EFFECT OF DEEP EXCAVATION SUPPORTED BY CONCRETE SOLIDER PILE WITH STEEL SHEET PILE LAGGING WALL ON ADJACENT EXISTING BUILDINGS

Mostafa Abdou [1]*, Ahamed Rushedy Towfeek [2], Waleed Hassan [3]
[1]prof. Dr., Civil Eng. Department, Assiut University, Egypt
[2] Lecturer, Civil Eng. Department, Al- Azhar University, Qena,. Egypt
[3] MSc,Civil Eng, Al- Azhar University, Qena,. Egypt

ABSTRACT: When retaining walls are constructed in-situ and deep excavations are made adjacent building horizontal and vertical displacements occur for the soil underneath adjacent building foundation. These soil movements due to excavation induce large settlement which may lead to structural distress and failure of the foundations supporting existing structures. Deep excavations are designed to be safe and to kept deformations due to excavation at acceptable limits on adjacent structures.

In this paper, 3D Finite element model is developed using PLAXIS 3D foundation software program to represent the performance of concrete solider pile with steel sheet pile lagging wall on the deformation characteristics of ground below adjacent building at different locations. The analysis is carried out considering non-linear behavior of soil using Mohr-coulomb failure criteria. The goals of this research are studying the factors affecting on the behavior of ground movement below adjacent building foundations such as excavation depth, pile diameter, soil type, adjacent building foundation depth, and the horizontal distance between adjacent building and excavation area. The effect of using concrete cap beam with different depth on the vertical and horizontal displacement of ground below adjacent building foundation was studied.

KEYWORDS: Solider pile, Lagging, Movements, Deep excavation, Adjacent buildings, Cap beam.

1 INTRODUCTION

It is a legal necessity with any new construction to provide protection to the adjacent structures when excavating to any appreciable depth. Without adequate lateral support the new excavation will almost certainly cause settlements, or lateral movements to existing property. New construction may include cut-and-cover work when public transportation or public utility systems are installed below ground and the depth is not sufficient to utilize tunneling operations. The new construction may include excavation depth up to 20 m or more below existing ground surface for placing any type of foundation from a spread footing to a mat, or for allowing one or more subbasements. All of this type of construction requires installation of a lateral retaining system of some type before excavation starts. Soldier piles with timber laggings have been used extensively as an excavation support system, particularly in soil conditions and where ground water ingress into the excavated area is not problematic (GCO, 1990 Tomlinson 1995; O'Rourke, 1975). Soldier pile walls have two basic components, soldier piles (vertical component) and lagging (horizontal component).

Deep excavations have been used worldwide for underground construction, but they also change the ground conditions and induce ground movements which might cause risks to adjacent infrastructure.

Many researchers have studied the effect of deep excavation on adjacent structure. Hamza (1999) showed the summary of measured settlements caused by the installation of concrete diaphragm walls and excavation for different projects in Cairo. Choy (2004) perform centrifuge modeling tests to study the effect of diaphragm wall installation on adjacent deep foundation for a soil of dense fine sand. (Abdel-Rahman, 2009) studied, a case history included performing deep excavation near existing buildings in Giza. Mostafa *et al.* (2011) studied the effect of deep excavation-induced lateral soil movements on the behavior of strip footing supported on reinforced sand. Czesław *et al.* (2014) studied the impact of deep foundations of building on the neighboring buildings using the subsidence surface of the land behind the housing wall of the excavation to assess the impact of additional displacements on the technical condition of facilities, through the determination of the distribution and the values of stresses in the estimated structure. Yupeng (2014) used advanced finite element to study the parameters governing the settlements of adjacent buildings and buried pipelines and the effectiveness of ground improvement on reducing the building settlement.

The main objective of the present study is to investigate the deformation characteristics of soil adjacent to deep excavation supported by solider pile with steel sheet pile lagging supporting system in sandy soil and factors affecting on this such as excavation depth, piles spacing, pile diameter, soil type, depth of adjacent building foundations, and distance from excavation area. For this purpose vertical and horizontal displacements for the soil underneath adjacent building are determined at various locations from excavation area. Three dimensional finite element modeling (3D FEM) was used to simulate the presented 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 per the Egyptian code of practice (ECP).

2 NUMERICAL MODELING AND SELECTED PARAMETERS

In order to make realistic prediction of the stability and deformation of the excavation and adjacent building, Mohr Coulomb model in PLAXIS program was applied for sand idealization. This model was adopted to characterize the behavior of excavation and adjacent building system and material properties.

2.1 Parameters and Material Modeling of Sandy Soil

The excavation soil is assumed to be a deposit of sandy soil as one layer. Two cases were chosen medium dense sand (relative density (Dr) =50%) and dense sand (relative density (Dr) =75%). The sand is modeled by 15-node triangular element in the analysis as an elastic perfectly plastic Mohr Coulomb model. The properties of medium sand are presented in Table (1) (Amr Radwan (2010).

