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Assessment of Effect of Deep Excavation on Adjacent Structures using Finite Element Analysis

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Abstract. Deep excavations and its impact on neighboring buildings is one of the most important issue when planning to construct new facility. In metropolitan city, it's a challenging task for the execution of underground construction due to limited space and high cost of land. Hence, this implies that deep excavation has become necessary for the proper utilization of available space. Therefore, it's important to make sure that adjacent structures are safe against deep excavation induced deformation. In this study a two-dimensional Finite Element Method in PLAXIS 2D has been choosen for the soil-structure analysis of deep excavation supported by contiguous pile wall located in Addis Ababa. For the numerical analysis two constitutive models Mohr-Coulomb and Hardening Soil have been applied in drained effective stress condition. The objective of this study is to investigate the effect of deep excavation on adjacent structures by considering support stiffness, ground water condition, neighboring building distance from face of excavation and building load. The analysis of this study monitors parameters like maximum lateral wall deflection (δhm), maximum settlement (δvm), angular distortion of the neighboring structures, horizontal strain, and maximum bending moment of contiguous pile wall. Moreover, normalization of lateral wall deflection (δhm/He) and settlement (δvm/He) to the excavation depth (He) and neighboring building distance-excavation (D/He) has been presented. Parametric studies have been carried out by varying parameters of diameter of contiguous pile wall, horizontal anchor spacing and pre-stress force of anchor. The analysis result has been recorded in terms of lateral wall deflection, ground settlement and bending moment.

Keywords: Deep excavation, Finite Element method, Plaxis 2D, Neighboring building, Soil-structure interaction.

1 Introduction

In many of the metropolitan cities alround the world are currently constructing residential houses, condominiums, high rise commercial buildings, transport facility and other infrastructures. The daily extension of urban areas due to increased population has caused the majority of civil engineering projects in urban areas require excavation. Deep excavations are becoming increasingly a common practice all over the world for the construction of high-rise structure, road tunnels, mass rapid transit systems and other facilities in densely built-up areas within the city and suburban areas. Since excavation is the basic phase for construction of any foundations or basement of high-rise buildings and, underground structures in metropolitan area, care must be taken for the safety of existing adjacent structure.

Many deep excavations have been carried out in a very poor subsoil condition and in a very close proximity to the existing buildings and infrastructures. Therefore, deep excavations in urban areas generally may result ground movements and excessive deformation that can induce significant damage to adjacent buildings and services. In such circumstance, the ability to predict ground deformation with certain accuracy and within an acceptable limit becomes important and the challenging task for geotechnical design. In order to reduce their impact, the excavations are supported by retaining systems such as, stiff diaphragm walls, secant pile wall or contiguous pile wall and their supporting struts and anchors, which are installed as the excavation progresses.

In highly congested urban areas like, there is a limitation for parking space and most of the vehicles park on the roadway. Such conditions will increase the traffic congestion in the city. Therefore, it's necessary to construct buildings having parking space at their basement level to minimize the traffic congestion by providing parking lots. In addition to that, in weak sub-soil conditions of shallower strata, excavation may proceed to greater depth in order to get firm foundation for high-rise structures. During the excavation and construction process proper design and assessment of the effect of deep excavation on the nearby structures must be done. Detail deformation and stability analysis of the retention system must be done in order to prevent damages of adjacent buildings and infrastructures around the excavation site.

The main objective of this study is to determine the parameters that affect buildings and infrastructures adjacent to deep excavation using Numerical modeling technique of Finite Element Method (FEM).

2 Literature Review

The construction of such tall buildings in Metropolitan city increase the demand of using underground space, and deep excavation have been carried out for a greater depth for basements of the structure. Many deep excavations have been carried out to construct various types of underground infrastructures such as deep basements, subways, underground roads and service tunnels. Excavations were considered shallow or deep depending on the ratio of their width to their depth. Simpson.et al. (2008) defines excavations with depths smaller than their widths as shallow excavations while excavations with depths larger than their widths as deep excavations. Terzaghi and Peck (1967) described that excavations whose depths were less than 6m could be defined as shallow excavations and those deeper than that as deep excavations.

