NUMERICAL ANALYSIS OF CONCRETE SOLIDER PILE WITH STEEL SHEET PILE LAGGING SUPPORTING SYSTEM IN SANDY SOIL

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ABSTRACT: Deep excavations have been used worldwide for underground construction, reliable prediction of ground deformations are essential in the design process for assessing the effects of excavation on adjacent facilities; and identifying sections where special remedial construction measures are required. Available techniques for estimating wall deflections and soil settlements involve either interpolation from existing empirical databases or numerical analyses using finite element methods, which is considered an effective way to investigate the performance of deep excavations. This paper presents numerical analysis of concrete solider pile with steel sheet pile lagging supporting system in sandy soil using three dimensional finite element modeling.

(3D FEM) PLAXIS 3D foundation software program was used in the analysis. A parametric study was performed to study the effect of spacing between piles, piles stiffness, type of sandy soil and the influence of using cap beam at piles head. Lateral displacement and bending moment of both solider pile and sheet pile lagging ware investigated and comparison between solider pile wall support system and sheet pile wall support system was achieved.

KEYWORDS: Solider pile, sheet pile lagging, deep excavation, cap beam.

1 INTRODUCTION

A deep excavation is typically defined as an excavation in soil or rock that is deeper than 15 ft (4.5 m). Deep excavations require careful design and planning especially when constructed in congested urban areas. Selecting and designing an appropriate earth retaining and support system can have significant impact on cost, time, and performance. Deep excavations involve two main systems, a) the retaining system that contains earth and water from entering directly into the excavated site, and b) the support system (or bracing system) that contains the resist forces generated by soil, surcharges, and water. (The term "Supporting System" for a deep excavation is a structural system that holds soil and water and keeps it from collapsing).

Different types of supporting systems are existing. Selection of the suitable supporting system depends on a wide range of factors such as: soil conditions, economical, protection of adjacent structures, environmental issues, ease of construction, and so on. Types of supporting systems involve sheet piling, soldier pile and lagging, soil mix walls, secant pile or tangent pile walls, and diaphragm walls. (Deep Excavation 2012 – User's Manual).

Soldier pile and timber lagging walls have been used extensively as excavation support systems, Soil loads are transferred to soldier piles partly by the lagging and partly by arching of soil. When the soil between soldier piles is able to self retain, the soil loads will transfer to the adjacent soldier piles, and no lagging will be needed. This soil load transfer is caused by soil arching. (Trenching and Shoring Manual 2011).

The main advantage of using soldier piles is their comparatively low cost and ease of installation compared to other forms of support systems such as diaphragm walls and bored piles. Since the soldier piles are not contiguous, fewer soldier piles are needed in comparison to sheet piles, thereby yielding significant savings in time and cost of installation and thus allowing excavation to commence with a minimum lead time.

Soldier piles are often designed and analyzed as contiguous wall systems even though they are, in reality, not so (Peck, 1969, Potts & Zdravković, 2001). The fact that, the soldier piles and timber laggings are vastly different construction and have very different values of stiffness that means, the interaction between the retaining system and the soil is three-dimensional (3D) in nature. However, most of the finite element (FE) analyses on soldier pile walls to date are two dimensional (2D) and based on the assumption of plane strain (O'Rourke, 1975; Clough et al., 1972; Tsui and Clough, 1974 and Gomes Correia and Guerra, 1997). Briaud and Lim (1999) used 3D FE analyses to study tie back soldier pile walls. However, their study focused on the parameters of the tiebacks and depth of soldier pile embedment rather the effects of different types of analyses. Furthermore, Briaud and Lim (1999) modeled the soldier piles with beam elements. As will be discussed later, beam elements may not realistically represent the interaction between the soldier piles and surrounding soil, owing to their inability to replicate the finite cross-sectional dimensions of real soldier piles. Hong et al (2002) used 3D FE analyses to study the behaviour of soldier piles and timber lagging support systems. Ramadan (2013) used 3D FE in analysis of piles supporting excavation adjacent to existing buildings. Yuepeng Dong (2014) applied advanced finite element analysis to investigate the performance of deep excavations.
Cao et al (2013) used the inclinometer measurements and finite element program to evaluate the solider pile wall performance in the clayey soils in downtown Toronto. Johansson and Sandeman (2014) used two-dimensional FE software PLAXIS 2D (PLAXIS), to model a multi-anchored SPW and comparing the results from these methods to in-situ measurements. Bo Liu and Wei Xu (2015) used 3D FE FLAC 3D finite element to study the effects of demolishing the deep excavation support system used for tall building construction on adjacent metro line.

The main objective of the present study is to investigate different aspects of the behavior of solider pile with steel sheet pile lagging support system in sandy soil. The main objectives for this research are:-

a) Staffing an analytical model to represent pragmatic behavior for the excavation and adjacent area.

b) Study the effect of the parameters affecting on the behavior of the chosen model such as spacing between pile, pile diameter and soil type.

C) Study the effect of using cap beam on the behavior of solider pile and sheet pile lagging.

Three dimensional finite element modeling (3D FEM) was used to simulate 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 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 the 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 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 and dense 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 diameters for piles 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	*d* = 0.4 m	*d* = 0.5 m	*d* = 0.6 m
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)	t	0.05
Young's modulus (KP_a)	E 1	2.1×10^{8}
	E 2	2.1×10^{8}
	E 3	2.1×10^{8}
shear modulus (KP_a)	G1	8.1×10^{7}
	G2	8.1×10^{7}
	G3	8.1×10^{7}
Unit Weight (KN/m^3)	γ	78.5
Poisson's ratio	υ	0.3

2.3 Adjacent Building Loads

Adjacent building modeled as area (12m*12m) subjected to vertical distributed load (q) (KN/m^2) at depth= 1.5 m from the ground surface.

2.4 Finite Element Model

The used finite element model for excavation and adjacent area are shown in Fig. (1).This figure shows a cut at the face of the excavation. model dimensions were selected so that the boundaries are far enough to do not 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 and caused stress on soil assumed to be 150 kN/m^2 at1.5 m depth below the ground surface. This stress is corresponding for the dense to medium sand soil bearing capacity. 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 whereas, 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 Fig. (2).