Table (1): Input physical and mechanical properties of soil

Parameter	Medium sand	dense sand
Unsaturated unit weight, γ_{unsat} (kN/m³)	16	18
Saturated unit weight, γ_{sat} (kN/m³)	18	20
Young's modulus, E_s (kN/m²)	25000	50000
Poisson's ratio, υ	0.3	0.25
Undrained cohesion, c_u (kN/m²)	1	1
Friction angle, φ (degree)	33	36
Dilatancy angle, ψ (degree)	3	6
Type of material behavior	Drained	Drained

2.2 Excavation Supporting System

2.2.1 Reinforced concrete pile

Three pile diameters were considered in the analysis, pile (A) of diameter = 0.4 m, pile (B) of diameter = 0.5m and pile (C) of diameter = 0.6 m. the pile length (L), excavation height (H) and spacing between piles (S) were considered. The pile was modeled by a circular vertical beam element. Pile parameters are presented in Table (2) *(Egyption code ECP 203 – 2006)*.

Table (2): Material properties of pile (circular vertical beam)

Parameter	Pile A	Pile B	Pile C
Diameter (m)	d = 0.4	d = 0.5	d = 0.6
Type of behavior	Linear elastic	Linear elastic	Linear elastic
Pile Young's modulus (E) (kPa)	2.2×10^7	2.2×10^7	2.2×10^7
Moment of inertia (I) (m^4)	0.00125	0.0031	0.00636
Unit Weight γ (kN/m^3)	24	24	24
Poisson's ratio υ	0.2	0.2	0.2
Interface	Rigid	Rigid	Rigid

2.2.2 Steel sheet pile lagging

Steel sheet pile lagging used to fill spacing between piles; the sheet pile lagging is modeled by wall element. Sheet pile parameters are presented in Table (3) (Egyption code ECP 205 – 2001)

Table (3): Material properties of sheet pile lagging.

Parameter	abbreviation	Sheet pile lagging
Type of behavior	model	Linear elastic
Thickness (m)	d	0.05
Young's modulus (KP_a)	E 1 E 2 E 3	2.1×10^8 2.1×10^8 2.1×10^8
shear modulus (KP_a)	G1 G2 G3	8.1×10^7 8.1×10^7 8.1×10^7
Unit Weight (kN/m^3)	γ	78.5
Poisson's ratio	υ	0.3

2.3 Adjacent Building.

The studied structure was assumed to be a reinforced concrete building consists of eight typical floors each 3.00 m height. Each floor consists of three bays 4, 4, 4 m width in X and Z directions. Four foundation levels are considered in this study as at 0,-0.5,-1, -1.5 m from ground level. This structure was assumed to be an office building. The concrete cube strength was assumed to be 24 Kpa. The floors were assumed to be 0.20 m thickness flat slab, fixed supported on columns with cross section 50 × 50 cm as shown in Figure (1), which are fixed supported on 0.8 m thickness raft foundation. These assumptions were checked by the structural analysis according to the Egyptian Code.

2.4 Finite Element Model

The used support system model for excavation and adjacent building are shown in Figure (2).This figure shows a cut at the face of the excavation. 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 12 m x 12 m to give an equal spacing between solider pile in case of using spacing 2, 3 and 4m and the existing building is assumed to be 12 m x 12 m in plane. The dimensions of model are 50 m x 30 m x 25 m and the mesh was generated as fine mesh at excavation area where the stresses are high and coarse mesh at the boundaries of the model where the stresses are low. The used finite element model for excavation and adjacent soil are shown in Figure (2). As illustrated in this figure:

Excavation area = 12.0 x 12.0 (m),
Depth of excavation = H (m),
Total height of pile = L (m),

Driven depth of pile = D (m),
Pile diameter = d (m),
Spacing between piles = S (m),
Depth of sheet pile lagging = depth of excavation = H (m)
Depth from ground level = Z (m)
Adjacent building area = 12.0 x 12.0 (m),
Adjacent building foundation depth = D_f (m),
Horizontal distance between adjacent building and excavation area = R_x (m)
Adjacent building load = live load (L.L) + cover (F.C) + wall = 3+ 2 + 3 = 8 (KN/m^2)

