Numerical Modeling of Various Support Systems to Stabilize Deep Excavations

M. Abdallah

Abstract—Urban development requires deep excavations near buildings and other structures. Deep excavation has become more a necessity for better utilization of space as the population of the world has dramatically increased. In Lebanon, some urban areas are very crowded and lack spaces for new buildings and underground projects, which makes the usage of underground space indispensable. In this paper, a numerical modeling is performed using the finite element method to study the deep excavation-diaphragm wall soil-structure interaction in the case of nonlinear soil behavior. The study is focused on a comparison of the results obtained using different support systems. Furthermore, a parametric study is performed according to the remoteness of the structure.

Keywords—Deep excavation, ground anchors, interaction, struts.

I. INTRODUCTION

LEBANON is one of the small countries in which the population is dramatically increasing over the years. Consequently, urban cities such as Beirut, Saida, and many other Lebanese cities lack now parking spaces and storage areas. The development and expansion of these cities require increasingly the usage of basements, which often requires excavating deeply near existing structures and public works in service. These excavations cause ground movement and affect the existing structures around it. Therefore, to overcome this challenging problem, it is primordial to study the soil-structure interaction. Many factors affect the movement of the soil and ground support systems around excavation [1]-[3]. The designer could control some of these factors, but unfortunately the others depend on the actual conditions of works.

II. NUMERICAL MODELING

The proposed project involves the study of soil-structure interaction in urban areas and particularly focuses on the influence of deep excavations on existing structures in service. The studied interaction, in this case, is often encountered in large cities due to congestion in urban infrastructure. The numerical modeling consists of a global analysis using finite element method studying the interaction excavation – soil – retaining wall - structure taking into account the elastoplastic behavior of the ground (Fig. 1) and that the Young's Modulus, E, of soil layer 1 increases with the depth according to the following expression:

$$E(z) = E_0 (P_m/P_0)^{0.5}$$

M. Abdallah is with the Civil and Environmental Engineering Department, Rafik Hariri University, Mechref, Damour – Lebanon (e-mail: abdallahma@rhu.edu.lb).

where P_m denotes the mean stress at depth z, E_0 is a constitutive parameter, which corresponds to the Young's Modulus with the mean pressure $P_m = P_0$. This expression takes into account the variation of the Young's Modulus with the mean pressure, which increases with the depth due to the soil self-weight [6], [7].

The studied site consists of two soil layers; an upper layer (13 m thick) underlying another layer (12 m thick), the length of soil domain is about 110 m, and its depth is about 25 m. The numerical modeling is performed with the finite element method in 2D using PLAXIS software [4]. The used mesh is shown in Fig. 2 and it comprises approximately 900 triangular 6-nodes elements.

The modeling of the vertical wall is achieved by beam elements with an axial stiffness EA = 1.7 x 10^7 kN and a bending stiffness EI = 3.542 x 10^5 kN .m^2. Two support systems are used to constraint the movement of the retaining wall: Option 1: Temporary support struts. Their Normal Stiffness (EA) is equal to 2.10^6 kN (Fig. 3). The modeling of retaining wall-soil requires the use of elements of zero thickness that can account for two phenomena: sliding or detachment. Option 2: Permanent ground anchors reinforcement system, which allows construction work to be carried in the excavated area. Concerning the properties of the ground anchors, two data sets of materials are needed: One of the Anchor type and one of the Geo grid type. For the Anchor rod (node-to-node anchor), Normal Stiffness (EA) is equal to 2 x 10^5 kN, spacing out of plane = 2.5 m, $F_{max, comp}$= 1x10^{15} kN and $F_{max, tens}$= 1x10^{15} kN. For the grout body (geo grid), Normal Stiffness (EA) is equal to 1 x 10^{15} kN/m (Fig. 4). The distance between two successive rows of reinforcement system in the vertical plane is equal to 3m.

