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A parametric investigation on effect of supporting arrangements on earth retention system

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Abstract. The effects of various supporting arrangements have been investigated on an excavation support system using a numerical tool. The purpose of providing different supporting arrangements was to limit the pile wall deflection in the range of 0.5% to 1% of the excavation depth. Firstly, a deep excavation supported by sheet pile wall was modeled and the effects of sheet pile wall thickness, excavation depth and distance to adjacent footings from sheet pile wall face were explored on the soil deformation and wall deflection. Further analysis was performed considering six different arrangements of tieback anchors and struts in order to limit the wall deflections. Case-01 represents the basic excavation geometry supported by sheet pile wall only. In Case-02, sheet pile wall was supported by struts. Case-03 is a sheet pile wall supported by tieback anchors. Likewise, for the Cases 04, 05 and 06, different arrangements of struts and tieback anchors were used. Finally, the effects of different supporting arrangements on soil deformation, sheet pile wall deflection, bending moments and anchor forces have been presented.

Keywords: deep excavation; excavation support system; FEM analysis; struts; tieback anchors

1. Introduction

Deep excavations are frequently needed for infrastructure development in urban areas due to the shortage of space and existing structures. The safe and economic design of deep excavations can only be performed by professionals with ample experience in structural design as well as a thorough understanding of soil mechanics and foundation engineering (Rasool *et al.* 2015, 2020). Generally, deep excavations cause soil movement both laterally and vertically where the first component is considered to be more perilous that causes damages to the adjacent structures (El Sawwaf and Nazir, 2012, Lam *et al.* 2014, Mandy *et al.* 2016, Ou *et al.* 1993). While excavating in urban areas, strict measures are taken to control the soil deformations and to minimize the possible damages to adjacent structures. Previous studies have shown that the most effective way of controlling soil deformations for deep excavation is providing excavation support walls (Farzi *et al.* 2018) that include diaphragm wall (Jasmine Nisha and Muttharam 2017), sheet pile wall (An *et al.* 2018, Fall *et al.* 2019), contiguous pile (Ramadan *et al.* 2018, Saleem, 2015) or secant pile wall (Cui *et al.* 2018).

Various researchers have explored the effects of excavation geometry such as excavation width, stratum depth, wall stiffness, and embedment depth on adjacent structures using three dimensional (3D) finite element modeling (FEM) tools. Goh and Mair (2014) studied the response of framed buildings to excavation-induced movements and concluded that the influence of frame action on building stiffness can be quantified using the results from the FEM models. Ramadan *et al.* (2018) performed a 3D FEM parametric study considering excavation depth, pile embedded depth, and wall stiffness and provided some design recommendations for a safe supporting system in clay. Elbaz *et al.* (2018) investigated the performance of deep excavation in sand covered karst and reported that the type of the founding structure could significantly affect the settlement development of the adjoining buildings. Voottipruex *et al.* (2019) studied the behavior of different types of walls under deep excavation by performing field tests and 3D simulations. They presented the measured and simulated results in terms of profiles of lateral displacement, settlement and bending moments. The lateral loads resulting from soil movements induce bending moments and deflections in the pile/wall supporting excavation that may lead to structural distress or failure of both the adjacent buildings as well as the excavation supporting system itself. Singh and Chatterjee (2020) studied the influence of a uniform surcharge load on a cantilever sheet pile wall at varying distances from the top of the wall under seismic conditions using finite difference based computer program. Goh *et al.* (2020) numerically

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studied the effects of groundwater drawdown on ground settlement for excavation in residual soils. The critical parameters that influence the ground settlement performance were identified as the excavation width, excavation depth, depth of groundwater drawdown, thickness of residual soil, average SPT-N value of the residual soil, location of moderately weathered rock, and stiffness of wall system. Subsequently, an artificial neural network (ANN) model was also developed to provide estimates of the maximum ground settlements. Zhang et al. (2020) presented the effects of Jet Grout Piles (JGP) on wall deflections and strut forces for deep excavations. Firstly, finite element analysis calibrated by an excavation case history improved by JGP was carried out, followed by parametric studies that investigated the effects of various JGP geometric and mechanical properties on the excavation performances. The numerical analyses indicated that increasing the number of piles and the areal extent of reinforcement area, as well as decreasing the pile spacing, can significantly reduce the wall deflections and strut forces for excavation in weak clay. Li and Zhang (2020) presented extensive finite element analysis to investigate the passive pile's lateral stress and deformation development using a centrifuge test study as model validation. The results showed that despite the conventional approach of ignoring intrinsic anisotropy of soil, it stands as a contributing factor in determining the pile behaviour since the soil displacement field is inevitably dependent on its inherent characteristics. Mu *et al.* (2021) employed analytical model to relate the wall deflection of braced excavation to the response of adjacent pile-supported buildings and thus formed a theoretical tool for determining the allowable deformation of excavation support structures based on the tolerance of buildings to distortion. Zhang *et al.* (2022) presented the results of extensive finite element analysis to investigate the influence of clay anisotropy on basal heave stability. The parameters that were considered include the ratio of the plane strain passive to the plane strain active shear strength, the ratio of the unloading/reloading shear modulus to the plane strain active shear strength, the plane strain active shear strength, soil unit weight, wall system stiffness, excavation width, excavation depth, and the wall penetration depth. The validations from case histories indicated that the proposed model can provide reasonable predictions of the basal heave stability in soft clay. Hong *et al.* (2023) studied an advanced reliability-based robust geotechnical design method which can consider multiple failures and uncertainty of statistical information. A universal design sample was conducted to verify the necessity of considering the uncertainty of statistical information. The results from this study indicated that the proposed method had a good performance in determining the optimal design with reasonable robustness and cost. Li *et al*. (2022) presented 3D FE analyses using the NGI-ADP soil constitutive model to assess the ground responses and adjacent building displacement for excavations in soft clays.

The results showed that anisotropic degree significantly influenced the soil displacements, which brought considerable differences in ground infrastructures. For top-down method adopted in this case history, the critical location of diaphragm walls and surrounding soil existed at the center depth of the two platform slabs. Jet grouting can be adopted before excavation to prevent larger deformation of soft clay.

