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TECHNICAL NOTE

Estimation of Design Parameters for Braced Excavation in Clays

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Abstract In this study, the optimum values of the design parameters (position of struts, embedment depth of the wall, thickness of the wall and the strut stiffness) for braced excavation in clayey soil have been determined by using the numerical tool, FLAC. The design parameters are determined by studying their effects on the factors such as strut force, wall deflection, wall moment and displacement of the ground surface adjacent to the braced excavation which play significant role in the design of braced excavation. The results of the present numerical model are compared with the observed values obtained from a case study on braced excavation in a clayey soil. A close agreement between the result as obtained from the present numerical study and that measured in the field has been observed. On the basis of the parametric studies done on two different clayey soil profiles, it is found that the most effective design of excavation in a clayey soil can be done when the embedment depth of the wall, the thickness of the wall and the strut stiffness are kept within the range of (80–100)% of the depth of excavation (6–7)% of the depth of excavation and (5–25) $\times$ 10^5 kN/m/m, respectively. The top strut can be kept at a height of (2–3) m below the ground level without endangering the safety of the system.

Keywords Braced excavation · Cohesive soil · FLAC · Wall deflection · Ground displacement

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1 Introduction

The development of infrastructures such as underground transport systems, basements, water pipelines and other structures in an urban area involves deep excavation in a congested area. However, due to space constraint, these excavations are to be done vertically beneath the ground surface. In order to support the lateral sides of the excavation, the retaining walls are to be constructed and supported at different levels by using beams (struts). The wall deflects laterally and the vertical movement of the adjacent ground surface occurs with the progress of the excavation. The level of damage to the nearby structures is related to the settlement of the adjacent ground (Boscardin and Cording 1989). The other important design factors are bending moment developed in the wall and axial forces that occur in the struts.

Many numerical and experimental studies have been performed on the braced excavation in sandy as well as clayey soils (Ng and Lings 1995; Vaziri 1996; Ng et al. 1998; Nakai et al. 1999; Seok et al. 2001;

Karlsrud and Andresen 2005; Zdravkovic et al. 2005; Tefera et al. 2006; Costa et al. 2007; Chungsik and Dongyeob 2008; Kung et al. 2009). By using finite element method, parametric study of a braced cut in clayey soil have been done by Bose and Som (1998) and it was found that the performance of a braced cut is affected by the width of the excavation, strut prestressing force and the wall length. Kung (2009) compared 26 numbers of case histories of excavation-induced wall deflection using top-down (TDM) and bottom-up construction methods (BUM) in Taipei silty clay and found that the maximum lateral wall deflection induced by TDM were 28% higher than that induced by BUM. Wang et al. (2010) collected and analyzed 300 case histories of wall displacements and ground settlements due to deep excavations in Shanghai soft soil and found that the ratio of the maximum ground surface settlement and the maximum lateral displacement of a wall lie in between 0.4 and 2.0. Also, it was found that wall displacement decreases with increasing system stiffness. Lim et al. (2010) evaluated the performance of the most commonly used constitutive models (modified Cam clay model, hardening soil model, hardening soil small strain model, $\phi = 0$ Mohr–Coulomb model and the undrained soft clay model) of clay for the analysis of a deep excavation under undrained condition. It was found that for $\phi = 0$, Mohr–Coulomb model with $E_u/s_u = 500$ (E_u and s_u are the undrained elastic modulus and shear strength of the clay, respectively), can result in good prediction for the wall deflection at the final stage of an excavation, but none of the other models can predict the ground settlement profiles properly.

The stability of a braced excavation and nearby ground surface depends primarily on the properties of struts (number of strut, stiffness of a strut and their vertical and horizontal spacings) and properties of the retaining wall (stiffness and embedment depth of a wall). Thus, it is required to study the effect of the above factors on a wall and ground movement and a range of values of the parameters (i.e., the number of struts, their positions and stiffness, the thickness of the wall and its embedded depth) has to be proposed so that optimum results can be found in terms of force in the struts, moment developed in the wall, deflection of the wall and the displacement of the adjacent ground surface. Based on a numerical study, Chowdhury et al. (2013) proposed the range of design parameters for a braced excavation in cohesionless soils. However, the recommendation proposed by the Chowdhury et al. (2013) may not be valid for the cohesive soils. Thus, in the present study, a numerical model for the analysis of a braced excavation in clay under undrained condition has been used to propose the design parameters for the braced excavation in clay. After studying different combinations of strut arrangement, wall thickness, D_b/D_e (D_b is the embedment depth of the wall and D_e is the depth of excavation) and strut stiffness, the optimum design parameters have been found for a braced excavation in a clayey soil.

2 Numerical Modeling

One half of the problem geometry and the definitions of the symbols used in the present study are shown in Fig. 1. In Fig. 1, the design factors, namely, depth of excavation at final stage, embedment depth of the retaining wall at final stage and its thickness are denoted by D_e, D_b and t_{wall}, respectively. The width of the excavation is B and half width i.e. $B/2$ is shown in Fig. 1. The symbols for the design parameters i.e. maximum horizontal wall deflection, maximum bending moment developed in the wall and maximum vertical ground surface displacement are u, M and v, respectively.

The numerical modeling is done using the computer program FLAC (Fast Lagrangian Analysis of Continua), as a two-dimensional plane strain problem. The numerical simulation is done for all the construction stages which are involved in the construction of a braced excavation. The initial stage is the installation of a diaphragm wall in the ground and static equilibrium is achieved under K_0 condition i.e. at rest condition of stress. The subsequent stages are modeled by considering dewatering below the excavation level, removal of soils and installation of support members. The construction sequence involving lowering of ground water table within excavation zone (by making the pore water pressure zero within the zone to be excavated), excavation up to the desired level (by removing the soil elements i.e. simulating with null model within the zone to be excavated) and installation of support member (by connecting one node of the support member with centre line node and the other node with the wall node) are simulated in FLAC. As the problem deals with cohesive soil layers, undrained condition is applicable to the soil layers.

