Analysis of Piles Supporting Excavation Adjacent to Existing Buildings

Analyse de pieux de bâtiments existant en cours de fouilles sous-jacentes

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ABSTRACT: In urban environment, excavation adjacent to existing buildings is common. Supporting excavation is important to prevent damaging of the adjacent buildings. There are many factors affecting the selection of the supporting system. Some of them are soil behavior, type of foundation, foundation level of the adjacent buildings, and the budget of the project under construction. In order to reduce the surrounding soil movement due to deep excavation, a three dimensional Finite Element (3D FE) study was carried out in this paper, considering soil-structure interaction. A piled supporting system was selected because it is common and relatively economic to use in cohesive soil in Egypt. A parametric study was performed to study the effect of the stiffness of the supporting system on minimizing the ground deformation. From the results, some recommendations are given in terms of excavation depth, soil-pile stiffness, and pile embedded depth.

RÉSUMÉ : En milieu urbain, les excavations sous-jacentes aux bâtiments existants sont courantes. Soutenir les fouilles pour prévenir des endommagements sur les bâtiments est donc très important. Il y a plusieurs facteurs qui influencent les choix des systèmes de renforcement. Par exemple, le comportement du sol, le type de fondation, la profondeur des fondations et enfin le coût des travaux. Afin de limiter les désordres occasionnés par une excavation profonde, une étude numérique tridimensionnelle (méthode aux éléments fins) a été réalisée dans cet article en prenant en compte l'interaction sol-structure. Un ensemble de pieux supports a été considéré car il est relativement économique et très commun dans les sols Egyptiens. Une étude paramétrique a été réalisée pour étudier la rigidité du système qui minimise les déformations du sol. A partir des résultats, des recommandations sont données en termes de profondeur d'excavation, de rigidité sol-pieu, et de profondeur de fondation.

KEYWORDS: excavation, pile wall, clay, adjacent building.

1 INTRODUCTION

In urban environment in Egypt most buildings in the same block area are adjacent to each other. No distance between buildings exists due to high population intensity along the river Nile Valley. These conditions increased the tendency to build high rise buildings. Most of these new high rise buildings are built adjacent to old existing buildings. The adjacent old buildings condition is usually critical either due to the weakness of the structure system of the building or the foundation level is at shallow depth. High rise buildings with basements need deeper excavation than the foundation level of the adjacent building. With the presence of adjacent shallow foundation, the excavation will cause large soil movement and damage to the adjacent building, as shown in Fig. (1). Many failure cases were observed due to unsupported excavations. It is common, in Egypt, to use contiguous pile wall to support the excavation on the adjacent buildings sides. Such type of wall is economic and effective in cohesive soil. The excavation will cause lateral and vertical soil movement, the first component is considered to be more critical for adjacent piles. The design of these excavations should include an estimation of the ground movement as well as stability check of the adjacent buildings. The lateral loads resulting from the soil movements induce bending moments and deflections in the piles supporting excavation, which may lead to structural distress or failure of both the existing building and the excavation supporting system. Indeed, several instances of structural damage to piles have been reported in the literature, for example, Hagertry and Peck 1971 and Finno et al. 1991, as reported by Chen and Poulos 1997.

Many theoretical and empirical methods have been established for solving certain types of excavation problems, for example, Poulos and Chen 1995, Hashash and Whittle 1996, Ou et. al 1996, Poulos and Chen 1996, Chen and Poulos 1997, Poulos and Chen 1997 and Leung et. al 2000. They studied the failure of the excavation with no adjacent buildings or additional loads close to the excavation. In other cases, they studied the effect of soil movement during the excavation on the behavior of adjacent existing piles. However, the design of supporting system for excavation adjacent to existing building founded on shallow foundation is not studied enough. Many parameters could affect the design of pile supporting excavation. This includes excavation height, soil properties, the foundation type and the foundation level of the adjacent building.

The present study mainly aims to provide recommendations for the design of contiguous pile wall in cohesive soil. Three Dimensional Finite Element Modeling (3D FEM) was used to carry out the study. PLAXIS 3D Foundation software was used in the analysis. Different parameters were considered in the study. The ranges of the selected parameters were limited to the common cases in Egypt and as recommended by the Egyptian Code of Practice (ECP).