Likewise, various researchers have performed model tests to investigate the behavior of excavation support system. FHA (1998) provides guidelines for model-scale wall tests and ground anchor tests. Georgiadis and Anagnostopoulos (1999) performed a series of model tests to study the displacement of structures adjacent to cantilever sheet pile walls and found that shallow foundation displacements are related to lateral sheet pile wall movement, the ratio of the distance between foundation and wall to the excavation depth and the safety factor against bearing capacity failure of the foundation. Chen *et al.* (2021) carried out a series of model tests to investigate the influence of inner strut length on the mechanical and deformation characteristics of the system consisting of inner strut, diaphragm wall and soil behind diaphragm wall. The results showed that a strict control on the horizontal displacement of braced excavation will lead to increment of axial force and the axial compression ratio of strut, which can pose a serious threat to the safety of the strut system. Cheng *et al.* (2016) performed model tests to investigate the mechanism of partial collapse and progressive collapse of cantilever retaining piles. The test results showed that partial collapse can cause a sudden increase in the bending moments of adjacent piles via an arching effect. During the progressive collapse, the previous failed pile could cause new stress arching; simultaneously, the soil behind certain nearest intact piles could become loosened and destroy the arch springing of the stress arching, causing the progressive collapse to cease gradually. Similarly, Bhatkar *et al.* (2017), Cui *et al.* (2018), Elbaz *et al.* (2016), Fok *et al*. (2012), Nisha and Muttharam (2017), and Moormann (2004) performed various case studies to study deep excavation supported by various elements.

Tieback anchors (Fall *et al.* 2019) and struts (Chowdhury *et al.* 2017) are commonly used to control bending moments and deflections in the supported walls. Analysis of different types of braced excavation systems have been studied by various researchers (Cui *et al.* 2018; Finno *et al.* 2007; A. Goh *et al.* 2017; Hsieh *et al.* 2013; Zhandos *et al.* 2015) using finite element modeling (FEM) techniques, mainly PLAXIS 3D software. However, most of previous studies are limited to the behavior of supporting wall, wall stiffness, wall embedment length, soil models, soil strata and use of single bracing system (i.e., either struts or tieback anchors). Only limited studies are available describing the use of different supporting arrangements and its feasibility in an excavation support system. This study presents the results of a parametric investigation on different excavation supporting systems. Firstly, a deep excavation supported by sheet pile wall was modeled and effects of variation of sheet pile wall thickness, excavation depth and distance of adjacent footings from the sheet pile wall face was observed on soil deformation and wall deflection. To ensure that the serviceability limit states are satisfied, a common design criterion is to limit the maximum wall deflection to a fraction of the excavation

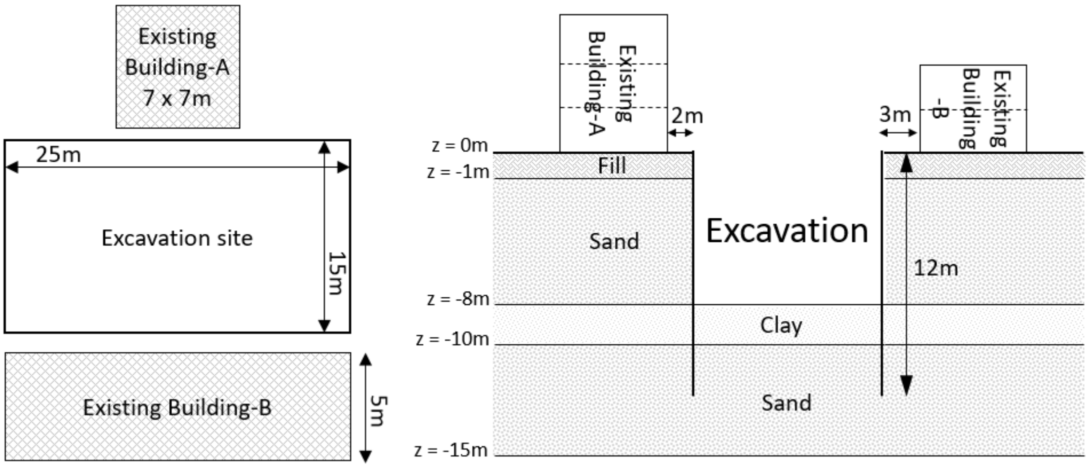

Fig. 1 Plan and section of excavation geometry

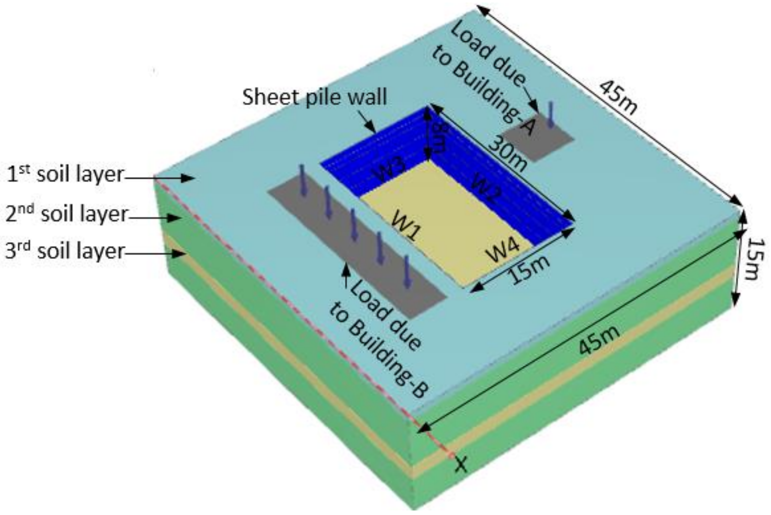

Fig. 2 3D model of excavation

depth, typically in the range of 0.5 to 1% of the excavation depth (Michael 2001, Moormann 2004). To counter the wall deflections, further analyses were performed by considering a total of six cases with different arrangements of tieback anchors and struts. Finally, the effects of these supporting arrangements on soil deformation, sheet pile wall deflection, bending moments and anchor forces have been studied and discussed.

2. Finite element model

PLAXIS 3D CEv20 (Plaxis3D, 2020) has been used for the analysis of excavation support system. The model geometry, soil parameters, analysis assumptions, excavation supporting system, properties of structural elements, and verification of numerical model have been presented in the following sections.