As illustrated in this figure:

Excavation area = 12.0 x 12.0 (m^2),

Depth of excavation = H (m),

Total length of pile = L (m),

Driven depth of pile = D (m),

Pile diameter = d (m),

Spacing between piles = S (m),

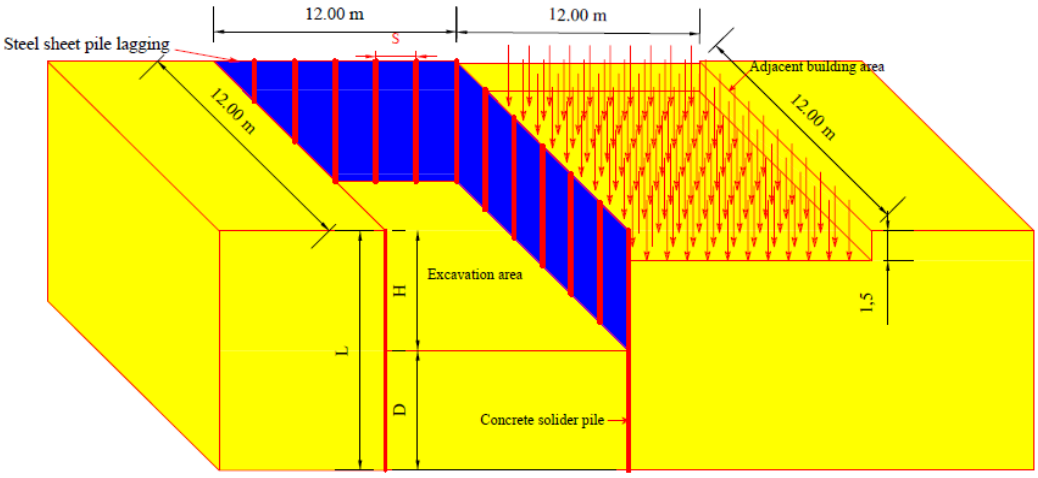
Adjacent building = 12.0 x 12.0 (m),

Adjacent area load = q (KN/m^2),

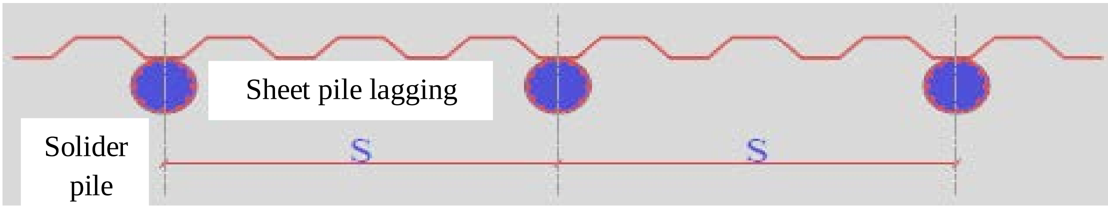
Adjacent area depth (foundation level) = 1.5 (m)

Depth of sheet pile lagging = depth of excavation = H (m)

Depth from ground surface = Z (m)



(a)



(b)

Figure (1): a- Model of excavation and adjacent building

b- Horizontal section in solider pile and sheet pile lagging wall

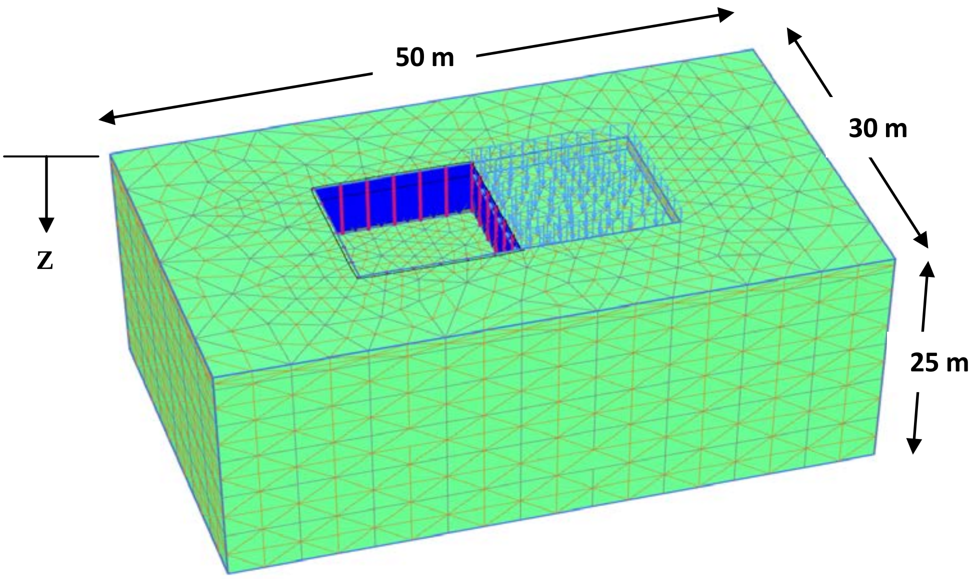


Figure (2): Finite element mesh for the model of deep excavation and adjacent building load

ISSN 2229-5518

2.5 ANALYSIS PROCESS

After entering the finite element model, calculation stages started up. The parameters taken into consideration in the analysis process are the excavation height (H) (five different height where chosen 4,5,6,7 and 8m), pile spacing (S) 2,3and 4m were used, pile diameter (d) 0.4, 0.5 and 0.6m were used, type of soil used, two types of sandy soil dense and medium sand and the adjacent building stress (q) assumed to be 100 and 150 kN/m^2 .

The analysis process was carried out in three steps. The first 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 and excavation depth level only). The second step was the excavation of the soil. The third step was applying the adjacent building stress at the foundation level.

In the current paper, only lateral displacement and bending moment of solider pile and sheet pile lagging outputs were used in the analysis. All the presented results are of the solider pile and sheet pile lagging were located at the middle side of excavation area beside adjacent building (critical pile and critical lagging). All cases used in this study are given in **Table (4).**

Table (4): Cases used in the numerical study

H (m)	D (m)	*TYPE OF SOIL*	Medium sand						Dense sand					
		d (m)	0.4		0.5		0.6		0.4		0.5		0. 6	
		q (kN/m^2) / *S* (m	100	150	100	150	100	150	100	150	100	150	100	150
4	8	2	1	2	3	4	5	6	7	8	9	10	11	12
		3	13	14	15	16	17	18	19	20	21	22	23	24
		4	25	26	27	28	29	30	31	32	33	34	35	36
5	9	2	37	38	39	40	41	42	43	44	45	46	47	48
		3	49	50	51	52	53	54	55	-----	56	57	58	59
		4	60	61	62	63	64	65	66	67	68	69	70	71
6	10	2	71	72	73	74	75	76	77	78	79	80	81	82
		3	83	84	85	86	87	88	89	90	91	92	93	94
		4	95	96	97	98	99	100	101	102	103	140	105	106
	11	2	107	108	109	110	111	112	113	114	115	116	117	118