A frame of 4 m height and a 5-m longitudinal span supported by two footings, which are 2 m wide, represent the superstructure with a uniform factored load q_u= 14.5 kN/m^2 [5].

In limit equilibrium stability analysis, many trial slip surfaces are required in order to find the critical slip surface that corresponds to the lowest value of factor of safety (Fig. 5). After that, and to make the deep excavation stable in absence and in presence of an adjacent structure at the surface, one of the proposed solutions is the usage of ground anchors. The effects of soil reinforcement by anchors can be incorporated (Fig. 4). The calculation of the pullout force, the specification of bond length, which is the grouted length, for the anchor, and the inclination of the anchors and many other parameters are necessary and already mentioned in the previous paragraph.

III. EFFECT OF THE NUMBER OF ROW OF THE TEMPORARY AND THE PERMANENT REINFORCEMENT SYSTEMS

The variation of the bending moment at mid-span of the structure induced by the excavation (Fig. 1) shows lower values of 33 to 38% at the end of the excavation when using ground anchors as reinforcement system (Fig. 6).
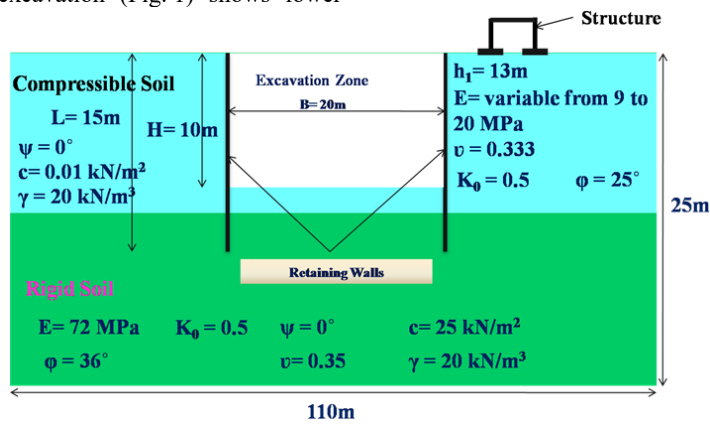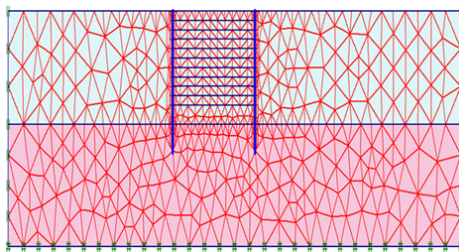

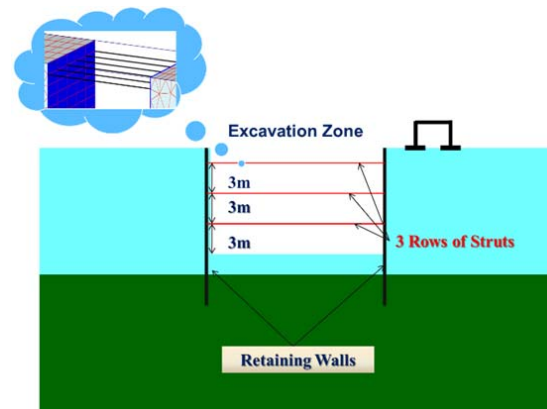Fig. 2 2D mesh [5]

