

# A Parametric Study of Braced Excavation Considering the Effect of Adjacent Structures and Foundations Types

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**Abstract** – In recent times, braced excavation is predominantly utilized for construction of underground facilities in all soil types owing to its simple construction technique, cost-effectivity and minimization of the excavation area. The stability of a braced excavation and nearby ground surface is influenced by the soil behaviour, the properties of the retaining and supporting structures, and the construction sequence. A number of research works have been carried out in the past and are still ongoing to evaluate the effect of excavation component properties on braced excavation but very few of them emphasized on the effect of nearby structures and type of foundation on braced excavation. The current study explores a numerical model of braced excavation under a 20 storied building having a double basement to obtain optimum design parameters for the braced excavation after investigating the influence of nearby structures and type of foundation on braced excavation by varying length and thickness of diaphragm wall and strut stiffness. The numerical modeling is done using Finite Element integrated PLAXIS 2D software. This parametric study aims to provide practical approach/guidelines to designing excavations by analyzing and comparing calculated data by monitoring general trends and comparative study of the obtained data. Moreover, the results obtained from this study is compared with a similar case study to validate the model. In this study, the impact of the adjacent structure and the type of foundation is obvious. In general, the pile foundation resists wall displacement better in response to both the presence and absence of surrounding structures. But findings from this study shows that Piled-raft or Mat foundation with 10m Diaphragm wall length and 0.39m thickness with strut stiffness of  $10 \times 10^5$  kN/m<sup>2</sup> is the most optimized design for braced excavation in terms of cost-effectivity and practical implementation.

**Keywords:** Braced Excavation, Lateral Displacement, Hardening Soil Model, Plaxis 2D, Diaphragm wall, Strut Stiffness, Foundation

## 1. Introduction

The development and advancement of infrastructures in a densely populated and congested city like Dhaka are highly dependent on effective utilization of underground space. It is believed that the demand for significant underground excavation will increase steadily with the increase of population. Hence, an appropriate plan strategy is in demand for deep, secure and temperate excavation. In recent times, braced excavation where stability is obtained by laterally supporting the straight vertical faces by a sheeting and bracing system until the structure is built, is predominantly utilized for underground facilities construction in all soil types due to its moderately simple construction technique, cost-effectivity, minimization of the excavation area and ensuring soil movement in such a way that it will not cause any harm or damage to adjacent structures. However, many cases of braced excavation collapse owing to design or execution flaws have been documented [1], [2].

The study of braced excavation is complicated and sophisticated, requiring a holistic approach to addressing the braced excavation design problem. According to Bose and Som [3] the design of braced excavation in soft soil is based on two distinct, yet interrelated requirements: (1) Adequate support system required for achieving excavation stability & (2) Control of ground movements without adversely affecting the adjoining structures. As stated by the study of Bose and Som [3] and that of Chowdhury et al. [4], the stability of a braced excavation and adjacent area fundamentally relies on the number of struts and its properties, their vertical and horizontal spacings, strut pre-stressing, different combination of strut arrangement, properties of the retaining wall, penetration depth of retaining wall below embedment depth, foundation of nearby structures, excavation width, groundwater table etc. Hence it is necessary to consider the impact of the mentioned factors on retaining

wall and ground movement of braced excavation to determine the optimum results in terms of strut force, wall deflection and adjacent ground surface settlement.

Several research works have been carried out in the past and are still ongoing to evaluate the effect of excavation component properties on braced excavation [3]–[5]. Numerical analysis, physical models of small and medium scale, and performance data from instrumented large-scale deep excavation projects have been used to assess the effect of braced excavation [5]–[7]. However, numerical modeling is an effective approach to study the performance of braced excavations and have been used by several researchers to assess various aspects of braced excavations. [8]. Finno et al. [9] evaluated the relative effects of commonly-made assumptions such as constitutive modeling, over-excavation, and retaining wall construction sequences on deformation behavior of braced excavations with coupled finite element formulations and discovered that these assumptions could approximate the retaining wall displacement but showed divergence in case of ground movements. Bose and Som [3] through finite element approach stated that the performance of a braced cut in clayey soil is impacted by the excavation width, strut prestressing force, and wall lengths. Y. P. Dong et al. [10] through extensive case studies, assessed the ability of sophisticated finite element analysis to reproduce the reported field performance of deep excavations. Xu et al. [11] determined the characteristics of braced excavation under asymmetrical loads to minimize the discrepancies between the results obtained from field instrumentation and calculated results. Li et al., [12] applied numerical analysis to the stability and safety analysis of braced excavation for subway station during construction, taking into account the influence of side slope. Thi et al. [13] directed an investigation of braced excavation using steel sheet pile wall in Thi Vai soft clay in Vietnam concentrating on stress-strain displacement behavior with field monitoring of lateral wall displacement and surrounding area settlement. R. Zhang et al. [14] concluded that the ratio of maximum ground surface settlement to maximum lateral wall displacement is between 0.4 and 2.0, by analyzing 300 case histories of wall displacements and ground settlements caused by deep excavations in Shanghai soft soil. Furthermore, it was discovered that when system stiffness increases, wall displacement reduces. For calculating the maximum wall deflection, a simple Polynomial Regression (PR) model was devised by W. Zhang et al. [15]. Ali Mangnejo et al. [16] investigated the influence of a neighboring excavation-induced stress release on single pile integrity in soft clay.