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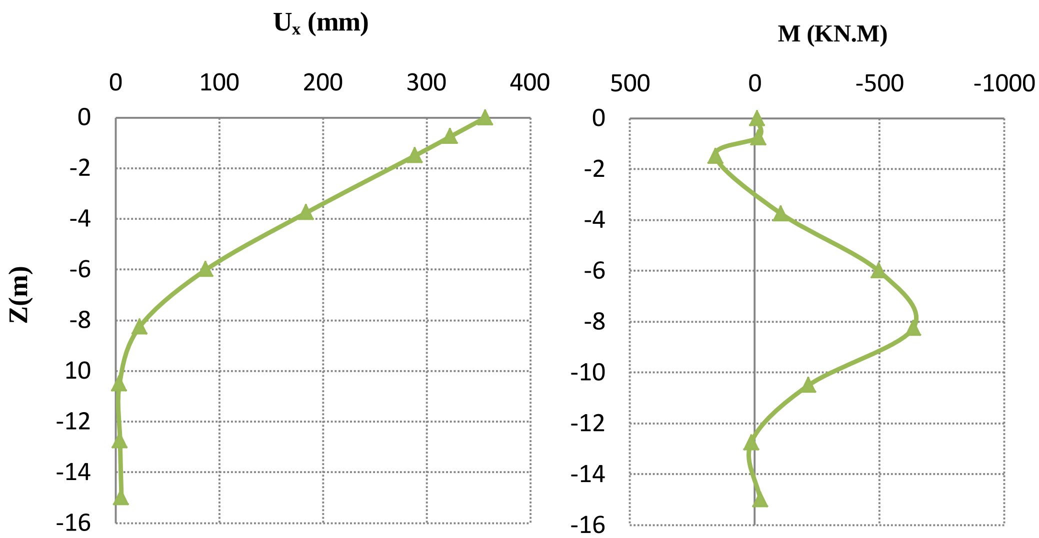
7		3	119	120	121	122	123	124	125	126	127	128	129	130
		4	131	132	133	134	135	136	137	138	139	140	141	142
		2	143	144	145	146	147	148	149	-----	150	151	152	153
8	12	3	154	155	156	157	158	159	160	161	162	163	164	165
		4	166	167	168	169	170	171	-----	172	173	174	-----	175

3 ANALYSES OF RESULTS AND DISCUSSION

This research presents the finite element results of lateral displacement (U_x) and bending moment (M) of solider pile and steel sheet pile lagging at excavation height = 6m, 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. Adjacent area load = 150 KN/m^2. The effect of this parameter on the lateral displacement (U_x) and bending moment (M) of solider pile and steel sheet pile lagging was studied.

3.1 Lateral Displacement and Bending Moment of Solider Pile

Figure (3) shows lateral displacement and bending moment of solider pile. For case study No (86) the pile located at the middle side of excavation area besides adjacent building. From the shown figures, the maximum lateral displacement of solider pile occur at the top of pile and decreasing by increasing pile depth until embedded depth (D)= 4.5m (pivot point) and begin in increasing by increase pile depth until end of pile length. and the maximum bending moment of solider pile occur at D = 2.25 m .

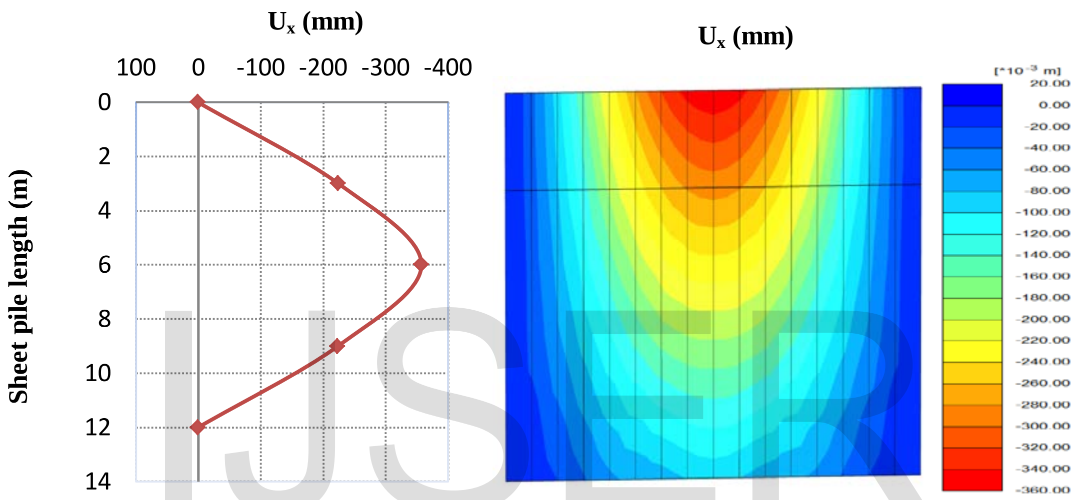


(a) Lateral displacement profile **(b)** Bending moment diagram

Figure (3): Lateral displacement and bending moment of solider pile in medium sand (H=6m, d=0.5 m and q=150 kN/m^2)

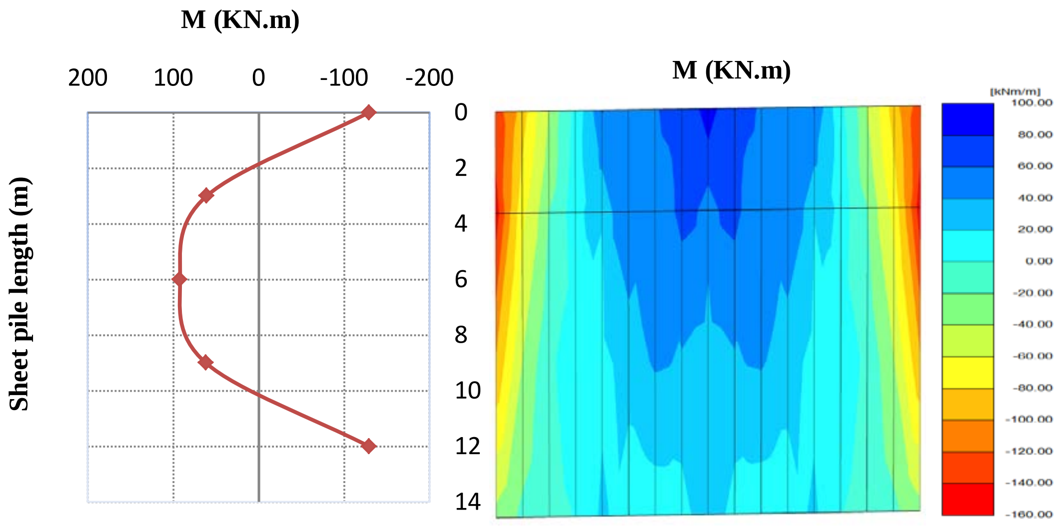
3.2 Lateral Displacement and Bending Moment of Sheet Pile Lagging

Figures (4) and (5) show lateral displacement and bending moment of sheet pile lagging, respectively, beside adjacent building in the case of piles has 0.5m diameter and spacing =3m in medium sand (case study No 86) . From the shown Figures the maximum lateral displacement and the maximum positive bending moment (M_{max}^{+}) occur at the middle span of sheet pile at ground surface and decrease at the end of lagging (corners of excavation when increasing sheet pile depth. the maximum negative bending moment (M_{max}^{-}) occurs at the end span of sheet pile (corners of excavation) at ground surface and deceases at the middle span of lagging when increasing sheet pile depth.