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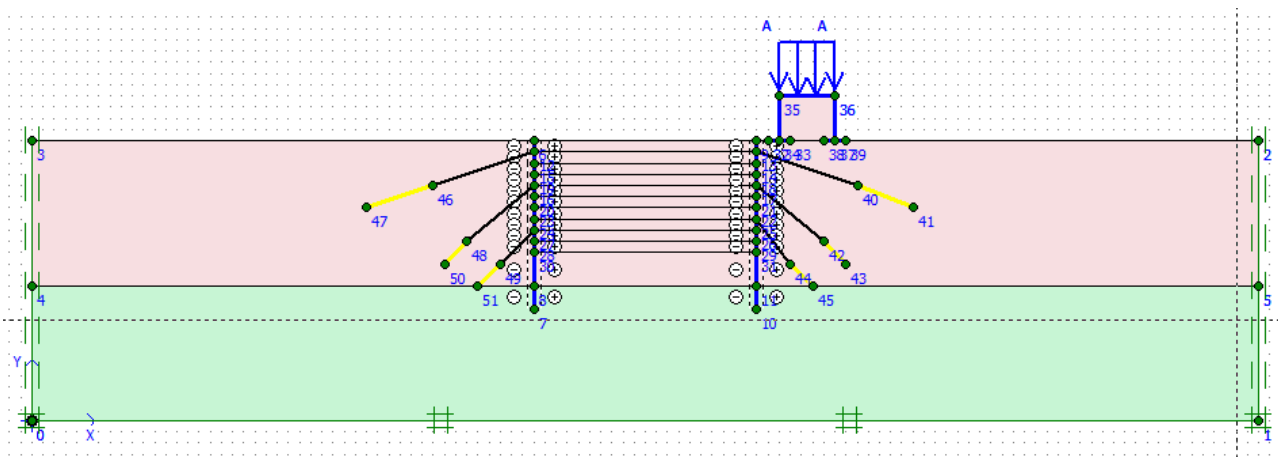Fig. 3 Illustration of the problem with the struts support systems [5]