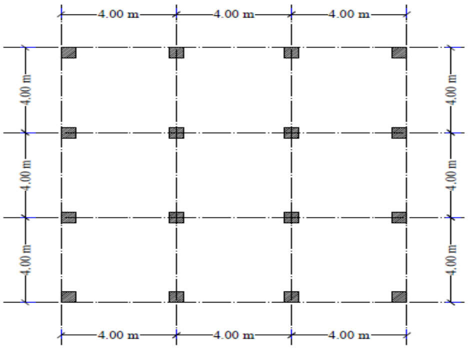

Figure (1): Plan view of adjacent building columns

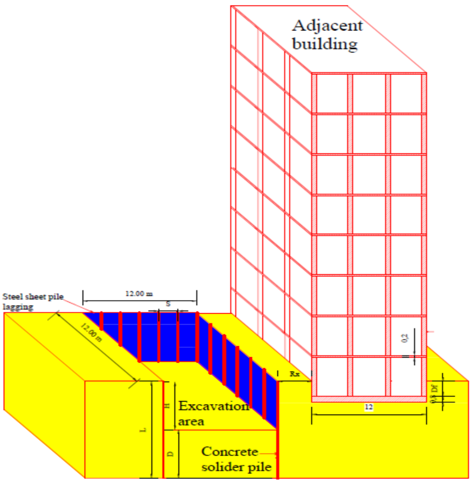

Figure (2): Model of excavation and adjacent building

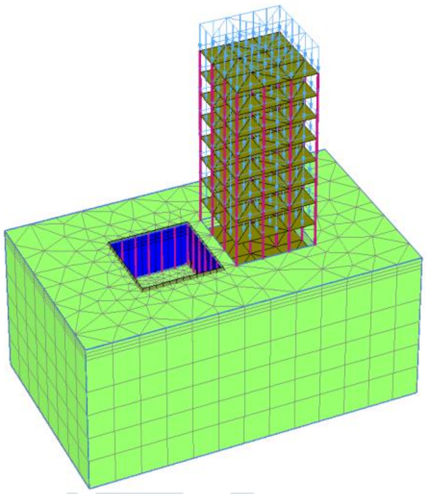

Figure (3): Finite element mesh for the model of deep excavation and adjacent building load

2.5 ANALYSIS PROCESS

The analysis process consists of many steps, choosing and generating the finite element model. Then, calculation stages started up. the parameters taken into consideration in the analysis process were the excavation height (H) (five different height 4,5,6,7 and 8m, were chosen), pile spacing (S) used 2,3 and 4 m spacing between pile, pile diameter (d) used 0.4,0.5and 0.6 m, type of soil used two types of sandy soil dense and medium dense sand. The analysis process was carried out in three steps. The first step was activation of the adjacent building. The second step was activation of the solider pile and sheet pile lagging wall in the soil, (Solider pile active in all levels of soil but sheet pile lagging active in the ground surface up to excavation depth level only). The third step was the excavation of the soil. In the current paper, only vertical and horizontal displacements for the soil underneath adjacent building were considered in the analysis. All cases used in this study are given in Table (4).

Table (4-a): Cases used in the numerical study

H (m)	*D_f (m)*	*R_x (m)*	*D (m)*	*Soil*	*Medium sand*			*Dense sand*		
				s(m) \ d(m)	0.4	0.5	0.6	0.4	0.5	0.6
4	-1	0.5	4	2	1	2	3	4	5	6
				3	7	8	9	10	11	12
				4	13	14	15	16	17	18
5	-1	0.5	5	2	19	20	21	22	23	24
				3	25	26	27	28	29	30
				4	31	32	33	34	35	36
6	-1	0.5	6	2	37	38	39	40	41	42

				3	43	44	45	46	47	48
				4	49	50	51	52	53	54
7	-1	0.5	7	2	55	56	57	58	59	60
				3	61	62	63	64	65	66
				4	67	68	69	70	71	72
8	-1	0.5	8	2	73	74	75	76	77	78
				3	79	80	81	82	83	84
				4	85	86	87	88	89	90

Table (4-a): Cases used in the numerical study

H (m)	*D(m)*	*S(m)*	*d (m)*	*Soil*	*Medium sand*			
				D_f(m) / R_x(m)	*0.00*	*-0.50*	*-1.00*	*-1.50*
8	8	2	40	1.00	91	92	93	94
				1.50	95	96	97	98
				2.00	99	100	101	102

ANALYSIS OF RESULTS AND DISCUSSION

This research presents the finite element results of horizontal displacement (U_x) and vertical displacement (U_y) of the soil underneath adjacent building at excavation height = 8m, pile spacing was 2m, 3m and 4m and pile diameter was 0.4m,0.5m and 0.6 m respectively in both of medium and dense sand. The effect of this parameter on the horizontal displacement (U_x) and vertical displacement (U_y) of the soil underneath adjacent building was studied.

