Numerical Analysis of the Basement Wall Behaviour nearby Unsupported Deep Excavation

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Abstract. This paper presents a numerical model of the influence of deep excavation on the behavior of a model of basement wall adjacent to an unsupported excavation. The examined wall has a wall that has completely faced excavation. The normal, shear, bending, and vertical and lateral displacements of walls have been examined. The finite element modeling by PLAXIS 3D has been adopted to investigate the problem. The soil strata studied is 25 m deep. The nearby excavation has a 1.0 m excavation width. The results show that as the excavation depth is equal to wall depth, the lateral displacement and the bending moment are reduced and zero along with wall depth. At the excavation depth of more than 2.0 m, the lateral wall displacement Ux increases but in the reverse direction (towards excavation). The increasing ratio of lateral displacement is 10 times before the excavation at the wall head as the excavation depth is 6.0 m. The soil collapses, and the failure happens at 7.0 m depth of excavation. At these stages, the calculation is not completed, and the expected results are probably more than obtained values.

Keywords: Deep excavation; unsupported; basement wall; numerical analysis; soil.

1. Introduction
In the civilian region, the planning and construction of the deep excavations have been permanently the great challenges. In a recent facility, the effect of deep excavation on the adjacent buildings has to be reduced, and the excavation deformation decreases. Especially in the case of the buildings with shallow foundations near the deep excavation, they are highly susceptible to movements caused by deformation of underneath and surrounding soil. In a large town, the intensity of the structure increased and subsequently increased the excavation dimensions of nearby structures. The excavation is governed by complex factors, such as the ground condition, type of retaining structure, the stiffness of supports, and the building conditions. The excavation advancement caused ground movements and variation of structure behavior such as forces and displacements. Consequently, the adjacent building’s settlement should be controlled within the allowable limits. The reductions of adjacent soil confinement have been studied experimentally and numerically by physical model and finite element modeling [1]. The horizontal distance and depth of excavation have been affected the bending moment and lateral displacement of a single pile [2-4].

Soil–structure interaction is denoted as the alteration process between responses of structures and adjacent soil. Two soil layers have been examined, the upper layer is classified as silty and clayey sand (SM-SC), but the lower layer is classified as low plasticity silt and clay (ML). The PLAXIS 2D modeling, hardening soil model with small-strain stiffness (HS-small), has been applied to examine a 17-story building beside a deep excavation with three approaches; a fixed-based structure model and
soil–structure, and a soil–structure–excavation interaction model. The maximum lateral displacement in the interaction and fixed-based models ranged between 19 and 27 cm and was located at the roof level. The story drift at the roof level in the fixed-based model was about 35% more than in the interaction models. The beam bending moment of the interaction models is more than that of the fixed-based model. Comparing the moment amount of the interaction models showed that excavation was an insignificant effect of bending moment. It was also observed that the moment of these two models has the same sign [5]. An experimental model has been designed to study the effect of deep excavation on the performance of an adjacent strip footing resting on cohesion-less soil. A comparison is made between the behavior of strip footing before and after soil reinforcement. The study considered the effect of horizontal distance of excavation regarding the strip footing, applied vertical load, relative density of granular soil, and the relative depth of footing concerning excavation. The results showed a high decrease in the lateral and vertical settlement for strengthened soil compared with natural soil. The amount of reduction depends on the horizontal distance from excavation. Also, the punching failure developed when the applied load on the footing increased adjacent to the deep excavation. [6].

The Finite element method (FEM) using PLAXIS 2D and the Hardening Soil model (HSM) has been used to expect the retaining wall lateral displacement and the settlement of nearby buildings of many projects having deep excavation in Ho Chi Minh City (HCMC). The excavation depth of examined projects has extended from 6.20 m to 18.8 m, the basement slabs range from two to five, and the number of the floor was 1-3 floors. Two types of retaining walls, the diaphragm wall and Sheet pile wall have been examined. Soil profiles for the examined project have soft soil for the upper layer and stiff clay to dense sand for deep layers. The assessments and correlation have been adopted between the field measurement and the result of modeling [7]. The subsidence surface methodologies for land by using the wall of housing excavation have been adopted. The performed measurement showed further internal forces with high rates resulting from the erection of a recent structure besides the existing building. Two basic static shapes of deep excavation effect have been noticed; excavation stage and building performance are shown in Figure 1. The series of physical model tests studied the effect of deep excavation-induced lateral soil movements on the behavior of the model strip footing adjacent to the excavation, which is supported on reinforced granular soil. The induced lateral soil movement caused by excavation work has been studied [8]. The traditional system has been employed to maintain the excavation projects and nearby structures in which sloping supports have been linked to the dike or foundation, as shown in Figure 2 [10].