However, little study has been done on the impact of adjacent structures and the type of foundation utilized in braced excavation. Hence in our study, a numerical model of a braced excavation under a 20 storied building having double basement has been considered to obtain optimum design parameters of braced excavation after investigating the influence of nearby structures and type of foundation on braced excavation by varying length and thickness of diaphragm wall and strut stiffness through Finite Element Analysis based software PLAXIS 2D.

## 2. Methodology

The research work was carried out in two stages. In first stage, soil parameters were obtained through field study and laboratory tests and in second stage modelling of braced excavation was done using data from the first phase by PLAXIS 2D software. Using data from Mohd Saim & Kasa (2018), a validation has also been performed [17].

The soil data is obtained primarily from the sub-soil investigation report of a project in Purbachal area. After performing field investigations, SPT tests were conducted as described in ASTM D 1586 (ASTM, 1989) at selected sites using the wash boring technique. Disturbed and undisturbed samples were collected while recording SPT N-value at an interval of 1.5 m depth up to 45 m. The index properties and strength properties of soil were determined by laboratory tests conducted according to ASTM 100 standards. Sub-soil condition of the study area was evaluated using Index and strength properties.

### 2.1. Stratified Soil Modelling

As per site investigation report, the soil profile is separated into three sub-layers based on differences in soil characteristics, physical and mechanical properties. The subsurface consists of a 10m layer of stiff silty clay followed by a 5 m and 30 m thick layer of medium dense fine sand and very dense silty fine sand respectively. Hardening Soil Model has been used in this study for modeling the nonlinearity of the soil due to its accurate calculation of soil stiffness by using three different stiffnesses (triaxial loading secant stiffness, triaxial unloading/reloading stiffness and oedometer loading tangent stiffness). The stiffness parameters were derived from the results of the triaxial test and consolidation test.  $K_{0nc}$ ,  $v_{ur}$  and  $R_f$  values were derived as per PLAXIS recommendation using Jacky's formula. The presence of groundwater table was found at 40 meters below the ground surface. Hence dewatering was not required due to the low groundwater table. The values of

Poisson's ratio of the soil layers were assumed as 0.3 in order to simulate its undrained condition. The roughness between the wall and soil interaction is defined by setting the strength reduction factor in the interface ( $R_{inter}$ ) to 0.7. The values of the soil parameters used in modelling is presented in Table 1.

Table 1: Soil parameters for Hardening Soil Model

Parameters	Unit	Stiff Silty Clay	Medium Dense Fine Sand	Very Dense Silty Fine Sand
Unsaturated Unit weight, $\gamma_{unsat}$	(kN/m <sup>3</sup> )	18	16	17
Saturated Unit weight, $\gamma_{sat}$	(kN/m <sup>3</sup> )	20	18	20
Secant Modulus of Elasticity, $E_{50}$	(kN/m <sup>2</sup> )	35000	43000	35000
Oedometer Modulus of Elasticity, $E_{oed}$	(kN/m <sup>2</sup> )	33000	22000	35000
Unloading/ Reloading Modulus of Elasticity, $E_{ur}$	(kN/m <sup>2</sup> )	105000	129000	105000
Cohesion, $c'$	(kN/m <sup>2</sup> )	31	0	0
Angle of Friction, $\phi$	Degree	14	31	33
Angle of Dilatancy, $\psi$	Degree	0	1	3

