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Impact of Seismic Loads on the Behavior of a Strutted Diaphragm Walls in Loose Sand

" تأثير الأحمال السيزمية على سلوك الحوائط الحاجزه المدعمه في التربة الرملية السائبه"

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Abstract. The diaphragm wall may collapse or the struts may fail as a result of the earthquake stresses. Because there has been little research on the dynamic performance and design of diaphragm walls and lateral braces, the present study focused on the behavior of diaphragm walls with lateral steel struts in sandy soil environment under seismic load using a finite difference modeling method using PLAXIS 2D software version 8.6. The experimental results were compared to the end-of-seismic-motion lateral displacements and bending moments in the wall. The study showed that in a post-seismic state, lateral displacement, bending moment, strut forces, and maximum ground surface displacement increased with excavation depth and the frequency of base acceleration when all other components were kept constant.

KEYWORDS: Braced excavation, considerable time period, diaphragm wall, displacement, design parameters, embedded depth and seismic development.

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Nomenclature			
N	Average value of standard penetration test	**Kst**	Bulk modulus in static condition
G0	Small strain shear modulus	**μ**	Poisson's ratio
Kd	Bulk modulus in dynamic condition	**ϕ**	Friction angle of soil
Gst	Shear modulus in static condition	ρ	Density
(PGA)	values of Peak Ground Acceleration	**Tp**	Predominant period
Q	Surcharge	**X**	Surcharge distance from the wall

1. INTRODUCTION

The cultural and scientific development in the field of geotechnical engineering deep excavation is frequently necessary in a congested urban region for the construction of subsurface transportation systems high-rise building basements and structures pipes for utilities, etc. Due to space vertically beneath the ground surface excavations like these are common constraints the diaphragm walls are built and maintained horizontal beams provide support at various levels struts that connect two opposing surfaces of an object and the main reason was the creation of solutions to all problems such as the problems that are facing modern facilities such as how to reach deepest depths below the ground level in order to use them as warehouses and garages and get rid of the slums of old facilities, s well as the creation of solutions to transportation problems.

Which is the refuge for underground structures, and how supporting the sides of the soil during drilling and reaching the target depths safely without collapsing the sides of the drilling due to the lateral force acting. The loads of seismic behavior, and the solution was to resort to the retaining walls that resist the lateral forces and the strength of the seismic behavior. Illustrative of the results, which is reaching a depth more than below the ground level in the conditions of a vertical load above the level of the barrier wall and its value (Q) and distance (X) and effective seismic force.

With varying values, an illustrative example with values in Chart Figures (1 and 2). Various studies have been conducted on this subject including laying out the research history and Evolution [4, 7]. Madabhushi and Zeng [8] investigated the seismicity of gravity quay walls with steel strut using both analytical and empirical methodologies. Caltabiano et al. [9] created a new pseudo-static model solution for the analysis of wall-soil systems. With the use of the numerical finite element method, gazetas et al. [10] studied the strength and distribution of dynamic earth pressures on L-shaped reinforced-concrete walls, piled walls with horizontal or steeply inclined anchors, and reinforced-soil walls. They found that as the degree of realism in the study increases, such retaining systems can work successfully during strong seismic shaking.

To use the finite element method, psarropoulos et al. [11] created dynamic soil pressure distribution on rigid and flexible surfaces. The conclusions of mononobe–okabe and elasticity-based solutions for structurally or rotationally flexible walls are identical, according to their research. By analyzing four retaining wall earth (MSE) walls under tecoman, Mexico, wartman et al. [12] analyzed the seismic behavior of earthquakes. The application and viability of the pseudo-static and sliding block solutions were discussed. They also developed an economic formula for designing these underground structures based on the system's flexibility. Chowdhury et al. [13] used finite difference numerical models to explore the seismic behavior of the diaphragm wall during three earthquakes with various peak ground accelerations (PGAS). They established a penetration depth and diaphragm wall thickness of 100 and 6% of the final excavation depth under seismic loads for a 10-20 m excavation.