3.1 Factors Affecting on the Horizontal Displacement (U_x) and Vertical Displacement (U_y) of the ground under adjacent building

3.1.1 Height of Excavation (H)

Figures (4) and (5) illustrate the change in the horizontal displacement (U_x) and vertical displacement (U_y) for the vertical section in the middle soil underneath adjacent building foundation respectively. For excavation height (H= 4,5,6,7, and 8 m), piles pacing (S) = 3.0m, foundation depth (D_f) = -1,0m, R_x = 0.5m and pile diameter (d) = 0.50m in medium dense sand. These Figures demonstrated that, the maximum horizontal displacement (U_x) occurred at the interface between solider pile wall and adjacent building and decreases by increasing distance from retaining wall, but the maximum value of vertical displacement (U_y) occurred at the side of adjacent building beside retaining wall and decreases by increasing distance from retaining wall and minimum value occurred at the interface between solider pile wall and adjacent building, both horizontal displacement (U_x) and vertical displacement (U_y) values increase by increasing excavation height. This can be interpreted as increasing excavation height will increase the lateral pressure on the solider pile wall and consequently increase the lateral force and lateral displacement on the wall.

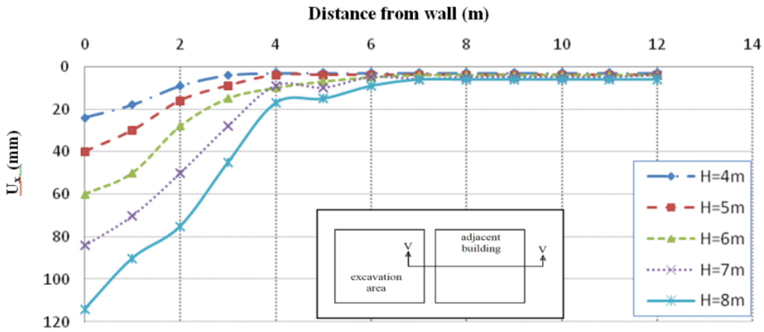

Figure (4): Horizontal displacement of soil underneath adjacent building foundation for different excavation height in medium sand (R_x= 0.5m, d=0.5 m, D_f = -1 and S= 3 m).

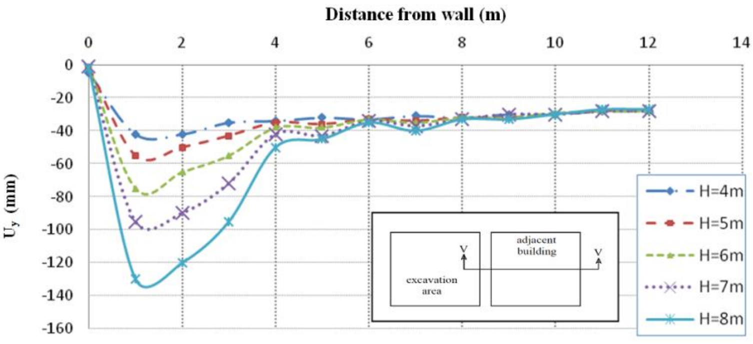

Figure (5): Vertical displacement of soil underneath adjacent building foundation for different excavation height in medium sand (R_x= 0.5m, d=0.5 m, D_f = -1 and S= 3 m).

3.1.2 Pile Diameter (d)

Figures (6) and (7) show the horizontal displacement (U_x) and vertical displacement (U_y) of the soil underneath adjacent building foundation respectively, for different pile diameters, d = 0.4, 0.5 and 0.6 m, at excavation height (H) = 8m and piles spacing (S) = 3m in medium dense sand. It is observed that the pile diameter effect on the value of (U_y) and decreased by around 30% when pile diameter increasing from 0.4m to 0.6m. On the other hand, in case of pile, of d=0.6 m, horizontal displacement (U_x) was less than that when d=0.4 and 0.5 m. This can be attributed to, increasing pile diameters increases stiffness of retaining wall and make it more rigid, resulting in reduce wall deformation and adjacent soil movements.

3.1.3 Soil Type Effect

Figures (8) and (9) showed the effect of change in sand properties on the horizontal displacement (U_x) and vertical displacement (U_y) of the soil underneath adjacent building foundation respectively, for medium dense and dense sand at excavation height (H) = 8m, piles spacing (S) = 3m, pile diameter (d) = 0.5m, R_x=0.5m and D_f = -1m. From the shown Figures we can noted that, the maximum value of (U_y) in medium sand increased by around 25% of its value in dense sand and horizontal displacement (U_x) in medium dense sand is large than that in dense sand, This can be interpreted as the coefficient of active lateral earth pressure (K_a) of dense sand less than that in medium dense sand, resulting in reduce lateral force on retaining wall and lateral displacement of wall and adjacent soil deformations.