(a) along sheet pile length (b) along sheet pile depth

Figure (4): lateral displacement of sheet pile



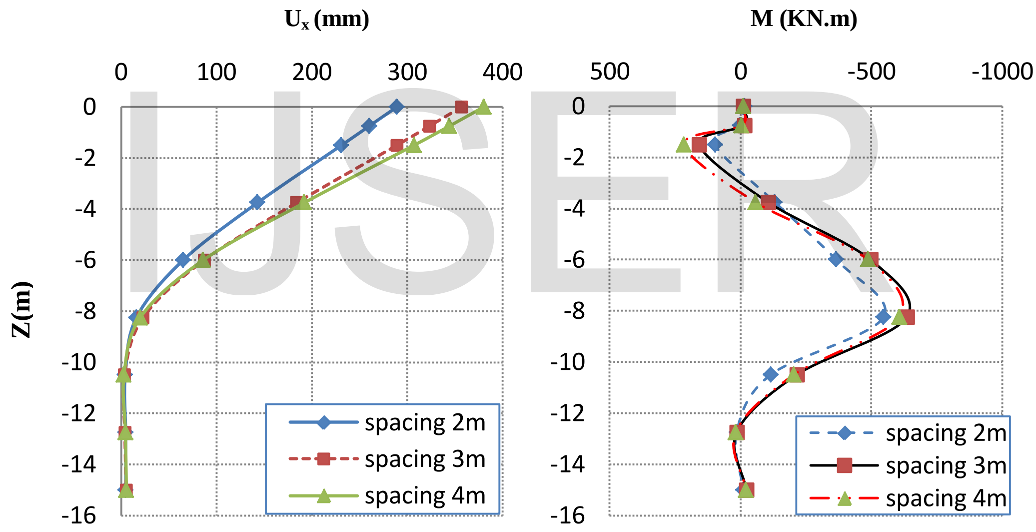
(a) along sheet pile length (b) along sheet pile depth

Figure (5): Bending moment of sheet pile lagging

3.3 Factors Affecting the Lateral Displacement (U_x) and Bending Moment (M) of Solider Pile and Sheet Pile Lagging

3.3.1 Spacing between Piles (S)

Figures (6) and (7) illustrate the change in the lateral displacement (U_x) and bending moment (M) of solider pile and sheet pile lagging, respectively, for piles spacing (S= 2,3,4m) and pile diameter (d)=0.5m. Solider pile located at the middle side of excavation area besides adjacent building in medium sand (q=*150 kN/m*^{2}). The concurred figures demonstrated that, the lateral displacement of solider pile was highly increased when *S* increased from 2 m to 3 m and little increasing was obtained when *S* increased from 3 m to 4 m. The lateral displacement of sheet pile lagging and maximum bending moment (M_{max}) of solider pile and sheet pile lagging increases by increasing spacing *(S)* from 2m to 3m to 4m.



(a) Lateral displacement profile **(b)** Bending moment diagram

Figure (6): Lateral displacement and bending moment of solider pile in medium sand (H=6m, d=0.5 m and q=150 kN/m^2)

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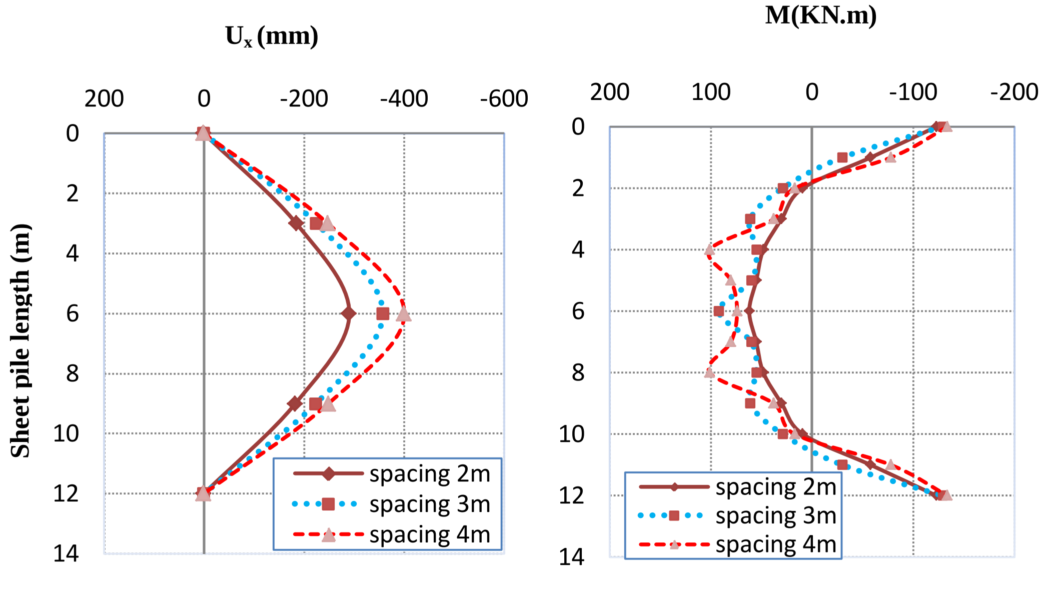
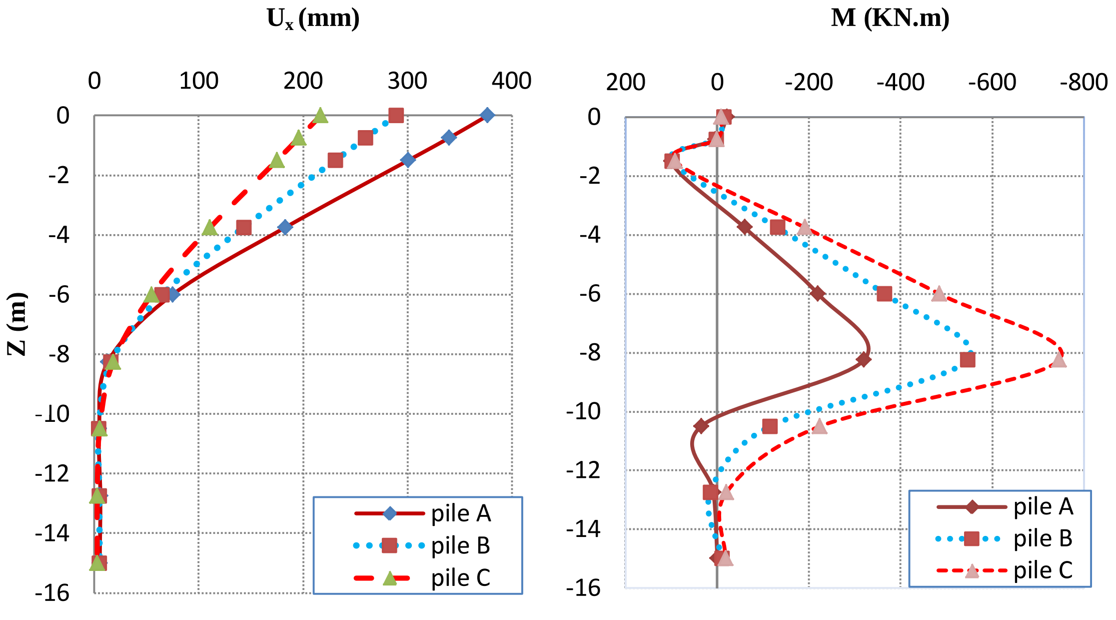