With experimental and analytical methods, Konai et al. [14] studied the seismic behavior of braced excavation in dry sand. Their study found that by increasing the depth of excavation and the width of the base they developed new quantitative absorption boundary methods and applied them to the free vibration model. Additionally Horizontal struts are used to keep diaphragm walls from moving horizontally. In the past, numerical methods were used to examine braced excavation in a static condition [1-4]. Additionally, the behavior of excavations in static mode is expected using empirical and semi-empirical techniques based on data from excavations all over the world [5-6]. The current paper is part of a series of studies on braced excavations that looked at the seismic performance and design of the diaphragm wall and steel strut.

It's worth mentioning that writers have already published the results of other experiments on braced excavation, giving out the study background and evolution [4]. Additionally (1989, Boscardin and Cording)[17]. To better study the requirements of braced excavation in a static situation, a variety of analytical and experimental studies have been completed. Bose and Som, 1998.[18]; Carrubba and Colonna, 2000.[19]. Costa et al., 2007.[20]. Day and Potts, 1993[21]. Finno and Harahap, 1991.[22]. His and Small, 1993; Hsiung, 2009.[23]. Karlsrud and Andresen, 2005.[24]. Ou and Hsieh, 2011.[3]. Yoon and Hsieh, 2011; Yoon and Hsieh, 2011. According to

Arai Y, Kusakabe O, Murata O, Konishi S [2]. Bahrami, M., Khodakarami, M. I., & Haddad, A. (2019). Seismic behavior and design of strutted diaphragm walls in sand [25].

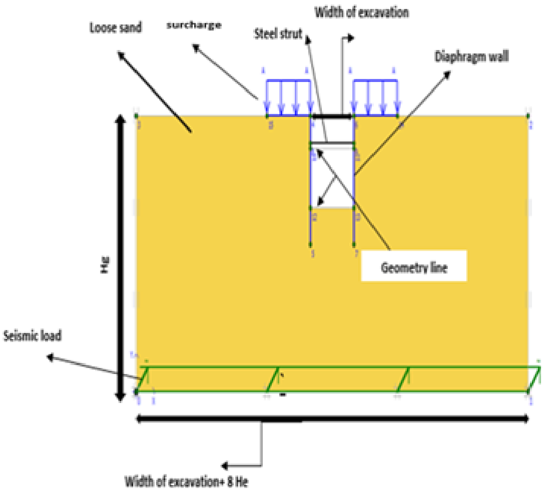

Fig.1.Geometry of finite element model

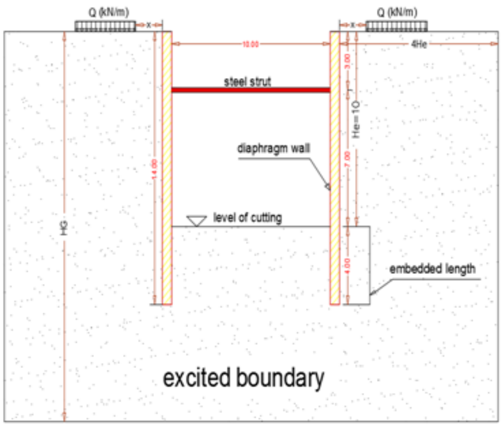

Fig.2. The Cross-Section of Model

1. Material and numerical model description

In preliminary design, the thickness of a diaphragm wall is often chosen at 4-8 percent of the excavation depth. According to Chowdhury et al. [13], the wall thickness was set at 6% of the excavation depth, and reinforcement design and nominal strength calculations were carried out using the so-called strength design method or LRFD methodology based on the ACI 318-14 code [15].

To simulate the silent boundary condition established by Lysmer and Kuhlemeyer [16], the main grids of the lateral boundaries were joined with the free-field using fluid obtained by dividing. Figure (1) presents the present state of boundary conditions in seismic analysis.

The width and depth of the excavation in this study are 10 m and 10 m, respectively, while the wall's penetration depth is 4 m. the bottom's horizontal boundary extends up to 30 meters below the toe of the wall Figures (1&2).