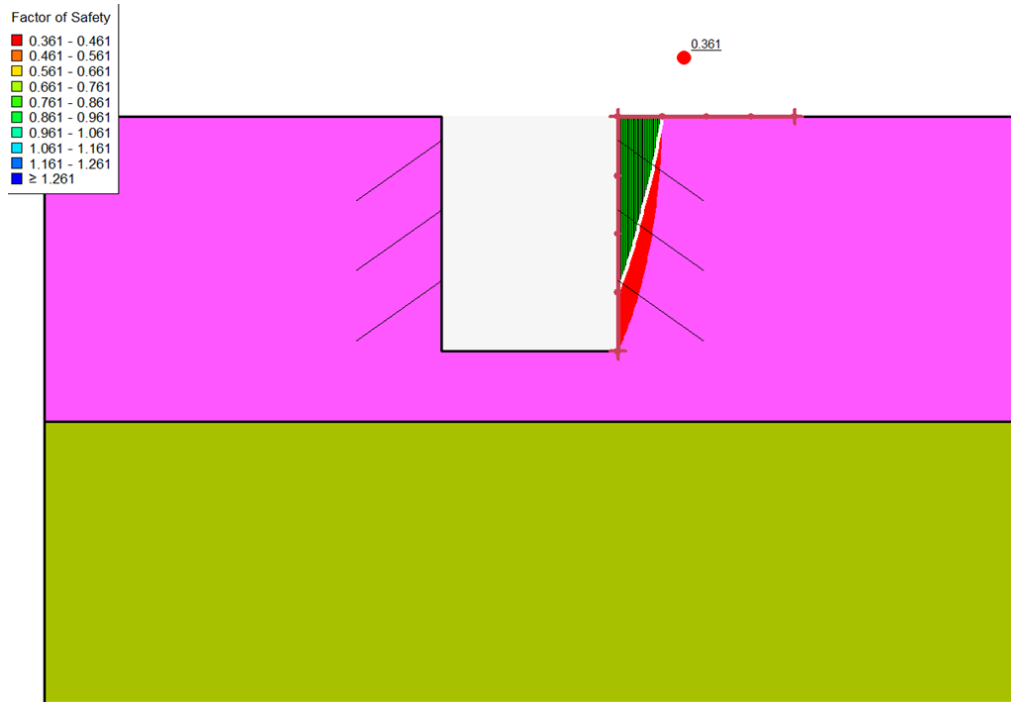Fig. 4 Illustration of the problem with the ground anchors support systems
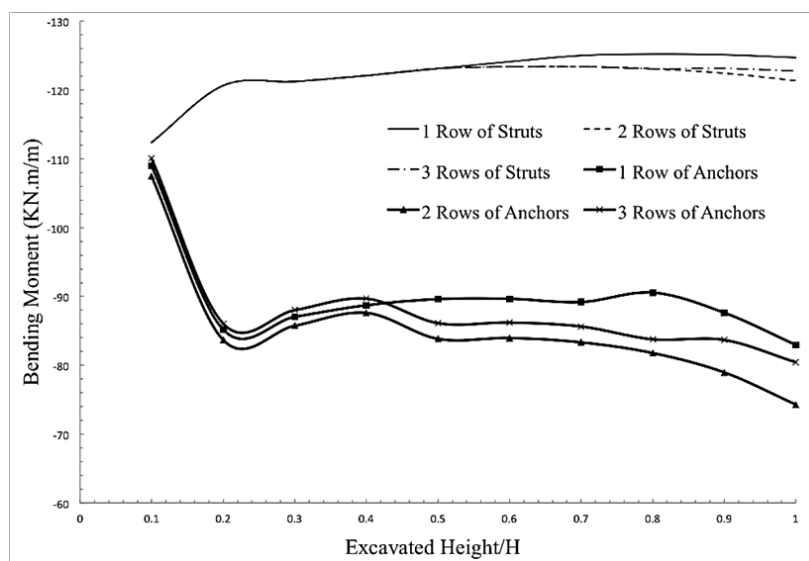
Fig. 5 Critical circular slip surface