![Figure 1](image_url)

**Figure 1.** basic static shapes of deep excavation effect on nearness structure a) the excavation stage; b) the building performance [8].
A 2D finite element analysis has been adopted; the excavation, nearby structure, and sloping supports have been modeled with their parameters. Mohr-Coulomb criterion was used for soil modeling. The results show that the nearby structure and underneath soil rigidity have been the main influence on execution besides the excavation depth. Also, soil and building settlement have been varied with soil stiffness, and the lateral displacement decreased as soil cohesion increased, the damage level increased as the excavation depth increased [11]. A huge triangle excavation was 22.8 m deep in two directions located in a trade region of Shanghai. The top of the retaining walls deflected by 70% of the maximum wall rebound despite the concrete supports that were cast at the start of the major excavation. And, through the construction continuing of concrete slab, the lateral displacement has been increased up to 50% [12].

Plane strain finite element examination considering the small strain was used to study the wall deformations upon excavations in soft clay strata braced by retaining walls. The polynomial regression (PR) model has been applied to simulate the maximum deformation of the wall. The results showed agreements with site results and the previous publications. The model was also simulated by 3D foundation nearby excavation by FLAC3D [13]. The size and excavation depth are considered a reason for danger. The greater the excavation depth, the highest the problems in performing and the stability of the neighbouring structures [14].

In this paper, the basement model is comprised of different parts, the raft base, walls, columns, and basement horizontal beam. These parts are subjected to line loads, concentric loads, and distributed loads. The embedment depth of footing is 2.0 m. The soil strata have been 25 m deep. The analysis includes the behavior of basement walls subjected to line load along the wall beside the concentric load on the column. The nearby excavation is 1.0 m the excavation width. The examined wall has wall1 that has completely faced the excavation. The normal forces, shear force, bending moments, and vertical and lateral displacements of walls have been examined. The finite element modeling by PLAXIS 3D has been adopted to investigate the problem [9].

2. Modeling of the pile-soil arrangement

The soil strata are 25 m deep, separated into three layers: the first layer is 5 m depth and consists of silty sand, and the second is 10m depth clayey layer. The final layer is a sandy layer of 10 m depth. (see Figure 3). Groundwater located is at depth 25.0 m from the natural ground level tables 1, 2, and 3 show the soil properties of each layer, respectively. The soil properties have been dependent on the geotechnical investigation of Baghdad city. The foundation is designed as a shallow square foundation (raft) of 20 m width (L) and 2.0 m raft embedment depth. The raft foundation consists of base, walls,
horizontal basement beams, and columns. Figures 4 and 5 and Table 4 and 5 summarize the properties of wall and column element. The applied load on a raft consists of a concentric load, line load, and distributed load. These loads are designed and calculated to represent a 4-story building. In this study, nearby excavation is drilled 10.0 m deep with a horizontal distance of 1.0 m. The PLAXIS 3D Foundation modeling has carried out a series of 3D finite element analyses to examine the effect of excavation of different depth on wall behavior. Figure 6 displays the modeling of basement walls. Wall1 has been selected in the examination as shown in Figure 6. A 10 nodded tetrahedron element is used for meshing in this paper. Mohr-Coulomb and Hardening soil model have been used for the sand and clay modeling respectively.