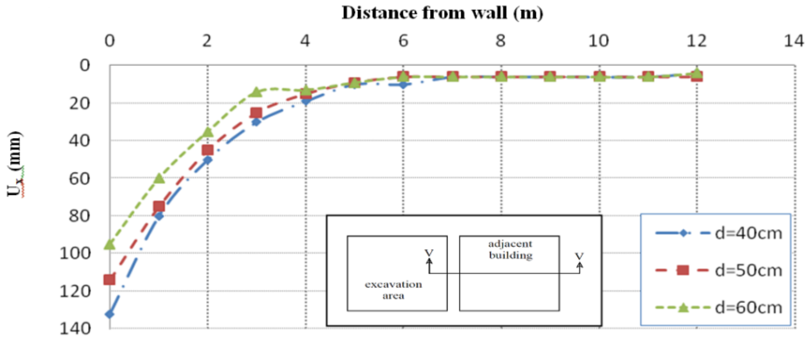

Figure (6): Horizontal displacement of soil underneath adjacent building foundation for different pile diameter in medium sand (R_x= 0.5m, H=8 m, D_f = -1 and S= 3 m).

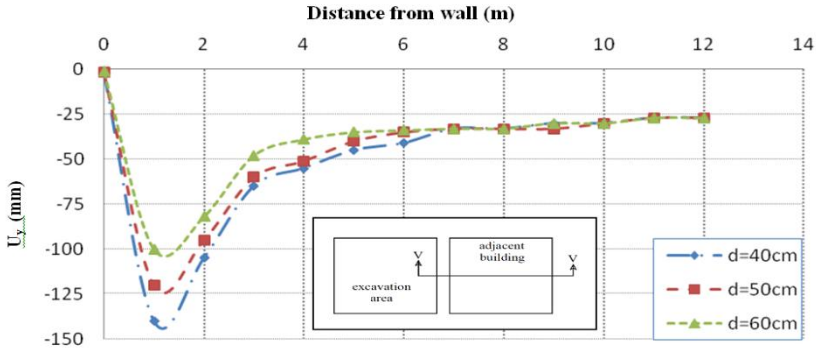

Figure (7): Vertical displacement of soil underneath adjacent building foundation for different pile diameter in medium sand (R_x= 0.5m, H=8 m, D_f = -1 and S= 3 m).

3.1.4 Effect of horizontal distance between adjacent building and excavation area (R_x)

To investigate the soil deformations underneath adjacent building foundation at different distance from the excavation three different values of (R_x) are applied in the current study (R_x = 1, 1.5 and 2m). Figures (10) and (11) show horizontal displacement (U_x) and vertical displacement (U_y) of the soil underneath adjacent building foundation respectively, for different values of (R_x) at excavation height (H) = 8m, piles spacing (S) = 2m, pile diameter (d) = 0.4m, and D_f = -1m in medium dense sand. It is observed that the maximum value of (U_x) and (U_y) decrease by large value when (R_x) increase from 1 to 1.5 m and minimum value when (R_x) increase from 1.5 to 2.0 m.

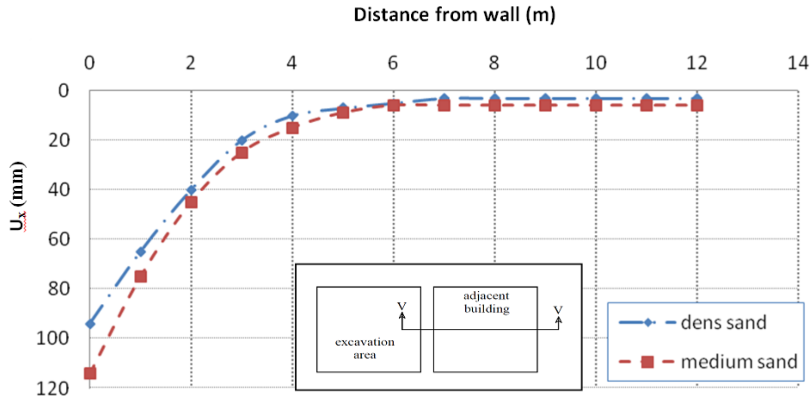

Figure (8): Horizontal displacement of soil underneath adjacent building foundation for different soil type (R_x= 0.5m, H=8 m, D_f = -1,d=0.5m and S= 3 m).

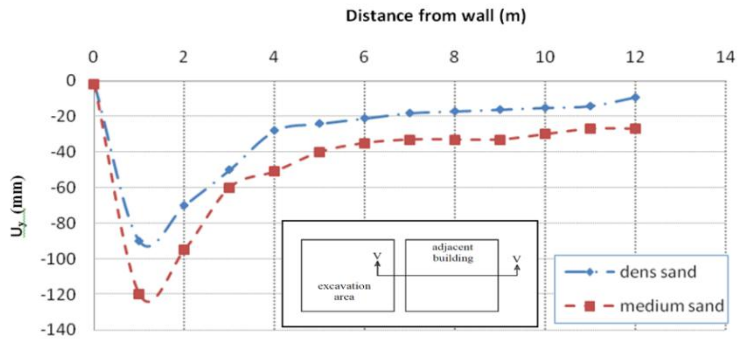

Figure (9): Vertical displacement of soil underneath adjacent building foundation for different soil type (R_x= 0.5m, H=8 m, D_f = -1, d=0.5m and S= 3 m).