Deep excavation is complex subject in geotechnical engineering and has been studied using various methods. Prediction of excavation induced ground movement is an essential part in the design of deep excavation, because of the possible adverse effects on the nearby structures and other existing facilities. Soek.et.al (2001) describe that the assessment of deformation associated with deep excavation depends on the presence of buildings in the vicinity of excavation. Because the existence of buildings near to the excavation modifies the induced deformation due to self-weight and stiffness of the building. Zuhair.A.H (2011) identified an effective method of reducing deformations in the surrounding soil and damages of the adjacent structure by using advanced excavation technique such as stiff diaphragm walls, secant pile walls and support construction. It is important to establish practical solution to predict the displacement deformation around the excavation more accurately.

Empirical methods are based on the experience gathered by researchers in various parts of the world whereas numerical modeling utilizes computing power and, using various modeling techniques, can be a precise way of solving very complex problems (Niousha.R, et.al, 2011). The physical (Centrifuge) model relies on achieving the stress similarity between the model and prototype. This is achieved by an inertial accelerating a model to induce an inertial radial acceleration field N times greater than the gravitational field strength on Earth.

Theoretical method provides some basic understanding of the performance of deep excavation in different way, but it has some limitation due to its simplicity and assumptions. The magnitude and distribution of induced deformation due to deep excavation depends on many factors such as soil and ground water condition, construction quality, excavation geometry, excavation sequence, duration of excavation, existence of adjacent buildings, wall stiffness, type and installation of lateral support. The prediction of deformation based on theoretical method would be very complex to obtain the interaction between those mentioned factors. Some of the theoretical methods are reviewed in these section.

The design of earth retaining walls requires the evaluation of active earth pressure which is largely based on the classic solutions of lateral earth pressure developed by Coulomb and Rankine. Coulomb (1976) first studied the earth pressure problem using the limit equilibrium method to consider the stability of a wedge of soil between a retaining wall and the failure plane. Rankine (1957) presented a solution for lateral earth pressures in retaining walls based on the plastic equilibrium. He assumed that there is no friction between the retaining wall and the soil, the soil is isotropic and homogenous, the friction resistance is uniform along the failure surface, and both the failure surface and the backfilled surface are planar. These theories are only applicable under certain conditions to estimate roughly the earth pressures on the wall. Moreover, they do not consider the construction process and give no indications on the wall deformations and ground movements in the more complex braced deep excavations.

Stability analysis is important in the design of reataining structures in clay, Terzaghi (1943) suggested a mechanism consisting of a soil column outside the excavation which creates a bearing capacity failure. The failure is resisted by the weight of a corresponding soil column inside the excavation and also by adhesion acting along the vertical edges of the mechanism.

The wall deflections are normally measured with inclinometers, but the readings need to be adjusted to be consistent to the surface survey, because inclinometers usually only record the deflection pattern of the wall by assuming no displacement at the toe of the wall (Yuepeng.D, 2014). In practice, however, a non-zero displacement at the toe of the wall is confirmed from both field measurements and numerical analyses (Simpson, 1992).

Ou, et al. (2000) presented the building responses and ground movements induced by an excavation using the top-down construction method in Taipei. They concluded that the building performance during the excavation may be affected by factors such as the type and size of foundation, the geometry of the excavation, and the shape of the settlement profile. A building near a relatively short excavation side may experience smaller inclination than if it is near a long excavation side. They also suggested that information regarding a building's location relative to the settlement influence zone is helpful in planning building protection measures during excavation.

3 Materials and Methodology

For the proper accomplishment of this work, it is required to review necessary and applicable materials, research findings and data on soil parameters of the selected site used for the analysis of soil-structure interaction. The deformation of the supporting system and its influence on the existing adjacent structure has been studied using Finite Element based software. Material model is a set of mathematical equations that describes the relationship between stress and strains. In the Plaxis software two constitutive models (MC &HS) have been selected for this study. Comparative analysis of the deformation of the supported soil and the contiguous pile wall deflection have been carried out. In addition to the deformation analysis, parametric study of supporting system has been performed. The soil and supporting wall parameters have been obtained from the geotechnical investigation report and from design of the shoring system. The derived soil parameters such as stiffness have been obtained from empirical correlations.