On a soil with seismic parameters, the diaphragm wall's Young's modulus(Ec), density (ρ),Poisson's ratio (μ) and thickness, respectively, were 24100 MPa, 2500 kg/m^3, 0.2 and 60 cm. The model was used to excavate and brace to a depth of 3 meters.

One strut was mounted after that excavate to a depth of 3.5 m using soil static properties finally, the seismic properties of the soil are determined. Also the material properties of diaphragm wall, steel strut, loose sand soil and details of considered earthquakes three cases in Egypt, Case(1), Case(2), And Case(3).Table (1,2,3 and 4),respectively.

Table (1) Material Properties of Diaphragm Wall.

Parameter	value
Axial Stiffness (EA)In kN/m	132000000
Flexural Rigidity(EI) In kN/m	3960000
Equivalent Thickness Of Plate (d) In m	0.6
Poisson's ratio μ	0.2
Weight Of Diaphragm Wall In kN/m	15
young's modulus (Ec) $4400\sqrt{fcu}\ MPa$ Fcu = 30 MPa (The compressive strength of concrete)	24100

Table (2) Material Properties of Steel Strut

Parameter		**value**
Axial Stiffness (Ea)In kN/m		2799000
L Spacing In M		10
Section provided	Cross-section area ($m^2 \times 10^{-4}$)	Second moment area ($m^2 \times 10^{-8}$)
H390×300×10×16	133.3	37900

Table (3) The properties of loose sand soil.

SPT-*N*	***G*0**	***K*d**	***G*st**	***K*st**	***μ***	***ϕ***	
values	**(*MPa*)**	**(*MPa*)**	**(*MPa*)**	**(*MPa*)**		**(Degree)**	**(*kN/m*^{3})**
5-10	53	58	15.9	17.4	0.3	30	14.4

Table (4) Details of Considered Earthquakes.

Earthquake name	**PGA (*g*)**	**Duration (*sec.*)**	**Significant duration**	***T*p**
			(*sec.*)	**(*sec.*)**
Case(1)	0.3	9	7	0.1
Case(2)	0.3	10	8	0.1
Case(3)	0.3	20	10	0.1

2. Analysis

A. The steps that were studied and represented by the paper during the design of the diaphragm wall are shown in Table No. (5).

1) As mentioned in the previous tables, loading the soil with a represented by value of (Q kN/m) and a distance of (X m).
2) A boundary wall is made.
3) Drilling is completed over more than a distance of 3.5 meter. The steel strut is then installed at a depth of 3 meter, with a border of 0.5 m to make the installation process much easier.
4) Excavation is completed to the required depth of 10 meter.
5) The soil is impacted by seismic load.
6) The strains action on the wall, as well as the volumetric change and displacements in the soil, are studied.

Table (5) Processes for Modeling.

Steps	Simulation details
Step 1	Initial equilibrium in the seismic soil properties.
Step 2	Construction of diaphragm wall in seismic soil properties.
Step 3	Reduced coefficient applied to the soil properties.
Step 4	Considering all displacements equal to zero and excavation up to a depth of 3.5 *m*.
Step 5	Installation of strut at depth of 3*m*.
Step 6	Excavation up to a depth of 10 *m*.
Step 7	Seismic soil properties applied to the model again.
Step 8	Applying dynamic boundaries and soil damping.
Step 9	Acceleration time history applied to the bedrock.

B. The effect of the responsible leader, Egypt earthquakes, on the behavior and design of strutted walls in static and dynamic settings, as well as variable and constant surcharge (Q kN/m) when distances are varied and constant (X m). In this research paper, the following factors were evaluated, researched, and compared. The static and dynamic states of effective of surcharge and distance from excavation cases are presented in Tables (6,7,8 & 9) ,respectively.

C. At the same tables, the forces acting on the lateral supports, as well as the bending moment and horizontal displacement acting on the wall, are studied, and the numerical simulation results are given in detail using PLAXIS software version 8.6.

Table (6) The straining action and displacement of the diaphragm wall in a static case At a constant distance (X=0m) and various surcharge values.