## 2.2. Construction Simulation

The Limit Equilibrium Method (LEM) was previously adopted to assess the efficiency of excavation; nevertheless, the LEM analysis is unable to anticipate the wall displacement. Hence, a numerical study employing the Finite Element Method (FEM) incorporated in the Plaxis 2D software computer program was used in this study. The finite element model, according to Y. Dong and Church [18], addresses both geotechnical and structural features like (i) detailed geometry of the excavation and retaining structures, (ii) realistic soil, structure, and soil-structure interface material models; and (iii) accurate construction sequences. Moreover, numerical analysis gives more precise and economic design compared to the conventional ones. Since braced excavation is a plane-strain problem hence in PLAXIS 2D software, the analysis is done using plane-strain condition and 15 noded triangular elements.

The numerical simulation is done for an excavation having length and width of 6 m and 10 m respectively. The initial stage starts with the activation of nearby structure load and installation of diaphragm wall which acts as retaining wall on both sides of the excavation under  $K_0$  condition to achieve static equilibrium. Slip or joint elements have been considered in the soil-wall interface to simulate full interaction between the plate and surrounding soil. The subsequent stages are modeled till excavation reached the desired level by removing soil mass and installation of the support members. Figure 1 shows the excavation was completed in three stages while installing two longitudinal struts. The simulation is finally completed with the activation of the foundation and building load.

The wall and the support members are modeled as plate elements and anchor elements respectively. Based on the numerical study as proposed by Chowdhury et al. [19] it is found that the most efficient excavation design in a clayey soil can be achieved when the wall embedment depth, thickness, and strut stiffness are all kept within the range of (80–100) % of the excavation depth, (6–7) % of the excavation depth and (5–25)  $\times 10^5$  kN/m/m, respectively. Hence for this study, the embedment depth and thickness of the diaphragm wall varies by (3-6) meters and (36-41) cm respectively. The load of the 20 storied building having double basement above the excavation is 288 kPa which is supported by the foundation. Three varying foundation type has been considered for this study which are Pile foundation, Mat foundation, Piled-raft foundation. A 10 storied building has been considered as nearby structure existing at a distance of 5 meters from the excavation whose load is taken as 144 kPa. The construction of diaphragm wall prior to excavation was assumed to have negligible impact on the in-situ stresses of soil. Figure 1 illustrates the cross-section of the braced excavation of the study area. Once the geometry model is specified adequately and material properties are assigned to all clusters and structural objects, mesh generation is done to inspect deformation occurrence by adjusting mesh coarseness to Fine mesh.

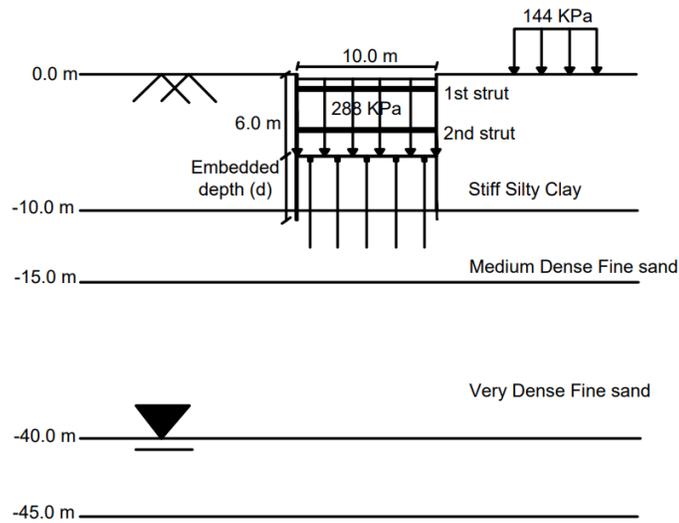


Figure 1: Cross-section of the braced excavation of the study area

### 3. Results and Discussions

#### 3.1 Validation

The developed numerical model is validated by comparing the results of the model with the observed value reported by [17]. The depth and width of the retaining wall taken from the model [17] is 6m and 2.4m respectively. The unsaturated unit weight, Young's Modulus and cohesion of the soil considered for validation is  $17 \text{ kN/m}^3$ ,  $80,000 \text{ kN/m}^2$  and  $2 \text{ kN/m}^2$  respectively. The soil property was analysed using Mohr–Coulomb model under drained condition. The geometry consists of a cantilever wall modelled as plate element where Young's modulus,  $E = 20 \text{ Mpa}$ , bending stiffness,  $EI = 2.083 \times 10^5 \text{ kN/m}^2/\text{m}$  and axial stiffness,  $EA = 1 \times 10^7 \text{ kN/m}$ , thickness,  $d = 0.5 \text{ m}$ . Figure 2 represents maximum total wall displacement from the present study. Table 2 shows 9.02% variation in the value of maximum total wall displacement between present study and observed study which is less than 10% and hence falls within allowable range. The model is thus validated.