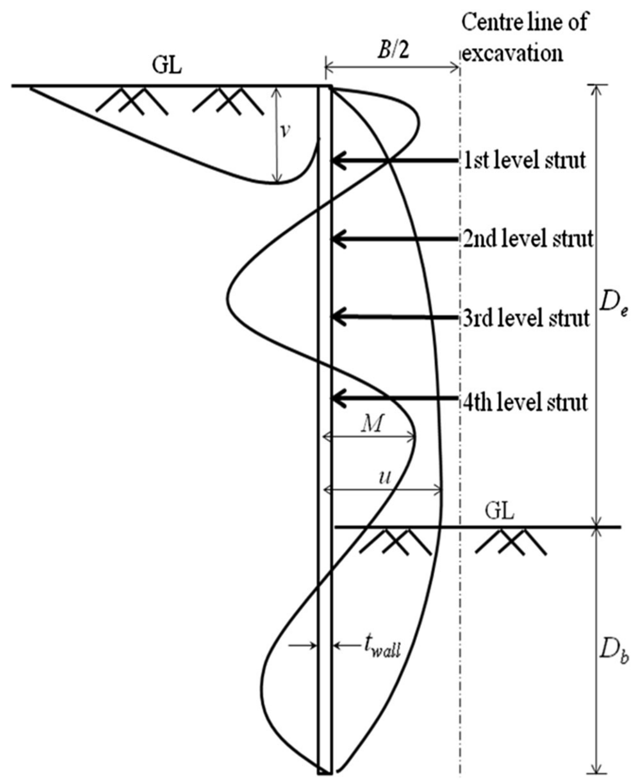

Fig. 1 Symbols for design parameters and design factors used in the present study

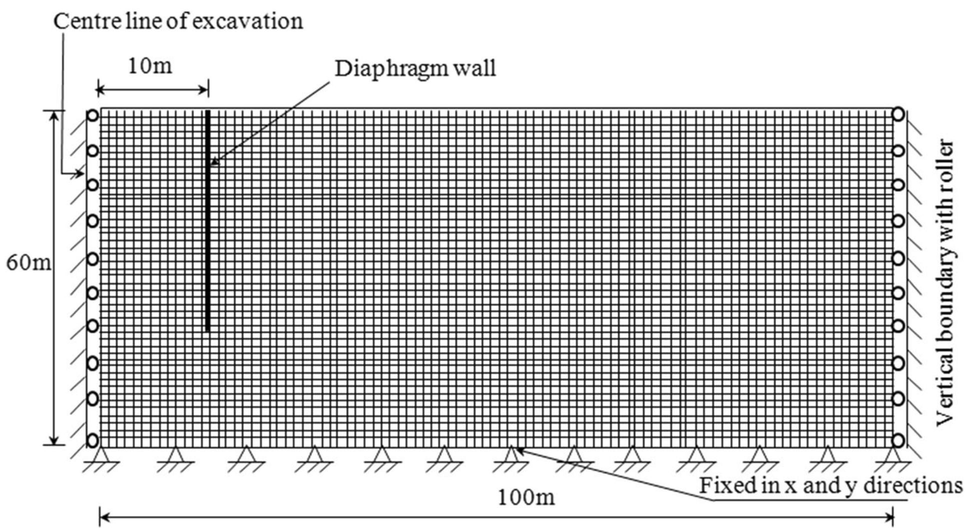

Fig. 2 Numerical model used in the parametric study

The undrained condition is simulated by considering the values of Poisson's ratio as 0.49 for the clay layers.

The numerical model used in the parametric analysis is shown in Fig. 2. As the problem is symmetric, thus, only one half of the whole problem is modeled.

Thus, one vertical boundary coincides with the line of symmetry of the excavation and the other one is located at a distance of 100 m from the edge of the wall. The nodes provided along the vertical boundaries are restrained against movement in the horizontal direction. However, the nodes provided along the bottom boundary are restrained against movement both in the vertical as well as in the horizontal direction. The water table is considered at the ground level. The model dimension is selected such that the boundaries are not affecting the model results. The selected model dimension is also satisfying the dimensions chosen by previously researchers for similar type of numerical modelling. The element size in the numerical model is taken as 1 m × 1 m which is found to be optimum, based on some trial runs with 0.5 m × 0.5 m and 2 m × 1 m element sizes.

A linearly elastic perfectly plastic Mohr–Coulomb model is used to describe the soil behavior. The coefficient of lateral earth pressure at rest is taken as 0.5 and the modulus of elasticity of the sand layer (if present) (E') is calculated as $(75 + 8\ N) \times 100$ kN/m^2 (Som and Das 2006), whereas, the undrained Young's modulus of the cohesive soil layers (E_u) is calculated as $500s_u$, where, N and s_u are the SPT value and the undrained shear strength value of the cohesionless and the cohesive layers, respectively. The bulk modulus (K) and the shear modulus (G) of the soil are calculated as

$$K = \frac{E}{3(1 - v)} \tag{1}$$

$$G = \frac{E}{2(1 + v)} \tag{2}$$

where ν is the Poisson's ratio of the soil, which may be equal to ν_u or ν' as the case may be.

The properties of the interface element located between the wall and the soil are the interface cohesion, friction angle, dilation angle, normal stiffness (K_n) and shear stiffness (K_s). The interface normal and shear stiffness are calculated as per FLAC manual (Itasca 2005) and given by

$$K_n = K_s = 10\frac{K + \frac{4}{3}G}{\Delta z_{\min}} \tag{3}$$

where K and G are the maximum values of the bulk and the shear modulus among all the layers encountered within the depth of the wall and $\Delta z_{\min}$ is the smallest width of the adjoining zone along the normal direction to the interface. Depending upon the depth of the wall and the types of the soil layers encountered within the depth of the wall, the values of the interface normal and shear stiffness are calculated accordingly. The interface cohesion and friction angle are taken as (2/3) of the values for the corresponding layer for which K_n and K_s are considered.

If the Young's modulus and the Poisson's ratio of the wall material are given by E_{wall} and μ_{wall} respectively, then the Young's modulus of the wall is given as $E_{wall}/(1 - \mu^2_{wall})$ to represent the plane strain condition. In FLAC software, the analysis is done under plane stress condition. However, braced excavation is a plane-strain problem and thus, Young's modulus of the continuous retaining wall is converted into plane strain condition by modifying E_{wall} to $E_{wall}/(1 - \mu^2_{wall})$ as per FLAC manual (Itasca 2005). The wall and the support members are modeled as beam elements. The two nodes on both ends of the support member are coincident with the two nodes located at the vertical boundary (along the center line of the excavation) and at the wall node. The node located at the centre line of the excavation is restraint from movement along the horizontal direction, i.e. it can only slide vertically along the centre line of the excavation. The other node connected at the wall is pin jointed i.e. it can rotate without any restraint.