For carrying out of deep excavation analysis of the support system and its influence on existing nearby structures Plaxis 2D V8.6 software has been used. In this research, plane strain analysis and 15 node element has been selected. Drained effective stress analysis has been chosen as a drainage condition of constitutive model for both HS & MC model. Parametric studies of contiguous pile wall have been carried out to observe its effect on adjacent structure. The building load has been considered in the analysis of the pile wall deflection and analysis of settlement trough. The lateral ground deformation and maximum settlement has been obtained by varying the adjacent building load and corresponding distance from the face of excavation.

In this study soil parameters were collected from geotechnical investigation report and the other parameters were taken as specified by ETG designers and Consultants ltd., and the same has been chosen for the analysis of deformation of supporting system and its influence on existing structures. Both Mohr-Coulomb (MC) and Hardening Soil (HS) model have been used to estimate the deflection of the Contiguous pile wall for comparative study of deformation of retained soil. With the absence of availability of appropriate test result for numerical modeling an empirical correlation with the SPT-N value can be used.

4 Modeling and Parametric Studies

4.1 Simulation of deep Excavation in Plaxis 2D

For the numerical simulation of deep excavation, two dimensional finite element code of PLAXIS v8.6 has been used in this study, The general procedure for deep excavation analysis in numerical simulation include the creation of geometric model, generation of finite element mesh, execution of finite element calculation, and evaluation of output result. The analysis was carried out by assuming plane strain condition. In this deep excavation analysis, two soil constitutive models were selected for comparing support wall deflections and deformation analysis. The linear elastic-perfectly plastic Mohr-Coulomb model contains five parameters, and the advanced Hardening Soil model contains ten input parameters. The support system, contiguous pile wall has been modeled as plate element and the anchors as node-to-node anchor. The grouting body simulated as geo-grid element. The adjacent building can be considered as simple elastic beam as proposed by Potts and Addenbrooke (1997) and modelling can be done as plate element in Plaxis.

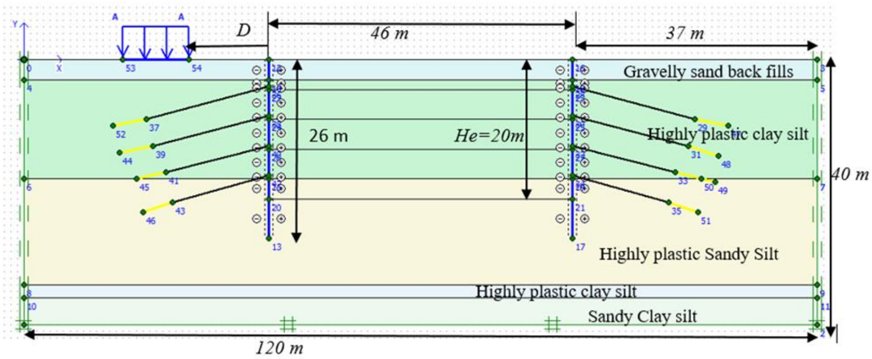

Fig. 1. Plaxis 2D modeling of deep excavation support system.

4.2 Parametric study of Contiguous pile wall

For the parametric study of retention system, the pile diameter (d), anchor spacing (L_s) and pre-stress force on settlement and lateral wall deflection have been considered for different loading condition.

4.2.1 The effect of pile diameter on settlement and lateral wall deflection: The deflection of supporting system in deep excavation depends on its stiffness. As it's indicated in Fig.1, the stiffness increase with increasing pile diameter for the model listed in Table. 1. The deflections of pile support have been determined from Plaxis simulation for different pile diameter by assuming the pile as plate and elastic element using both HS and MC models.

Table 1. Stiffness parameter of contiguous pile wall for different diameter

Parameter	Name	Contiguous Pile Parameter			
Model No.		**Pile-1**	**Pile-2**	**Pile3**	**Pile-4**
Contiguous pile wall	(m)	0.4	0.6	0.8	1.0
Diameter	d, (m)	0.02	0.02	0.02	0.02
No. of Reinforcement	No.	8	11	15	18
Area of Reinforcement	A_s, (m^2)	0.00251	0.00346	0.00471	0.00565
Weight	W, kN/m	8.66	12.99	17.32	21.65

For the parametric study, the loading condition (Li) and diameter of piles (d) both vary by fixing the building load distance (D). The neighboring building distance (D=4m) and different loading condition have been applied to determine the maximum lateral wall deflection. The relationship between maximum lateral wall deflection and support stiffness has been shown in Table. 2 for different loading condition.