(a) Lateral displacement profile **(b)** Bending moment diagram

Figure (7): Lateral displacement and bending moment of sheet pile lagging in medium sand (H=6m, d=0.5 m and q=150 kN/m^2)

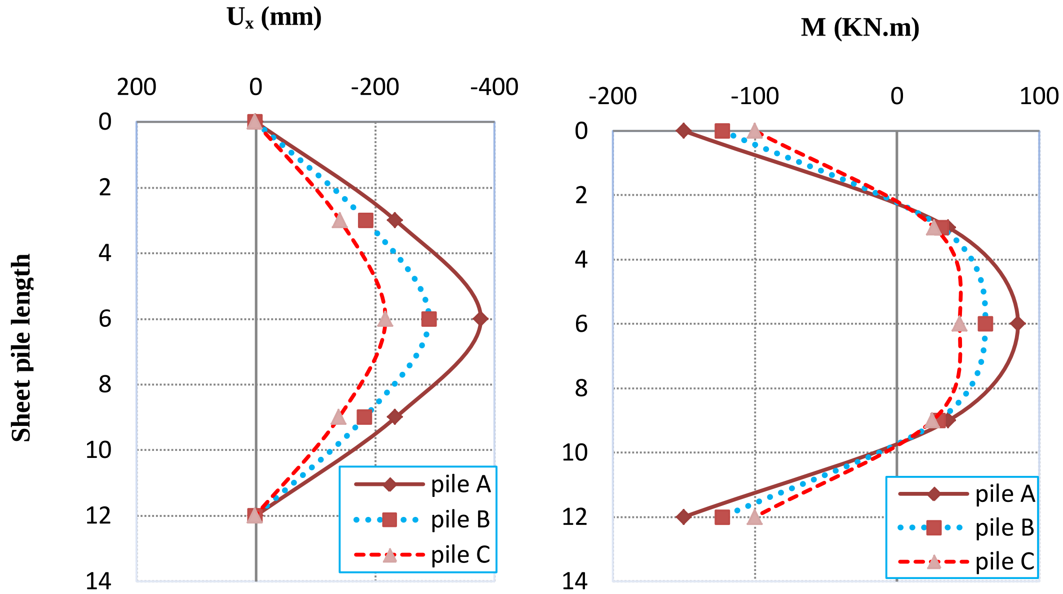
3.3.2 Pile Diameter (d)

Figures (8) and (9) revealed that, increasing pile diameter (d) from 0.4 m (pile A) to 0.5 m (pile B) to 0.6 m (pile C), reduced lateral displacements of solider pile but increased bending moment. Whereas, increasing pile diameter from 0.4m to 0.5 to 0.6m decreased lateral displacements and bending moment in case of sheet pile lagging.



(a) Lateral displacement profile **(b)** Bending moment diagram

Figure (8): Lateral displacement and bending moment of solider pile in medium sand (H=6m, S=2 m and q=150 kN/m^2)

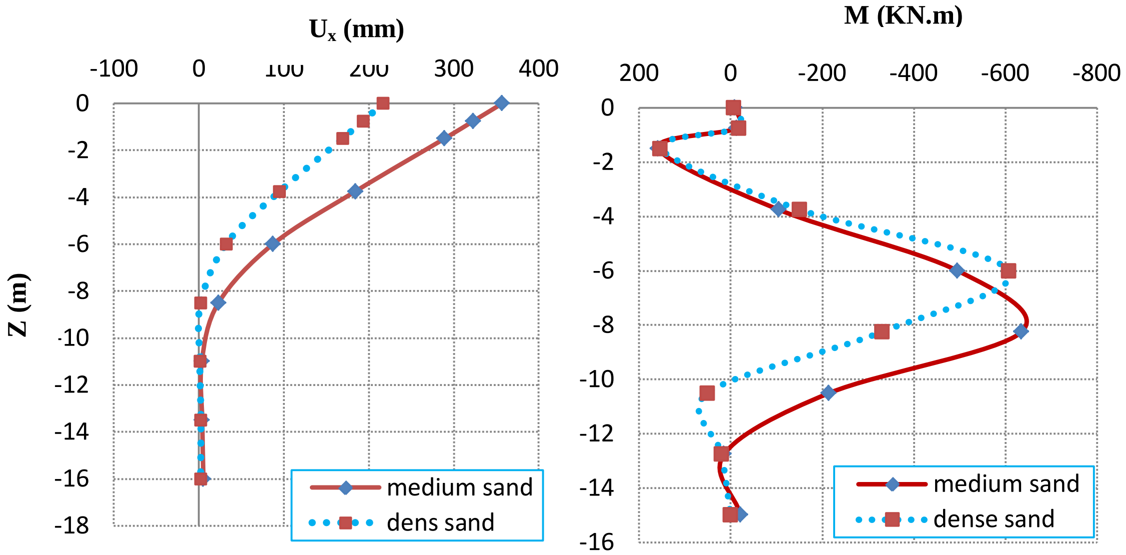


(a) Lateral displacement profile **(b)** Bending moment diagram

Figure (9): Lateral displacement and bending moment of sheet pile lagging in medium sand (H=6m, S=2 m and q=150 kN/m^2)