2.1 Excavation geometry

The geometrical details of a proposed deep excavation are shown in Fig. 1. The dimensions of finite element model were selected to avoid any strain localization at the boundaries. There are two existing buildings along longer sides of the excavation. Building-A with three stories, 2 m away from the excavation has dimensions of 7 x 7 m and Building-B with two stories, 3 m away from the excavation has dimensions of 25 x 5 m. The total in-plane dimensions of the model are 25 x 25 m. To avoid any stress or strain concentration, the boundary limits of model are kept at a distance of 15 and 30 m from the edge of the excavation. Chang-Yu *et al.* (1996) stated that in a three-dimensional analyses, the density of mesh has significant effects on the results. For the current model, a coarser mesh was generated at the boundaries of the model where the stress concentration is assumed to be low. Whereas a relatively finer mesh was created at sheet pile wall. A three-dimensional view of the finite element model with excavation and surcharge loads of adjacent buildings is shown in Fig. 2. All sides of excavation were supported with sheet pile wall. A total of six different cases have been analyzed in this study with various combinations of struts and tieback anchors. The details of these cases are described in the subsequent sections.

Table 1 Stiffness and other properties of the soil model used in this study

Layer	Type	Level (below EGL)		Unit weight (kN/m³)		k_x (m/day)	k_y (m/day)	C (kPa)	ϕ^o (deg)	Ψ (deg)	E_{50}^{ref} (kN/m²)	E_{oed}^{ref} (kN/m²)	E_{ur}^{ref} (kN/m²)	m (-)	R_{inter} (-)
		Start	Finish	γ_{unsat}	γ_{sat}										
Fill	Drained	0	-1	18	20	0.1	0.01	1.0	33	3	6800	5500	81600	0.5	0.7
Sand	Drained	-1	-8	18	20	1.0	0.1	1.0	35	5	50000	50000	150000	0.5	0.7
Clay	Undrained	-8	-10	11	17	0.01	0.001	10	34	0	6200	3100	2700	1.0	0.5
Sand	Drained	-10	-15	18	20	1.0	0.1	1.0	35	5	50000	50000	150000	0.5	0.7

2.2 Soil stratigraphy

PLAXIS simulates material behavior with different constitutive models which include Soft-Soil-Creep (SS), Hardening Soil (HS), Mohr-Coulomb (MC), and Elastic (EM) model. Commonly used models are Hardening Soil and Mohr-Coulomb model. Mohr-Coulomb failure criterion represents the potential failure plane of the soil and the failure is said to occur when shear stress on any plane in soil element touches the failure envelope (Lim *et al.* 2010). MC model is linear-elastic and perfectly plastic model with the first-order approximation of the soil behavior. HS model is an anisotropic model to predict the non-linear behavior of loose to dense sands and over-consolidated clays. The main difference between HS and MC models is the stress dependency of the soil stiffness and hyperbolic relationship between stress and strain (Wu and Tung 2020). The soil behavior in HS model is simulated by defining three moduli i.e., secant modulus (E_{50}) at mobilization of 50% of maximum shear strength, the oedometer modulus (E_{oed}) and the un-loading reloading modulus (E_{ur}). Three soil layers have been considered in this study and their properties are listed in Table 1. The value of Poison's ratio (ν_{ur}) is taken as 0.3 in the unloading-reloading conditions for all soil layers.

2.3 Analysis assumptions

Due to some construction and site constraints, the following assumptions are made in performing parametric analysis of the proposed excavation support system using 3D FEM analysis:

i. The study deals with only a single propped excavation system.
ii. The struts are not placed inclined at the corners.
iii. Groundwater level is assumed much below the excavation depth.

2.4 Excavation support system

Fig. 3 shows a total of six cases analyzed to investigate the effects of different supporting systems on deep excavation. Case-01 shows the basic excavation geometry supported by sheet pile wall only. In Case-02, sheet pile wall is supported by installing struts in short direction at a distance of 5.0 m. In Case-03, sheet pile wall is supported by tieback anchors in both directions with center-to-center distance of 5.0 m. In Case-04, 05 and 06, different arrangements of struts and tieback anchors have been used to study their effects on the excavation supporting system.

2.5 Defining the structural elements

Fig. 4 shows the details and properties of all structural elements including sheet pile walls, wailing, struts and tieback anchors used in this study. The sheet pile walls are modeled as elastic, non-isotropic material by assigning plate element properties. Two sheet pile walls have been simulated as plate elements. The basic properties of sheet pile wall simulated in PLAXIS were derived from the material data sheets provided by the manufacturer. The interpreted properties of each sheet pile wall are shown in Table 2. The tieback anchors used in this study are modeled as node-to-node anchors with pre-stress force of 50 kN. All structural elements like wailing, struts and tie back anchors are assigned as an elastic material. The construction sequence adopted in this study has been schematically shown in Fig. 5(a). As mentioned earlier that a total of six different cases have been analyzed in this study, therefore the construction phases may increase or decrease depending on each case. However, a general construction sequence as shown in Fig. 5(b) is described as follows. In Phase-1, sheet piles are installed and top 1.0 m layer of soil is excavated in Phase-2. The tieback anchors and wailing beams are installed in Phase-3 and 4, respectively. In Phase-5, the struts are installed and finally in the Phase-6, excavation is proceeded up to 8.0 m depth of excavation.

2.6 Model validation

The validation of any finite element model is vital to

Table 2 Sheet pile wall properties used in this study

Sheet Pile Section	Sheet-1	Sheet-2
Equivalent Height, d (m)	0.40	0.50
γ (kN/m³)	3.55	3.35
E_1 (kN/m²)	1.80×10^7	1.85×10^7
E_2 (kN/m²)	9.00×10^5	9.10×10^5
ν_{12}	0	0
G_{12} (kN/m²)	9.00×10^5	9.10×10^5
G_{13} (kN/m²)	1.55×10^6	1.50×10^6
G_{23} (kN/m²)	4.70×10^5	4.50×10^5