2 FINITE ELEMENT MODEL (FEM)

2.1 *Geometry and meshing*

FEM meshing and geometry is shown in Fig. (2). The figure shows a cut at the face of the excavation. Soil above the foundation level was removed only to show footing shape in the figure. However, it was included in the analysis. Model dimensions were selected so that the boundaries are far enough to cause any restriction or strain localization to the analysis. The excavation area is 10 x 10 m. For simplicity, the foundation of the adjacent building was assumed to be three strip footings of 10 m length and 2 m width each and in between distance of 2 m.

The foundation level was assumed to be at 1.5 m depth from the ground surface. The mesh was generated as fine mesh at piles where the stresses are expected to be high. Coarse mesh was used at the boundaries of the model where the stresses are low.

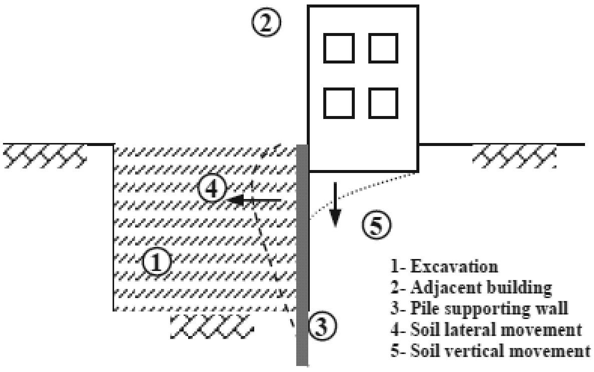

Figure 1. Problem under study

2.2 *Soil modeling*

Soil is assumed to be a deposit of clay. Fifteen node triangular element was used to model the soil. Soil material was assumed to behave as an elastic perfectly plastic material following Mohr-Coulomb model. The soil parameters are presented in Table 1.

2.3 *Pile and foundation modeling*

Piles were modeled as a massive circular concrete pile. Pile Young's modulus (E) was 2.1 x 10^7 kPa. Both pile diameters (d) of 0.3 m and 0.4 m was considered in the study. They have flexural stiffness (EI) of 8350 kN.m^2 and 26390 kN.m^2 respectively.

The adjacent building foundation is modeled as plate of thickness of 0.5 m. Foundation was idealized with six nodes triangular plate element in the analysis. Interface element was used to represent the contact between plate elements and soil.

Table 1. Clay input parameters in FEM

Parameter	Soft to Medium Clay	Medium Clay	Unit
Dry unit weight, γ_d	18	18	kN/m^3
Wet unit weight, γ_{wet}	20	20	kN/m^3
Young's modulus, E_s	4000	8000	kN/m^2
Poisson's ratio, υ	0.3	0.3	-
Undrained cohesion, c_u	25	50	kN/m^2
Friction angle, φ	12	14	degree
Dilatancy angle, ψ	0	0	degree
Interface reduction factor, R	1	1	-------

2.4 *Analysis procedure*

The variable parameters used in the analysis are the excavation height (H), pile embedded depth (D), and pile diameter (d) as shown in Fig. (2). Also, both soft to medium clay and medium clay soil were used in the analysis. Pile diameter was assumed to be 0.3 m and 0.4 m with spacing of pile diameter between pile edges.

The analysis was carried out in steps. The first step was applying the stress of the adjacent building at the foundation level without the pile wall and the excavation. The second step was activation of the pile wall in the soil. The third step was the excavation of the soil.

In the present paper, only bending moment of pile and pile lateral displacement outputs were used in the analysis. All the presented results are of the pile at the middle of the supporting wall. It was found from the results that this pile is the most critical in both lateral deflection and bending moment. The piles at the ends of the wall have the lowest lateral deflection and bending moment profiles. The stress on the foundation level was assumed to be 100 kN/m^2. This stress is corresponding to a bearing capacity factor of safety of 2 for the soft to medium clay case.