3.1.5 Effect of adjacent building foundation depth (D_f)

Increasing depth of building foundation from ground surface increase bearing capacity of soil and reduce deformation of soil underneath building foundation before excavation. To study the effect of foundation depth (D_f) on the deformation of soil underneath building foundation after excavation, adjacent building foundation applied in four different level (D_f = 0, -0.5, -1.00 and -1.5m) from ground surface level at excavation depth (H) = 8m (Rx=0.5, S = 2m and d= 0.5 m) in medium dense sand as shown in Figures (12) and (13). It is observed that increased foundation depth from 0 to -1.5m below ground surface level leads to decrease vertical displacement (U_y) by around 32% and no effect change in the value of horizontal displacement (U_x).

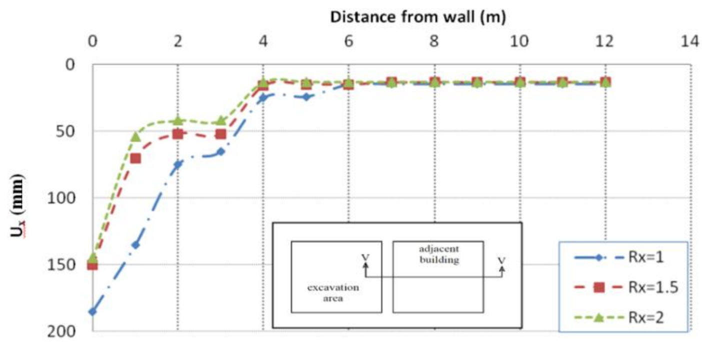

Figure (10): Horizontal displacement of soil underneath adjacent building foundation for different value of R_x in medium sand (H=8 m, D_f = -1,d=0.4m and S= 2 m).

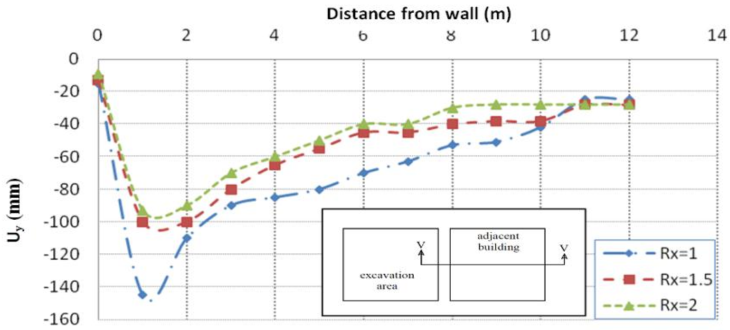

Figure (11): Vertical displacement of soil underneath adjacent building foundation for different value of R_x in medium sand (H=8 m, D_f = -1,d=0.4m and S= 2 m).

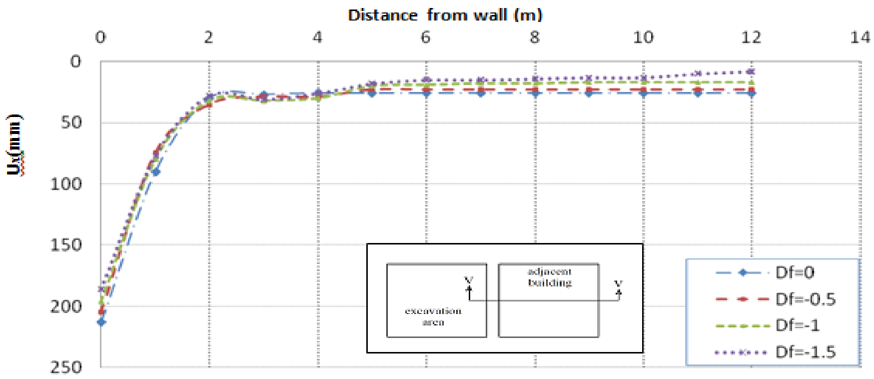

Figure (12): Horizontal displacement of soil underneath adjacent building foundation for different value of Df in medium sand (H=8 m, Rx = 0.5m,d=0.5m and S= 2 m).