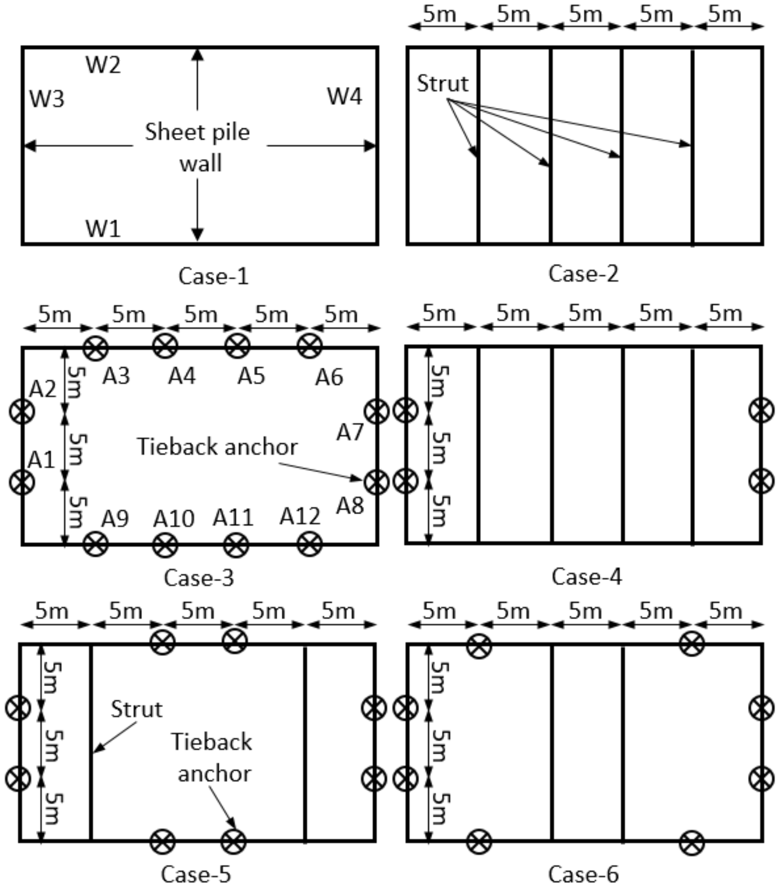

Fig. 3 Different excavation supporting systems

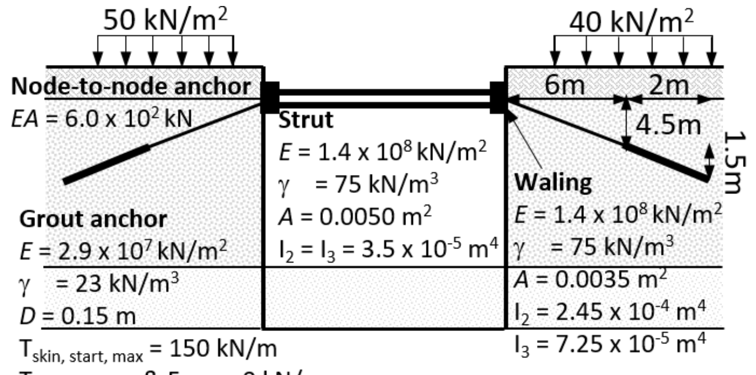

Fig. 4 Details of the structural elements

ensure that the proposed elements, geometry and meshing refinement are adequate for analysis. Due to non-availability of laboratory and field data, the model opted in this research was verified using the results of a pioneer and commonly cited study by Poulos and Chen (1996). The other recent studies available on the physical modeling of the topic under consideration are Li *et al.* (2023), Zhang *et al.* (2022), Li *et al.* (2021), Zhang *et al*. (2020), Goh *et al.* (2020), and Li and Zhang (2020). The problem (as shown in Fig. 6(a)) with a similar geometry and parameters used by Poulos and Chen 1996) has been verified in PLAXIS 3D.

The soil is assumed as a uniform clay layer in undrained conditions during the excavation. Sheet pile is idealized as an elastic beam and soil as an elastic continuum, but with a limiting pressure at the interface to allow consideration of local failure of soil. In the verification model, the unit weight of the soil was 20 kN/m^3, undrained shear strength was 50 kPa, and the Modulus of Elasticity (Es) was taken as 20 MPa. Analysis results in Fig. 6(b) show that the results obtained from PLAXIS 3D are in good agreement with results obtained by Poulos and Chen (1996).

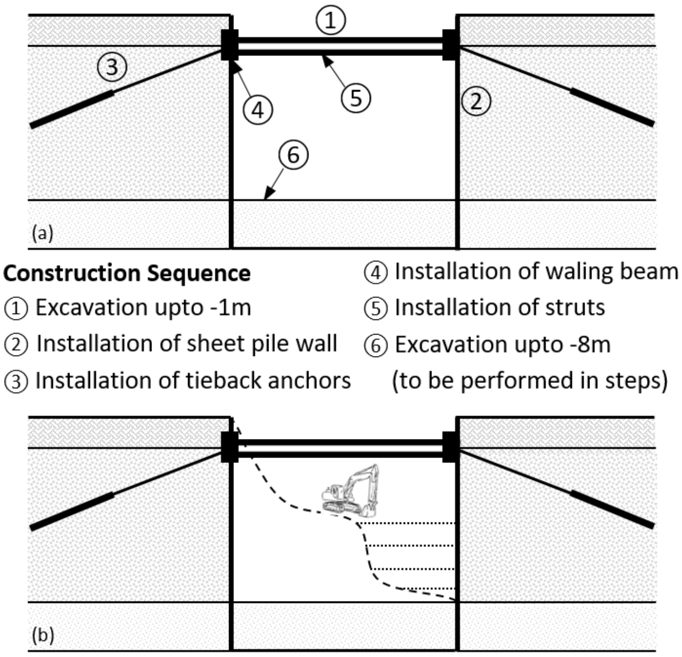

Fig. 5 Execution of the proposed deep excavation (a) construction sequence and (b) schematic representation of various phases of excavation