3.3.3 Soil Type Effect

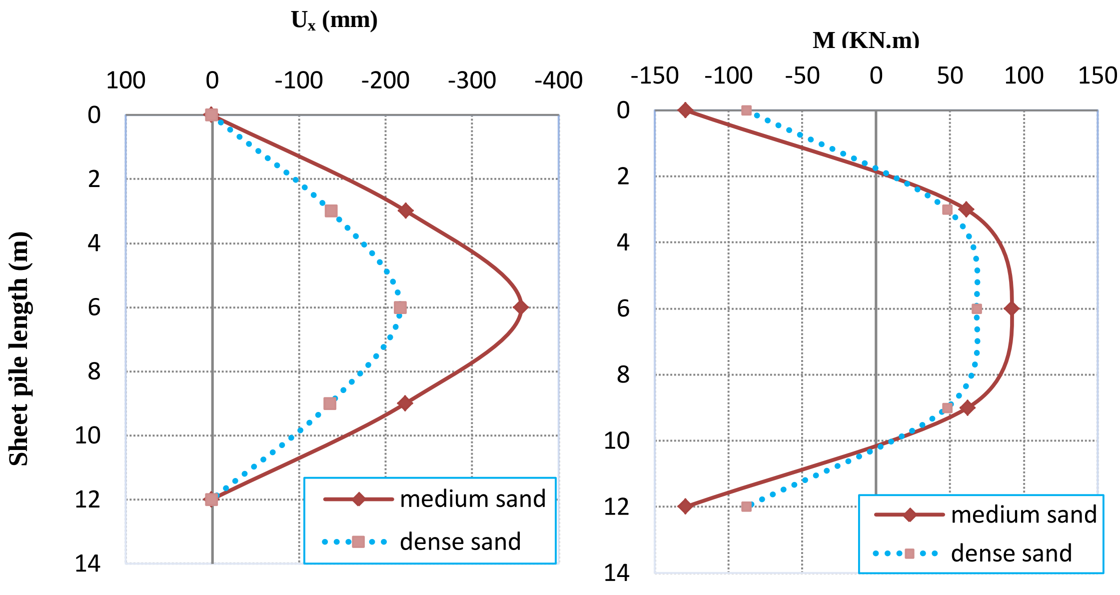
Figures (10) and (11) show the effect of change in sand states on the lateral displacement and bending moment of solider pile and sheet pile lagging respectively. From the shown figures, lateral displacement of solider pile, lateral displacement and bending moment of sheet pile increased with the decreasing of friction angle, φ of sand from 36^o (dense sand) to 33^o (medium sand) and no change in the position of maximum value. The maximum value of bending moment of solider pile and its position change with the change of friction angle, φ. Maximum negative B.M increased by decreasing friction angle, φ. But maximum positive B.M increased by increasing friction angle, φ of sandy soil.



(a) Lateral displacement **(b)** Bending moment

Figure (10) Lateral displacement and bending moment of solider pile at the middle side of excavation area besides adjacent building (H=6m, s =3m,d=0.5 m and q=150 kN/m^2)

ISSN 2229-5518



(a) Lateral displacement **(b)** Bending moment

Figure (11) Lateral displacement and bending moment of sheet pile lagging beside adjacent building at ground level *(*H=6m, s=*3 m*,d=*0.5m and* q=*150 kN/m*^{2}*)*

3.3.4 Cap Beam Effect

From the previous study the values of lateral displacement and bending moment of solider pile and sheet pile lagging were very high. So, proposed of using concrete cap beam was studied with width (b=d $_{pile}$) and three different depths (d_c = 0.5 m , 0.75m and 1.00 m) to improve the behavior of pile and lagging .

Figures (12) and (13) showed the high decreasing of the lateral displacement (U_x) and bending moment (M) of solider pile and sheet pile lagging respectively in case of using concrete cap beam with section *(0.5m * 0.5m)* and excavation depth (H) = 6m, S=3m, d= 0.5 m and q= 150 KN/m^2 in medium sand. Due to using the cap beam, it converted solider pile support system from free to fixed at ground surface. This beam may reduce both lateral displacement and bending moment for both solider pile and sheet pile lagging.

Figures (14) and (15) indicate the effect of change in depth of cap beam (d_c) on the lateral displacement (U_x) and bending moment (M) of solider pile and sheet pile lagging respectively in case of using concrete cap beam with section [(0.5m * 0.5m),(0.5m *0.75m) and (0.5m * 1.00m)] and excavation depth (H) = 6m, S=3m, d= 0.5 m and q = 150 KN/m^2 in case of medium sand. From the shown figures the lateral displacement and bending moment for both solider pile and sheet pile lagging were decreased with the increasing of cap beam depth.

This can be attributed to, increasing cap beam depth increases fixed length for both solider pile and sheet pile lagging.