3. Finite element modeling results

The PLAXIS 3D software is used to simulate the case in hand through a series of 3D finite element analyses [9]. The vertical axial force $N_1$ and the longitudinal axial force $N_2$, shear force $(Q)$, bending moments $M_{11}$ and $M_{22}$, (Figure 6 display the direction of 1 and 2 axes), lateral displacement $(U_x$ and $U_y)$, and vertical displacements $(U_z)$ have been examined for the wall of the basement (Wall1), which is completely faced to excavation. The nearby excavation has a 1.0 m horizontal distance to the raft edge and a 1.0 m excavation width. The excavation process has been performed gradually from 1.0 m to 10.0 m deep. In addition, another stage of calculation has been separately performed where the excavation
depth was 10.0 m in one step. The wall behavior has been examined to study the performance of the wall at each stage of excavation separately and to compare the performance of the loading process (before excavation). The wall behavior has been examined at a cross-section located at the wall center to study the variation of the parameters with depth. Each wall has been designed as a plate element and strengthened with a column element that has been applied at each 5.0 m of 2.0 m deep.

**Table 1.** Material properties of silty sand.

| Parameter           | Name       | Value   |
|---------------------|------------|---------|
| Material used       | Model      | Mohr-Coulomb |
| Type of analysis    | Type       | Drained |
| Soil unit weight (kN/m³) | γ          | 17.00   |
| Initial void ratio  | e₀         | 0.65    |
| Stiffness (kN/m²)   | E          | 10000   |
| Poisson’s ratio     | ν           | 0.30    |
| Cohesion (kN/m²)    | Cref       | 20.0    |
| Angle of internal friction (°) | φ         | 15.0    |
| Dilatancy angle     | ψ          | 0.0     |
| R inter             | -          | 0.7     |
| Data set            | -          | USDA    |
| Model               | -          | Van Genuchten |

**Table 2.** Material properties of clayey soil.

| Parameter           | Name       | Value   |
|---------------------|------------|---------|
| Material used       | Model      | Hardening soil model |
| Type of analysis    | Type       | Undrained (A) |
| Soil unit weight (kN/m³) | γ          | 18.00   |
| Initial void ratio  | e₀         | 0.95    |
| Stiffness (kN/m²)   | E₀ref      | 9500    |
|                     | E₀ed ref   | 14600   |
|                     | E₀ur ref   | 36000   |
| Cohesion (kN/m²)    | Cref       | 25.0    |
| Angle of internal friction (°) | φ         | 5.0     |
| Dilatancy angle     | ψ          | 0.0     |
| R inter             | -          | 0.7     |
| Data Set            | -          | USDA    |

3.1. Axial Forces

Figure 7 and 8 display the forces N₁ and N₂ variation along the vertical axis, and the x-axis represents the entire width of wall₁ (L) and along the excavation process. The excavation depth ranged from 1.0 m to 10.0 m deep in two cases. Firstly, the excavation process is performed gradually, and the other case is performed to reach 10.0 m in one step. It can be seen that the maximum forces N₁ and N₂ have been noticed at columns location for loading (before excavation) and at all excavation depth. But, the force variations have lower values at other locations of the walls. The points of maximum forces range from 3000 to -5000 KN. To examine the force variations along with the wall depth (2.0 m), the wall behavior at a cross-section at the wall center is considered in figure 9 and figure 10. In general, the values of axial force (N₁ and N₂) reduced gradually from head to base of the wall, and the highest value notices at the wall head for all depths of excavation and before excavation. The axial forces N₁ increases with excavations depths, and for excavation depth, 6.0 m, the rate of increase does not exceed 1% at the upper
part of the wall and reaches 20% at the lower part of the wall. In addition, for 7.0 and 10.0 m excavation depth. The axial force $N_1$ increasing rates about 12% at the upper part and reaches 40% at the lower part of the wall.

The axial force $N_2$ increases with excavations depth and for the excavation depth 6.0 m, the rate of increasing about 20% for the wall upper part while for the lower part of the wall, the axial force $N_2$ decreases by rate reaches about 20%. A high reduction of $N_2$ force is observed at 7.0 and 10.0 m excavation depth along the wall depth by rate ranges 0.80 to 2.0 times before excavation. The wall head showed the highest values of both axial forces $N_1$ and $N_2$ of about 5000 kN.