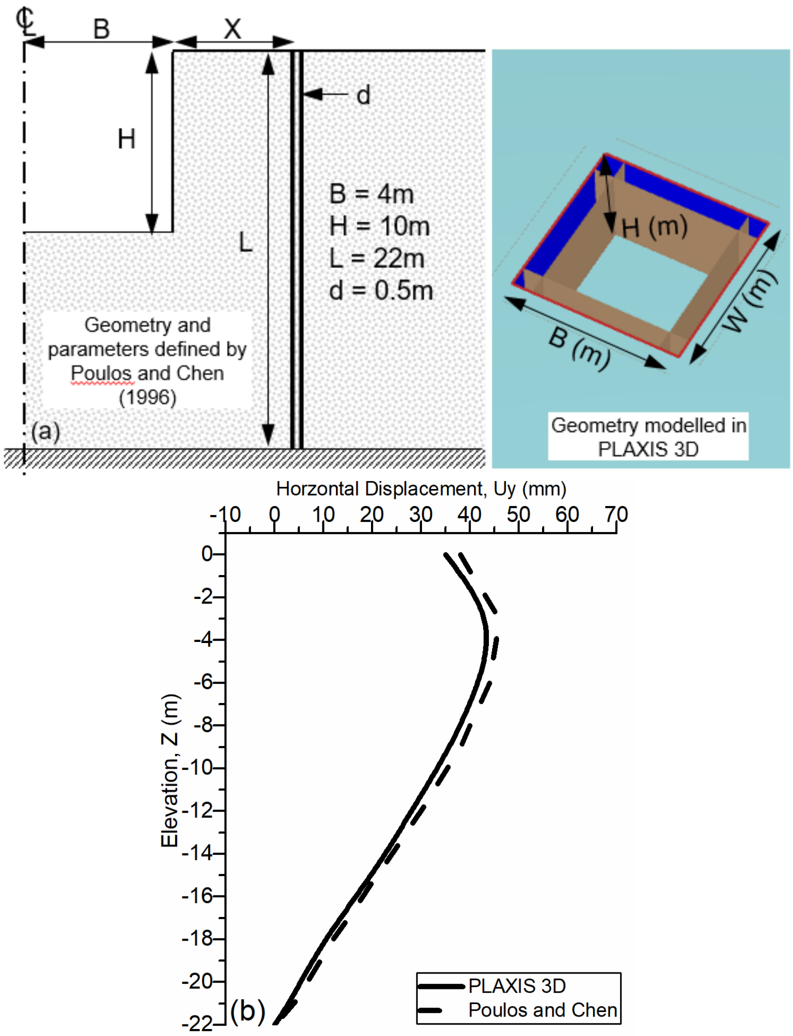

Fig. 6. Verification of numerical model (a) standard problem (b) comparison of lateral displacement of the wall

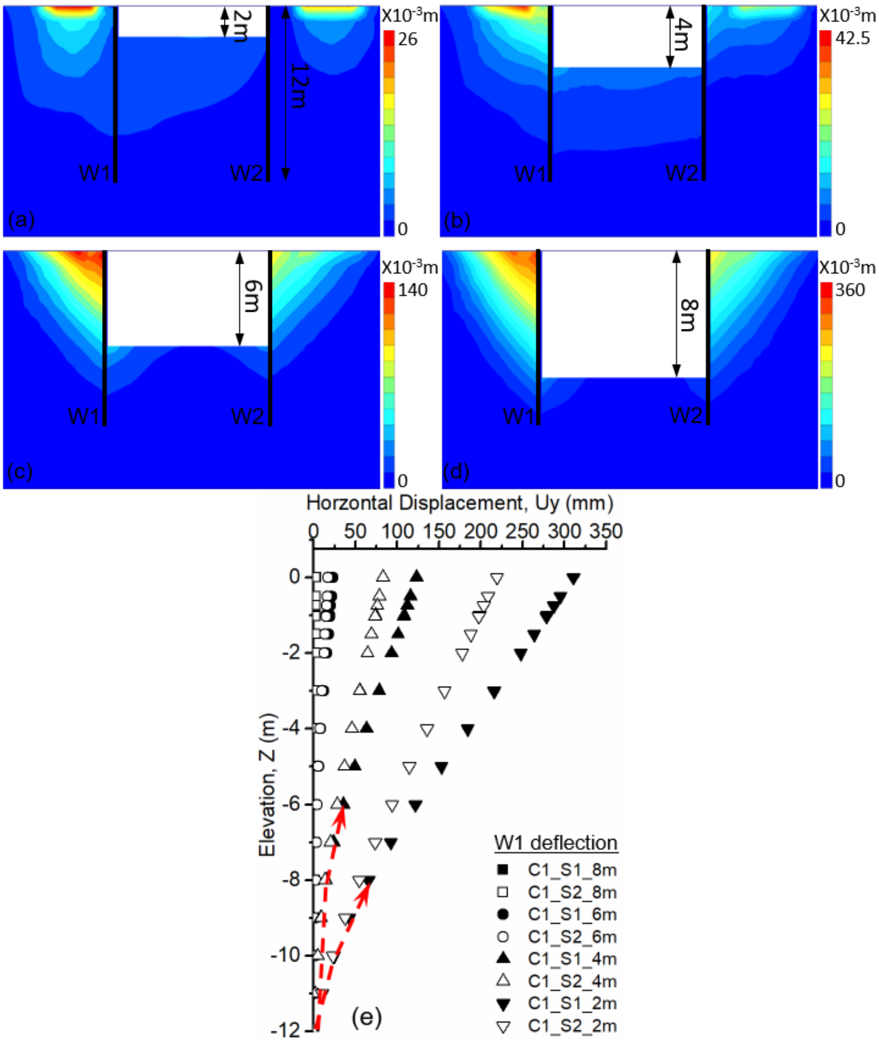

Fig. 7 Effect of excavation depth on soil deformation at depths (a) 2.0 m, (b) 4.0 m, (c) 6.0 m, (d) 8.0 m with Sheet (S1) and (e) sheet pile wall deflection with sheets (S1 & S2)

3. Results and discussions

The objective of the parametric investigations performed on excavation supporting systems using 3D FEM analysis is to evaluate the effects of sheet pile wall thickness, excavation depth and distance to adjacent footings on the soil deformations and wall deflections. To keep the wall deflections within tolerable limits, further analyses are performed by considering different arrangements of tieback anchors and struts. The effects of different supporting arrangements on soil deformation, sheet pile wall deflection, bending moments and anchor forces have been discussed in the subsequent sections.

3.1 Effect of excavation depth

The effect of excavation depth on excavation supported by sheet pile wall only (Case-01) was studied and the results are shown in Fig. 7. Figs. 7(a)-7(d) shows the analysis results when excavation supported with sheet (S1) was proceeded with the intervals of 2.0 m. It can be seen that soil deformation increases from 26 mm at 2.0 m excavation to 360 mm at 8.0 m excavation near wall (W1) side. Similarly, lateral displacement in the wall (W1) also increased with increase in excavation. However, when the excavation system was analyzed with Sheet-2, the lateral displacements decreased as shown in Fig. 7(e). A maximum decrease in lateral displacement due to change in sheet pile wall properties was observed at an excavation depth of 8.0 m. Only minor deflections were observed in embedded part of the wall up to an excavation of 6.0 m. However, at an excavation of 8.0 m, large deflections can be seen due to the decrease in embedded length. Further increase in lateral displacement of the wall with the depth was observed due to significant increase in the lateral earth pressure on the wall.