X (distance)	**Q (surcharge)**	**Bending moment**	**Horizontal displacement of the wall**
m	kN/m	(kN.m)	m
0	0	235.3	$16.94*10^{-3}$
0	100	455.5	$37.44*10^{-3}$
0	200	650.32	$80.76*10^{-3}$
0	300	720.32	$95.59*10^{-3}$
0	400	850.62	$101.94*10^{-3}$

Table (7) The straining action and displacement of the diaphragm wall in a static case At a constant surcharge (Q=400kN/m) and various distance values.

X (distance)	**Q (surcharge)**	**Bending moment**	**Horizontal displacement of the wall**
m	kN/m	(kN.m)	m
4	400	705.2	$81.44*10^{-3}$
8	400	602.5	$75.64*10^{-3}$
12	400	465.6	$62.76*10^{-3}$
16	400	320.7	$35.59*10^{-3}$
20	400	235.3	$16.94*10^{-3}$

Table (8) The straining action and displacement of the diaphragm wall in a dynamic case At a constant distance (X=0m) and various surcharge values.

Case(1)			
X (distance)	**Q (surcharge)**	**Bending moment**	**Horizontal displacement of the wall**
m	kN/m	(kN.m)	m
0	0	334.6	$61.06*10^{-3}$
0	100	560.8	$150.64*10^{-3}$
0	200	850.46	$*10^{-3}1.1132$
0	300	1015.42	$241.18 *10^{-3}$
0	400	1100.82	$*10^{-3}5.2462$
Case(2)			
0	0	55350.	$6*10^{-3}4.65$
0	100	87570.	$160.64*10^{-3}$
0	200	76890.	$256.33*10^{-3}$
0	300	641200.	$244.18 *10^{-3}$
0	400	591350.	$266.2*10^{-3}$
Case(3)			
0	0	610.63	$.06*10^{-3}73$
0	100	39590.	$4*10^{-3}5175.$
0	200	34892.	$288.3*10^{-3}$

0	300	14325.1	8 *10^{-3}3264.
0	400	261420.	269.3*10^{-3}

Table (9) The straining action and displacement of the diaphragm wall in a dynamic case At a constant surcharge (Q=400kN/m) and various distance values.

Case(1)			
X (distance)	**Q (surcharge)**	**Bending moment**	**Horizontal displacement of the wall**
m	kN/m	(kN.m)	m
4	400	950.33	175.06*10^{-3}
8	400	920.73	150.64*10^{-3}
12	400	850.66	133.3 *10^{-3}
16	400	770.42	122.18 *10^{-3}
20	400	334.62	61.06*10^{-3}
Case(2)			
4	400	591150.	206.2*10^{-3}
8	400	87950.	160.64*10^{-3}
12	400	76870.	172.33*10^{-3}
16	400	64786.	168.32 *10^{-3}
20	400	55350.	6*10^{-3}4.65
Case(3)			
4	400	1320.22	257.06*10^{-3}
8	400	990.45	4*10^{-3}5220.
12	400	63920.	189.3*10^{-3}
16	400	44866.	8 *10^{-3}3175.
20	400	360.63	.06*10^{-3}73

D. The variable and constant surcharge (Q kN/m) and distance (X m) values in the static and dynamic stages have a sizable effect on the design of the effective mean stress, deformation, the longitudinal and volumetric change of the soil, and the amount of change in the value of the vertical, horizontal, and total slope failure of the loose sand soil. The static and dynamic states of shifting surcharges and distance are represented in tables (10,11,12&13).

Table (10) The deformation shapes and displacements for loose sand soil in the static case At a constant distance (X=0m) and various surcharge values.