### Table 3. Material properties of sand.

| Parameter          | Value  |
|--------------------|--------|
| Material used      | Mohr-Coulomb |
| Type of analysis   | Type Drained |
| Soil unit weight (kN/m³) | γ | 19.00 |
| Initial void ratio | $e_0$ | 0.60 |
| Stiffness (kN/m²)  | $E$ | 20000 |
| Poisson’s ratio    | $\nu$ | 0.25 |
| Cohesion (kN/m²)   | $C_{ref}$ | 5.0 |
| Angle of internal friction (°) | $\varphi$ | 33.0 |
| Dilatancy angle    | $\psi$ | 3.0 |
| R inter            | - | 0.7 |
| Data Set           | - | USDA |
| Model              | - | Van Genuchten |

### Table 4. Properties of column element.

| Parameter          | Value  |
|--------------------|--------|
| Identification     | Column |
| Area (m²)          | $A$ | 0.16 |
| Stiffness (kN/m²)  | $E$ | $2 \times 10^6$ |
| unit weight (kN/m³) | $\gamma$ | 24.00 |
| Moment of inertia (m⁴) | $I_1$ | $2.13 \times 10^{-3}$ |
|                    | $I_2$ | $2.13 \times 10^{-3}$ |

### Table 5. Properties of wall elements.

| Parameter          | Value  |
|--------------------|--------|
| Identification     | Wall   |
| Thickness (m)      | $d$ | 0.30 |
| unit weight (kN/m³) | $\gamma$ | 15.00 |
|                    | $E_1$ | $30 \times 10^6$ |
| Stiffness (kN/m²)  | $E_2$ | $30 \times 10^6$ |
|                    | $\nu$ | 0.15 |

### 3.2. Shear force

Figure 11 shows the shear force variation along with wall depth. The maximum shear force is shown at the wall head and reduces significantly with wall depth. It can be seen that the variation of shear force is insignificant along the wall depth at all the excavation stages up to 6.0 m depth. At excavation depths, 7.0 m and 10.0 m. The shear force variation is not exceeding 10% of the shear force value at the wall head.
**Figure 7.** Normal force $N_1$ variation along the length (L) of wall 1 before and after excavation.

**Figure 8.** Normal force $N_2$ variation along the length (L) of wall 1 before and after excavation.

**Figure 9.** Normal force $N_1$ variation at cross-section of center wall 1 before and after excavation.
3.3. Bending moment

The bending moment variation (M_{11}) is shown in Figure 12. Generally, the bending moment increased with wall depth, and the maximum amount is observed at the wall base for most examined cases. It can be seen that the value of maximum bending moment before excavation is about 80 kN.m (Tension), and it decreased with excavation depth until 3.0 m. The amount of bending moment is about zero at 3.0 m depth of excavation along the wall. Then, the bending moment increases slightly until excavation depth 6.0 m, with a value of 10 kN.m (Compression) at the wall base. With expanding the excavation depth, the bending moment starts to re-increase in tension to about 30 and 40 kN.m (Tension) at 7.0 and 10.0 m excavation depth, respectively. The failure happens at 7.0 m and 10.0 m. Figure 13 shows the bending moment variation (M_{22}) along the wall depth and for all examined excavation depth. The same trend has been noticed as bending moment variation (M_{11}), where the bending moment increases with depth, and the maximum bending moment is noticed at the wall base. The excavation process reduces the bending moment along the wall till 3.0 m, and after that, the bending moment is zero along with wall depth for excavation depth between 3.0 to 6.0 m. Then, as the excavation depth proceeds to 7.0 m and 10.0 m the bending moment varies in different trends along the wall depth and ranges from 16.0 kN.m at wall head to 5.0 kN.m for 7.0 m excavation depth. It ranges from 20.0 kN.m at wall head to 6.0 kN.m for 10.0 m of excavation depth.

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**Figure 10.** Normal force N_2 variation at cross-section of center wall before and after excavation.