3.2 Effect of footing depth and distance from sheet pile wall

Fig. 8 shows that the maximum soil deformation and pile wall deflection was observed at an excavation depth of 8.0 m. A few analyses were performed by varying footing depth and distance from the excavation face to evaluate the reduction in soil deformation and wall deflection without

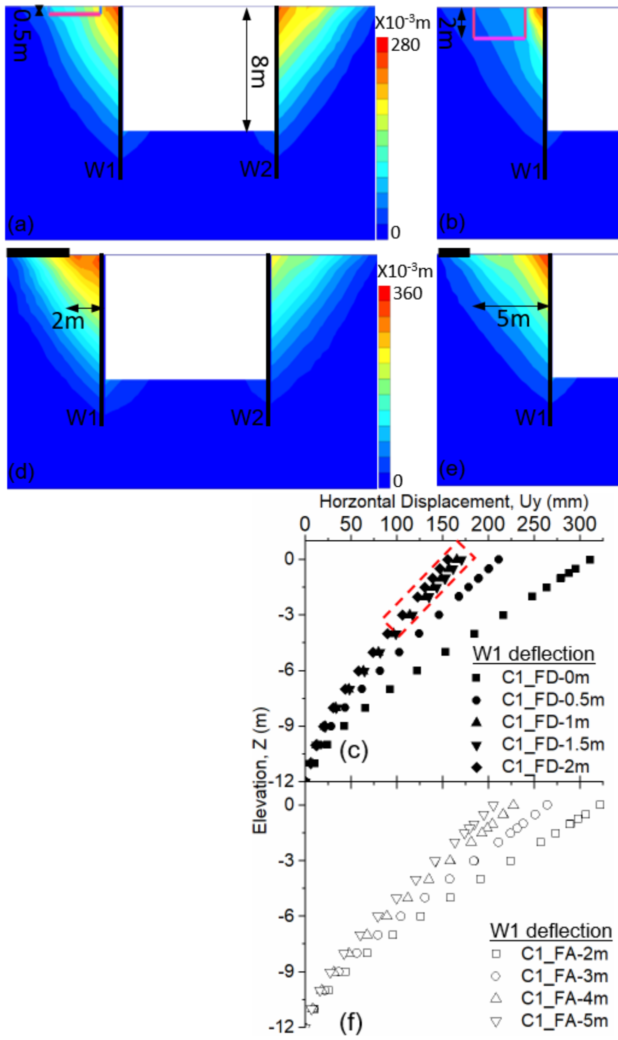

Fig. 8 Effect of footing depth on, (a), (b) soil deformation, (c) wall deflection and effect of footing distance from sheet pile wall (d), (e) soil deformation, and (f) wall deflection

providing tieback anchors and struts. The footings were placed at depths of 0.5, 1.0, 1.5 m and 2.0 m near the wall (W1). It was observed that the soil deformations near wall (W1) decreased with increase in footing depth, whereas no change was observed near other walls. Fig. 8(c) shows a large decrease in wall displacement (i.e., from 311 mm to 215 mm) when the footing was placed at a depth of 0.5 m. However, not much decrease was found when footing depth was further decreased to 1.5 and 2.0 m. Figs. 8(d) and 8(e) show the soil deformation near the pile walls when the distance of footing was increased from the wall edge. The analyses were performed by placing footing at 2.0, 3.0, 4.0 and 5.0 m away from the wall edge and it was found that soil deformation decreased from 360 mm (when footing was placed at 2.0 m from wall edge) to 260 mm (when the footing was placed at 5.0 m from the wall edge). The pile wall displacement was also decreased from 311 mm to 225 mm as shown in Fig. 8(f). Although the pile wall deflection is somewhat decreased by increasing the footing depth and increasing the distance from the face of sheet pile wall. However, the deflection still exceeds the limits of 80 mm i.e., 1% of the excavation depth. Hence, further analyses are performed by providing different arrangements of tieback anchors and struts.

3.3 Effects of different supporting arrangements

A total of six cases with different supporting arrangements (Fig. 9) were performed to explore their effects on the wall deflection. In Case-01, excavation was supported by sheet pile wall only and wall showed maximum deflection of 311 mm. To minimize the sheet pile wall deflection, struts (Case-02) were installed along shorter direction at an interval of 5.0 m. Installation of struts drastically decreased the deflection of the walls W1 & W2 from 311 mm to 15 mm at top and 29 mm in the middle. However, as no supporting elements (e.g., tieback anchor or strut) were installed in the walls W3 & W4, the maximum deflection observed in these walls was 90 mm. The analysis results of Case-02 are shown in Fig. 9(b). In Case-03, the sheet pile wall was supported by tieback anchors at an interval of 5.0 m in both directions. The analysis results in Fig. 9(c) showed that the installation of tieback anchors reduced the maximum wall deflection from 311 mm to 250

