the building was assumed to be elastic and its interface with the soil to be rough.

Soil Stratigraphy and Geotechnical Parameters. For the characteristic model, the soil stratigraphy adopted in finite element analysis is the one specific to Bucharest. Data regarding this soil stratigraphy and geotechnical parameters were gathered from the technical literature (*e.g.* Saidel *et al.*, 2010, Tschughnigg and Schweiger, 2010).
For the general case of deep excavation, in which parts of the soil encounters stress path changes due to unloading and other parts due to reloading or primary loading, constitutive soil models with two yield surfaces lead to proper results (Schweiger, 2008). In numerical analysis, this is achieved by part of the mesh experiencing primary loading (in shear) and other part unloading. Such a constitutive model is the hardening soil model (Schanz *et al.*, 1999), implemented in PLAXIS code (Brinkgreve et al., 2006) and which, was used for the current analysis.

Table 2. Geotechnical parameters of the soil layers for the parametric study

Parameter		Meaning	Layer			
			Silty clay	Sand with gravel	Clay	Fine sand
h	[m]	Layer depth	6	12	7	25
γ	[kN/m^3]	Unsaturated unit weight	18	20	19	20
γ_{sat}	[kN/m^3]	Saturated unit weight	20	21	20	21
φ	[°]	Angle of internal friction	14	28	17	30
c	[kPa]	Cohesion	25	0	25	0
ψ	[°]	Dilatancy angle	0	0	0	0
ν_{ur}	[–]	Poisson ratio for unloading/reloading	0.20	0.20	0.20	0.20
E_{50}^{ref}	[kN/m^2]	Secant stiffness modulus in standard drained triaxial test	15000	30000	20000	35000
E_{oed}^{ref}	[kN/m^2]	Oedometer modulus	15000	30000	20000	35000
E_{ur}^{ref}	[kN/m^2]	Unloading/ reloading stiffness modulus	60000	90000	80000	105000
m	[–]	Power for stress dependency (acc. to von Soos, 2001)	0.7	0.6	0.7	0.5
p^{ref}	[kPa]	Reference pressure	100	100	100	100
$k_0^{(NC)}$	[–]	At rest earth pressure coefficient	0.700	0.530	0.750	0.500

Geotechnical parameters adopted in the calculations together with the thickness of layers are presented in Table 2. The groundwater level is considered to be located at a medium depth of 7m bellow the ground surface.

Finite Element Model Boundaries. The model boundaries were settled based upon the recommendations issued by Bakker (2005). Geometry of the characteristic model is presented in Fig. 4.

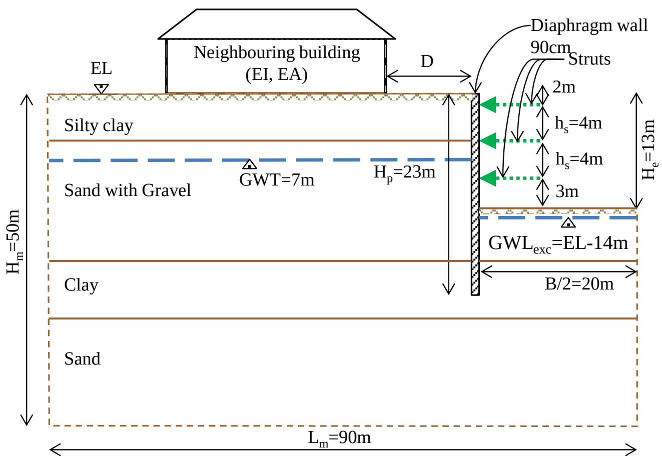

Fig. 4. Geometry of the FE model for the parametric study.

During the FEM analysis, the following calculation steps were performed, but only results for the final stage are referred to in the current paper.
–Step 0: Initial phase (k_0 procedure: $\sigma'_v=\gamma\times h$; $\sigma'_h=k_0\times\sigma'_v$);
–Step 1: Simulation of building (surface beam);
–Step 2: Activate wall (wished-in-place), set displacements to zero;
–Step 3: Excavation to level EL–2.50m;
–Step 4: Activate strut at level EL–2.0m;
–Step 5: Excavation to level EL–6.50m;
–Step 6: Activate strut at level EL–6.0m;
–Step 7: Lowering of GW table to –11.50 m inside the excavation pit;
–Step 8: Excavation to level EL–10.50m;
–Step 9: Activate strut at level EL –10.0m;
–Step 10: Lowering of GW table to EL–14.00m inside the excavation pit;
–Step 11: Excavation to level EL–13.00 m.