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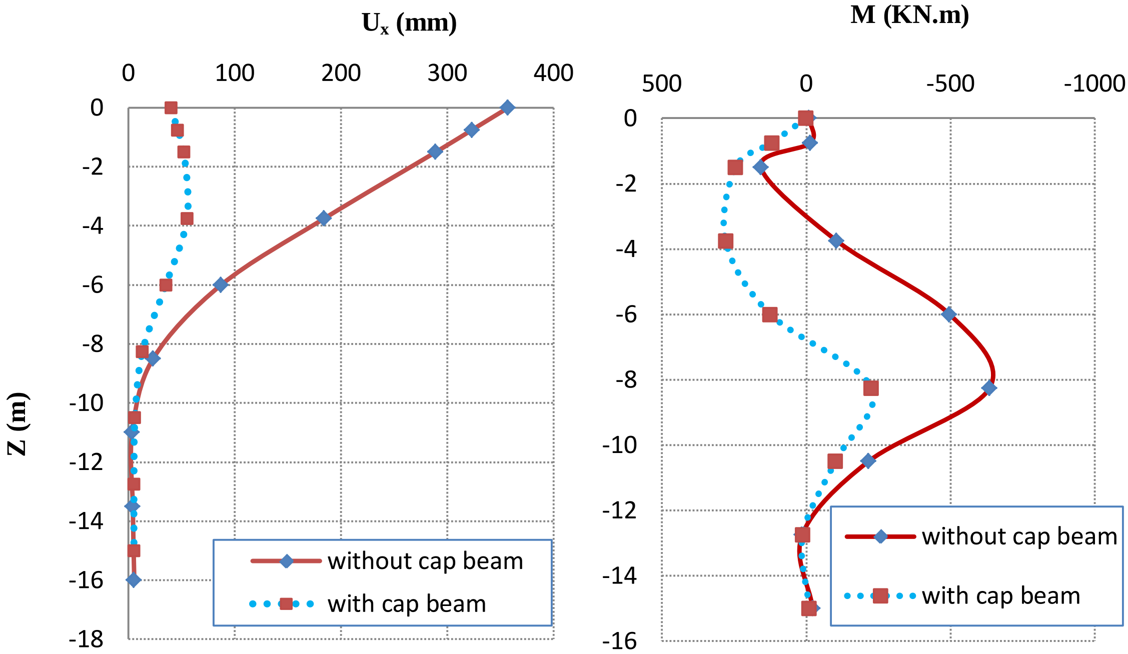
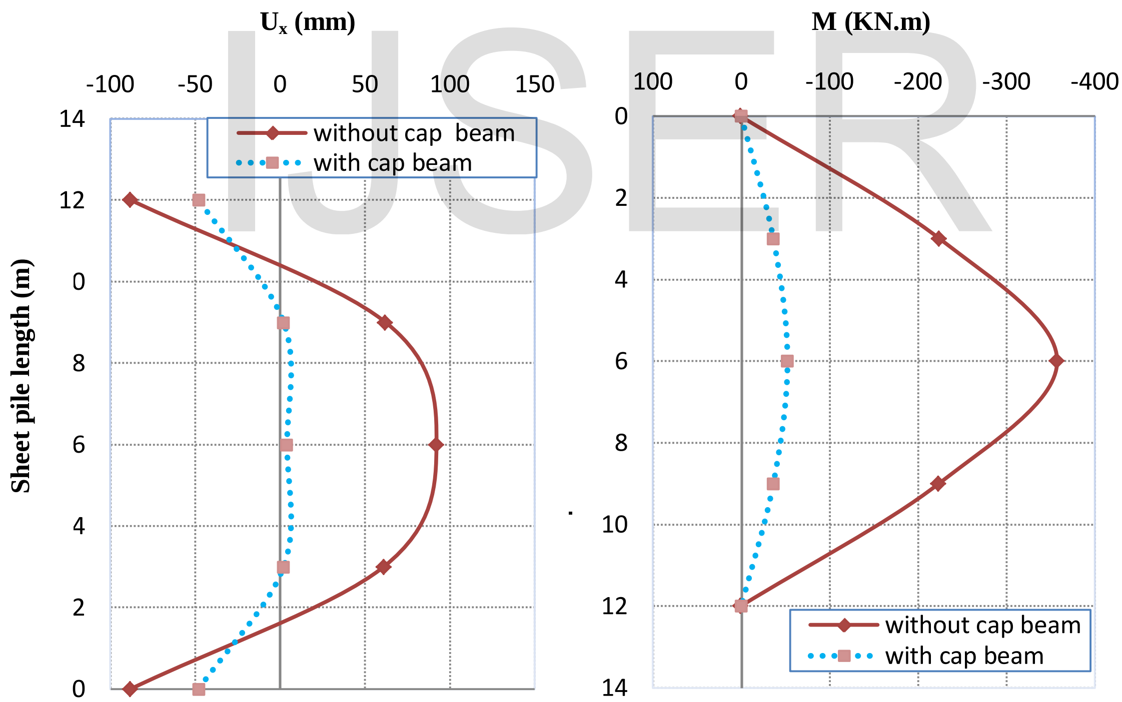


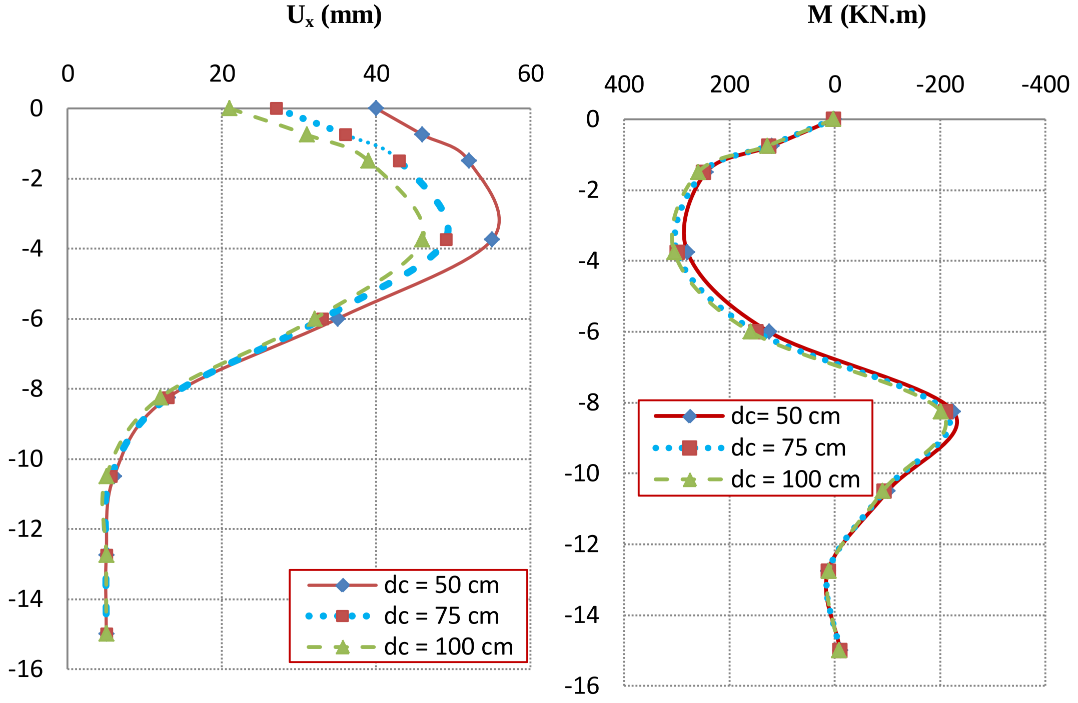
(a) Lateral displacement **(b)** Bending moment

Figure (12) Lateral displacement and bending moment of solider pile at the middle side of excavation area besides adjacent building (H=6m, S =3m,d=0.5 m and q=150 kN/m^2)



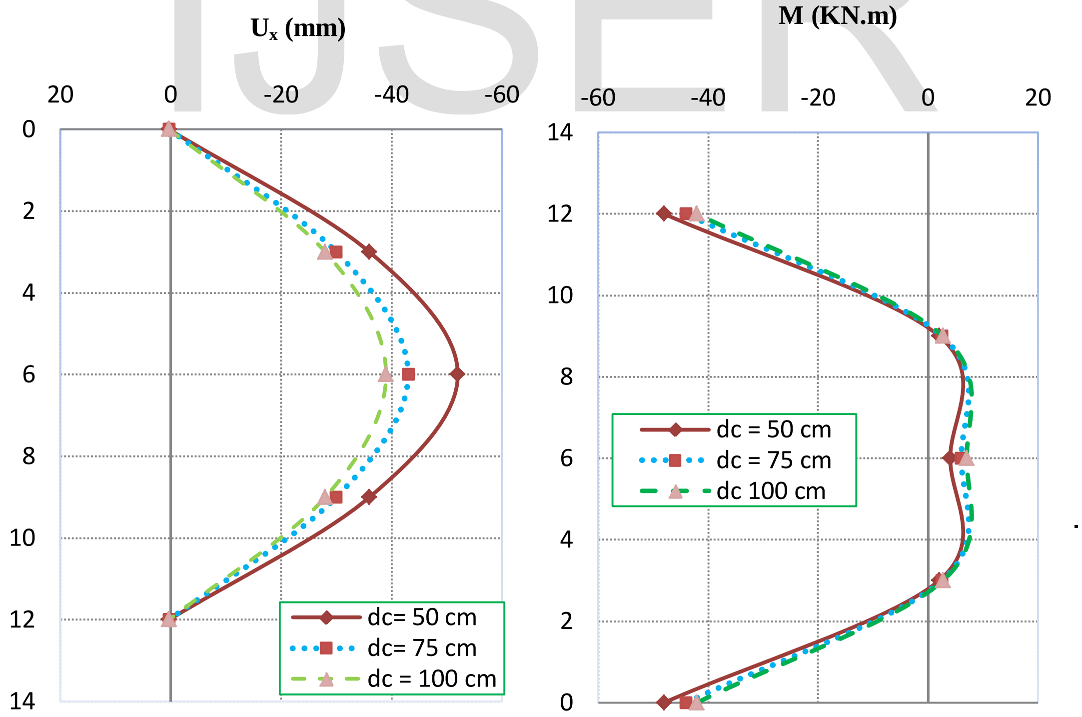
(a) Lateral displacement **(b)** Bending moment