Table 2. maximum lateral wall deflection (δhm) with Pile diameter (d)

Load Type	Model	
	Mohr-Coulomb	Hardening-Soil
L-1	$\delta_{hm} = 74.311e^{-0.138d}$	$\delta_{hm} = 66.705e^{-0.175d}$
L-2	$\delta_{hm}= 75.288e^{-0.149d}$	$\delta_{hm}= 66.318e^{-0.163d}$
L-3	$\delta_{hm}= 74.481e^{-0.133d}$	$\delta_{hm}= 66.885e^{-0.176d}$
L-4	$\delta_{hm}= 73.197e^{-0.105d}$	$\delta_{hm}= 67.202e^{-0.191d}$

From this analysis it has been noted that, the maximum lateral wall deflection occurs at smaller values of pile stiffness in both MC and HS models. On the other hand, the bending moment increases with increasing support stiffness for both cases as indicated in Fig. 2 and 3. The maximum lateral wall deflection expressed in terms of pile diameter in Table 2.

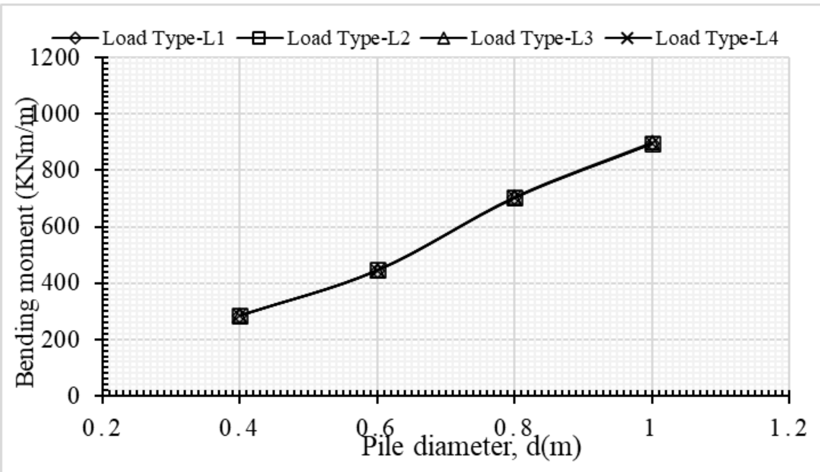

Fig. 2. Variation of maximum bending moment with support stiffnessin MC model

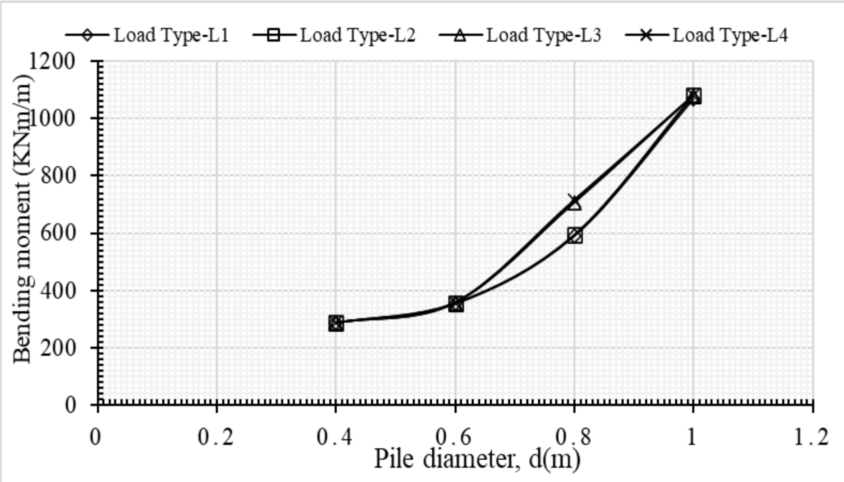

Fig. 3. Variation of maximum bending moment with support stiffnessin HS model

4.2.2 Effect of horizontal anchor-spacing (S) on settlement and lateral wall deflection: For the parametric study of contiguous pile walls, the horizontal anchor spacing is another important parameter for the study of wall deflection and maximum settlement in deep excavation. For the simulation process five anchor spacing has been considered as shown in Table.3.