Parametric study. The variables considered in the parametric studies were the overburden load of the neighboring building, the stiffness of the building and the distance between the excavation and the neighboring building. Table 3 presents the distances between the excavations and the neighboring building considered for the parametric study.

Results of the parametric study.

This section provides the results of the parametric study by means of FEM analysis. To analyze the effects of the existing buildings on designing new excavations and the influence of excavations on existing buildings, in the numerical analysis there were monitored following parameters: maximum lateral displacement of the retaining wall, settlements and angular deformations of the neighboring building, lateral movements the building corners, maximum bending moment in the retaining wall, axial forces in the propping levels.

Table 3. Distances between the excavation and the neighboring building considered in the parametric study

Case	D1	D2	D3	D4	D5	D6	D7
Distance (m)	1.3m (=0.1 H_e)	2.6m (=0.2 H_e)	3.9m (=0.3 H_e)	5.2m (=0.4 H_e)	1.3m (=0.5 H_e)	10m (≈0.75H_e)	13m (=1.0 H_e)

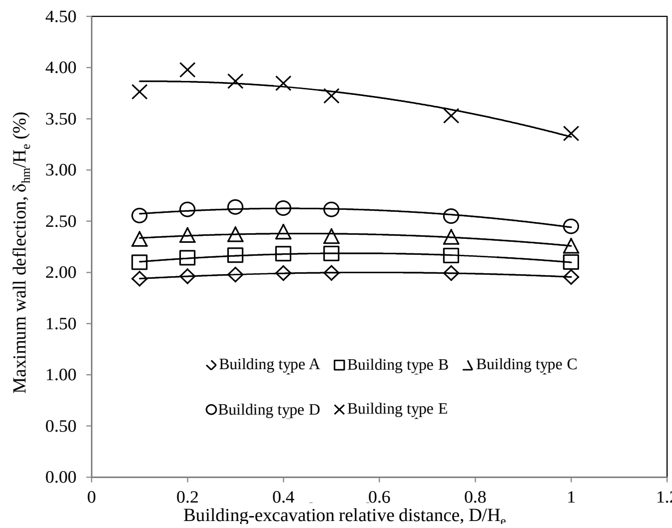

Fig. 5. Variation of normalized maximum lateral wall deflections with relative distance excavation-building.

Displacements of the retaining wall. The variation of retaining wall's maximum horizontal displacements with excavation-neighboring building distance, depending on the type of building (rigidity and total load) is represented in Fig 5. Following the normalization of these values, with the excavation depth, one can observe that the relationship between the maximum lateral wall deflection (δ_{hm}) and the distance excavation-neighboring building (D) might be expressed by equation (1):

$$(\delta_{hm}/H_e)= a_i(D/H_e)^2 + b_i(D/H_e) + c_i \quad (1)$$

The parameters a_i, b_i and c_i in equation (1) depend, for a certain soil stratigraphy, on the type of neighboring building and the overburden load (Căpraru, 2012).

Settlements of the neighboring buildings. According to the case studies compiled in the extended database, values of the excavation induced settlements are known for approx. 40% of the case studies (130 case studies). Thus, within the total available data, maximum settlements values are comprised in the range 0÷600 mm, while for the case studies with diaphragm retaining walls (120 case studies) the maximum ground settlements are comprised in the range 2÷220mm. This clearly emphasizes a reduction of the settlements values which could be put on the diaphragm wall larger stiffness, compared to other retaining wall types recorded in the extended database. For the characteristic model analyzed in the current study, the values of maximum settlements of the neighboring buildings have resulted within 6 to 48mm. Comparing these values with the ones reported in the extended database, one may conclude that the maximum building settlements are framed within the acceptable limits. From Fig. 6 it is observed that, regardless of the building height regimen, maximum normalized settlement (divided by the excavation depth) decreases with increasing distance excavation-building (D). The gradient of this trend depends, in this case, on the rigidity of the building: the buildings whose flexural rigidity is higher (buildings with more than 1 story, or for which the ratio length/height is smaller, as reported by Boscardin and Cording, 1989) will encounter a greater settlement gradual decrease.