X (distance)	**Q(surcharge)**	**Effective mean stresses**	**Deformed mesh**	**Volumetric strains**	**Horizontal Displacement Of soil**	**Total displacement of soil**
m	**kN/m**	**kN/m^2**	**m**	**%**	**m**	**m**
0	0	299.07	57.99*10^{-3}	728.52*10^{-3}	12.57*10^{-3}	57 .99*10^{-3}
0	100	320.57	70.16*10^{-3}	574.48*10^{-3}	25.49*10^{-3}	70.16*10^{-3}
0	200	450.21	112.26*10^{-3}	919.18 *10^{-3}	40.79 *10^{-3}	112.26*10^{-3}
0	300	560.86	134.72 *10^{-3}	965.14 *10^{-3}	48.99 *10^{-3}	134.72*10^{-3}
0	400	590.32	143.7*10^{-3}	998.3 *10^{-3}	52.256 *10^{-3}	143.9*10^{-3}

Table (11) The deformation shapes and displacements for loose sand soil in the static stage At a constant surcharge (Q=400kN/m) and various distance values.

X (distance)	Q(surcharge)	Effective mean stresses	Deformed mesh	Volumetric strains	Horizontal Displacement Of soil	Total displacement of soil
m	kN/m	kN/m^2	m	%	m	m
4	400	520.07	133.93*10^{-3}	965.33*10^{-3}	45.57*10^{-3}	141 .99*10^{-3}
8	400	320.27	123.11*10^{-3}	850.44*10^{-3}	35.49*10^{-3}	130.16*10^{-3}
12	400	310.31	115.25*10^{-3}	810.11 *10^{-3}	30.79 *10^{-3}	122.6*10^{-3}
16	400	305.87	106.73 *10^{-3}	766.17 *10^{-3}	25.99 *10^{-3}	114.72*10^{-3}
20	400	299.07	57.99*10^{-3}	728.52*10^{-3}	12.57*10^{-3}	57 .99*10^{-3}

Table (12) The deformation shapes and displacements for loose sand soil in the dynamic stage At a constant distance (X=0m) and various surcharge values.

Case(1)						
X (distance)	Q(surcharge)	Effective mean stresses	Deformed mesh	Volumetric strains	Horizontal Displacement Of soil	Total displacement of soil
m	kN/m	kN/m^2	m	%	m	m
0	0	335.16	71.76*10^{-3}	1.89	50.25*10^{-3}	71.78*10^{-3}
0	100	382.32	170.87*10^{-3}	4.30	120.53*10^{-3}	162.58*10^{-3}
0	200	620.72	260.44*10^{-3}	6.71	135.61*10^{-3}	266.46*10^{-3}
0	300	720.86	315.35*10^{-3}	8.23	242.43*10^{-3}	312.32*10^{-3}
0	400	866.31	333.26*10^{-3}	8.66	252.32*10^{-3}	320.29*10^{-3}
Case(2)						
0	0	7.1413	8*10^{-3}9.83	1.90	5*10^{-3}9.95	*10^{-3}891.8
0	100	420.3	8*10^{-3}3172.	4.42	135.23*10^{-3}	*10^{-3}8195.6
0	200	610.53	1*10^{-3}2270.	6.49	155.51*10^{-3}	*10^{-3}3277.4
0	300	792.35	1*10^{-3}6321.	8.56	243.33*10^{-3}	*10^{-3}6333.2
0	400	877.66	7*10^{-3}4366.	8.77	261.42*10^{-3}	*10^{-3}9366.1
Case(3)						
0	0	33.473	.62*10^{-3}89	1.92	*10^{-3}62.34	*10^{-3}82.31
0	100	43451.	210.65*10^{-3}	4.79	*10^{-3}31155.	*10^{-3}23175.
0	200	83666.	6*10^{-3}6290.	6.95	196.32*10^{-3}	277.41*10^{-3}
0	300	855.32	3*10^{-3}2366.	8.55	256.31*10^{-3}	350.33*10^{-3}
0	400	65900.	4*10^{-3}3420.	8.89	275.32*10^{-3}	370.32*10^{-3}

Table (13) The deformation shapes and displacements for loose sand soil in the dynamic stage At a constant surcharge (Q=400kN/m) and various distance values.

