Analysis of Design Parameters Affecting Deformation Behaviour of a Braced Excavation in Soft Clay: Numerical Study

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Abstract - *Adequate prediction of ground movement during braced excavation is critically important as excessive soil displacement damage adjacent properties. Various factors like diaphragm wall thickness, wall embedment depth, strut locations influence the magnitudes and patterns of ground movement and wall deflection. In present paper an analysis of design parameters affecting deformation characteristics of braced excavation has been performed using finite element analysis. The importance of correct estimation of soil parameters for braced excavation design is also documented. The finite element analysis of typical braced excavations is implemented in soft clayey deposits using the software package Plaxis 2D, employing the soft soil creep constitutive model. On the basis of parametric investigation a design guideline is recommended which may be handy for design engineers..*

Key Words: Finite element analysis, ground movement, soft soil creep model, excavation, wall deflection.

1.INTRODUCTION

In the recent years, rapid infrastructure development and scarcity of space for new constructions in urban India have resulted in constructions such as underground commuter (metro) railway, tall buildings with multiple basement floors, tunnels, and similar other structures that require excavations to significant depths. These excavations require vertical sides with bracings (instead of sloped sides) for lack of space, and continuously braced wall structures are often used to ensure the stability of the excavations and to reduce the detrimental construction effects on the neighboring structures and underground utilities. Vertical cuts with bracings, if not properly designed, may lead to excessive ground movement and wall deflections, which may cause distress to neighboring structures. Therefore, ground movement and wall displacements should be estimated carefully and accurately while designing the braced excavation systems.

Early studies on braced excavations were based on field observations, and those studies focused on excavation-base instability caused by bottom heave, lateral movement of support systems, ground settlement adjacent to excavations, effects of soil type and excavation geometry on the performance of the excavation system, and earth pressure on braced walls (Terzaghi 1943, Bjerrum and Eide 1956, Peck 1969, Lambe 1970, Goldberg et al. 1976). Lambe (1970) concluded that the state of the art for design and analysis of braced excavations was far from satisfactory, and suggested the use of finite element method in conjunction with field studies as the way forward for gaining proper understanding of deep excavation performance. Palmer et al (1972) evaluated influences of different variables on braced excavations where interaction and behaviour of soil and supporting materials were taken into consideration. From their observation it was found that soil deformation modulus, wall stiffness and strut stiffness have influence most on the behaviour of excavation. Other parameters like soil shear strength, initial in-situ stress, soil to wall adhesion have lesser impact. O'Rourke (1981) pointed out the importance of site preparation in ground excavation work and related the lateral movement of excavations to ground settlements, based on field observations. Clough and O'Rourke (1990) categorized movements in a braced cut into two types: movement related to excavation and support process, and movement related to auxiliary construction activities. Finno and Harahap (1991) simulated the construction of a 40-ft-deep braced excavation in saturated clays in Chicago by using a coupled finite element (FE) analysis. Tefera et al. (2006) studied the ground settlement and wall deformation of a sheet pile wall during different stages of excavation using a large-scale model test in dry sand bed and compared the results with those of FE analysis. Finno et al. (2007) used the FE software PLAXIS for conducting a parametric study to show the effects of excavation geometry on the deformation behaviour of soil around braced excavations. They observed that when the ratio of the excavated length to excavated depth of a wall is greater than 6, plane strain simulations yield the same displacements in the centre of the wall as those obtained from three-dimensional FE analysis. Hsiung (2009) investigated the deformation characteristics of several excavations in Kaohsiung, Taiwan, and found that the maximum lateral wall displacement (δ_{hm}) is approximately 0.03-0.3% of maximum excavation depth and that the ratio of maximum surface settlement (δ_{vm}) to maximum wall displacement (δ_{hm}) varies over 0.5-0.7 for the excavations constructed by bottom-up method and over 1.3-1.8 for the excavations using a semi-top-down method. Hsiung (2009) observed that the subsidence of the ground surface behind the diaphragm wall extended to a distance of up to three times the maximum excavation depth. Whittle et al. (1993) performed coupled FE analysis, combining flow and deformation, of a top-down construction for a seven-story, underground parking garage in Boston. De Lyra Nogueira et al. (2009) also conducted coupled FE analysis on braced excavations with different constitutive models and different excavation rates and showed that the choice of the constitutive model affects the magnitude and distribution of excess pore pressure. Hashash and Whittle (2002) presented a detailed interpretation of the evolution of stresses around a braced excavation in a deep layer of soft clay considering anisotropic stress-strain-strength relationships, small strain nonlinearity, and hysteretic response upon load reversal. Babu et al. (2011) used the finite difference software FLAC to perform a two-dimensional (2D) analysis of a vibration isolated system using open trenches. Nogueira et al. (2011) performed FE analysis of an instrumented, unsupported excavation constructed in a soft clay deposit using a non-associated elastoplastic constitutive model. Chowdhury et al. (2013) performed numerical analysis of a braced excavation and studied the impact of various design parameters on the excavation behaviour. These apart, empirical and semi-empirical methods have been used for estimating the ground surface settlement induced by braced excavations (Bowles 1988; Ou et al. 1993; Hsieh and Ou 1998). Dang et al (2014) proposed simplified method to measure effect of parameter uncertainty in analysis of braced excavation. First order approximation method was used to quantify variations of wall and soil responses due to uncertainty in input parameters. Xiang et al (2018) developed a regression model accounting excavation geometrical parameters, soil parameters, strut stiffness and other related parameters. Influence of various design variables were studied on wall deflections. Dong et al (2020) optimized critical parameters (like pile diameter, embedment ratio etc) of supported retaining piles in granular soils using finite element method. Equations were presented to calculate maximum vertical displacement of surrounding soil and horizontal displacement of pile. Though deformation behaviours of braced excavations were studied depending upon variations of excavation parameters in literatures, still limited works have been done on systematic parametric analysis of braced excavation presenting design guidelines to achieve optimized deformation values.

In present study, a systematic investigation of the deformation characteristics of braced excavations in soft clayey soil of Kolkata is performed using two-dimensional (2D) finite element (FE) analysis and the accuracy of analysis is verified against the results obtained from observed ground deformations reported by Som et al (2000). The numerical analysis is performed for parametric study to investigate influence of different excavation parameters on ground deformation behaviour causing from braced excavation as proper assessment of influence of factors like wall embedment depth, strut location, wall thickness on stability of braced excavation can limit excessive deformation. Further soil properties are varied to study the effect of sensitivity of the soil properties on the response of the braced wall. A design guideline is presented from parametric investigation which may help engineers to get optimum ground deformations.

2. NUMERICAL ANALYSIS

FE analysis using creep model is being performed on excavation in Kolkata soil for a specific metro construction site in Central Kolkata (Som et al. (2000)) and validated using results reported in literature.

The Kolkata metro excavation was performed using the cut and cover method, and vertical excavations were stabilized with the help of diaphragm walls and horizontal struts. Typically, the following construction sequence was followed: (1) construction of diaphragm walls, (2) excavation of soil between the diaphragm walls to a desired depth, and (3) installation of struts to support the diaphragm wall. Steps 2 and 3 are sequentially repeated until the final depth of excavation is reached. In order to connect the study to real field conditions, a particular metro railway construction site in central Kolkata (Som et al. (2000)) is selected where a braced excavation was constructed. The soil profile at the site is shown in Table 1.