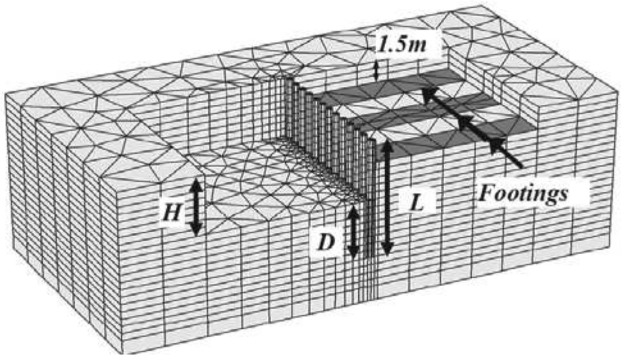

Figure 2. FEM geometry and meshing

3 FEM RESULTS AND DISCUSSIONS

3.1 *Effect of supporting excavation*

Excavation height (H) and cohesion of clay (c_u) are two main parameters in the design of the pile wall. It was found that results should better be related to a factor has both the effect of excavation height (H) and undrained soil shear strength (c_u). The stability factor (N_c) joins both H and c_u parameters in the following relationship as recommended by Polous and Chen (1996):

$$N_c = \frac{\gamma \cdot H}{c_u} \tag{1}$$

where γ is the unit weight of the soil.

Figure (3) shows lateral displacement profile (U_x) versus depth (Z). Both the profile of unsupported soil lateral displacement and pile lateral deflection are shown in Fig. (3). Large soil movement can be observed due to the stress of the adjacent building in the case of unsupported excavation. The lateral displacement increases rapidly as the excavation height increases. Maximum lateral displacement increased from about 0.06 m to 0.2 m when N_c increased from 1.9 to 3.2. However, the maximum lateral displacement increased to very large value of 1.2 m for N_c = 4.5. This means that the excavation is failed at N_c = 4.5. When the excavation is supported using contiguous pile wall, soil movement decreases in the zone above the excavation level. However, below the excavation level, there is no obvious decrease in soil movement. It should be noted that in all cases the pile wall is translated horizontally.

3.2 *Effect of excavation height*

Pile wall lateral deflection increases as excavation height (H) or the stability factor (N_c) increases. As N_c increases pile wall movement changes from translation (H =3 m) to both translation and rotation (H = 5 m and 7 m) as shown in Fig. (4). Maximum lateral deflection was observed at (0.6 to 0.8 H) with the lowest value for small N_c. Figure (5) shows normalized bending moment ($M.d/EI$) profiles for different N_c values. It is clear that bending moment increases by increasing N_c. The location of maximum bending moment is at (0.7 to 0.8 H) with the lowest value for small N_c.

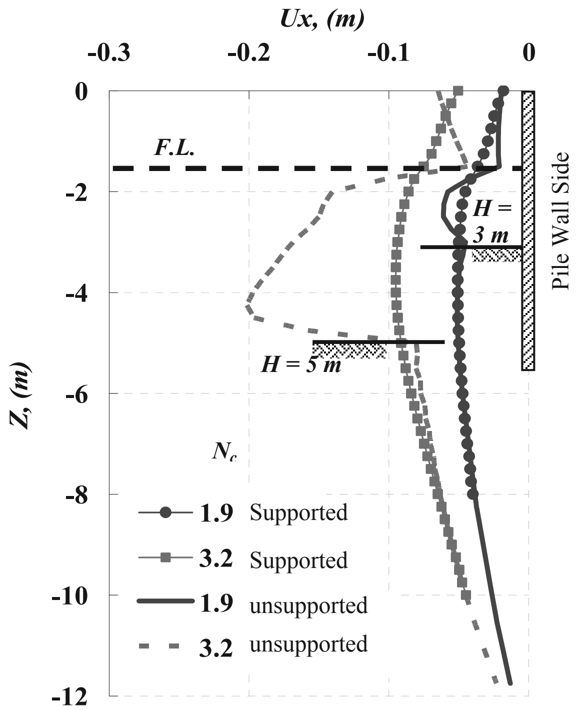

Figure 3. Lateral displacement profile of unsupported and supported excavation

3.3 *Effect of pile wall embedded depth*

Figures (4) and (5) show no change in the normalized lateral pile wall deflection (U_x / d) and ($M.d$ / EI), respectively, for N_c values of 1.9 and 3.2 and for D values of 3 m and 5 m. At N_c = 4.5, U_x / d decreases when D increases from 3 m to 5 m. The same trend can be seen in Fig. (5) for $M.d$ / EI. For N_c = 4.5 (H = 7m), the increase of D has a significant effect on both lateral deflection and bending moment of pile wall. By increasing D both U_x / d and $M.d$ / EI decreases. Figure (6) shows the relation between $U_{x\ max}$ / d versus D. The effect of D on the system stability is clear to be effective in case of N_c = 4.5. However, the increase of D more than 7 m (H/D = 1) has no contribution to the system stability.