Table 3. Parameters for horizontal anchor spacing (S)

Anchor Spacing, S(m)	S_1	S_2	S_3	S_4	S_5
	1.4	1.6	1.8	2.0	2.2

For this analysis the neighboring-building distance (D_2) is assumed to be at 4 m from the face of excavation and the maximum lateral wall deflection obtained by varying the anchor lateral spacing (S). The soil stratification is similar to the initial model. The contiguous pile walls diameter (d_3) is taken as 0.8 m for both MC and HS models. The variation of maximum wall deflection with horizontal anchor spacing is given by the equation as indicated in Table. 4. It is observed that the maximum support wall deflection increases with increasing anchor spacing (S) and neighboring building load.

Table 4. maximum lateral wall deflection (δhm) with horizontal anchor spacing (S)

Load Type	Model	
	Mohr-Coulomb	Hardening-Soil
L-1	$\delta_{hm} = 67.80e^{0.0171S}$	$\delta_{hm} = 38.20e^{0.0406S}$
L-2	$\delta_{hm} = 67.51e^{0.0215S}$	$\delta_{hm} = 39.25e^{0.0291S}$
L-3	$\delta_{hm} = 67.94e^{0.0207S}$	$\delta_{hm} = 39.95e^{0.0536S}$
L-4	$\delta_{hm} = 68.97e^{0.0138S}$	$\delta_{hm} = 40.76e^{0.0187S}$

In the Mohr-Coulomb model for the loading condition L4, the maximum lateral wall deflection (δ_{hm}) is given by $\delta_{hm} = 68.97e^{0.0138S}$. From Table. 4, for an anchor spacing of 1.8 m, the maximum lateral wall deflection calculated as $\delta_{hm} =$

68.97e0.0138*1.8 =70.70 mm. Similarly, for the same loading condition in HS model the maximum lateral wall deflection (δ_{hm}) is calculated as δ_{hm}= 40.76$e^{0.0187*1.8}$ =42.15 mm. From this result, it has been observed that the maximum lateral wall deflection obtained using MC model is about 40.4% greater than those obtained from HS model.

As it has been indicated in Fig.4 and 5, the wall bending moment increase gradually with increasing horizontal anchor spacing. The estimated bending moment obtained in Mohr-Coulomb model is much higher than Hardening Soil model. This indicate that Mohr-Coulomb model overestimate the maximum lateral wall deflection as compared to Hardening Soil model. For loading condition L4 as the anchor spacing (S) increase by 0.2m, the maximum bending moment increase with 0.29 % and 0.41 % in HS and MC model respectively.