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Table -1: Typical Kolkata soil profile

Soil layers	Depth from ground surface(m)	Unsaturated unit weight, γ(kN/m^3)	Saturated unit weight, γ_{sat} (kN/m^3)	Undrained shear strength, c_u (kN/m^2)	Initial void ratio, e_0	Poisson's ratio, ν_s	Coefficient of earth pressure at rest, K_0
L1 - Light brown/ brownish grey silty clay/ clayey silt	0-3	19	21	40	0.55	0.3	0.79
L2 - Grey/dark grey silty clay/ Clayey silt with semi-decomposed timber pieces	3-14	20	20	25	0.65	0.3	0.74
L3 - Bluish grey silty clay with calcareous modules	14-20	20	20	60	0.8	0.3	0.83
L4 -Yellowish brown clayey silt with sand	20-30	21	21	45	0.5	0.3	0.43

The constructed excavation was 30 m wide and 14 m deep. Diaphragm walls 17 m deep and 0.6 m thick were used to retain the earth. The wall was supported by horizontal struts placed at a horizontal interval of 4.25 m. The detail of the excavation is shown in Figure 1. First the diaphragm walls were installed, and then excavation was carried out to a depth of 3 m followed by the placement of first row of struts at a depth of 2 m. Subsequently, the second stage of excavation was done to a depth of 8 m, and the second layer of strut was placed at a depth of 4.5 m from the ground surface. Thereafter, excavations were performed in multiple stages, as described in Figure 1, along with the placement of the third (bottom) layer of struts at a depth of 10.6 m from the ground surface. The final depth of excavation reached was 14 m below the ground surface. The diaphragm wall is assumed to behave as a precast-concrete, elastic plate with normal stiffness $E_wA_w = 2.0 \times 10^7$kN, flexural rigidity $E_wI_w = 6.14 \times 10^5$ kNm^2/m (E_w = Young's modulus of wall, A_w = cross sectional area of wall, and I_w = second moment of inertia of the wall section), and Poisson's ratio 0.15. The struts are assumed to be compression elements with stiffness $E_{st}A_{st} = 3.36 \times 10^6$ KN (E_{st} = Young's modulus of strut, and A_{st}= cross sectional area of strut), and the average spacing between consecutive struts s_{st} = 4.25 m.

The braced excavation described in the preceding paragraphs is used as the reference braced excavation and the ensuing parametric study is performed by varying the different dimensions of this reference excavation. In the parametric study, the soil profile and properties are maintained the same for most of the simulations as that of the reference excavation (except for one set of study in which the properties were varied to study the effect of sensitivity of the soil properties on the response of the braced wall) as these represent the typical Kolkata soil profile with typical properties.

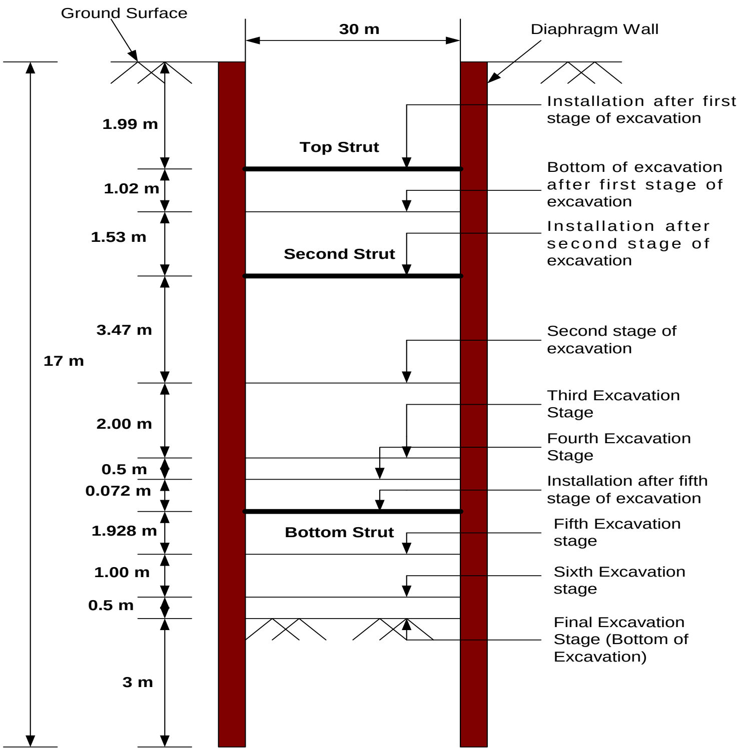


Fig -1: Construction sequence and a cross section of a typical braced excavation at a site in central Kolkata

The soft soil creep model (SSCM) available in Plaxis 2D is used in the FE analysis. The input parameters of SSCM are described in Table 2 and the values of these parameters are obtained partly from Table 1 and partly from Dan and Sahu (2018).

Table-2: Input parameters for soft soil creep model (SSCM) in Plaxis 2D

Input parameter	Description	Parameter values			
		L1	L2	L3	L4
λ^*	Modified compression index	0.080	0.142	0.064	0.060
κ^*	Modified swelling index	0.016	0.028	0.013	0.012
μ^*	Modified creep index	5.30×10^{-3}	9.53×10^{-3}	4.26×10^{-3}	4×10^{-3}
ν_{ur}	Poisson's ratio for unloading-reloading	0.2	0.18	0.18	0.15
K_0	Horizontal to vertical stress ratio at rest	0.792	0.741	0.826	0.426
c_u	Undrained shear strength (KN/m^2)	40	25	60	45

2.1 Finite Element Analysis

Plane strain FE analysis of the braced excavation is performed using Plaxis 2D (Brinkgreve RBJ, Vermeer PA (2002)) in which one-half of the physical domain is used for the analysis considering the vertical symmetry in the problem and in shown in figure 2.

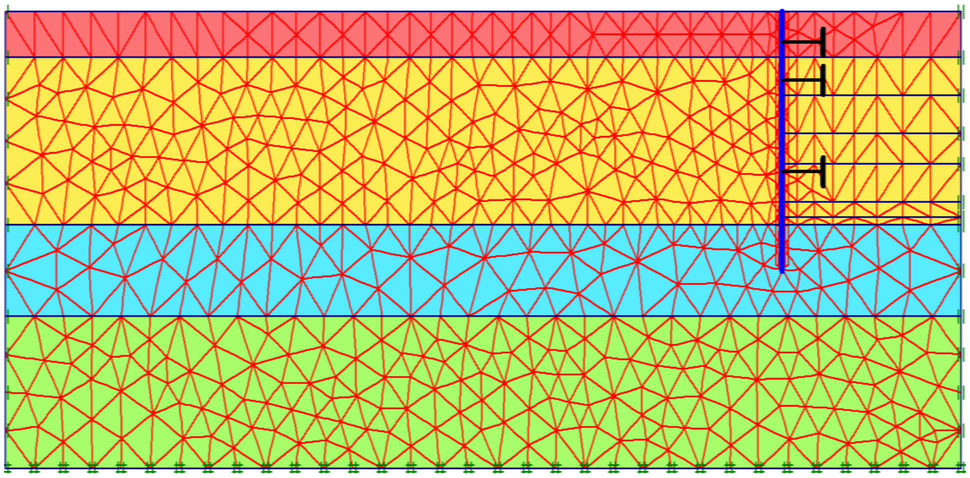


Fig -2: Finite Element Model of a typical braced excavation at a site in central Kolkata

The horizontal distance to the left vertical boundary is maintained at 65 m from the face of the diaphragm wall. The vertical distance to the bottom horizontal boundary from the base of the diaphragm wall is maintained at 13 m. These distances to the FE domain boundaries are chosen by trial and error to ensure that the boundary effects are absent. Fifteen-noded triangular elements are used and a typical FE mesh consists of 1144 elements with 9485 nodes (mesh size is varied through a convergence study to obtain the final mesh topology ensuring that the results are independent of mesh). The ground water table is maintained at 2.5 m below the ground surface. Drainage is allowed at the ground surface along the top horizontal boundary of the FE domain and at the bottom of the mesh along the bottom horizontal boundary of the FE domain because there is a presence of sandy layer beneath the bottom soil layer considered in the FE domain (the excess pore pressure at the nodes along the drainage boundaries are set to zero). The vertical boundaries on the two sides are assumed to be sealed with no flow across these boundaries. The staged construction sequence of braced excavations is simulated in the FE analysis although the effects of stress change and disturbance on the soil properties caused by the construction (which are expected to be minimal as no driving or jacked penetration is generally involved in braced wall construction) are not considered in the analysis (i.e., in situ soil properties are used as inputs).