**Figure 11.** Shear force variation at cross section of centre wall before and after excavation.
3.4. Wall displacement

3.4.1. Lateral Displacement of the Wall.

Figure 14 displays the lateral wall displacement (Ux) along with the wall depth before and during the excavation process that has been taken place gradually from 1.0 m to 10.0 m. Before the excavation process, the wall displacement Ux was 5.6 mm at wall head, and this value has been slightly reduced with wall depth. As the excavation process proceeds, lateral displacement Ux decreases with increasing the excavation depth and reaches about 1.9 mm at an excavation depth of 2.0 m. At the excavation depth of 2.0 m, the wall lateral displacement Ux increased in the reverse direction (towards excavation). The lateral displacement was 60.1 mm at the wall head as the excavation depth 6.0 m. The results showed that the failure happened at 7.0 m, and the calculations cannot be continued after that depth. The excavation depth of 10.0 m was performed in one step of calculation from 1.0 to 10.0 m. It can be seen the wall lateral displacement Ux has more than 300 mm at the wall head and has reduced slightly with depth. While the lateral wall displacement Uy showed insignificant variation during the excavation process.
3.4.2. Vertical Displacement of the Wall.

Figure 15 displays the vertical wall displacement ($U_z$) along with the wall depth before the excavation and during the excavation process, the vertical wall settlement slightly decreased till 2.0 m excavation depth, and after that, the vertical settlement increased with increasing depth of excavation. Before the excavation process, the wall was settled by 220 mm while at 6.0 m excavation depth, the wall settlement was 338 mm. In addition, the excavation depth of 7.0 m has not been completed, and the failure has happened. The wall has settled by 556 mm. The excavation depth of 10.0 m was performed in one step of calculation from 1.0 to 10.0 m. It can be seen the wall vertical displacement $U_z$ highly increased and reached about 800 mm.

Little previous studies have examined the unsupported excavation [1-4], and these studies have been considered the deep foundation (single pile) both in the experimental and the numerical model. The other previous searches have been examined shallow foundation, but the excavation was supported [8,10]. It is not easy to compare the performance of the examined shallow foundation, which has been subjected to different types of loading and consists of different parts in behavior during the excavation process.

![Figure 14. Lateral displacement $U_x$ variation at cross-section of center wall before and after excavation.](image1)

![Figure 15. Lateral displacement $U_z$ variation at cross-section of center wall before and after excavation.](image2)
4. Conclusions

1) As the excavation depth equals wall depth, the lateral displacement and the bending moment are reduced and approach zero along with wall depth.

2) As the excavation process happens gradually, the soil collapses, and the failure happens at 7.0 m depth of excavation. The failure happens at 10.0 m deep if the excavation process is done in one step. The calculation is not completed at these stages, and the expected results are probably more than obtained values.

3) The maximum forces N₁ and N₂ have been noticed at the location of the columns compared with other walls' locations for loading (before excavation) and at all excavation depth. The peak points of forces (columns) range from 3000 to -5000 kN.

4) The axial forces N₁ increases with excavations depths, and for excavation depth, 6.0 m, the rate of increase does not exceed 1% at the upper part of the wall and reaches 20% at the lower part of the wall. In addition, for 7.0 and 10.0 m excavation depth, the axial force N₁ increasing rates about 12% at the upper part and reaches 40% at the lower part of the wall.

5) The axial force N₂ increases with excavations depth and for the excavation depth 6.0 m, the rate of increasing about 20% for the wall upper part while for the lower part of the wall, the axial force N₂ decreases by rate reaches about 20%. A high reduction of N₂ force is observed at 7.0 and 10.0 m excavation depth along the wall depth by rate ranges 0.80 to 2.0 times about before excavation.

6) The vertical wall displacement slightly decreases till 2.0m excavation depth, and after that depth the vertical displacement increases with increasing depth of excavation. The increasing rate of vertical wall displacement is 50% for 6.0 m excavation depth.

7) As the excavation depth is 7.0 m and 10.0 m, the shear force variation has not exceeded 10% at the wall head.

8) The maximum bending moment decreased with excavation depth until 3.0 m; the bending moment was about zero at 3.0 m depth of excavation along the wall. Then, the bending moment has increased slightly till excavation depth 6.0m. At the excavation depth of more than 6.0m has the bending moment has re-increased in tension.

9) As the excavation process proceeds, lateral displacement Uₓ decreased with increasing the depth of excavation. The reduction ratio was 66% about the lateral displacement before the excavation at an excavation depth 2.0 m. At the excavation depth of more than 2.0 m, the wall lateral displacement Uₓ increased but in the reverse direction (towards excavation). The increasing ratio of lateral displacement was 10 times before the excavation at the wall head as the excavation depth 6.0 m.

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