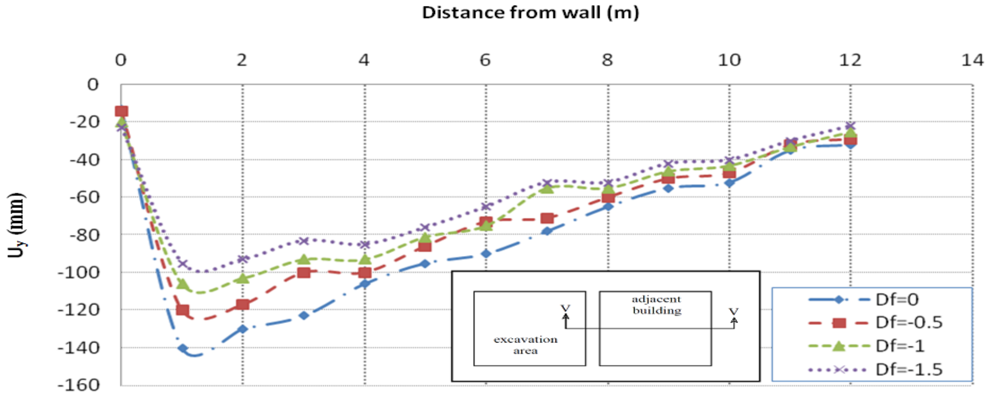

Figure (13): Vertical displacement of soil underneath adjacent building foundation for different value of D_f in medium sand (H=8 m, R_x = 0.5m,d=0.5m and S= 2 m).

3.1.6 Effect of cap Beam

Using concrete cap beam was studied with width (b=d pile) and three different depth (dc = b, 1.5b, and 2b) to improve the behaviour of both solider pile with steel sheet pile lagging wall and soil underneath adjacent building foundation.

Figures (14) and (15) illustrate the change in the distribution of horizontal displacement (U_x) and vertical displacement (U_y) of soil underneath adjacent building foundation respectively in case of using concrete cap beam with section(0.4m * 0.4m) at excavation depth (H) = 8m, S=4m, R_x=0.5m, D_f = -1.00 m and d= 0.4 m in medium dense sand. It is observed that using cap beam has a great effect on the deformation of ground under adjacent building foundation. Horizontal displacement (U_x) decreased by around 66% when cap beam applied, while vertical displacement (U_y) decreased by around 52%. Using cap beam, it converted solider pile support system from fixed in soil free at ground level to fixed in soil fixed at ground level. This beam make the support system more stiff, resulting in reduce both lateral displacement of solider pile and sheet pile lagging wall and deformation of ground under adjacent building.

Figures (16) and (17) indicate the effect of change in depth of cap beam (d_c) on the horizontal displacement (U_x) and vertical displacement (U_y) of soil underneath adjacent building foundation respectively in case of using concrete cap beam with section [(0.4m * 0.4m),(0.4m *0.6m) and (0.4m * 0.80 m)] at excavation depth (H) = 8m, S=4m, d= 0.4 m, Rx=0.5m and D_f = -1.00m in medium dense sand. From these Figures, it can be found that both horizontal displacement (U_x) and vertical displacement (U_y) of soil underneath adjacent building foundation were decreased with the increasing of cap beam depth. This can be attributed to, increasing cap beam depth increases fixed length of support system and make it more stiff.

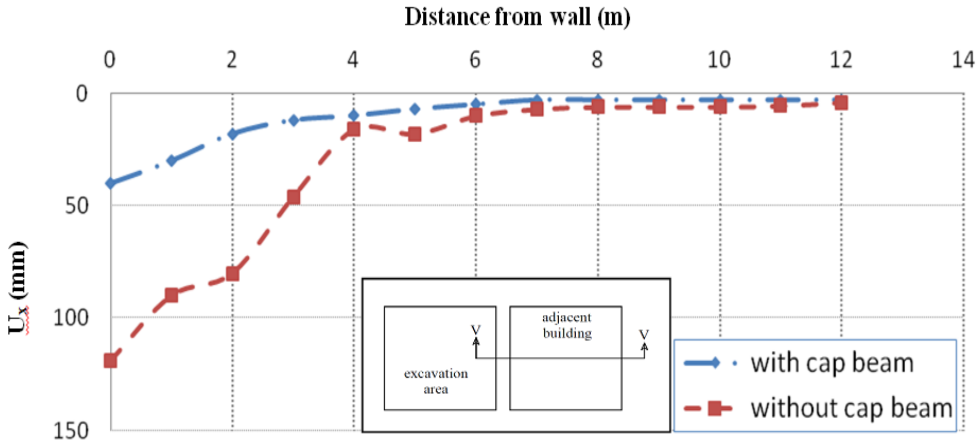

Figure (14): Horizontal displacement of soil underneath adjacent building in medium sand (H=8 m, R_x= 0.5m, d=0.4m, D_f = -1 m and S= 4 m).