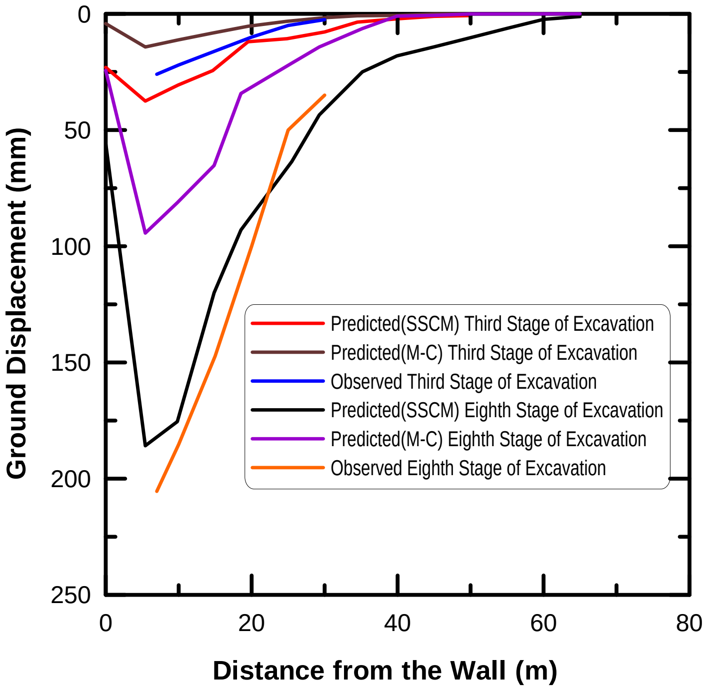


Fig -3: Predicted and observed ground settlement for a braced excavation at a metro railway construction site in central Kolkata

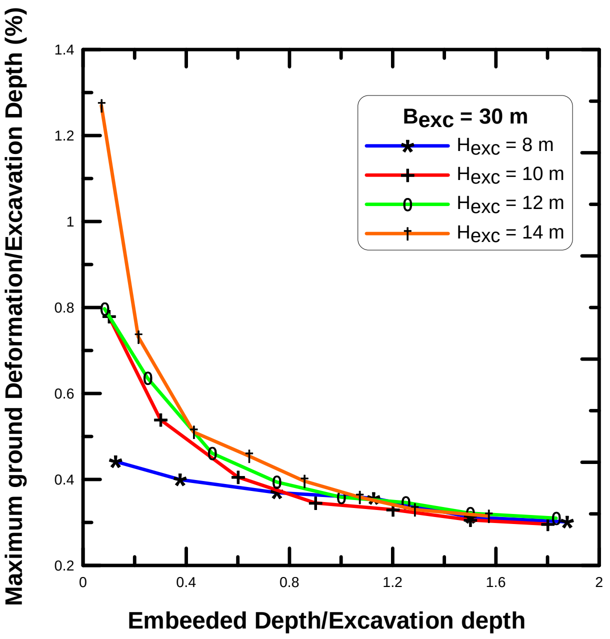
The results obtained from FE analysis are compared with observed values to establish appropriateness of present FE model. The predicted settlements of the adjacent ground for the third and eighth stages of excavation, along with the actual observed settlement (Som 2000) are shown in Figure 3, and the match is reasonably good. Also plotted in the figure are the FE simulations performed using the Mohr-Coulomb (M-C) constitutive model. It is quite clear that the Mohr-Coulomb model cannot capture the field behaviour and the soft soil creep model (SSCM) used in this study is more appropriate.

3. PARAMETRIC STUDY

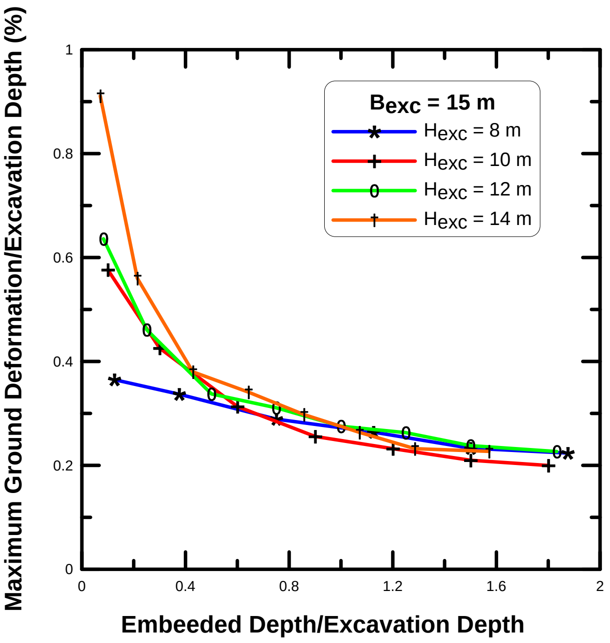
Parametric study has been conducted to investigate influence of design parameters on ground and wall deformation. Four excavation depths, 8 m, 10 m, 12 m and 14 m are considered for analysis. For excavation depths 8 m and 10 m two levels of struts are assumed to be placed at 2 m and 6 m below the ground surface. When excavation depth is beyond 10 m (for excavation depth 12 m and 14 m) three levels of struts are considered which are located at 2 m, 6 m and 9 m (for excavation depth 12 m) and at 2 m, 6 m and 11 m (for excavation depth 14 m). Three excavation widths, 15 m, 30 m and 45 m are taken in present study. For different excavation depths and widths, wall embedment depth, location of struts and diaphragm wall thickness are varied to study their impact on soil surface displacement and wall deformation. The soil profile and properties are maintained the same as that of the reference excavation used for validation of FE model. It is further assumed that the excavation is done at a standard rate of 10 days/m (0.1 m/day) and the time taken for installation of struts is 7 days.

3.1 Effect of wall embedment depth

In present analysis maximum ground displacement ($\delta_{g,max}$) and maximum wall displacement ($\delta_{w,max}$) are normalized with respect to the excavation depth (H_{exc}) and expressed in percentage. Wall embedded depth (D) is expressed normalizing it with respect to excavation depth (H_{exc}) and excavation width (B_{exc}). The effect of normalized wall embedment depth (D) on deformation behaviour during excavation is investigated. The variations of normalized maximum ground displacement and maximum wall displacement with non-dimensional parameter 'D/ H_{exc}' are presented in Figures 4 (4(a), 4(b), 4(c) and 4(d)). Similar figures are plotted between normalized maximum ground and wall deformation and parameter 'D/ B_{exc}' and these are shown in Figures 5 (5(a), 5(b), 5(c) and 5(d)).



(a)