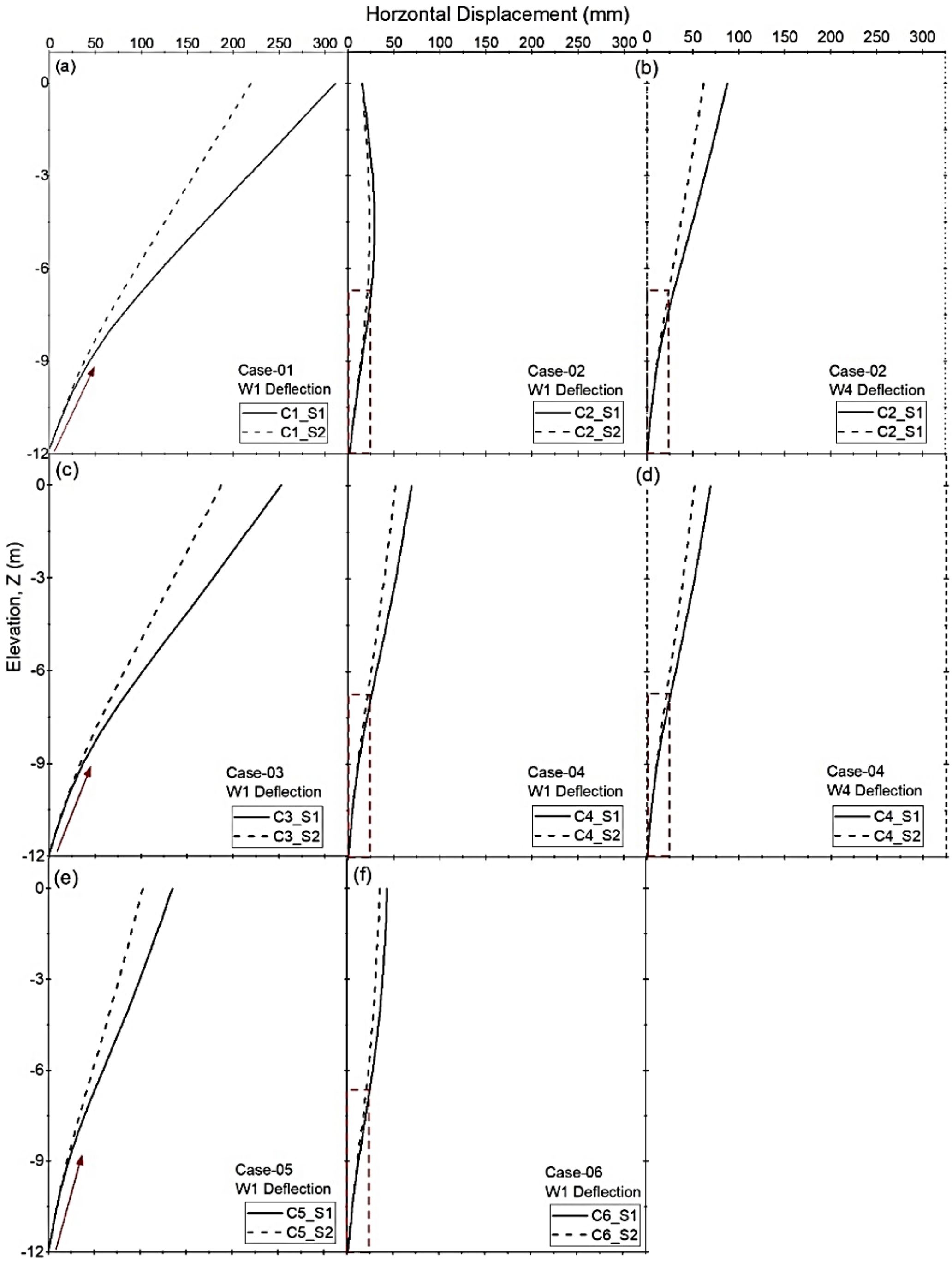

Fig. 9 Effect of different supporting arrangements on wall deflection

mm. Different combinations of struts and tieback anchors were analyzed in Case-04, 05 and 06. In Case-04, the struts were installed in longer direction and tieback anchors were installed in the shorter direction. The analysis showed satisfactory results and maximum deflection in all the walls was reduced to 75 mm as shown in Fig. 9(d). In Case-05, two struts were installed at 5.0 m from the sheet pile wall and tieback anchors were installed at the remaining location including the shorter side, at an interval of 5.0 m each. The analysis results in Fig. 9(e) show a maximum wall deflection of 135 mm. Finally, in Case-06, two struts were installed in the middle of sheet pile wall at a distance of 5.0 m, whereas, the tieback anchors were installed at the remaining locations including the shorter side, at interval of 5.0 m each. Fig. 9(f) shows the maximum wall deflection of 43 mm. It can also be noted that in Case-01, 03 and 05, the sheet pile wall showed large deflection starting from the bottom of the wall, whereas, not much deflections were observed in Case-02, 04, and 06 up to the proposed excavation depth of 8.0 m.

When the analysis was performed by changing sheet pile wall properties from S1 to S2, a decrease in wall deflection was observed in all cases, but Case-02 (W1, W2) and Case-06 (all walls) didn’t show much difference in wall

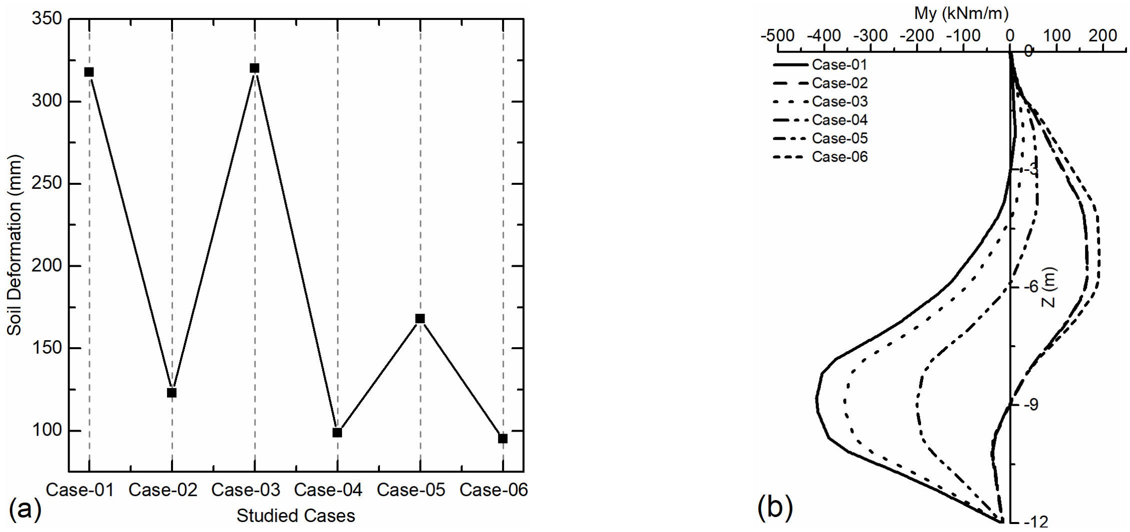

Fig. 10 All six cases with sheet S1 (a) deformations in soil and (b) maximum bending moment at center of the sheet pile wall