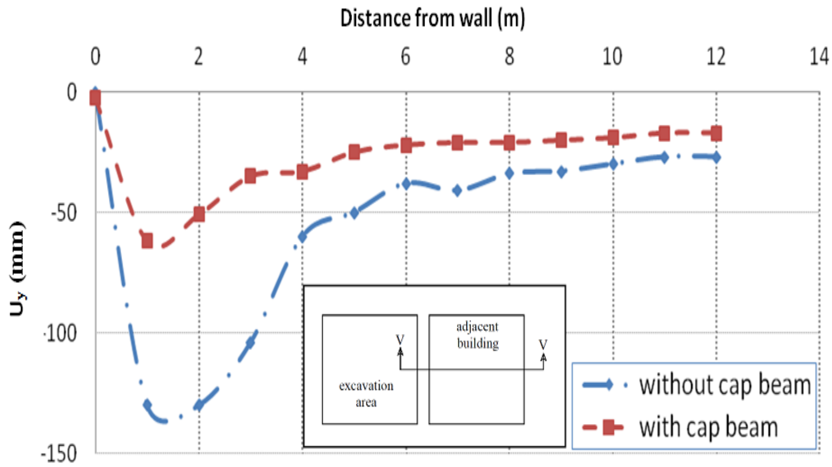

Figure (15): Vertical displacement of soil underneath adjacent building in medium sand (H=8 m, Rx= 0.5m, d=0.4m, Df = -1 m and S= 4 m).

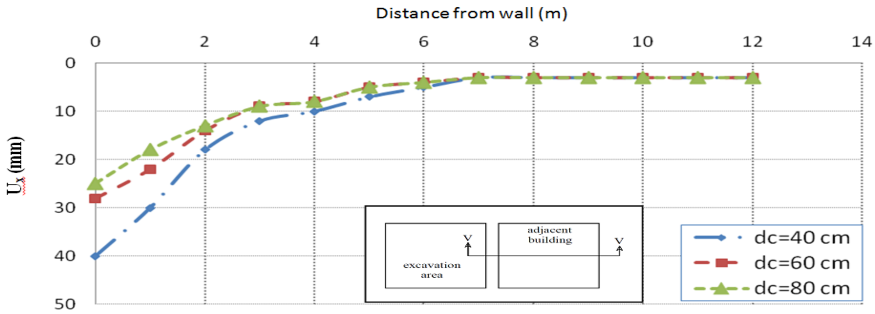

Figure (16): Horizontal displacement of soil underneath adjacent building for different depth of cap beam in medium sand (H=8 m, R_x= 0.5m, d=0.4m, D_f = -1 m and S= 4 m).

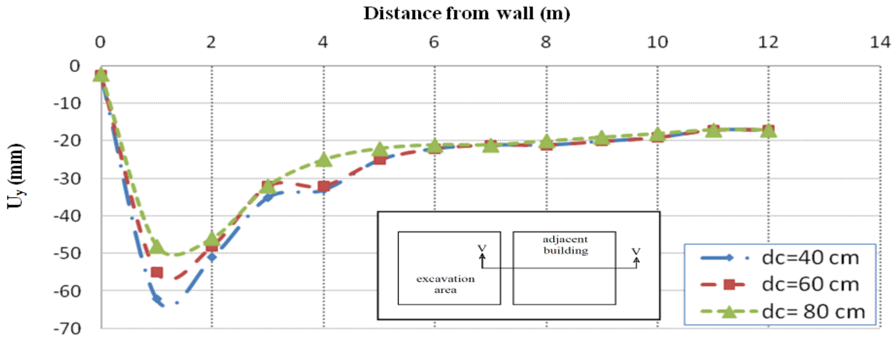

Figure (17): Vertical displacement of soil underneath adjacent building for different depth of cap beam in medium sand (H=8 m, R_x= 0.5m, d=0.4m, D_f = -1 m and S= 4 m).

4. CONCLUSIONS

The results provide an understanding of the effect of deep excavation supported by concrete solider pile with steel sheet pile lagging wall on adjacent existing buildings to decrease the soil deformation underneath adjacent building foundation during deep excavation. The following are some important inferences from the present study.

1- Increasing excavation height, H, increases both horizontal displacement (U_x) and vertical displacement (U_y) of soil underneath adjacent building foundation.
2- Vertical displacement (U_y) decreased by around 30% when pile diameter increasing from 0.4m to 0.6m and horizontal displacement (U_x) in case of pile, of d=0.6 m, less than that when d=0.4 and 0.5 m.
3- The maximum value of vertical displacement (U_y) in medium dense sand increased by around 25% of its value in dense sand. Whereas, horizontal displacement (U_x) in medium dense sand is larger than that in dense sand.
4- Increasing horizontal distance between adjacent building and excavation area (R_x), decreases both horizontal displacement (U_x) and vertical displacement (U_y) of soil underneath adjacent building foundation.
5- Increasing foundation depth from 0 to -1.5m below ground surface level decrease vertical displacement (U_y) by around 32% and no effect change in the value of horizontal displacement (U_x).
6- Using cap beam has a great effect on the deformation of soil underneath adjacent building foundation and decreased horizontal displacement (U_x) by around 66% and vertical displacement (U_y) by around 52% of its value without using cap beam.
7- Both horizontal displacement (U_x) and vertical displacement (U_y) of ground under adjacent building foundation were decreased with the increasing of cap beam stiffness.

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