3 Results and Discussions

3.1 Validation

To validate the developed numerical model, the results of the model are compared with the observed (based on field study) values as reported by Ou et al. (1998). The problem geometry taken from Ou et al. (1998) consists of support members (struts), diaphragm wall (900 mm thick and 35 m overall depth) and final depth of excavation of 19.7 m. The soil profile (with their properties) and excavation levels in the construction sequence considered for validation is shown in Fig. 3. The construction sequence is as per Ou et al. (1998). Figures 4 and 5 show the lateral deflection of the wall and the ground surface displacement as obtained from the field data (Ou et al. 1998) and from the present study, respectively. It may be seen from Fig. 4 that the profile of the lateral wall deflection as obtained from

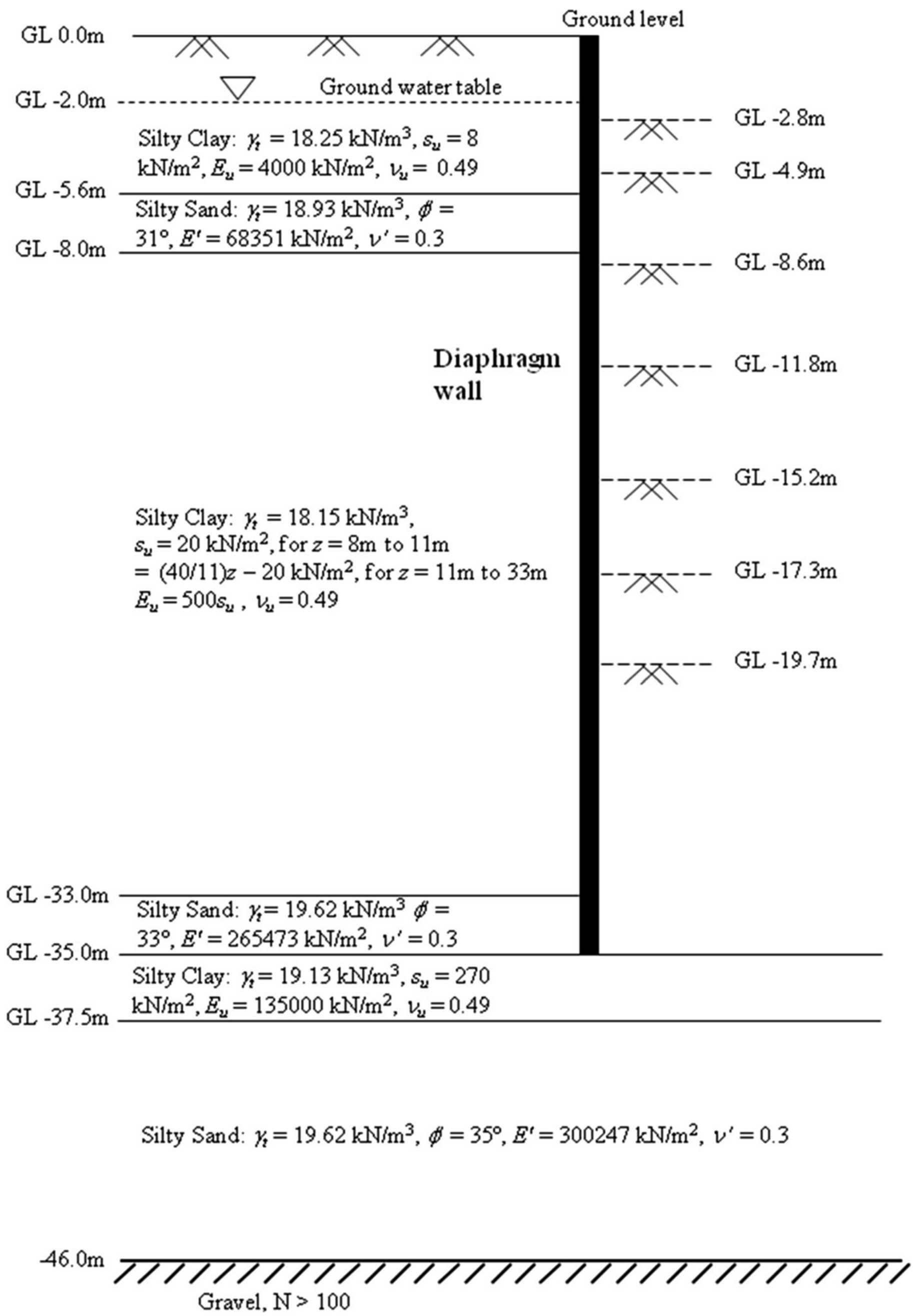

Fig. 3 Soil parameters used in the undrained analysis for validation

the present model lies close to the field observation profiles from two different inclinometer readings (I − 1 and I − 3). Also from Fig. 5, it may be found that the ground surface displacement values predicted by the present model matches closely with the observed data (Ou et al. 1998). The maximum value of the ground surface displacement as predicted by the present model is about 15% smaller than the observed values. This is may be due to the fact that in the numerical modelling, the interface material properties are chosen based on the guidelines provided by FLAC. These properties may not be very accurately

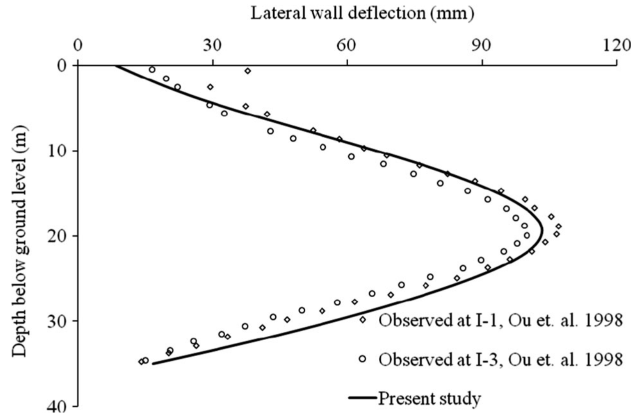

Fig. 4 Wall deflection profiles for observed and present study

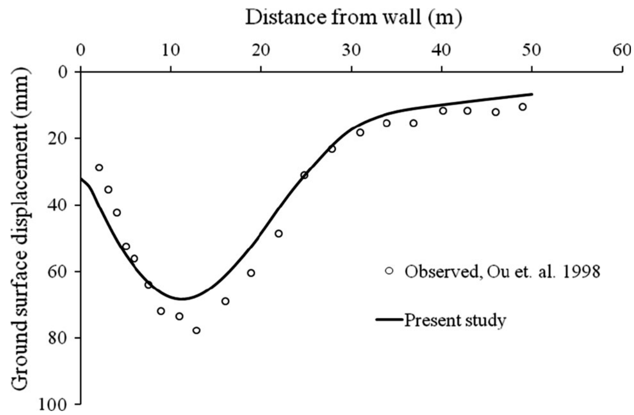

Fig. 5 Ground surface displacement profiles for observed and present study

representing the actual interface behaviour. However, determination of actual interface properties by experiment is also very difficult. The use of Mohr–Coulomb model, though much accepted in geotechnical engineering has some limitations/approximations in modelling the complicated soil-structure interaction problems like the present one. Considering all these limitations, the comparison between the field data and numerical analysis is quite reasonable.