3.4 *Effect of pile diameter and soil-pile stiffness*

The Egyptian Code of Practice recommends pile diameter ranges between 0.3 m and 0.5 m for contiguous pile wall. It is clear from Figs. (7) and (8) that increasing pile diameter (d) from 0.3 m to 0.4 m decreases both lateral deflection and bending moment. In Fig. (8), $M_{max}.d/EI$ increases with the increase of ($H^2/d.L_o$). L_o is soil-pile stiffness factor. The soil-pile stiffness can be defined as follows:

$$L_o = \sqrt[4]{\frac{4EI}{E_s}} \qquad (2)$$

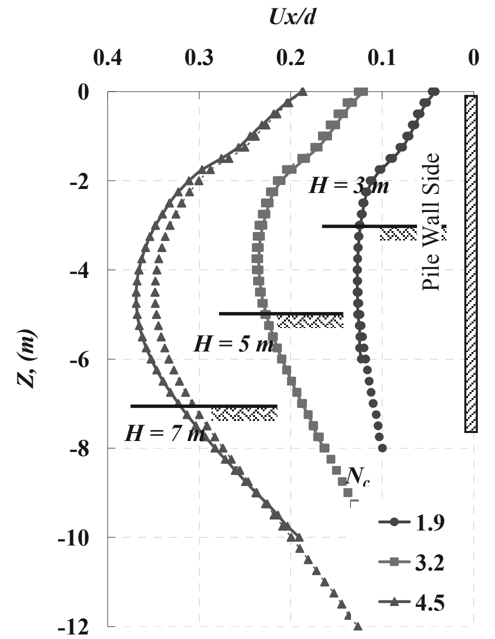

Figure 4. Lateral displacement profile of contiguous pile wall for different Nc values (solid line for D= 3 m, dashed line for D = 5 m)

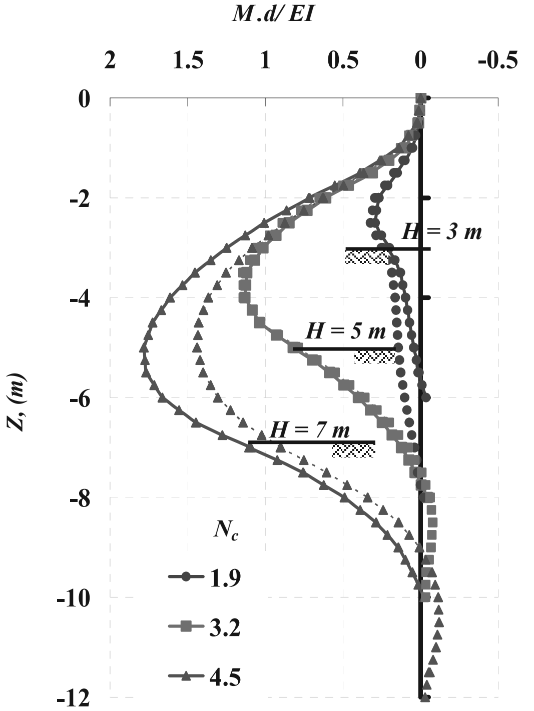

Figure 5. Normalized bending moment profile of contiguous pile wall for different N_c values (solid line for D= 3 m, dashed line for D = 5 m)

It can be observed from Figs. (7) and (8) that at N_c = 4 both pile wall maximum lateral deflection and maximum bending moment are not increasing. This means that the pile wall starts to be more effective at N_c = 4 at which the unsupported excavation fails.