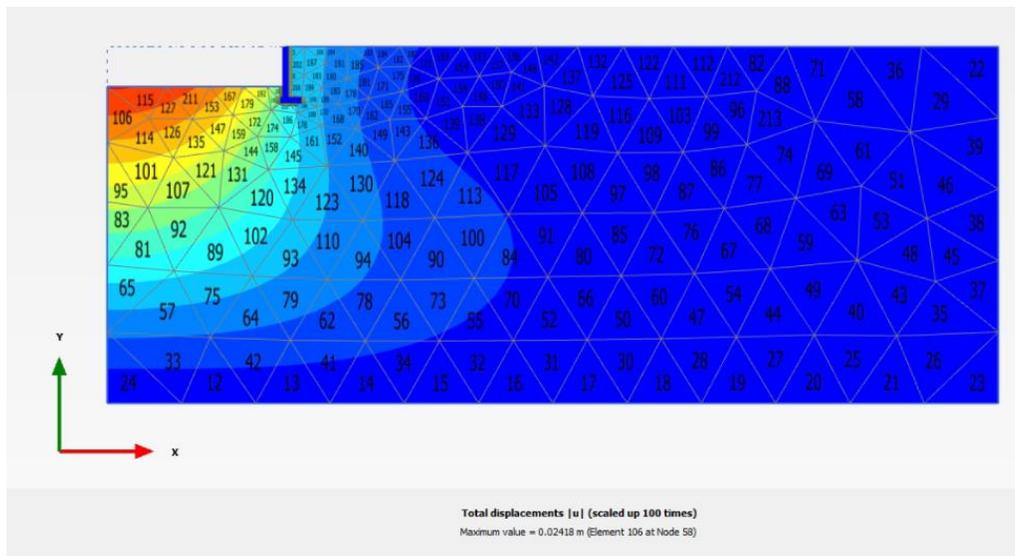


Figure 2: Maximum total wall displacement

Table 2: Data comparison for validation

Case	Present study	Observed study	Variation
Maximum Total Wall Displacement	0.024	0.022	9.02%

### 3.2 Parametric Study

The performance of a braced excavation is related to both stability and deformation. In this study, the ratio of wall depth and excavation depth has been provided according to different studies to ensure safety against wall instability and excessive base heave. In this study, the factors of concern in the performance of braced excavation at hand were restricted to wall deflection after the retaining structure was strengthened. Depth vs Lateral wall displacement graphs are generated considering the variations of the thickness and embedment depth of retaining wall and strut stiffness. The right side of the retaining wall has been considered due to its proximity to the nearby structures. Moreover, the positive value of horizontal displacement indicates that the wall may be pushed into the soil retained and the negative value of horizontal displacement represent the wall may tilt away from the soil retained for this particular study.

#### 3.2.1. Variation in strut stiffness

A strut is an inclined structural component which functions by transferring the earth pressure coming from the surrounding soil to the diaphragm walls. The fluctuation of the lateral displacement of the wall has been investigated in this work by considering struts of varied stiffness. From Figure 3, it is observed that, the more the stiffness of the strut, the more the resisting capability of the strut to minimize the lateral displacement of the retaining wall although it does not differ much. Among the three foundations that were considered for this study, it is observed that Pile foundations show better resistance against lateral wall displacement whereas Mat foundations show the least resistance against lateral wall displacement. Pile foundation with strut stiffness of  $10 \times 10^5$  kN/m<sup>2</sup> results the diaphragm wall to displace by 47.2 mm whereas Matt and Piled-Raft foundation with same strut stiffness causes a wall displacement of 49 mm. Since Pile foundation is costly in terms of construction hence Matt or Piled-raft foundation with strut stiffness of  $10 \times 10^5$  kN/m<sup>2</sup> is the most optimized one. In general, the maximum displacement of the diaphragm wall for mat foundation, Pile foundation and Piled Raft foundations is 0.894%, 0.866% and 0.890% of excavation depth respectively.