Case(1)						
X (distance)	**Q(surcharge)**	**Effective mean stresses**	**Deformed mesh**	**Volumetric strains**	**Horizontal Displacement Of soil**	**Total displacement of soil**
m	**kN/m**	**kN/m^2**	**m**	**%**	**m**	**m**
4	400	850.16	321.78*10^{-3}	8.23	243.25*10^{-3}	310.78*10^{-3}
8	400	752.33	311.49*10^{-3}	7.42	232.26*10^{-3}	319.58*10^{-3}
12	400	642.76	279.54*10^{-3}	6.95	195.32*10^{-3}	279.46*10^{-3}
16	400	611.84	215.66*10^{-3}	5.43	163.2*10^{-3}	199.32*10^{-3}
20	400	335.16	71.74*10^{-3}	1.89	50.25*10^{-3}	71.78*10^{-3}
Case(2)						
4	400	7855.1	356.67*10^{-3}	8.32	251.65*10^{-3}	*10^{-3}9355.6
8	400	766.34	321.39*10^{-3}	7.55	242.63*10^{-3}	*10^{-3}8342.6
12	400	665.63	288.51*10^{-3}	6.92	210.51*10^{-3}	*10^{-3}3289.6
16	400	633.55	226.71*10^{-3}	5.66	156.63*10^{-3}	*10^{-3}6252.2
20	400	7.1413	.68*10^{-3}83	1.90	5*10^{-3}9.95	*10^{-3}891.8
Case(3)						
4	400	53877.	410.62*10^{-3}	8.35	265.63*10^{-3}	366.23 *10^{-3}
8	400	792.33	366.55*10^{-3}	7.92	*10^{-3}1243.2	1*10^{-3}2349.
12	400	752.25	322.66*10^{-3}	6.96	233.62*10^{-3}	266.42*10^{-3}
16	400	655.32	301.33*10^{-3}	5.55	167.41*10^{-3}	259.36*10^{-3}
20	400	33.473	.62*10^{-3}89	1.92	*10^{-3}62.34	*10^{-3}82.31

E. The steel strut force is seriously impacted by varied and constant surcharge values (Q kN/m) in the static and dynamic stages, which was analyzed and compared when different and constant distances (X m) were studied. Tables (14,15,16,17) show the static and dynamic states of different charges and distances, respectively.

Table(14) Strut Force Table in Static Mode At a constant distance (X=0m) and various surcharge values.

X(distance)	Q(surcharge)	Static Force
m	**kN/m**	**kN/m**
0	0	151.4
0	100	355.6
0	200	665.3
0	300	832.2
0	400	942.3

Table(15) Strut Force Table in Static Mode At a constant surcharge (Q=400kN/m) and various distance values.

X(distance)	Q(surcharge)	Static Force
m	**kN/m**	**kN/m**
4	400	900.2
8	400	660.2
12	400	533.3
16	400	455.2
20	400	151.4

Table (16) Strut Force Table in dynamic Mode At a constant distance (X=0m) and various surcharge values.

Case(1)		
X(distance)	**Q(surcharge)**	**Dynamic Force**
m	**kN/m**	**kN/m**
0	0	232.7
0	100	490.2
0	200	870.3
0	300	1200.4
0	400	1400.5
Case(2)		
0	0	279.24
0	100	598.86
0	200	974.25
0	300	1343.62
0	400	1568.36
Case(3)		
0	0	312.79
0	100	674.32
0	200	1197.23
0	300	1494.46
0	400	1794.92

Table (16) Strut Force Table in dynamic Mode At a constant surcharge (Q=400kN/m) and various distance values.

Case(1)		
X(distance)	**Q(surcharge)**	**Dynamic Force**
m	**kN/m**	**kN/m**
4	400	1150.32
8	400	950.62
12	400	866.42
16	400	795.63
20	400	232.77
Case(2)		
4	400	1500.32
8	400	1220.63
12	400	962.46
16	400	869.21
20	400	279.24
Case(3)		
4	400	1650.36
8	400	1523.26
12	400	1010.36
16	400	955.62
20	400	312.79