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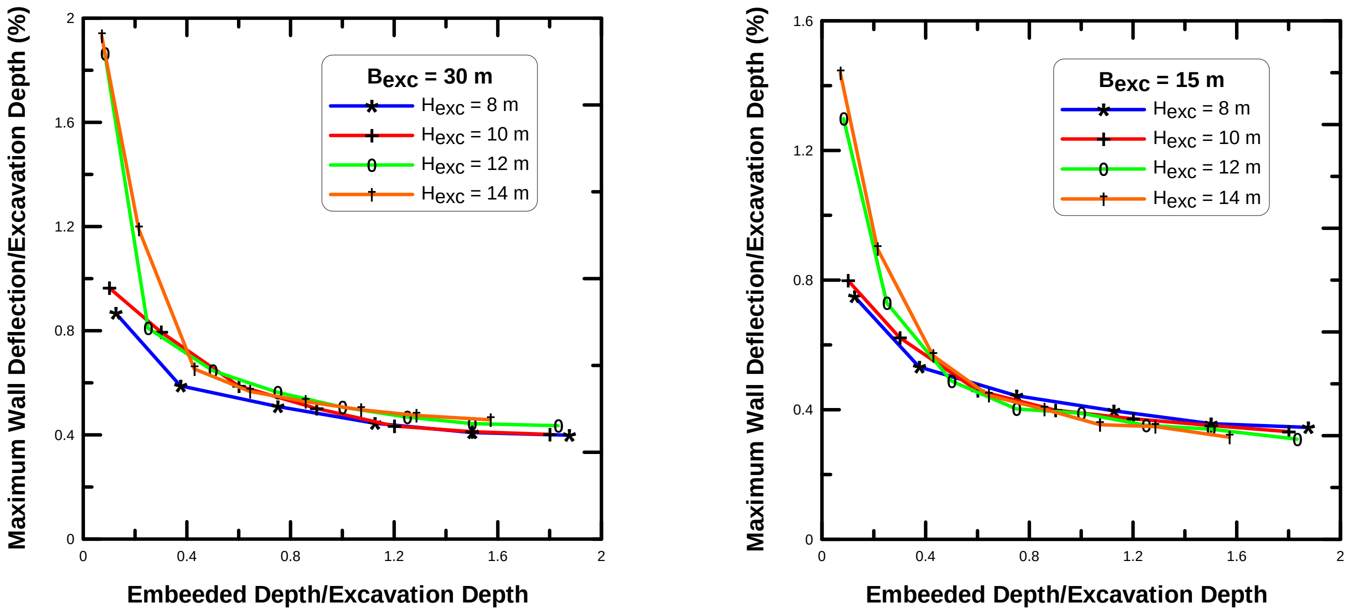
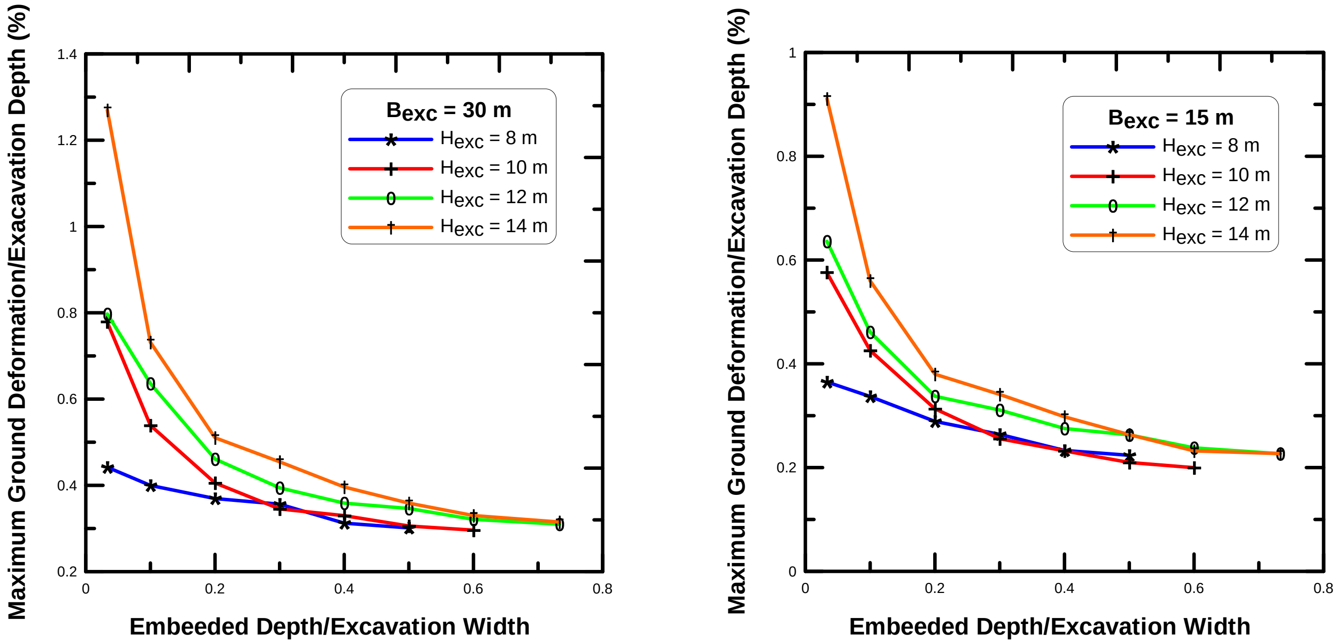
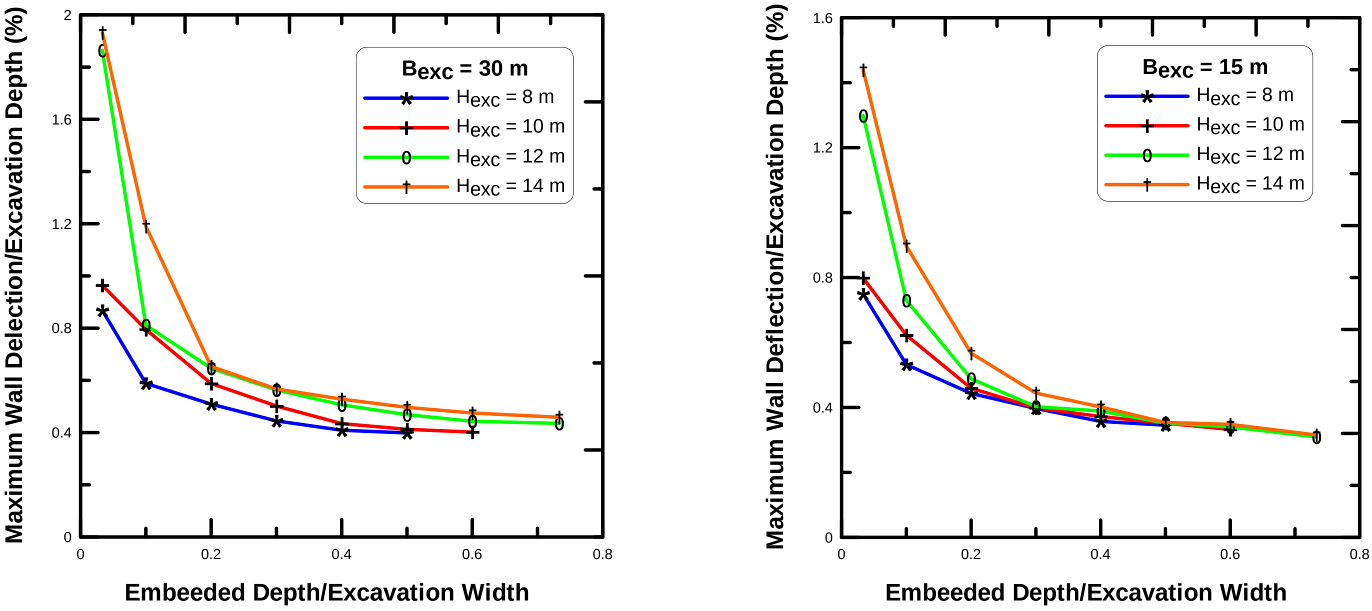


(c) (d)

Fig -4: Effect of embedment depth on the ground deformation with respect to excavation depth (a) for width of excavation 30 m, (b) for width of excavation 15 m. Effect of embedment depth on the wall displacement with respect to excavation depth (c) for width of excavation 30 m, (d) for width of excavation 15 m.



(a) (b)



(c) (d)

Fig -5: Effect of embedment depth on the ground deformation with respect to excavation width for (a) width of excavation 30 m, (b) width of excavation 15 m. Effect of embedment depth on the wall displacement with respect to excavation depth for (c) width of excavation 30 m, (d) width of excavation 15 m.