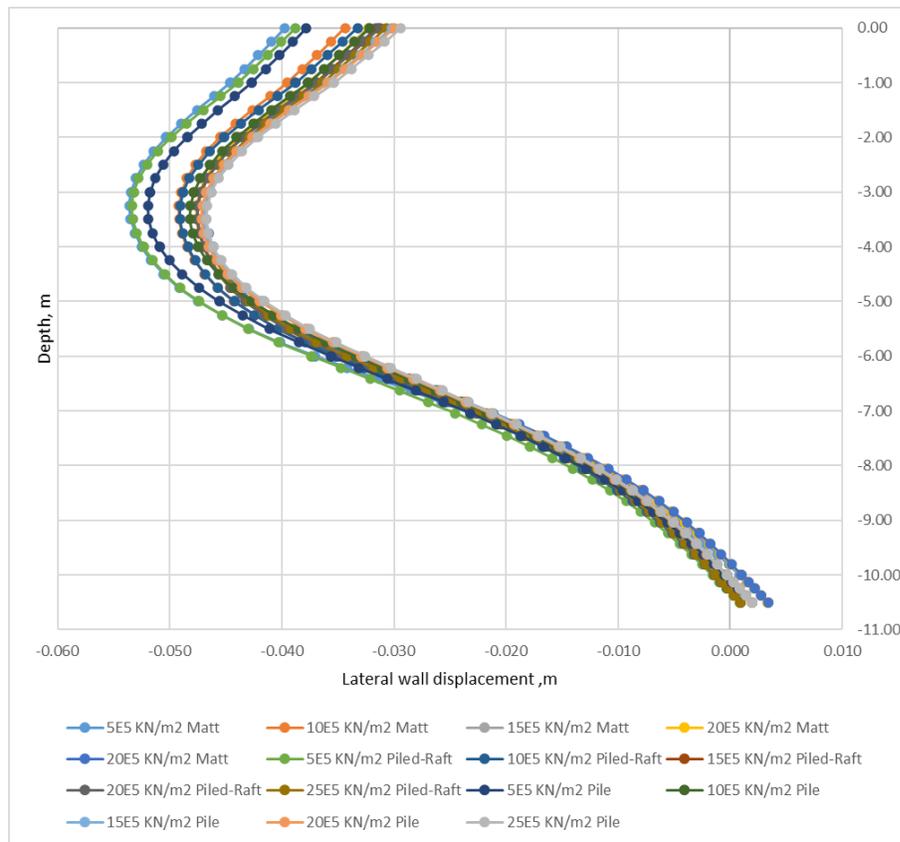


Figure 3: Depth vs Lateral wall displacement considering strut stiffness

## .2.2 Variation in Diaphragm wall length and thickness

Figure 4 represents Lateral wall displacement for Mat, Piled-raft and Pile foundation by varying the length of Diaphragm wall from (9-12) m. with 1m interval. From Figure 4, it is seen that deformation decreases when the length of the diaphragm wall increases from 9m to 12m. Overall, Pile foundation has the lowest displacement whereas Piled-Raft has the highest displacement. But observation from Figure 4 shows that Piled-Raft and Pile foundation having 10m diaphragm wall length results in wall displacement of 52.4 mm and 51.8 mm respectively. But considering cost effectivity, Piled-raft foundation is more efficient in this case than pile foundation.

Figure 5 represents Lateral wall displacement for Mat, Piled-raft and Pile foundation by varying the thickness of Diaphragm wall from (36-41) cm. with 1 cm interval. In general, the maximum displacement of diaphragm wall for mat foundation, Pile foundation and Piled Raft foundations is 0.89%, 0.881% and 0.889% of excavation depth respectively. From Figure 5, it is seen that deformation decreases when the thickness of the diaphragm wall increases from 36 cm to 41 cm although the displacement of the wall is within the allowable range. The overall diaphragm wall displacement varies a lot up to 7m depth but after 7 m, the displacement is nearly the same. If foundation type is taken into account, it is observed that the Pile foundation has the lowest displacement. Although at first Mat foundation with wall thickness of 0.36m has highest displacement but midway it converges with Piled-raft foundation of 0.37m wall thickness and is displaced by 53.4 mm which is maximum value considering these 18 cases. Similarly, Mat and Piled Raft foundation of 0.39m wall thickness also converges midway and is displaced by 51 mm thus making it the most optimized one.