Fig. 6 Variation of the bending moment at mid-span of the structure induced by the excavation

The maximum differential settlement is not reached at the end of excavation but at 1 m of excavation when two or three rows of reinforcement system are used. Indeed, the usage of anchors is more efficient since the differential settlement decreases of at least 90% when we compare the same configuration of the two types of reinforcement (Fig. 7).

IV. PARAMETRIC STUDY

A parametric study is performed on how far is the structure from the excavation. The shape of the horizontal displacement of the wall shows a decrease when the structure becomes farther from the retaining wall; in addition, the maximum value moves from the top of the wall, when the struts are used as reinforcement system, to its middle, when the used reinforcement system is the anchors (Fig. 8).
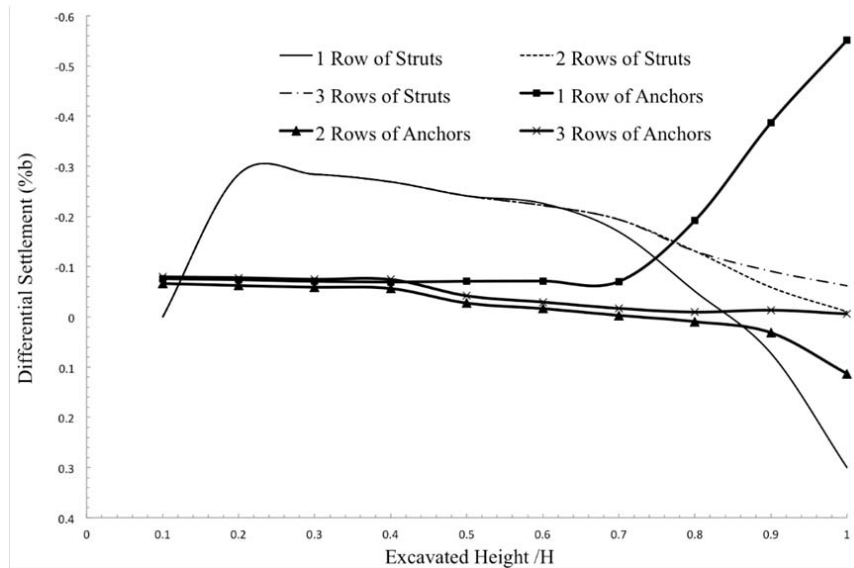
Fig. 7 Evolution of the differential settlement between shallow footings induced by excavation
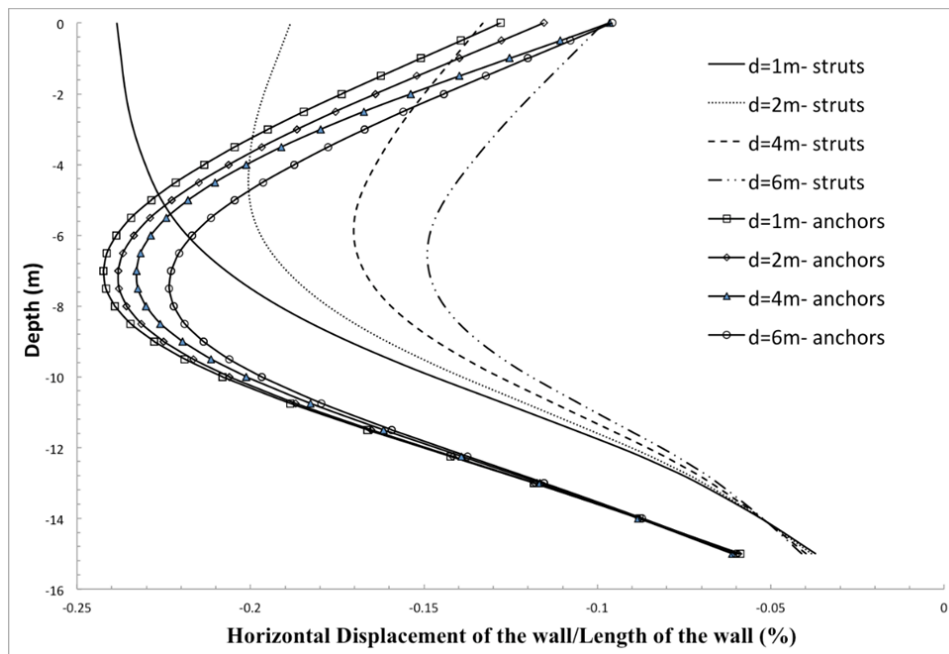

Fig. 8 Variation of the horizontal displacement of the retaining wall with d, which is the distance between the retaining wall and the footing of the structure

The maximum bending moment of the retaining wall is not reached at the end of excavation but at 8 m. However, this value increases with the usage of anchors as reinforcement system and increases when the structure becomes farthest to a certain value of d at which the bending moment starts to decrease. This can be explained as the decreasing of the effect of the structure on the retaining wall until they can be considered as two independent structural elements (Fig. 9). The maximum differential settlement is reached when the struts system is used, and the maximum value decreases when the distance between the structure and the retaining wall

increases. This maximum value moves from the top of the excavation to its bottom; at d = 1 m, the maximum differential settlement (≈-0.58%b) is reached at 3 m of the excavation and when d reaches 6 m, the maximum value of the differential settlement (≈ -0.27%b) is reached at 10m of the excavation. On the other hand, when the anchors are used as the reinforcement system, the maximum value of the differential settlement is reached when the structure is at 2 m from the retaining wall and starts to decrease when d becomes greater. In addition, the maximum differential settlement is always