From figures 4(a) and 4(b) it is clearly seen that with increase of 'D/ H_{exc}' , normalized maximum ground displacement decreases and then after D/ H_{exc} equal to 1.0 displacement values remains almost constant. For higher excavation depth maximum variation (between largest and smallest normalized ground deformation at different normalized embedment depth) of normalized maximum ground displacement is quite large. When excavation depth is 14 m these variations are nearly 75% for both excavation width 30 m and 15 m. While for excavation depth 8 m variations are around 30%. So change in embedment depth significantly affects the maximum ground deformation especially for higher excavation depth. Figures 4(c) and 4(d) reveal similar kind of results. Here normalized maximum wall displacements attain minimum values at 'D/ H_{exc}' equal to 0.7 and then remain almost constant. For excavation depth 14 m maximum deviations of normalized wall displacements are almost 76.9% and 77.7% for excavation width 30 m and 15 m. When taken excavation depth at 8 m these deviations are 26.8% and 42.1% for excavation width 30 m and 15 m respectively . So it appears that wall displacement is very sensitive with respect to 'D/ H_{exc}' value and small increase of 'D/ H_{exc}' can reduce wall deformation considerably for 'D/ H_{exc}' value ranges from 0.125 to 0.6. From figures 5(a) and 5(b) it is observed that in all cases normalized maximum ground displacements decrease with increase of 'D/ B_{exc}' up to 'D/ B_{exc}' equal to 0.3 to 0.4 but then rate of decrement is very gradual. Figures 5(c) and 5(d) depict that normalized maximum wall displacements reach minimum values at 'D/ B_{exc}' equal to 0.2 to 0.4 and thereafter no substantial variations are observed. So, from observations it can be said that for braced excavation in soft to medium clay if embedded depth of the wall is kept between 0.7 to 1.0 of excavation depth and 0.2 to 0.4 of excavation width then ground and wall deformation will be in control and damage due to deformation will be minimum. In soft to medium clay maximum wall displacement occurs at or near the excavation depth level or depth of wall fixity. When excavation is done in stiff soil maximum wall displacement takes place at well above excavation level. So, in this case required wall embedment depth for deformation control will be less.

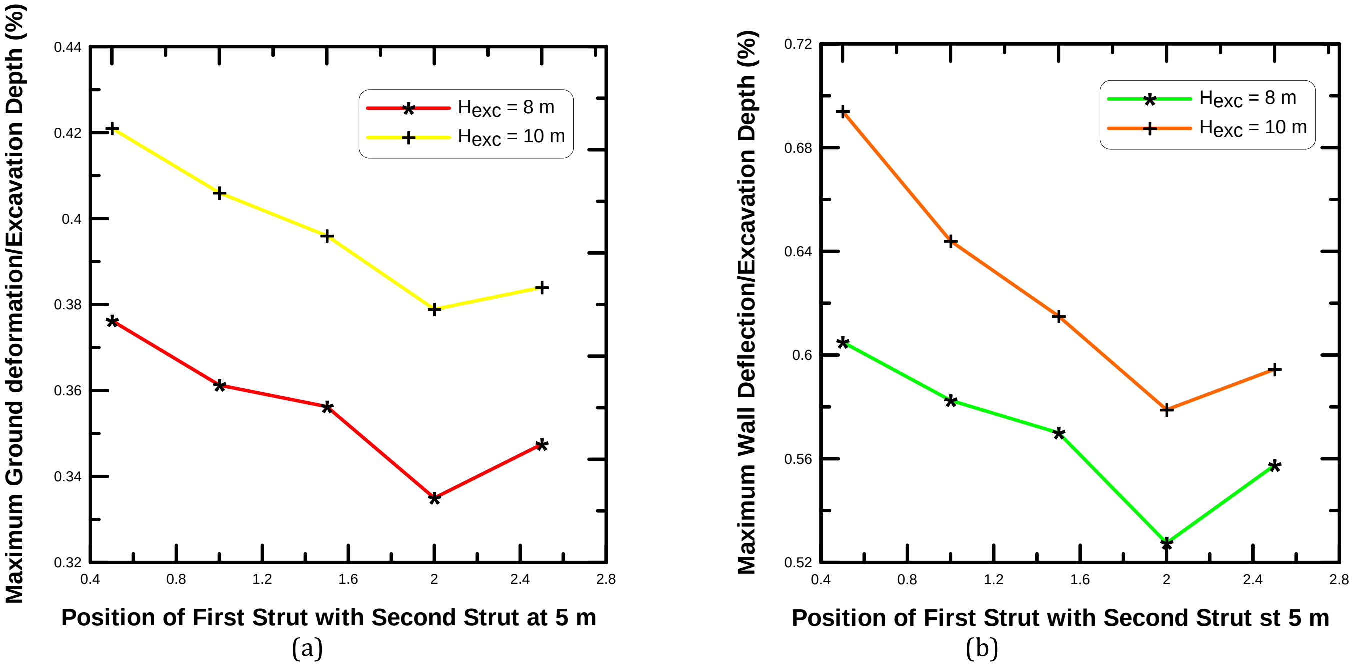
3.2 Effect of strut location

Here effects of different strut locations on normalized maximum ground and wall deformations are investigated. Excavation width and wall thickness are kept at 30 m and 0.6 m respectively. Normalized wall embedment depth (D/ H_{exc}) is set at 1.0 as from previous study it is found that optimum deformation behaviour is achieved at 'D/ H_{exc}' equal to 1.0 for excavation in soft to medium clay. First set of strut arrangements used in present study are tabulated in Table 3(a).

Table-3a: First set of strut arrangements

Cases	Types	Depth of excavation	Strut 1 level	Strut 2 level	Strut 3 level
1	1a	8 m	0.5 m	5 m	-
	1b		1 m	5 m	-
	1c		1.5 m	5 m	-
	1d		2 m	5 m	-
	1e		2.5 m	5 m	-
2	2a	10 m	0.5 m	5 m	-
	2b		1 m	5 m	-
	2c		1.5 m	5 m	-
	2d		2 m	5 m	-
	2e		2.5 m	5 m	-

At first, study has been carried out for excavation depth 8 m and 10 m where two levels of struts are assumed to be placed. For case 1 excavation depth is taken as 8 m with 2nd strut level is fixed at 5 m and 1st strut position is varied. Similarly for case 2 same kind of strut arrangements are considered with excavation depth taken as 10 m. For these two cases variation of normalized maximum ground deformation and normalized maximum wall deflection with change of strut positions are plotted and shown in Figures 6(a) and 6(b) respectively.

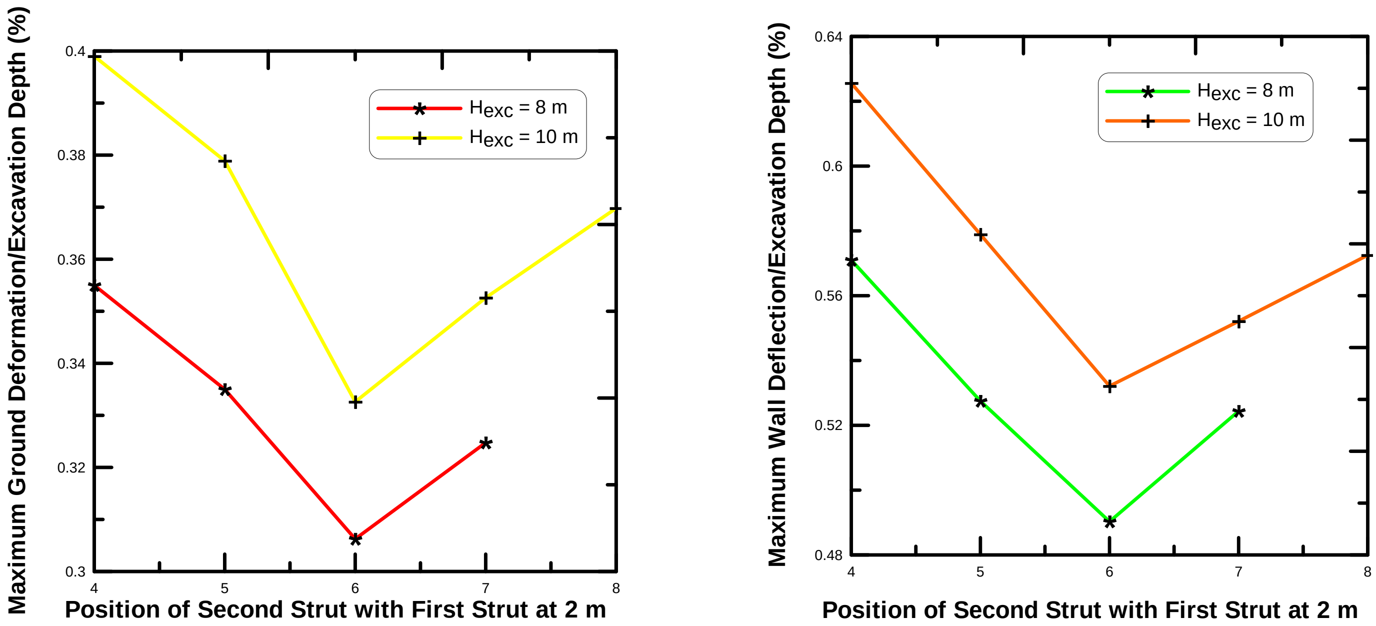


(a) (b)

Fig -6: Effect of first strut location with second strut position fixed at 5 m on (a) maximum ground deformation, (b) maximum wall displacement.