3.2 Parametric Study

After establishing the validation of the numerical model, the parametric study is done for two different soil profiles. The soil profile—1 (in which there is an intermediate weak layer) is taken from Wang et al. (2010) and presented in Table 1(a). The soil profile is slightly modified. The medium clay layer at the top is considered to be extended up to a depth of 6 m below the ground level, neglecting the top fill layer. The other soil profile (profile—2) where, the weak layer is present at the top and the strength of layers increases with the depth below the ground level is presented in Table 1(b). In soil profile—1, there is an intermediate weak layer (6–16 and 16–26 m below GL), but in profile—2, the strength of the layers increase with depth below GL (by interchanging properties of 1st and 3rd layer keeping their thickness same as that for profile—1). Two soil profiles are chosen to analyse whether any variation in the results is occurring or not.

The angle of internal friction for cohesive and cohesionless soil layers are denoted by ϕ_u (total stress parameter under undrained condition) and ϕ' (effective stress parameter under drained condition), respectively. Similarly, Young's modulus and Poisson's ratio of clay and sand under drained and undrained conditions are denoted by (E' and E_u) and (ν' and ν_u), respectively. The width (B) and the depth (D_e) of the excavation are taken as 20 m each. The different strut arrangements considered are presented in Table 2. The position of the 1st, 2nd, 3rd and 4th level struts are varied from (2–5), (6–8), (10–13) and (15–18) m,

Table 1 Description of soil profiles—1, 2 and related soil parameters considered in parametric studies (after Wang et al. 2010)

Depth below ground level (m)	Description of soil	Approximate total unit weight (kN/m^3)	s_u (kN/m^2)	Angle of internal friction (ϕ_u or ϕ') (deg.)	e	Young's modulus (E_u or E') (kN/m^2)	Poisson's ratio (ν_u or ν')
(a) Profile—1							
0–6	Medium clay	19	53.5	0	1.0	26,750	0.49
6–16	Very soft silty clay	18	34	0	1.2	17,000	0.49
16–26	Very soft clay	17	32.5	0	1.4	16,250	0.49
26–33	Silty clay	18.5	95	0	1.2	47,500	0.49
33–39	Stiff clay	20	130	0	0.8	65,000	0.49
39–50	Fine to very fine sand	19.5	0	36	0.8	39,500[a]	0.30
(b) Profile—2							
0–6	Very soft clay	17.0	32.5	0	1.4	16,250	0.49
6–16	Very soft silty clay	18.0	34.0	0	1.2	17,000	0.49
16–26	Medium clay	19.0	53.5	0	1.0	26,750	0.49
26–33	Silty clay	18.5	95.0	0	1.2	47,500	0.49
33–39	Stiff clay	20.0	130.0	0	0.8	65,000	0.49
39–50	Fine to very fine sand	19.5	0.0	36	0.8	39,500[a]	0.30

[a] Calculated from $(75 + 8N) \times 100$ kN/m^2, where, N (= 40) is the SPT value of the sand layer given in Wang et al. (2010)

Table 2 Different types of arrangement of struts used in parametric study

System numbers	Depth of excavation, D_e (m)	Depth of each strut below ground level (m)			
		1st strut	2nd strut	3rd strut	4th strut
System—1	20	2	6	11	16
System—2		2	6	10	15
System—3		2	7	12	17
System—4		3	7	11	16
System—5		3	7	11	17
System—6		3	8	13	18
System—7		4	7	12	17
System—8		5	8	12	17
System—9		5	8	13	18

respectively. For each of the strut arrangement, the ratio of the embedment depth (D_b) to the excavation depth i.e. D_b/D_e is varied from 0.4 to 1.4, but the values of the other parameters are kept constant (wall thickness, $t_{wall} = 0.8$ m i.e. 4% of D_e, strut stiffness, $k_{strut} = 5 \times 10^5$ kN/m/m). The position of the struts, the embedment depth of the wall are varied to study their influence on the major design factors like (1) maximum strut force at each level, (2) maximum bending moment in the wall, (3) maximum lateral displacement of the wall and (4) maximum ground surface displacement.

The variation of the wall deflection with D_b/D_e for different strut systems is shown in Figs. 6 and 7 for the soil profile—1 and 2, respectively. It may be found from Fig. 6 that the variation (decrement) of the wall deflection is 67.6% (for System—9) and around 5% (for the Systems—1, 4 and 8) when D_b/D_e varies from 0.4 to 0.8 and from 0.8 to 1.0, respectively. It is also seen that the above variation is only around 3% (for all systems except Systems—1 and 5) when the ratio of the embedment depth to the excavation depth varies from 1.0 to 1.4. It can be found from Fig. 7 that for the soil profile—2, the wall deflection decreases with the increase in D_b/D_e. For the soil profile—2, when D_b/D_e varies from 0.4 to 0.8, 0.8 to 1.0 and 1.0 to 1.4, the variation (decrement) of the wall deflection is around 16, 1 and 2% for the Systems—1 to 7. However, when D_b/D_e varies from 0.4 to 1.4, the variation of the wall deflection is not significant for the Systems—8 to 9. Moreover, it has been found that the lateral wall deflection as obtained in the Systems 8 and 9 for soil profile—2 are 23 and 26% higher than that obtained for the System 3. It may be found from the above discussion that for majority of the strut arrangements, the variation of the wall deflection is minimum when D_b/D_e varies from 0.8 to 1.0. It is also observed that for the soil profile—2 i.e. if a weak soil layer is present at the top, the Systems—8 and 9 cannot be selected.