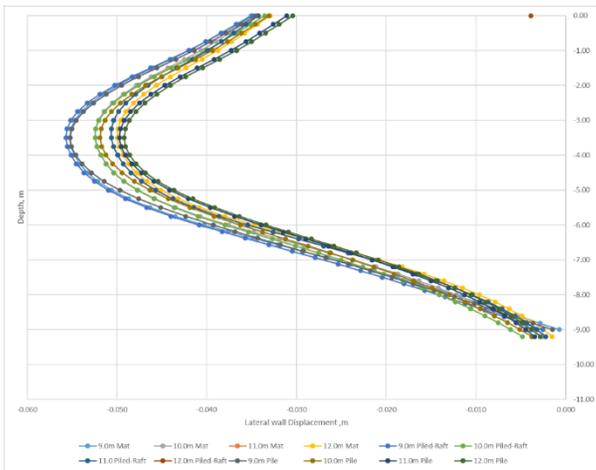


Figure 4: Depth vs Lateral wall displacement considering varying diaphragm wall length

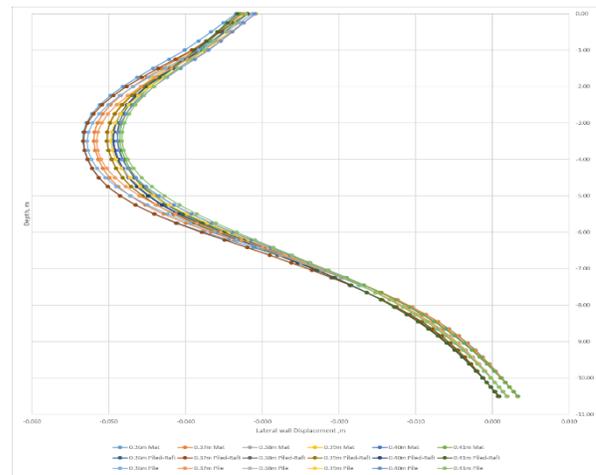


Figure 5: Depth vs Lateral wall displacement considering varying diaphragm wall thickness

### 3.2.3. Effect of adjacent structures

Table 3 shows a comparative study of wall displacement in different cases with or without the presence of adjacent structure. There is a structure adjacent to the excavation area on the right side of the wall, but there was none on the left side.

Table 3: Comparison of the displacement of both right side and left side wall for different cases

Wall thickness (cm)	Right-side wall			Left-side wall			Strut stiffness $\times 10^5$ kN/m <sup>2</sup>	Right-side wall			Left-side wall		
	Lateral wall displacement			Lateral wall displacement				Lateral wall displacement			Lateral wall displacement		
	Mat	Piled-raft	Pile	Mat	Piled-raft	Pile		Mat	Piled-raft	Pile	Mat	Piled-raft	Pile
36.00	51.1	51.2	50.6	4.5	4.4	1.8	5	53.6	53.4	51.9	4.6	4.6	1.8
37.00	53.4	53.3	52.8	4.4	4.3	1.7	10	49.2	49.0	48.2	4.1	4.1	1.4
38.00	51.9	53.3	51.6	4.3	4.2	1.6	15	47.5	47.5	46.9	3.9	3.8	1.3
39.00	50.3	50.3	49.7	4.2	4.1	1.5	20	47.6	47.5	47.1	3.9	3.8	1.4
40.00	49.4	49.5	48.9	4.2	4.1	1.5	25	46.8	47.0	46.6	3.8	3.8	1.3
41.00	48.6	48.9	48.3	4.1	3.9	1.4							

## 4. Conclusion

The following conclusions can be drawn based on the findings of the parametric studies:

- Displacement reduces with the increase of wall length and thickness and strut stiffness, but the changes aren't substantial.
- Although the designer has some flexibility in selecting a preferred wall length and thickness and strut stiffness due to non-substantial change of wall displacement but from this study it can be concluded that Piled-Raft or Matt foundation with 10m Diaphragm wall length and 0.39m thickness with strut stiffness of  $10 \times 10^5$  kN/m<sup>2</sup> is the most optimized design for braced excavation in terms of cost-effectivity and practical implementation.
- When there are adjacent structures near the excavation region, the lateral wall displacements increase significantly. During the design process, designers should consider the impact of nearby structures.

Further study can be conducted in the future considering the effect of several factors of braced excavation such as varying number of struts and their vertical and horizontal spacings, strut preloading force, excavation width, change of groundwater table etc. on wall displacement as well as ground settlement.

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