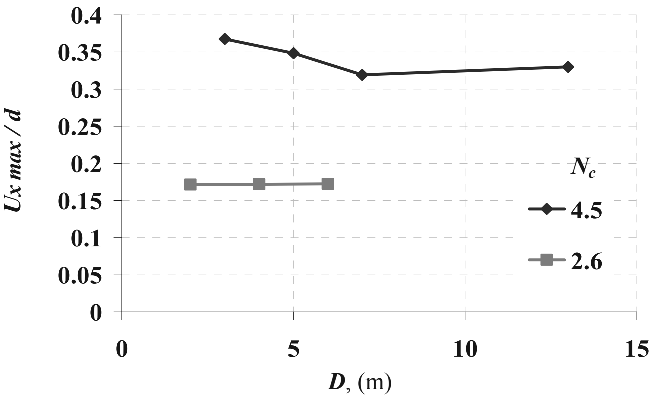

Figure 6. Normalized maximum lateral pile wall displacement versus pile wall embedded depth

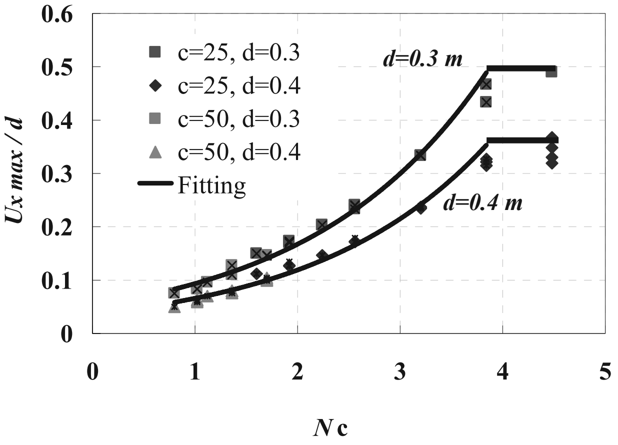

Figure 7. Normalized maximum lateral pile wall displacement versus the stability factor N_c

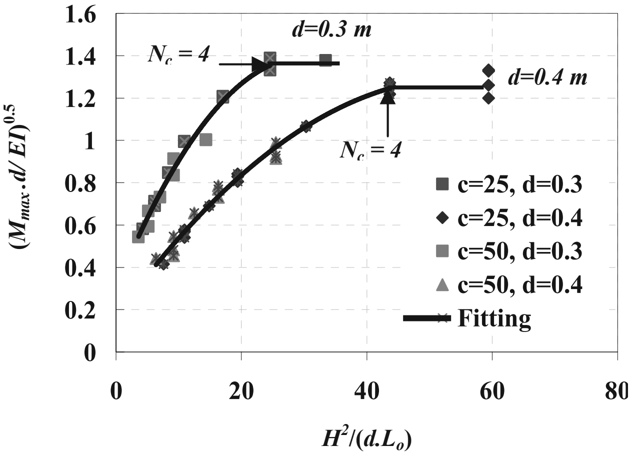

Figure 8. Normalized maximum bending moment of pile wall versus $H^2/(d*L_o)$

4 CONCLUSIONS

3D FEM study was carried out to provide recommendations for the design of contiguous pile wall in cohesive soil. Pile diameter was considered to be 0.3 m and 0.4 m as recommended by ECP. The vertical stress at the foundation level of the adjacent building assumed to satisfy a bearing capacity factor of 2 for soft to medium clay case. From the previous discussion the following design recommendations can be concluded:

1. At stability factor, $N_c = 4$, the unsupported excavation starts to fail due to the stress of the adjacent building.

2. Contiguous pile wall decreases the lateral soil displacement between the foundation level of the adjacent building and the bottom of the excavation. However, the pile wall does not decrease lateral soil displacement at the foundation level and below the bottom of the excavation.

3. Increasing pile diameter (*d*) from 0.3 m to 0.4 m decreases both lateral deflection and bending moment.

4. Pile wall embedded depth, (*D*) has no obvious effect on the stability of the supporting system for N_c value up to 4. It starts to be more effective for $N_c > 4$ up to $H/D = 1$. Using *D* values larger than $H/D = 1$ is ineffective and uneconomic.

5. Contiguous pile wall starts to be more effective when $N_c > 4$ as it prevents the unsupported excavation from failure.

6. It is recommended to check the use of connecting beam at piles head to improve the supporting system for excavation conditions of $N_c > 4$.

5 FUTURE RESEARCH

The present paper is the beginning of an ongoing research on designing deep excavation. The design of the contiguous pile wall will be extended to check the stability and safety of the adjacent building. Also, using braced excavation will be considered. A method will be derived to predict the earth pressure on the contiguous pile wall.

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