It may be seen that as the depth of the topmost strut increases below ground level, the lateral wall deflection remains almost constant or slightly decreases for soil profile—1 which is not the case for cohesionless soil as obtained from Chowdhury et al. (2013). However, analysis with the other soil profile reveals that there is significant difference between the deflection values among different strut arrangements for a particular value of D_b/D_e. This may be due to the fact that cohesive soil can stand freely without support up to a certain depth below ground level. It is further observed that as the depth of topmost strut below ground level increases the ground surface displacement also increases significantly for cohesionless soil (Chowdhury et al. 2013), but it remains almost similar or slightly decreases for the case of cohesive soil. However, if a weak soil layer is present at top, placement of top strut at greater depth is not recommended.

It may be seen from Table 3 that when D_b/D_e lies in the range 0.8–1.0, the minimum and maximum values of strut force at 1st, 2nd, 3rd and 4th levels for soil profile—1 are 3.44 kN/m (System—1, 2) and 5.50 kN/m (for System 6); 9.91 kN/m (System—2) and 19.56 kN/m (System—9); 16.31 kN/m (System—9) and 18.10 kN/m (System—6); 3.02 kN/m (Systems—9) and 14.84 kN/m (System—2), respectively. For the other soil profile, the minimum and maximum values of strut force at 1st, 2nd, 3rd and 4th levels for soil profile—1 are 2.76 kN/m (System—1, 2) and 4.37 kN/m (for System 6); 6.63 kN/m (System—2) and 11.10 kN/m (System—9); 10.31 kN/m (System—2) and 15.37 kN/m (System—5); 3.10 kN/m (Systems—9) and 13.15 kN/m (System—2), respectively. The minimum and maximum wall deflections as may be seen from Fig. 6 are 164.2 and 194.6 mm for soil profile—1 and Systems—8 and 6, respectively. Similarly, the minimum and maximum wall deflections as can be found from Fig. 7 are 84.7 and 111.9 mm for soil profile—2 and Systems—4 and 8, respectively. From the above discussion, it is observed that on the basis of analysis considering different strut arrangements and two selected of soil profiles, the lateral wall deflection for systems—8 and 9 are much higher as compared to the values obtained for other strut systems for soil profile—2. So, these strut arrangements have not been selected for the parametric studies. Apart from systems—8 and 9, any strut arrangements can be chosen for parametric study. However, System—3 is selected for the above purpose as the forces (1st, 2nd, 3rd and 4th level strut forces are 4.24 and 3.42, 15.22 and 8.47, 17.58 and 13.17 and 7.45 and 6.75 kN/m, respectively, for profile—1 and

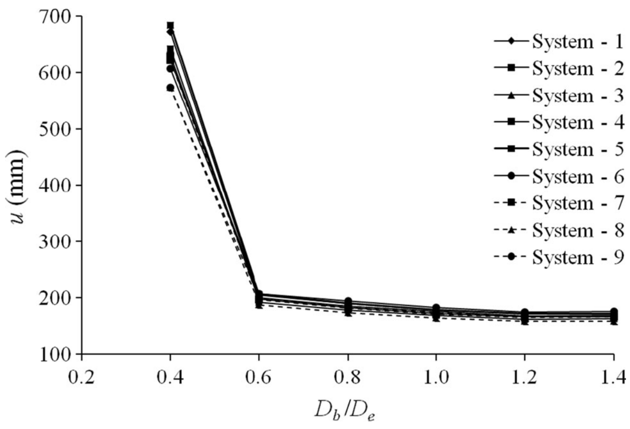

Fig. 6 Variation of wall deflection with D_b/D_e for different strut arrangements (soil profile—1)

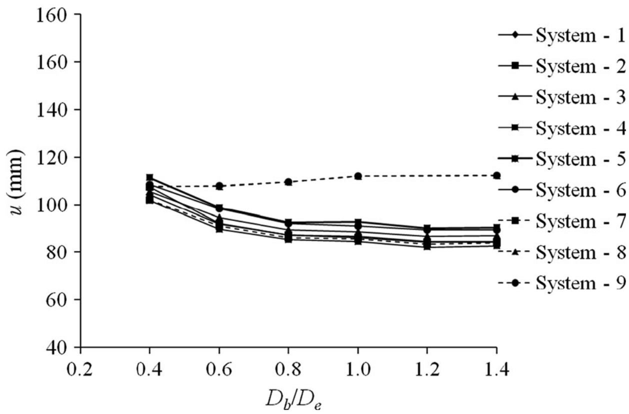

Fig. 7 Variation of wall deflection with D_b/D_e for different strut arrangements (soil profile—2)

2) in 1st and 4th level struts are on the lower side and the other strut forces lie near the average value of the maximum and minimum. Moreover, the values of wall deflection in system—3 are slightly above the mean value of the range.

The influence of wall thickness on the strut forces has been presented in Table 4. It may be found from Table 4 that within the recommended range of D_b/D_e i.e. 0.8–1.0, there is no significant variation of the values of the strut forces. The effects of wall thickness (t_{wall}) on the bending moment (M), wall deflection (u) and ground surface displacement (v) for System—3 strut arrangement and $D_b/D_e = 0.8$, 1.0, 1.2 and 1.4 are shown in Figs. 8, 9 and 10, respectively for soil profile 2. It can be found from Fig. 8 that the bending moment developed in the wall increases with t_{wall}/D_e. It may be found from Fig. 9 that for all values of D_b/D_e the wall deflection decreases with increase in t_{wall}/D_e. Moreover, it may be observed from Fig. 10 that the ground surface displacement decreases with t_{wall}/D_e except for $D_b/D_e = 0.8$, where it decreases up to $t_{wall}/D_e = 0.06$, beyond which it remains almost constant. Thus, to get optimum value of the design factors and giving equal preference to bending moment, wall defection and ground surface displacement the range of wall thickness can be taken as (6–7) % of excavation depth under the recommended range of D_b/D_e value (i.e. 0.8–1.0).