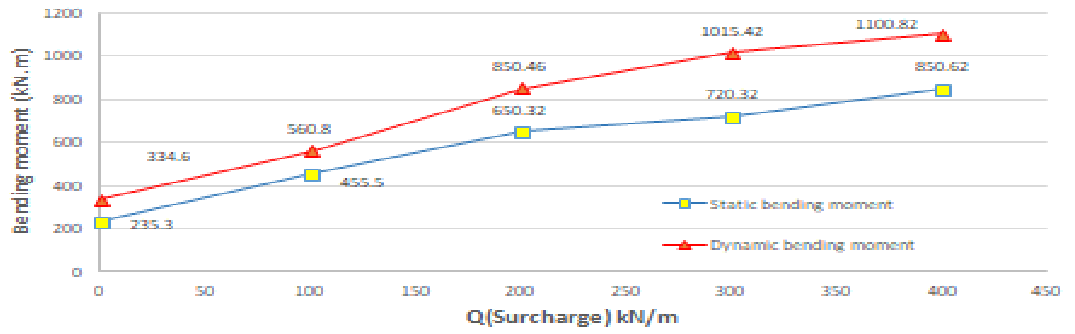

Fig.3. The bending moment of case (1) at a constant distance (x=0m).

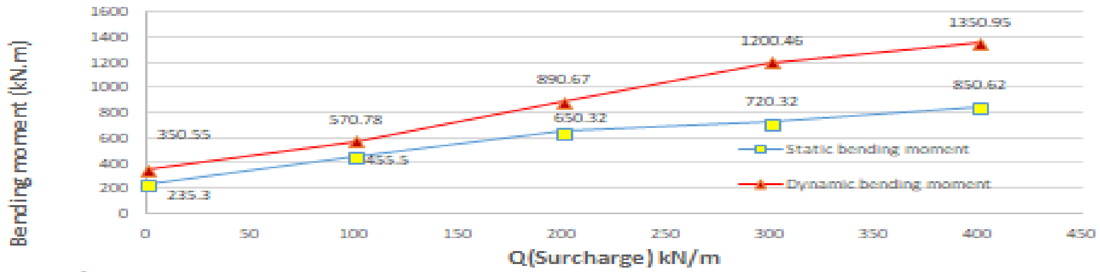

Fig.4. The bending moment of case (2) at a constant distance (x=0m).

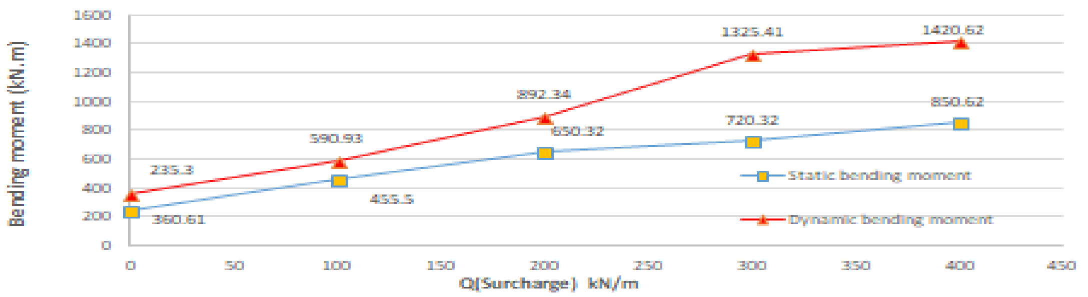

Fig.5. The bending moment of case (3) at a constant distance (x=0m).

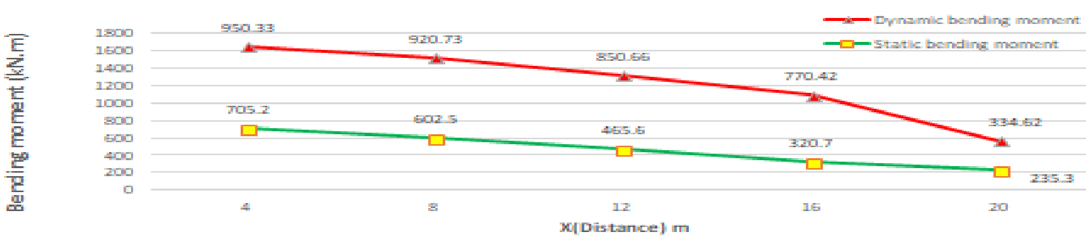

Fig.6. The bending moment of case (1) at a constant surcharge (Q=400kN/m).