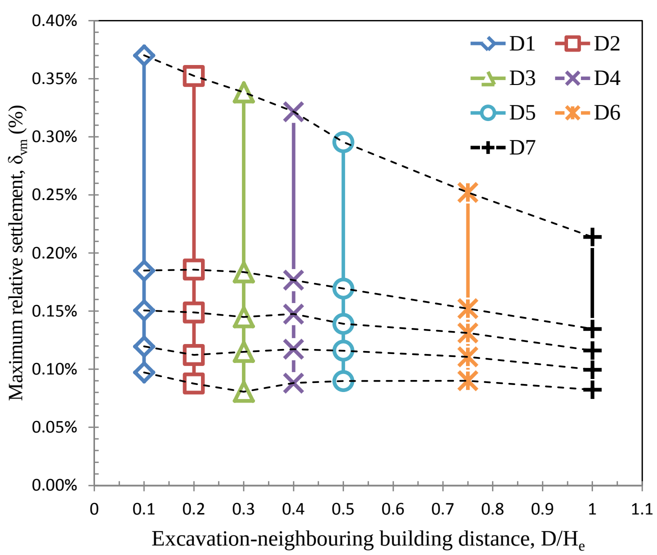

Fig. 6 Variation of neighboring buildings' normalized maximum settlements with excavation-building distance.

Figure 7 presents the variation of maximum retaining wall deflections with maximum settlements. This presentation proposes for the validation of the results achieved within the parametric study. As it can be seen in Fig. 7, the values of maximum settlements resulting from numerical analysis, are bordered within the range $0.4\delta_{hm}$÷$1.0\delta_{hm}$, while for the case studies data recorded in the extended database, these limits are set in the range $0.4\delta_{hm}$÷$3.0\delta_{hm}$, (there are few cases for which these values are exceeded).

<u>The relation between the retaining wall lateral displacements and the neighboring building settlements</u>. Calculated lateral displacements were in the range 22mm (for the case with no neighboring building) to 51mm (for building type E located at a distance $D2=0.2H_e=2.6$m), while the maximum displacement recorded in the database were in the range 1÷160mm (for the 120 cases with diaphragm walls). These aspects lead to the conclusion that there is a critical distance between the excavation and the neighboring building $D_{cr}=0.1H_e$÷$0.5H_e$ for which the buildings will record a maximum settlement and for which the retaining wall will record a maximum lateral deflection.

Considering that the characteristic model resulted following a statistical analysis of a quite large database of excavations case studies, the results of the parametric study are considered appropriate. It should be noted, however, that each excavation is unique in its own way, through its influencing factors. Therefore, it has to be conducted a detailed analysis of the influencing factors and the way they interact.

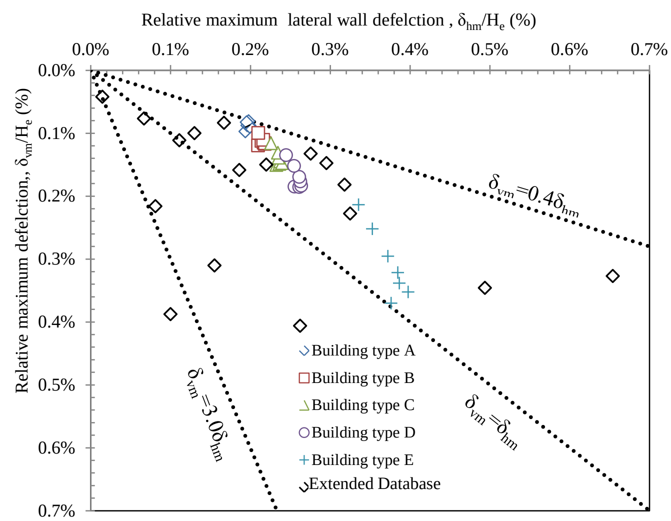

Fig. 7 Normalized maximum retaining wall deflections vs. normalized maximum settlement.

Analysis in terms of induced angular distortion (β) and tensile lateral strains (ε_h) of the neighboring buildings leads us to the conclusion that, deep excavations, having a certain depth H_e, located at a distance smaller than $0.5H_e$ in relation to an existing building could generate to this a degree of damage included in classes Negligible to Slight (acc. to the criteria proposed by Son and Cording, 2005). To emphasize this, Fig. 8 presents the positioning of excavation-induced degree of damage to neighboring buildings. The chart is designed following the provisions of the limiting deformation criterion proposed by Boscardin and Cording (1989), and improved by Son and Cording (2005).

Conjoining the points in Fig. 7, representing the calculated displacements for the characteristic model, will result in curves whose gradients define the maximum settlement based on the retaining wall lateral deflection. Thus, we define this gradient as an Excavation Influence Index (c_{ie}).