Figure (13) Lateral displacement and bending moment of sheet pile lagging beside adjacent building at foundation level (H=6m, s=*3 m*,d=*0.5m and* q=*150 kN/m^2*)



(a) Lateral displacement **(b)** Bending moment

Figure (14**)** Lateral displacement and bending moment of solider pile at the middle side of excavation area besides adjacent building (H=6m, S =3m,d=0.5 m and q=150 kN/m^2*)*



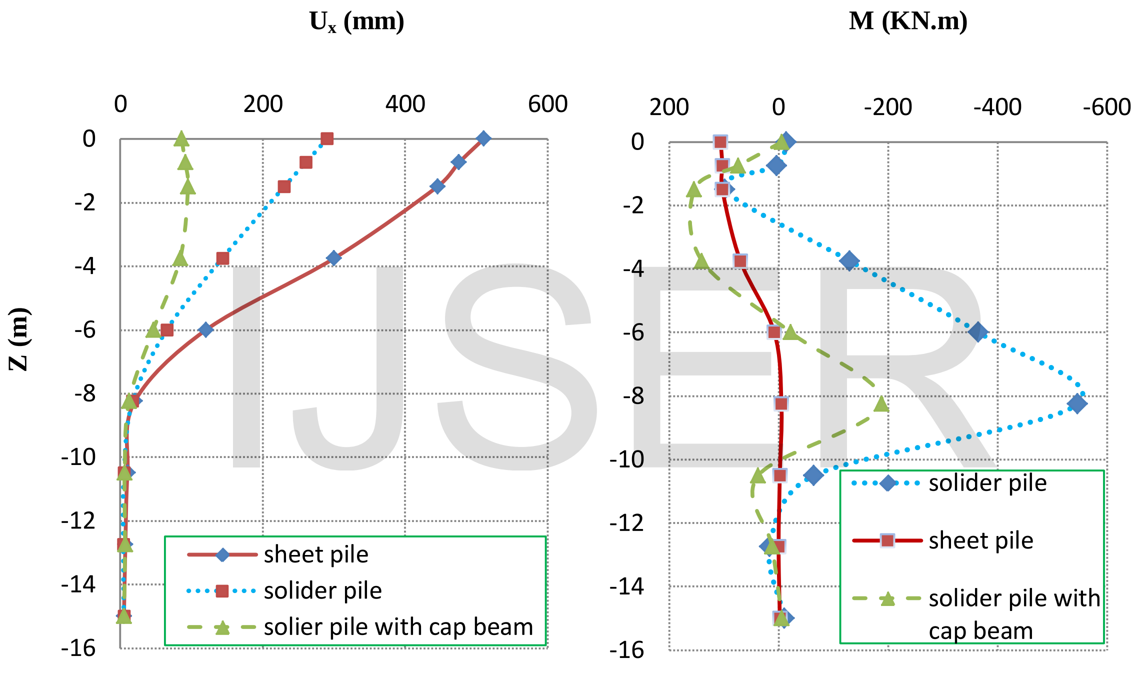
a) Lateral displacement **(b)** Bending moment

Figure (15) Lateral displacement and bending moment of sheet pile lagging beside adjacent building at foundation level *(*H=6m, s=*3 m*,d=*0.5m and* q=*150 kN/m^2)*

4. COMPARISONS BETWEEN SHEET PILE WALL AND SOLIDER PILE WALL

Figure (16) illustrates the effect of change of type of supporting system from sheet pile wall system to solider pile wall system to on the lateral displacement and bending moment. The applied values were, (H= 6m, S=2m, d=50cm, d_c = 50cm and q=150 kN/m^2) in case of medium sand.

From the concerned figure it can be noted that the lateral displacement in case of sheet pile wall system is higher than that if solider pile wall system but, the maximum bending moment in case of sheet pile wall system was lower than solider pile wall system, In case of using cap beam and without cap beam. This observation can be referred to the stiffness of solider pile system is more than that of sheet pile.



(a) Lateral displacement **(b)** Bending moment

Figure (16) Comparison between lateral displacement and bending moment of sheet pile wall and solider pile wall at the middle side of excavation area beside adjacent building (H=6m, S =2m,d=0.5 m and q=150 kN/m^2)

5. CONCLUSIONS

Numerical study was achieved to provide recommendations for the design of concrete solider pile with steel sheet pile lagging wall in sandy soil.

From the previous results and discussion the following conclusions can be summarized:-

(1) Increasing spacing between solider piles (s) increased both lateral displacement and bending moment on the solider pile and sheet pile lagging.
(2) Increasing pile diameter (d) from 0.4 m to 0.5 m to 0.6 m decreased lateral displacement on both solider pile and sheet pile lagging and bending moment of sheet pile lagging, but increased bending moment on solider pile.
(3) In case of dense sand, the maximum value of bending moment of solider pile was located at the excavation level, but in case of medium sand, was located under the excavation level.
(4) Maximum value of lateral displacement and bending moment of solider pile and sheet pile lagging in medium sand were higher than that for dense sand.
(5) Using cap beam improve the behavior of both solider pile and sheet pile lagging where caused reduction the values of bending moment and lateral displacement for both.
(6) Increasing depth of cap beam reduced both lateral displacement and bending moment on both solider pile and sheet pile lagging.
(7) Higher stiffness value of solider pile wall system than sheet pile wall supporting system, decreased the lateral displacement of wall, but increased bending moment.
(8) Solider pile with steel sheet pile lagging supporting system is more effective in case of sand soil than other systems.

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