From figures 6, minimum normalized deformation values are obtained when 1st strut is placed at 2 m level which means if 1st strut is placed at 0.2-0.25 times the depth of excavation optimum values can be obtained.

Second set of strut arrangements are presented in Table 3(b). In these cases (case 3 and case 4) 1st strut is fixed at 2 m level and 2nd strut location is varied to study the effect on deformation characteristic.



(a) (b)

Fig -7: Effect of second strut location with first strut position fixed at 2 m on (a) maximum ground deformation, (b) maximum wall displacement.

Figures 7 (7(a) and 7(b)) show that normalized maximum ground and wall displacement is decreased as location of 2nd strut is lowering from 4 m to 6 m. Further lowering of 2nd strut causes increment of normalized maximum ground and wall displacement. This is because if 2nd strut is close to 1st strut or very distant from 1st strut unsupported length is increased resulting greater deformation.

Table-3b: Second set of strut arrangements

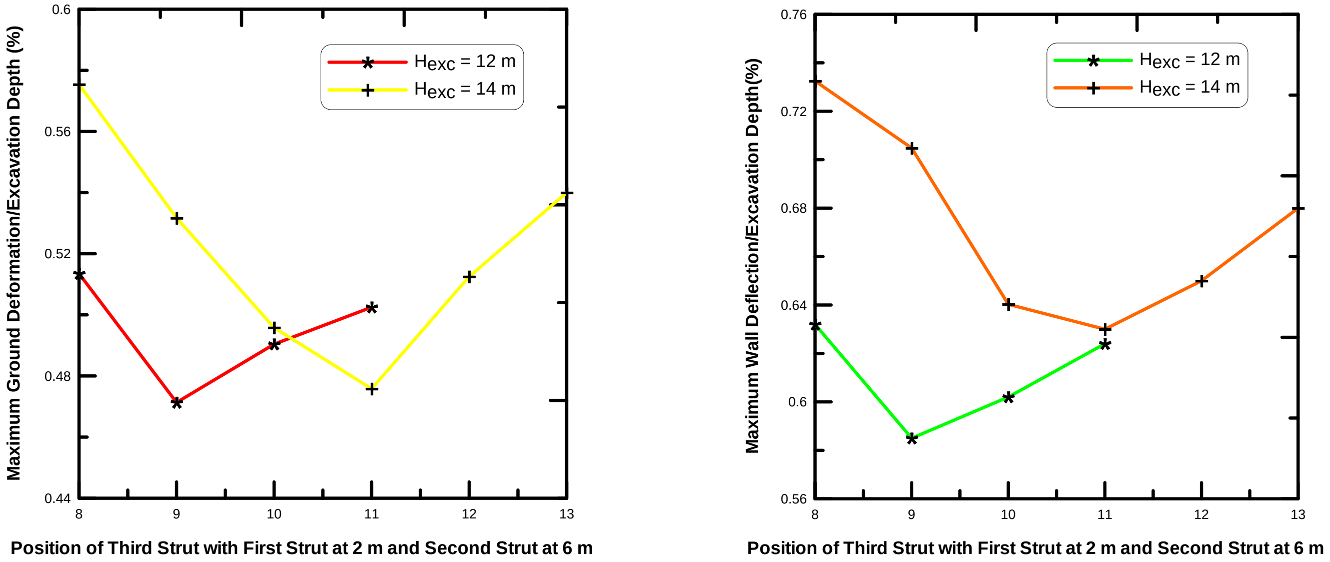
Cases	Types	Depth of excavation	Strut 1 level	Strut 2 level	Strut 3 level
3	3a	8 m	2 m	4 m	-
	3b		2 m	5 m	-
	3c		2 m	6 m	-
	3d		2 m	7 m	-
4	4a	10 m	2 m	4 m	-
	4b		2 m	5 m	-
	4c		2 m	6 m	-
	4d		2 m	7 m	-
	4e		2 m	8 m	-

So it is suggested that level of 2nd strut is to be fixed at 0.6-0.7 times the depth of excavation so that minimum deformation can be obtained. This is when two level of strut is installed to stable excavation.

Next greater excavation depth is taken into account and three level of strut is installed. Strut arrangements are shown in Table 3(c). 1st and 2nd strut are placed at 2 m and 6 m. The location of third strut is changed at different positions like at 8 m, 9 m, 10 m, 11 m when excavation depth is 12 m (case 5) and at 8 m, 9 m, 10 m, 11 m, 12 m, 13 m (case 6). Variations of normalized maximum ground deformation and normalized maximum wall deflection with position of third strut are presented in figures 8(a) and 8(b) respectively.

Table-3c: Third set of strut arrangements

Cases	Types	Depth of excavation	Strut 1 level	Strut 2 level	Strut 3 level
5	5a	12 m	2 m	6 m	8 m
	5b		2 m	6 m	9 m
	5c		2 m	6 m	10 m
	5d		2 m	6 m	11 m
6	6a	14 m	2 m	6 m	8 m
	6b		2 m	6 m	9 m
	6c		2 m	6 m	10 m
	6d		2 m	6 m	11 m
	6e		2 m	6 m	12 m
	6f		2 m	6 m	13 m



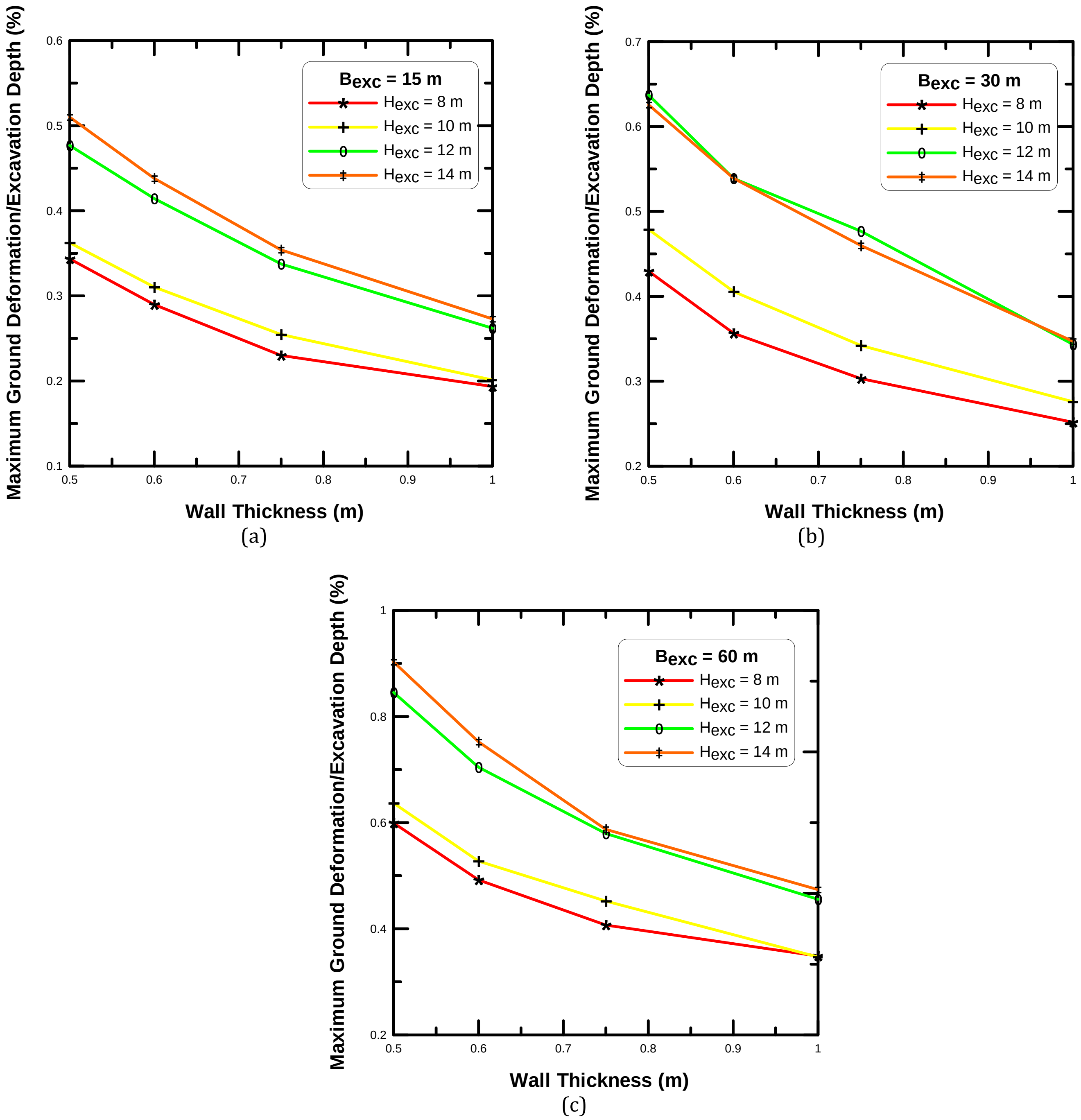
(a) (b)