To study the influence of strut stiffness (k_{strut}) on the design factors, analysis has been done by varying k_{strut} from 1×10^5 to 25×10^5 kN/m/m. The effect of stiffness variation on strut force is shown in Table 5. The effect of strut stiffness on bending moment is shown in Fig. 11 for soil profile—1. It can be seen from Table 5 that the strut forces increase with the increase in strut stiffness. When k_{strut} varies from 1×10^5 to 5×10^5 kN/m/m, forces in 1st, 2nd, 3rd and 4th level struts increase by 6.8 and 5.6% (profile—1 and 2), 12.4 and 17.5% (profile—1 and 2), 18.8 and 20.5% (profile—1 and 2) and 19.2 and 22.8% (profile—1 and 2), respectively when D_b/D_e lies in the range of 0.8–1.0. However, the variations are 4.5% and 4.1 (profile—1 and 2), 3.9 and 5.4% (profile—1 and 2), 12.5 and 8.9% (profile—1 and 2) and 19.8 and 17.3% (profile—1 and 2) when k_{strut} varies from 5×10^5 to 25×10^5 kN/m/m. Thus, from the study of the variation of strut forces, it has been revealed that when k_{strut} varies from 5×10^5 to 25×10^5 kN/m/m there is very small variation in the strut forces as compared to the case when k_{strut} varies from 1×10^5 to 5×10^5 kN/m/m, except for the 4th strut level for which the variation remains almost same. Thus, the optimum range of strut stiffness may be taken as 5×10^5 to 25×10^5 kN/m/m when the strut force is taken under consideration. From the Fig. 11 it is found that there is decrement in the value of the design factor when strut stiffness varies from 1×10^5 to 5×10^5 kN/m/m and it remains almost constant when k_{strut} varies from 5×10^5 to 25×10^5 kN/m/m. Thus, it is found that for optimum values of the design parameters, the stiffness of strut lies in the range (5×10^5–25×10^5) kN/m/m under the recommended range of D_b/D_e value (i.e. 0.8–1.0).

On the basis of the present study, the optimum design parameters for excavation in cohesive soil are presented in Table 6 which is the main objective of the present study. From the present study it is observed that the chosen strut arrangements have significant effect on one of the design factors i.e. wall deflection when soil profile—2 is considered (i.e. if a weak layer

Table 3 Variation of F with D_b/D_e for systems—1 to 9

System number	Strut level	Depth of strut/D_e	Maximum strut force (F) × 10^3 (kN/m)											
			D_b/D_e											
			0.4		0.6		0.8		1.0		1.2		1.4	
			Type of soil profile											
			1	2	1	2	1	2	1	2	1	2	1	2
1	1st	0.10	3.43	2.71	3.40	2.72	3.44	2.76	3.48	2.80	3.51	2.82	3.54	2.86
	2nd	0.30	15.72	8.34	14.03	8.36	13.92	8.38	13.87	8.41	13.56	8.34	13.56	8.33
	3rd	0.55	27.66	13.17	19.59	11.63	17.22	11.36	16.86	11.27	16.56	11.06	16.60	11.02
	4th	0.80	20.66	12.05	10.49	11.31	11.27	10.16	9.49	9.90	8.85	9.45	8.76	9.43
2	1st	0.10	3.42	2.71	3.41	2.73	3.44	2.76	3.48	2.80	3.50	2.82	3.54	2.85
	2nd	0.30	11.09	6.59	9.97	6.59	9.95	6.63	9.91	6.65	9.73	6.62	9.77	6.66
	3rd	0.50	25.52	11.59	20.32	10.55	17.94	10.37	17.80	10.31	17.66	10.18	17.70	10.14
	4th	0.75	26.45	15.97	14.29	14.21	14.84	13.15	12.82	12.82	12.10	12.33	11.96	12.38
3	1st	0.10	4.22	3.33	4.16	3.35	4.18	3.38	4.24	3.42	4.26	3.45	4.30	3.49
	2nd	0.35	17.53	8.52	15.67	8.47	15.22	8.45	15.17	8.47	14.84	8.49	14.85	8.50
	3rd	0.60	27.49	15.38	19.53	13.77	17.58	13.17	16.39	12.95	16.25	12.53	16.25	12.55
	4th	0.85	15.39	8.27	6.89	7.65	7.45	6.75	6.32	6.56	5.60	6.28	5.61	6.25
4	1st	0.15	4.41	3.50	4.35	3.52	4.37	3.55	4.41	3.58	4.44	3.61	4.47	3.64
	2nd	0.35	13.75	7.15	12.00	7.15	11.94	7.16	11.96	7.20	11.74	7.16	11.78	7.19
	3rd	0.55	28.93	13.61	20.49	12.05	18.04	11.94	17.56	11.84	17.27	11.39	17.38	11.43
	4th	0.80	20.37	12.02	10.57	11.29	11.18	9.92	9.47	9.62	8.71	9.35	8.66	9.41
5	1st	0.15	4.41	3.51	4.36	3.51	4.38	3.54	4.41	3.59	4.43	3.61	4.47	3.65
	2nd	0.35	13.64	7.14	12.02	7.15	11.90	7.19	12.04	7.18	11.74	7.16	11.81	7.17
	3rd	0.55	34.43	17.98	24.92	16.12	22.42	15.36	21.33	15.37	20.99	14.85	20.86	14.89
	4th	0.85	14.74	8.10	6.61	7.31	7.22	6.55	5.84	6.19	5.14	5.94	5.21	5.92
6	1st	0.15	5.59	4.29	5.48	4.30	5.46	4.33	5.50	4.37	5.52	4.39	5.55	4.43
	2nd	0.40	19.42	9.32	17.64	9.11	16.79	9.11	16.74	9.07	16.28	9.10	16.35	9.10
	3rd	0.65	28.74	17.12	19.06	15.68	18.10	14.60	16.38	14.36	16.09	13.78	16.11	13.79
	4th	0.90	9.76	4.52	3.55	3.60	3.56	3.27	3.11	3.22	2.29	3.08	2.23	3.12
7	1st	0.20	4.27	3.44	4.21	3.46	4.24	3.48	4.25	3.50	4.26	3.51	4.30	3.55
	2nd	0.35	20.14	10.25	17.87	10.11	17.40	10.12	17.52	10.18	17.08	10.09	17.20	10.07
	3rd	0.60	27.80	14.83	19.45	13.22	17.41	12.70	16.45	12.53	16.25	12.13	16.18	12.20
	4th	0.85	14.56	8.17	6.84	7.62	7.52	6.67	6.15	6.46	5.47	6.23	5.46	6.19
8	1st	0.25	5.40	4.33	5.32	4.31	5.30	4.31	5.30	4.33	5.31	4.35	5.34	4.35
	2nd	0.40	17.67	8.89	15.53	8.81	15.30	8.87	15.28	8.87	15.00	8.86	15.07	8.89
	3rd	0.60	28.93	15.36	20.21	13.64	17.96	13.18	17.21	13.01	17.01	12.66	16.81	12.67
	4th	0.85	13.82	7.87	6.77	7.50	7.41	6.55	6.02	6.41	5.31	6.11	5.44	6.10
9	1st	0.25	5.39	4.33	5.31	4.32	5.31	4.32	5.31	4.33	5.30	4.35	5.33	4.37
	2nd	0.40	22.60	11.20	20.57	11.04	19.75	11.10	19.56	11.10	19.29	11.11	19.35	11.13
	3rd	0.65	27.74	16.51	18.85	15.13	17.67	14.17	16.31	14.00	15.94	13.43	15.80	13.38
	4th	0.90	9.24	4.41	3.34	3.57	3.61	3.20	3.02	3.10	2.16	3.01	2.25	3.06