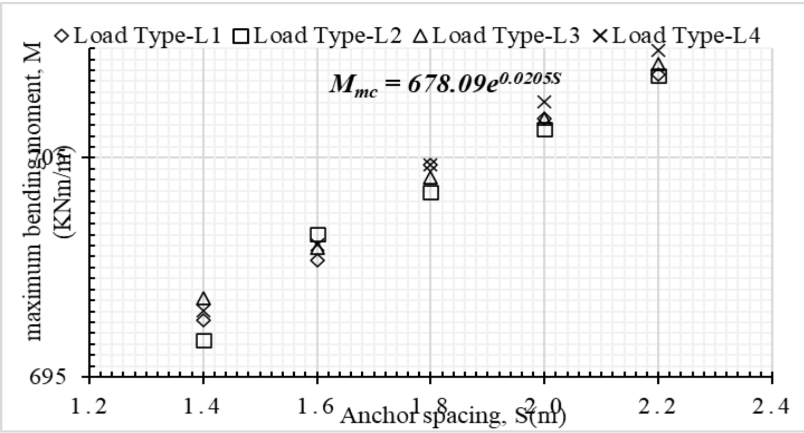

Fig. 4. Variation of maximum bending moment with anchor spacing in MC model

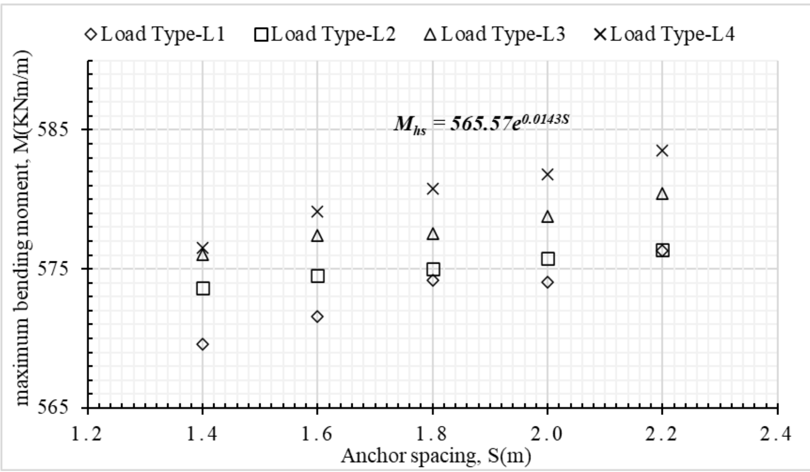

Fig. 5. Variation of maximum bending moment with anchor spacing in HS model

4.2.3 Effect of anchor pre-stress force on settlement and lateral wall deflection: For this parametric study, the maximum lateral wall deflection and settlement obtained by varying pre-stress force with depth of excavation. The neighboring building distance (D2), pile diameter (d3), depth of excavation (He) and loading condition L4 assumed to be constant as shown in Table. 5.

Table 5. Pre-stress force of anchor system (p)

Anchor pre-stress	P_1	P_2	P_3	P_4
Force, P (kN/m)	362	462	562	662

From this analysis, the maximum lateral wall deflection increase with decreasing the anchor pre-stress force in both MC and HS models. The lateral wall deflection decrease rapidly below the maximum depth of excavation for all pre-stressing condition in MC model.

Fig. 6-7 shows the variation of horizontal wall deflection with depth and pre-stress force wrt MC and HS models respectively. Whereas, Fig. 8-9 shows variation of wall bending moment with depth and pre-stress force wrt MC and HS models respectively. From this analysis result, the bending moment occurs for higher values of pre-stress force to depth of about 10 m and then decrease within increasing the pre-stress force to depth of excavation (He). The maximum bending moment occurs at about a depth (He) of 20 m for all pre-stress force.

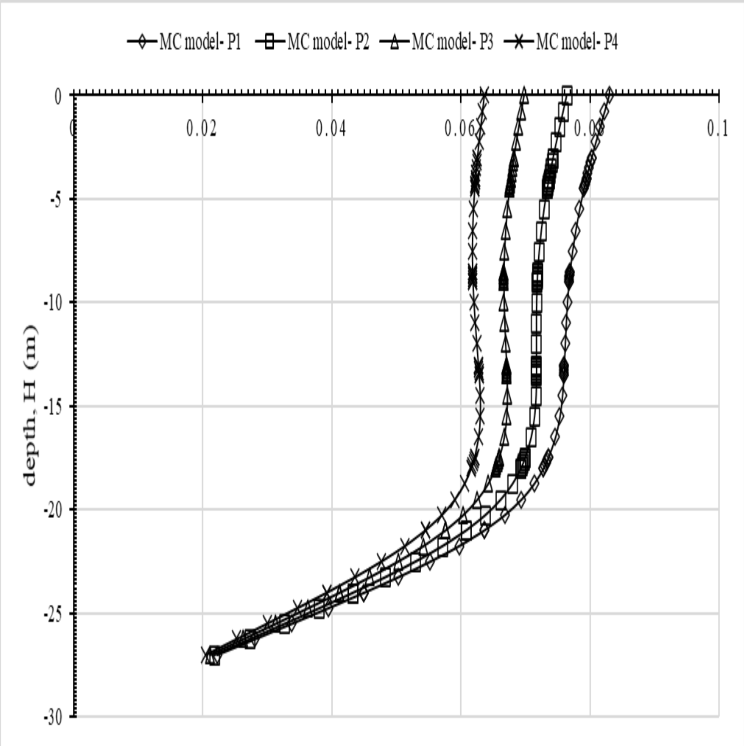

Fig. 6. Variation of horizontal wall deflection with depth and pre-stress force in MC model.