Fig -8: Effect of third strut location with first strut and second strut position fixed at 2 m and 6 m respectively on (a) maximum ground deformation, (b) maximum wall displacement.

From figures 8 it can be seen that minimum normalized deformation values (both ground and wall deformation) are obtained when third strut is placed at 9 m in case of excavation depth 12 m and at 11 m when excavation depth is 14m. Thus if third strut is install at 0.75-0.80 times the depth of excavation then lower range of normalized maximum ground and wall deformations are achieved. So when exaction depth is more than 10 m then 1st, 2nd and 3rd levels of struts are to be placed at 0.14-0.17, 0.42-0.5 and 0.75-0.80 times of excavation to obtain optimum deformation values. If excavation depth is less or equal to 10 m two levels of struts may be used which are required to be placed at 0.2-0.25, 0.6-0.7 times the depth of excavation to get minimum deformation values.

3.3 Effect of wall thickness

It is attempted to study the effect of diaphragm wall thickness (T_{wall}) on normalized maximum ground displacement ($\delta_{g,}$max/Hexc) and normalized maximum wall deflection ($\delta_{w,}$max/Hexc). Normalized wall embedment depth (D/ H_{exc}) is set at 1.0. For excavation depth 8 m and 10 m two stages of struts are considered (at 2 m and 6 m) and when excavation depth beyond 10 m three stages of struts (at 2 m, 6 m and 10 m for H_{exc} equal to 12 m and at 2 m, 6 m and 12 m for H_{exc} equal to 14 m) are taken. Four different values of wall thickness 0.5 m, 0.6 m, 0.75 m and 1.0 m are employed for present study and variations of 'δ_{vm}/H_{exc}' in percentage with wall thickness (T_{wall}) are plotted (Figs 9). With increase of wall thickness 'δ_{vm}/H_{exc} (%)' decreases steadily.

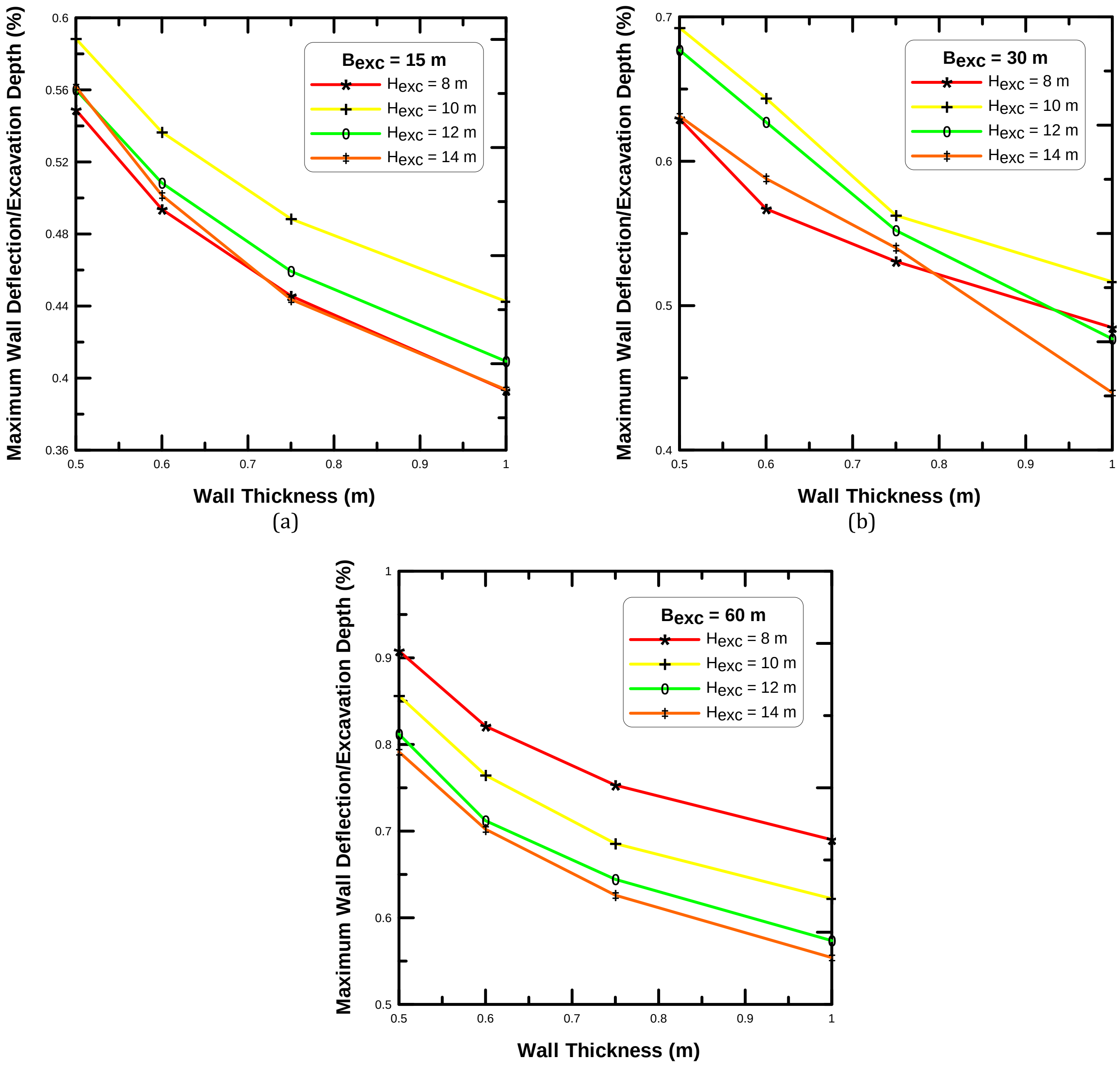


(a) (b)

(c)

Fig -9: Effect of wall thickness on the ground deformation for (a) width of excavation 15 m, (b) width of excavation 30 m, (c) width of excavation 60 m.

From figures 9(a), 9(b) and 9(c) the maximum variations of maximum normalized ground displacement are 45% - 47% for excavation depth of 14 m with various excavation width. In case of excavation depth of 8 m maximum variations are within 38 – 44%.



(a)

(b)

(c)

Fig -10: Effect of wall thickness on the wall displacement for (a) width of excavation 15 m, (b) width of excavation 30 m, (c) width of excavation 60 m.