reached at 1 m of the excavation and decreases due to the installation of the three rows of the anchors (Fig. 10).
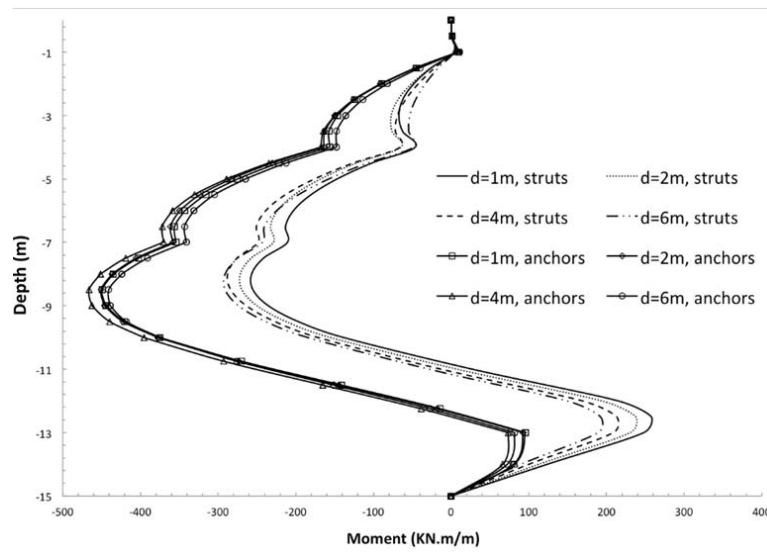

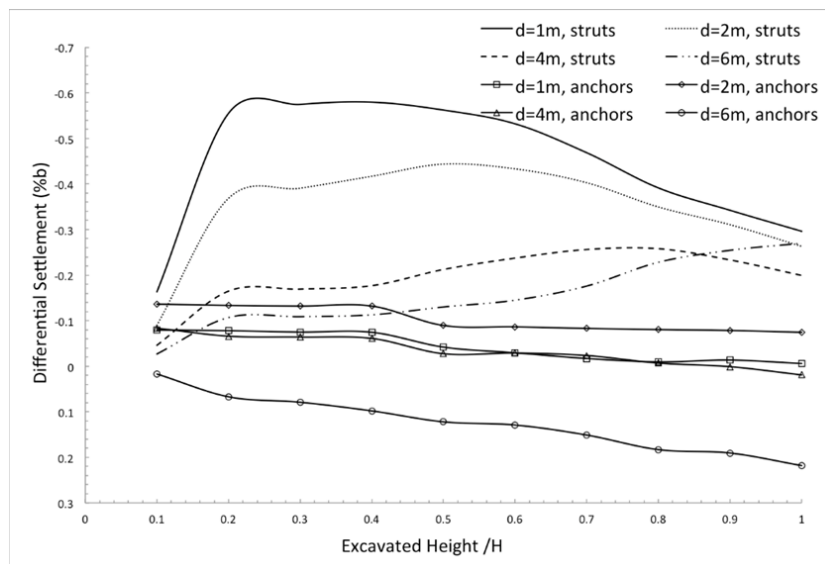Fig. 9 Variation of the bending moment of the retaining wall with d

Fig. 10 Evolution of the differential settlement between shallow footings induced by excavation for different values of d

V. CONCLUSIONS

This paper presents a numerical analysis of a deep excavation in presence of an adjacent structure using two different reinforcement systems. It also represents the effect of structure's location on the movement induced due to the excavation. The excavation-retaining wall-soil-structure interaction is a major geotechnical problem. It is often encountered especially in large cities due to congestion. In this paper, a finite element study of the influence of deep excavation on soil behavior and surface structure was presented. The modeling was carried out in the bi-dimensional case where the behavior of the soil is nonlinear. It has been shown that taking into account structural elements affects the movements of the soil and walls induced by excavation work and that the excavation near a foundation strongly affects the movement of the latter and hence the structure that it supports.

From the above results, it is necessary to reinforce the walls of the supports in order to limit their movement and consequently the deformation of the ground behind these walls. And it is better to use anchors as reinforcement system to minimize the excavation effect on the soil and the surface structure. Then, the effect of the position of the structure from the edge of the excavation was investigated. The importance of this effect was observed, where the horizontal displacement

of the retaining wall, the induced moment in the retaining wall, and the differential settlement between the footings are well affected.

This work requires a continuation to address the following aspects: take into account the fluid-skeleton interaction and its influence on the forces induced in the structures; carry out analyzes for different types of soil encountered in Lebanon with the aim of establishing practical recommendations for the calculation and construction of underground structures in cities and make an economic study between the usages of these two different reinforcement systems.

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