Table 4 Variation of F with t_{wall}/D_e

D_b/D_e	Strut level	Maximum strut force $F \times 10^3$ (kN/m)													
		t_{wall}/D_e													
		0.04		0.05		0.06		0.07		0.08		0.09		0.10	
		Type of soil profile													
		1	2	1	2	1	2	1	2	1	2	1	2	1	2
0.8	1st	4.18	3.38	4.55	3.65	5.01	3.97	5.52	4.38	6.06	4.78	6.58	5.20	7.12	5.64
	2nd	15.22	8.45	14.83	9.02	14.75	9.80	14.65	10.45	14.88	11.15	15.49	11.67	16.14	12.09
	3rd	17.58	13.17	17.98	12.59	18.39	12.34	18.42	12.34	18.27	12.47	17.97	12.79	18.87	13.19
	4th	7.45	6.75	7.34	7.11	7.24	7.40	7.69	7.47	9.09	7.21	11.02	7.14	12.58	7.45
1.0	1st	4.24	3.42	4.58	3.71	5.05	4.01	5.52	4.43	6.04	4.81	6.56	5.20	7.10	5.59
	2nd	15.17	8.47	14.95	8.99	14.66	9.84	14.57	10.38	14.54	11.04	14.72	11.66	15.09	12.19
	3rd	16.39	12.95	16.07	12.47	16.10	12.11	16.33	12.24	16.82	12.16	16.88	12.19	16.97	12.49
	4th	6.32	6.56	6.95	6.59	7.72	6.71	8.12	6.70	7.50	6.78	7.82	6.88	8.35	6.95
1.2	1st	4.26	3.45	4.60	3.74	5.05	4.05	5.53	4.46	6.01	4.82	6.50	5.19	6.98	5.58
	2nd	14.84	8.49	14.49	8.97	14.28	9.70	14.09	10.21	14.04	10.76	14.07	11.30	14.22	11.72
	3rd	16.25	12.53	15.90	12.03	15.44	11.78	15.02	11.85	14.60	11.87	14.26	11.94	14.01	12.15
	4th	5.60	6.28	5.30	6.11	5.27	5.97	5.55	5.83	5.64	5.79	5.84	5.68	5.89	5.56
1.4	1st	4.30	3.49	4.65	3.77	5.10	4.13	5.57	4.49	6.04	4.84	6.53	5.22	7.01	5.60
	2nd	14.85	8.50	14.40	9.01	14.29	9.64	14.04	10.22	13.93	10.77	13.95	11.20	14.01	11.63
	3rd	16.25	12.55	15.91	12.04	15.27	11.82	14.85	11.85	14.42	11.79	14.05	11.85	13.78	12.04
	4th	5.61	6.25	5.49	6.15	5.35	5.97	5.52	5.86	5.46	5.80	5.33	5.71	5.26	5.61

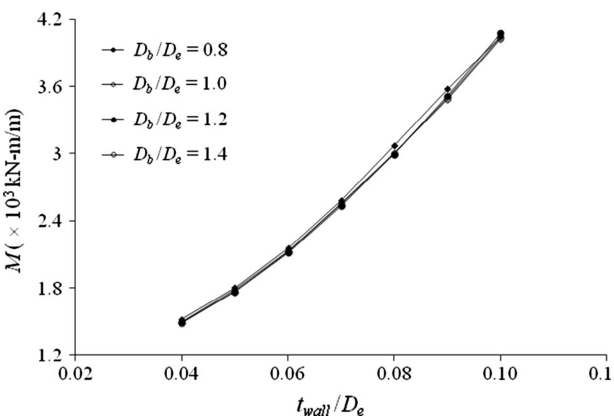

Fig. 8 Variation of bending moment with t_{wall}/D_e for soil profile—2

is present at the top). Thus, among all the strut arrangements considered in the present analysis, system—1 to 7 may be selected, where the topmost strut below ground level has been kept at a depth of (2–4) m below ground level. However, it is recommended to keep the 1st level strut within (2–3) m below ground level because if it is kept at 4 m below ground level then there will be very little space available for construction between 1st and 2nd strut levels as the 2nd strut level is chosen to keep at 7 m below ground. The spacing between the other strut levels is also chosen in such a way that sufficient space for construction is available (3rd level strut 10–12 m and 4th level of strut 16–17 m below ground level). It

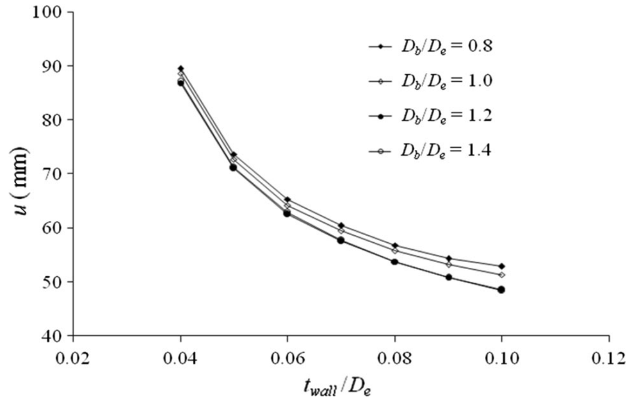

Fig. 9 Variation of wall deflection with t_{wall}/D_e for soil profile—2

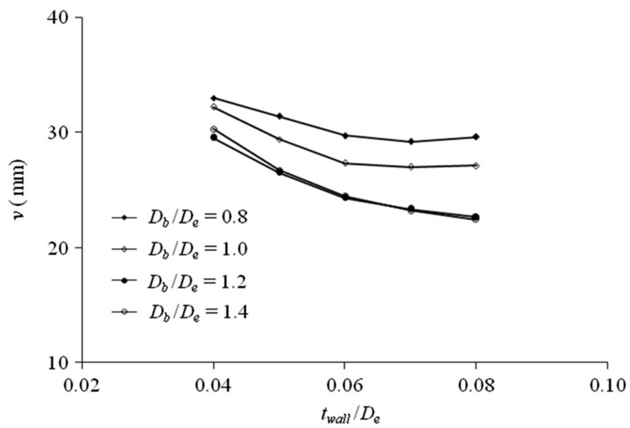

Fig. 10 Variation of ground surface displacement with t_{wall}/D_e for soil profile—2

is also noted that if a weak layer is present at top, placement of 1st strut at greater depth is not recommended. However, designer can select the position of the struts based on the design requirement.