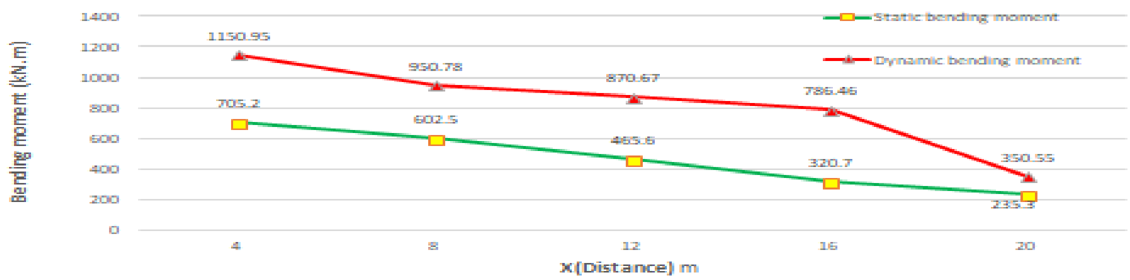

Fig.7. The bending moment of case (2) at a constant surcharge (Q=400kN/m).

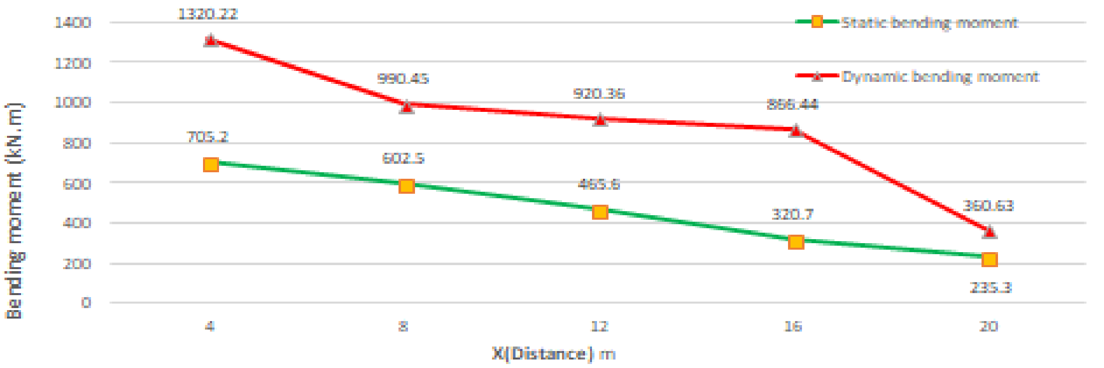

Fig.8. The bending moment of case (3) at a constant surcharge (Q=400kN/m).

3. Conclusions

The seismic behavior of a diaphragm wall in loose sandy soil was studied. The following conclusions can be drawn from the study:

1) It was defined that the mutual support system is acceptable in both static and dynamic loads, considering the depth of excavation and interment to ensure adequate safety in the event of seismic loads, as well as the compressor strength and embedded length in the dynamic load.

2) When results of the previous numerical analysis are compared with the results of the ACI 318 design methodology, it is shown that diaphragm walls designed under static loads have important characteristics and are thus suitable for excavation design.

3) When the results of the previous numerical analysis are compared with the ACI 318 design methodology, it becomes clear that seismic diaphragm walls are 2.8 times larger than the relative allowable limits. As a result, special attention should be taken while designing diaphragm walls in accordance with the ACI 318 code.

4) A large variety of wall and ground surface movements should be considered when studying the seismic condition, as it has a significant impact on wall and ground surface deformations such as surcharge values and distance from the wall.

5) The strut deformations and axial force increase as the surcharge distance from the wall decreases and the surcharge value increases.

6) The position of both the maximum displacements of the wall and the ground surface is affected by changes in the length and width of the excavation.
7) Two opposite walls in a braced excavation can create different seismic reactions.
8) In actuality, the length of an earthquake is a major consideration when planning an underground wall.

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