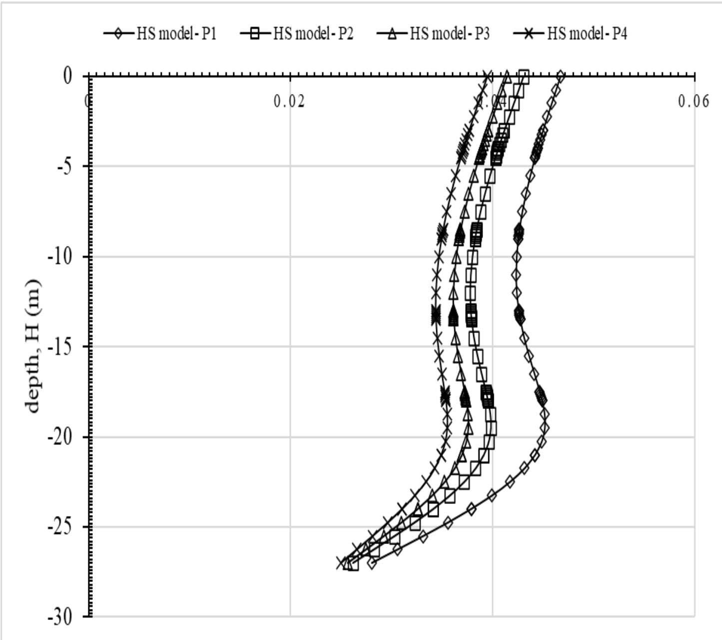

Fig. 7. Variation of horizontal wall deflection with depth and pre-stress force in HS model.

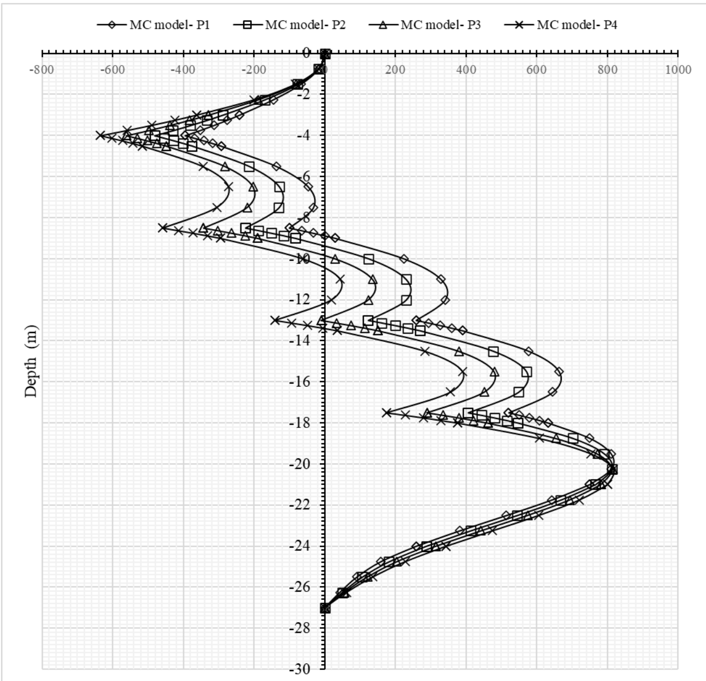

Fig.8. Variation of wall bending moment with depth and pre-stress force in MC model

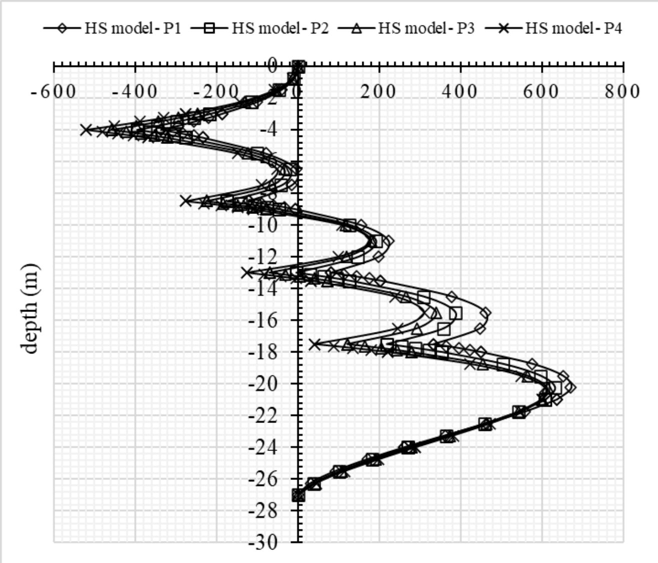

Fig.9. Variation of wall bending moment with depth and pre-stress force in HS model