In the present study, the observed range of maximum excavation-induced wall deflection is 0.43–0.5% of the excavation depth which is within the range (0.22–0.67%) observed from the 26 case studies in Taipei silty clay presented by Kung (2009). It is also observed that the embedment depth of the wall used in the case studies is in the range of 56–176% of the excavation depth. However, most of the field cases (around 70%) the range is around 70–105% of the excavation depth. The recommended range of embedment depth (80–100% of the excavation depth) based on the present study is also similar to the range used in the most of the field cases. The case study in cohesionless soil presented by Hsiung (2009) also shows that the embedment depth of excavation is 84% of the excavation depth which is exactly within the range (80–100%) presented by Chowdhury et al. (2013) for cohesionless soil. The thickness of the wall used in the case studies is in the range of 4–6% of the excavation depth, whereas the recommended wall thickness for excavation based on present study is 6–7% of the excavation depth. Thus, the recommended range is slightly in higher side as compared to the range used in the case studied. From the numerical study it is observed that as the thickness of the wall increases the wall deflection and ground deformation decrease whereas, the wall moment increases. The recommended range of wall thickness is proposed based on the equal preference given to the design factors. However, designer can choose lower thickness of the wall by giving preference to the wall moment. Similarly, as the stiffness of the strut increases wall moment, wall deflection and ground deformation decrease and strut force increases. Thus, designer also can choose a value of the strut stiffness based on the preference given to particular design factors. In the present study, the recommended range of strut stiffness (5–25) $\times$ 10^5 kN/m/m is chosen based on the

Table 5 Variation of F with k_{strut}

D_b/D_e	Strut level	Maximum strut force $F \times 10^3$ (kN/m)					
		$k_{strut} \times 10^5$ kN/m/m					
		1		5		25	
		Type of soil profile					
		1	2	1	2	1	2
0.8	1st	3.93	3.20	4.18	3.38	4.37	3.52
	2nd	13.54	7.19	15.22	8.45	15.68	8.91
	3rd	14.95	10.93	17.58	13.17	19.78	14.35
	4th	6.25	5.55	7.45	6.75	8.91	7.92
1.0	1st	3.97	3.24	4.24	3.42	4.40	3.56
	2nd	13.51	7.23	15.17	8.47	15.77	8.93
	3rd	13.80	10.79	16.39	12.95	17.74	14.10
	4th	5.34	5.34	6.32	6.56	7.57	7.26
1.2	1st	4.00	3.26	4.26	3.45	4.42	3.58
	2nd	13.13	7.16	14.84	8.49	15.35	8.86
	3rd	13.76	10.44	16.25	12.53	17.33	13.50
	4th	4.58	5.19	5.60	6.28	6.06	6.72
1.4	1st	4.03	3.30	4.30	3.49	4.45	3.61
	2nd	12.98	7.16	14.85	8.50	15.36	8.86
	3rd	13.80	10.50	16.25	12.55	17.30	13.55
	4th	4.69	5.14	5.61	6.25	6.05	6.69

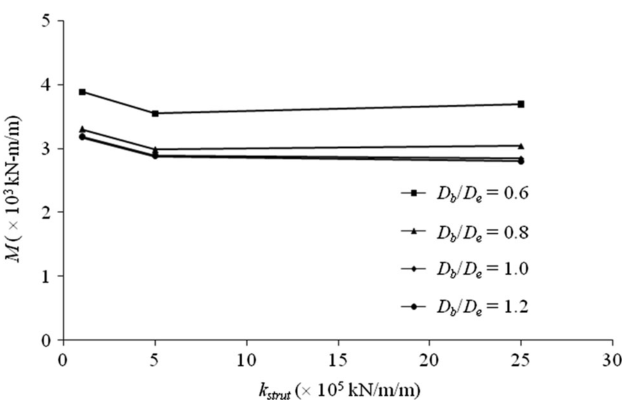

Fig. 11 Variation of bending moment with stiffness of strut for soil profile—1

Table 6 Optimum values of the design parameters for braced excavation in cohesive soil

Optimum design parameters	Range
Depth of 1st strut below ground level	(2–3) m
Depth of 2nd strut below ground level	(6–7) m
Depth of 3rd strut below ground level	(10–12) m
Depth of 4th strut below ground level	(16–17) m
Thickness of wall (% of excavation depth)	(6–7)
Embedment depth of wall (% of excavation depth)	(80–100)
Stiffness of support member (strut)	(5–25) $\times 10^5$ kN/m/m

preference given to wall moment, wall deflection and ground deformation. However, if preference is given to strut force then lower value of strut stiffness can also be chosen. In such cases, the present results can also help to choose proper values of design parameters.

4 Conclusions

In the present study an attempt has been made to estimate the optimum design parameters for a braced excavation in a cohesive soil deposit. Among all the system of struts which are studied, it can be concluded that the optimum value of strut force, wall moment, wall defection and ground surface displacement are obtained when D_b/D_e is within the range 0.8–1.0. The position of the 1st, 2nd, 3rd and 4th level struts is recommended in the range of (2–3), (6–7), (10–12) and (16–17)m below the ground level, respectively. The study with the variation in the wall thickness and the strut stiffness revealed that when the value of t_{wall}/D_e lies between 0.06 and 0.07, both the parameters like wall deflection and ground displacement reaches minimum value, beyond which they again increase. The same situation occurs for the variation of strut stiffness when it lies within the range of 5×10^5 and 25×10^5 kN/m/m.

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