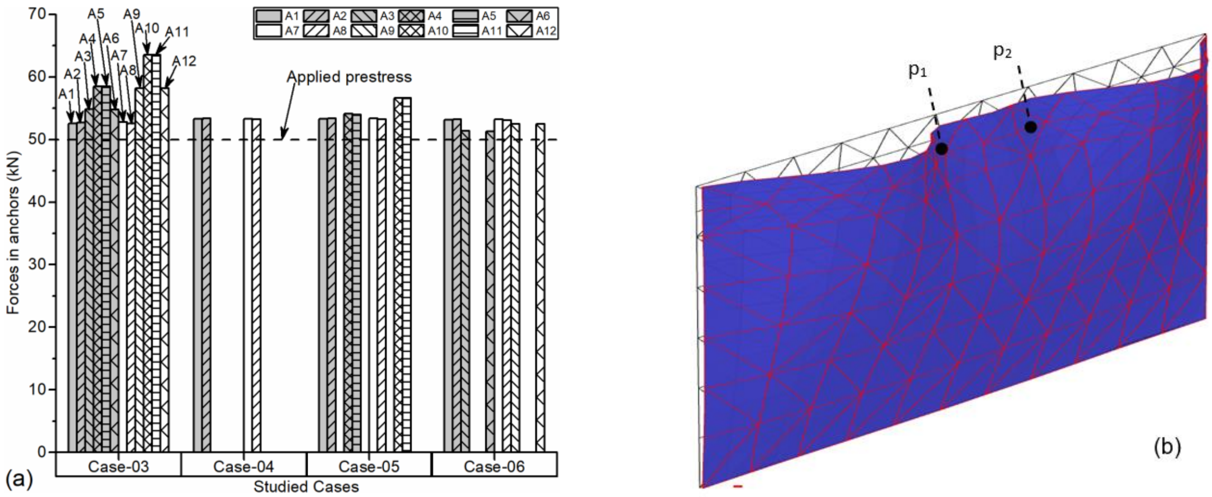

Fig. 11 (a) Forces in anchors after achieving desired excavation level for all six cases with sheet S1 and (b) deformed shape of the sheet pile wall (S1) for Case-06

deflection with both sheets S1 and S2. This shows that for Case-06, changing the sheet pile wall properties does not affect the wall deflection. Fig. 10(a) shows soil deformation for all six cases with sheet S1. It can be seen that Case-02, 04 and 06 showed lesser deformation in soil as compared to Case-01, 03 and 05, where minimum deformation was observed in Case-06. Similarly, Case-02, 04 and 06 showed lesser bending moment in sheet pile wall as compared to Case-01, 03 and 05 as shown in Fig. 10(b). A comparison of anchor forces is shown in Fig. 11(a) and it can be seen that, except for the Case-01, there is no difference between the applied pre-stress and the stress during the final excavation stage when the desired excavation is achieved. In Case-01, some anchors showed higher stress values, whereas, in Case-06 all anchors showed same stress vales as that of the applied prestress. Based on the analysis results, it can be stated that Case-06 is the most effective supporting arrangement for the proposed deep excavation as it showed minimum wall deflection, soil deformation, bending moment and stresses the anchor close to the applied prestress. Fig. 11(b) shows typical representation of the sheet pile wall after deformation. The points p_1 and p_2 on the figure shows the location where tieback anchors are installed, and it can be observed that almost no deformation was observed at these points. Whereas some deformations can be observed in the sheet pile away from these points where the tieback anchors have been installed. The amount of deformation varies from case to case. Fig. 11(b) shows the deformed shape of sheet pile wall (Wall-1, Case-06) after achieving desired excavation depth which gives minimum deformation throughout the wall.

4 Conclusions

Sheet piles, tie back anchors and horizontal struts are used in various combinations to design the soil supporting system for deep excavation. A number of combinations are possible and for practical applications, may not be analyzed due to computational and time constraint. Therefore, in this numerical study a detailed parametric investigation is conducted on soil supporting system for deep excavation using 3D FE analysis to evaluate the effects of sheet pile wall thickness, tie back anchors and horizontal struts, excavation depth, and distance to adjacent footings on the soil deformations and wall deflections. The findings of the study are summarized in the following.

- Soil deformation increased nonlinearly with the excavation depth, it increased from 26 mm to 360 mm as excavation depth was increased from 2 m to 8m respectively. Wall displacements also increased with the increase in excavation depth. However, the lateral displacements decreased by using sheet piles with increased thickness. The decrease in lateral displacements is primarily due to increased stiffness of the soil supporting system.
- The footing depth of adjacent structures influenced the lateral soil deformation. The lateral displacement of soil decreased with the increase in footing depth of the adjacent building. A significant decrease in lateral displacement of soil; i.e., from 311 mm to 215 mm, occurred when the footing was placed at a depth of 0.5 m at a distance of 2.0 m from the wall. Importantly, further increase in footing depth to 1.5 and 2.0 m marginally influenced the lateral soil deformation. Hence, the soil pressure from shallow depth footing of the adjacent building ingress the deleterious lateral soil displacement.
- Unsupported sheet pile wall showed a maximum deflection of 311 mm (Case-01). Hence, if the limiting top lateral displacement is the design criteria, then unsupported sheet pile may not be recommended for the deep excavation, however, installing struts (Case-02) decreased wall deflection to 90 mm. Installing tieback anchors (Case-03) decreased wall deflection to 250 mm.
- Tieback anchor and struts increased the lateral stiffness of the soil supporting system, hence resulted in decrease in lateral displacement of soil. Installing struts in longer direction and tieback anchors in the shorter direction (Case-04) decreased wall deflection to 75 mm. similarly, installing struts at 5.0 m from the sheet pile wall and tieback anchors at the remaining locations including the shorter side (Case-05) decreased wall deflection to 135 mm.

Considering the structural action of sheet piles, tie back anchors and horizontal struts in resisting the lateral deflections, it is proposed and verified by the numerical simulation that coupling the sheet piles, tie back anchors and horizontal struts result into decreased wall displacement hence reduced lateral soil deformations. Accordingly, in Case-06, horizontal struts are provided in the middle of long direction at an interval of 5 m and tieback anchors are provided in short directions and also adjacent to the corners in the longer directions. The analysis results reveal that Case-06 is found to be the most effective supporting arrangement for deep excavation, as it showed minimum wall deflection, soil deformation, bending moment in sheet pile wall and stress anchor close to applied prestress. Moreover, the working space is also not compromised in proposed soil retention system.

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