4.2.4 Effect of depth of Excavation on Contiguous pile wall: For this parametric study, the pile diameter d3=0.8 m, neighboring building distance D2 = 4 m and loading condition L1 considered. Lateral deflection of contiguous pile wall and bending moment determined by varying the depth of excavation. As the depth of excavation increases, the horizontal ground deformation increases to certain maximum value and then decrease as indicated in Fig. 10. The bending moment decrease at location of Anchor installation as indicated by sharp curve from the Fig. 9.

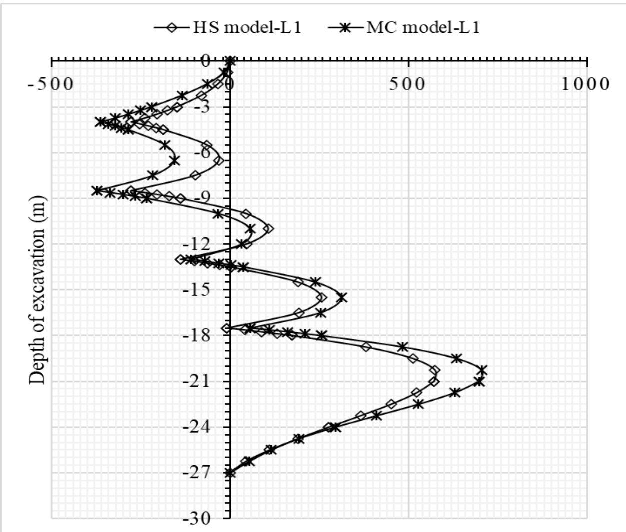

Fig. 10. Variation of bending moment with depth of excavation in both HS & MC model

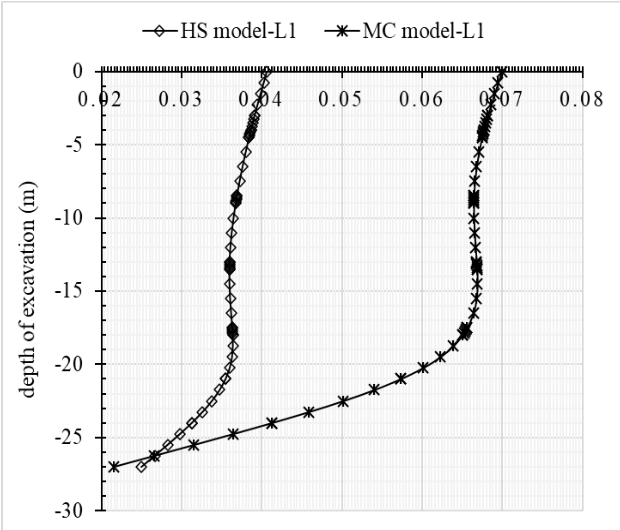

Fig. 11. Variation of lateral wall deflection with depth of excavation in both HS & MC model

5 Conclusions

1 Maximum lateral wall deflection occurs at smaller values of pile stiffness in both MC and HS models. Whereas, the bending moment increases with increasing support stiffness.
2 For horizontal anchor spacing, the maximum lateral wall deflection obtained using MC model is about 40.4% greater than those obtained from HS model. For loading condition L4 as the anchor spacing (S) increase by 0.2m, the maximum bending moment increase with 0.29 % and 0.41 % in HS and MC model respectively.
3 The bending moment occurs for higher values of pre-stress force to depth of about 10 m and then decrease within increasing the pre-stress force to depth of excavation (He). The maximum bending moment occurs at about a depth (He) of 20 m for all pre-stress force.
4 As the depth of excavation increases, the horizontal ground deformation increases to certain maximum value and then decrease thereafter. The bending moment decrease at location of Anchor installation as indicated by sharp curve.

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