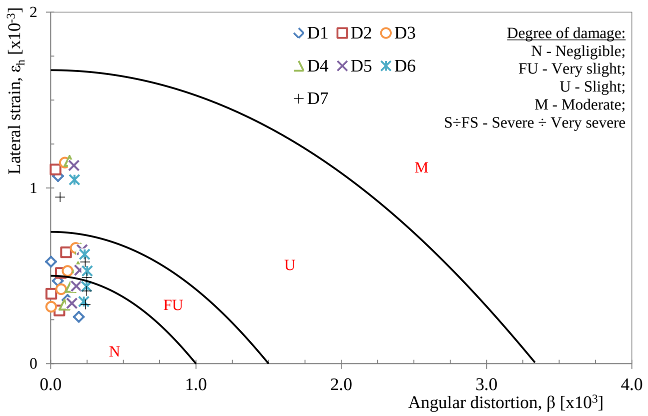

Fig. 8. Comparison of damage level for the neighboring buildings to chart of Boscardin and Cording (1989).

Figure 9 presents the variation of the excavation influence index with the number of stories of the neighboring building. One might say that this index incorporates factors such as the building's weight (represented as an overburden dead load), its stiffness and excavation-neighboring building excavation distance (D).

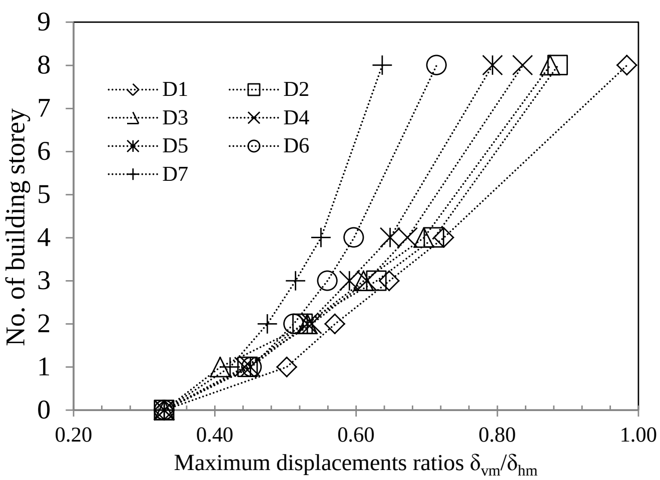

Fig. 9. Ratio of the maximum settlement and the maximum lateral deflection of the retaining wall δ_{vm}/δ_{hm} versus the number of stories of the neighboring building.

To formulate the basis of this index, Fig. 9 plots the ratio of the maximum settlement and the maximum lateral deflection of the retaining wall versus the number of stories of the neighboring building.

It should be mentioned that zero levels (in Fig. 9 and Fig. 10) represent the case where there is no building in the vicinity of a new excavation.

Figure 10 presents the variation of the excavation influence index with the number of the stories of a possible neighboring building to a deep excavation. In this figure, the index (c_{ie}) is represented in a log scale and it emphasizes that for a certain building, closed to a deep excavation the settlement of the building might be easily determined based on the lateral deflection of the retaining wall.

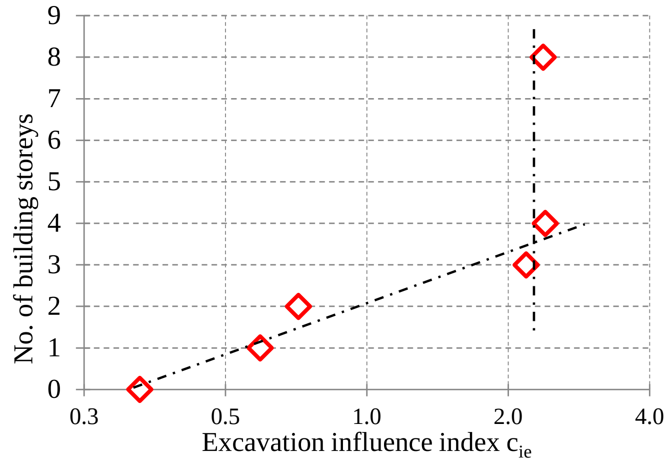

Fig. 10. Excavation Influence Index vs. number of stories of the neighboring buildings.

CONCLUSIONS

Different complex issues arise in the design of deep excavations in densely built urban areas. In the Romanian current practice, great care has to be taken in the design process of the retaining structure and the support system of deep excavation due to the importance of the neighboring buildings. Trying to ease these issues, the paper describes a parametric study on a geotechnical model of a deep excavation, proper to Bucharest subsoil. The model of the excavation resulted following a statistically analysis of an extended database on retaining walls and excavation induced ground movements.

Results of the parametric study are validated by comparison to the data recorded in the extended database. Following the analysis of the results concluded form the parametric study, there is proposed and index of excavation influence. Based on the neighboring building's number of stories, the index relates the maximum settlement to the maximum lateral deflection of the retaining wall.

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