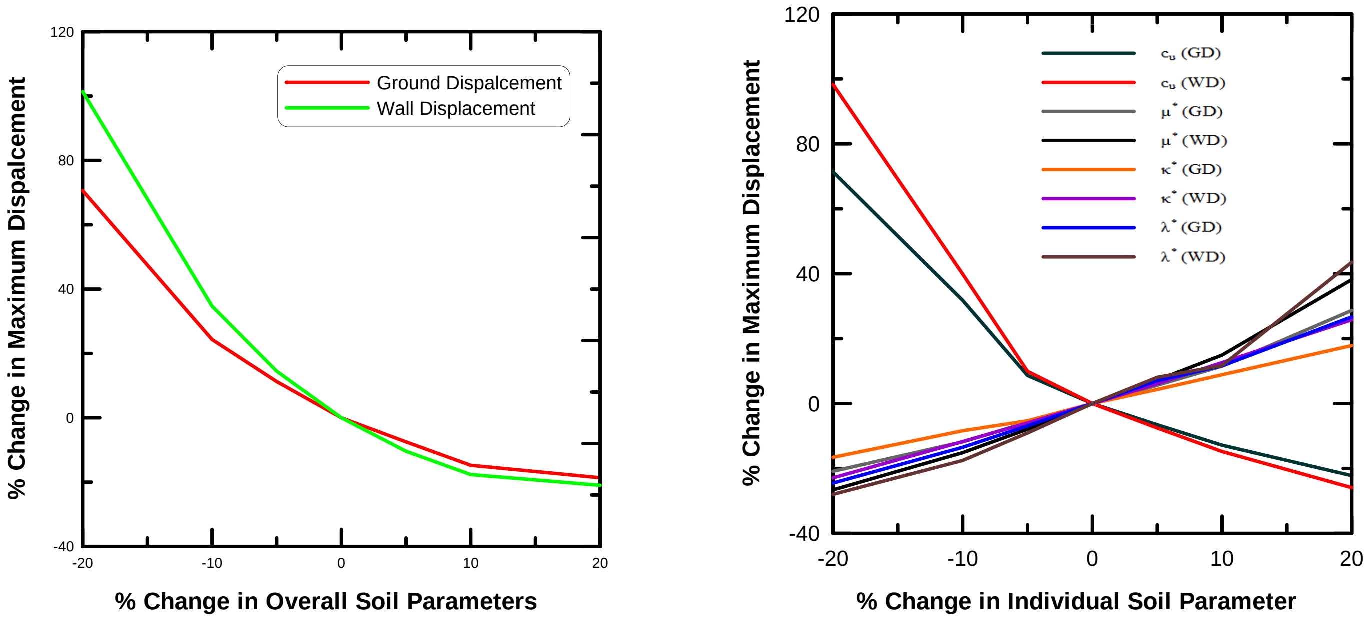
From figures 10 variations of normalized maximum wall displacement (δ_{hm}/H_{exc}) with different wall thickness are observed. Maximum changes of 'δ_{hm}/H_{exc}' due to increase of wall thickness are 29.8 – 30.3% for excavation depth 14 m and excavation width of 15 m, 30 m and 60 m. While for excavation depth 10 m and various excavation width as mentioned the maximum variations of 'δ_{hm}/H_{exc}' are in between 24.7 – 27.3%. From results it is evident that significant change of ground and wall deformations observed when wall thickness is increased. Though no clear optimum value of wall thickness can be obtained from results, still rate of decrement of deformation decreased with increase of wall thickness. It is suggested that wall thickness may be kept between 0.8 m to 1 m for excavation depth beyond 10 m (i.e. 12 or 14 m) which implies that wall thickness of 0.06 to 0.08 times of excavation depth can be provided. If excavation is within 10 m then wall thickness may be restricted to 0.75 m as after 0.75 m, rate of reduction of normalized ground deformation is gradual.

3.4 Sensitivity of Soil Parameters

The accuracy of ground and wall deformation prediction depends upon proper modelling of soil behaviour in FE analysis. It is difficult to model soil behaviour correctly as behaviour of soil behind the wall is difficult to characterize and special apparatus is required to measure soil parameters at low strain level. In present analysis impact on soil deformation during braced excavation due to slight variations of soil parameters is observed.

At first the values of all the parameters are simultaneously increased and decreased by 5%, 10%, and 20%, and the impact of such changes on the braced wall system is studied. The study was performed for the braced wall described in Figure 1. Figure 11(a) shows that an increase in the values of all the parameters has an almost linear impact on the braced wall system — 20% increase leads to about 20% reduction in δ_{hm} (maximum horizontal deflection of wall) and δ_{vm} (maximum vertical ground surface settlement). However, a simultaneous decrease in the values of the soil parameters has an amplified impact on the braced wall — 20% decrease leads to about 100% increase in δ_{hm} and 70% increase in δ_{vm}. Obviously, these are artificially exaggerated values because simultaneous increase or decrease in all the parameters is a remote possibility. Nevertheless, the engineer must be mindful of the impacts of possible variability of soil properties, particularly if the braced wall is constructed in a soft patch within the Kolkata area.

The impact of soil variability is further investigated by altering, one at a time, the four most important soil parameters — c_u, λ^*, κ^*, and μ^* — by ±5%, ±10%, and ±20% for the same braced excavation. Figure 11(b) shows that δ_{hm} and δ_{vm} decrease with an increase in c_u, which appears to be the most sensitive parameter, and increase with increase in λ^*, κ^*, and μ^*. The sensitivities of λ^*, κ^* and μ^* on the braced wall system responses are more or less the same and are less than that of c_u.



(a) (b)

Fig -11: Effect of variability of soil parameters on the wall and ground displacements: (a) overall variation of soil parameters and (b) individual variation of soil parameters (GD = Ground Deformation, WD = Wall Deflection)

4. DESIGN GUIDELINES

The following design guidelines are proposed here.

1. The wall embedment depth should be kept between 0.7 to 1.0 times of excavation depth and 0.2 to 0.4 times of excavation width when construction of braced excavation is done in soft to medium clay soil. For excavation depth greater than 10 m these should be strictly followed to resist excessive ground movement.
2. When excavation is less than 10 m two level of struts can be installed but for greater excavation depth three or more struts should be fixed.
3. The position of first strut should be at 0.2-0.25 times the depth of excavation to get optimum deflection values. If first strut is placed below that specified level, cantilever height of wall is increased producing larger deformation. When strut is very close to ground level unsupported wall length increases.
4. The second strut should be placed in such a way that spacing between struts are not large. For excavation depth up to 10 m, 2nd strut may be installed at 0.6-0.7 times the depth of excavation.

5. When excavation depth is more than 10 m three levels of struts are needed to be installed. In this situation location of 1st, 2nd and 3rd levels of struts are as follows
   1st strut: at 0.14 to 0.17 times the depth of excavation
   2nd strut: at 0.42 to 0.5 times the depth of excavation
   3rd strut: at 0.75 to 0.80 times the depth of excavation
6. Though it is hard to obtain optimum wall thickness still it is recommended that wall thickness can be provided such that it is around 0.06 to 0.09 times of the depth of excavation. There is not much change of displacement values when wall thickness is approximately 0.08 times of depth of excavation.
7. Correct estimation of soil parameters is very critical as little variability can change estimated results largely using FE analysis. Special care should be taken to measure soil parameters using tri-axial apparatus at low strain (10^{-5} to 10^{-3}). Undrained shear strength of clay has greater influence than consolidation parameters on soil deformation during braced excavation.

5. CONCLUSIONS

In present study a parametric study has been done to investigate the influence of different design parameters on deformation behaviour. Based on the results design guidelines are proposed such that optimum values of various parameters like wall embedment depth, wall thickness and strut arrangements are determined. Wall embedment depth should be at least 0.7 to 1.0 times of depth of excavation to avoid excessive ground movement when excavation is done in soft clay. Strut arrangement should be such that unsupported wall length is not large. For depth of excavation more than 10 m three level strut system is recommended with struts are located at 0.14-0.17 H_{exc}, 0.42-0.5 H_{exc} and 0.75-0.80 H_{exc} respectively to achieve minimum displacement values. With greater wall thickness small deformation values are obtained. Wall thickness may be kept as 0.08 times of depth of excavation to get optimum result. Values of soil strength and consolidation parameters should be chosen or estimated carefully as little variation produce marked different deformation results using FE analysis.

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