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Numerical Study on Prediction over Behaviour of Braced Excavation in Heterogeneous Soil

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Abstract. Construction works in urban areas have become a challenge to the construction industry. The lack of adequate space in the urban areas has compelled me to excavate deeper into the ground. With a recent rise in commercial/residential multi-storied buildings, there has been increasing requirements for car parking and other utilities. Unusual features of urban settings are insufficient space for equipment, restricted movements, foundation interaction, soil heterogeneity, and effects of changes in the water table. Deep excavation for the construction of buildings has become an important part of construction work. Structures in the close vicinity of excavations, dense traffic state have made excavations a difficult task to execute in urban areas. The faces of the deep excavation cuts need to be protected by retention systems. The role of a Geotechnical Engineer is to provide a safe and economic design of retention systems to execute deep excavation without affecting the surrounding. Because of the importance of the protection of deep excavation numerical study is carried out. The present study aims to perform a numerical analysis of braced deep excavation using finite element analysis tool PLAXIS 2D. In this study, two soil profiles are considered each consisting of 5 layers, (soil profile 1) in which stiffness increased with depth, (soil profile 2) in which stiffness decreased with depth. The study on the behavior of wall displacement concerning the depth of retaining systems; determination of settlement of retention systems concerning distance from the back wall is carried out. Also, the depth of embedment is varied in different ratios to predict the behavior of the wall. In 1st soil profile, as the depth of excavation increases the lateral wall displacement also increases, and in the 2nd soil profile, due to reduced soil stiffness, the vertical settlement of the ground surface increases with an increase in depth of excavation.

Keywords: Deep excavation, Retention system, Numerical analysis, Braced excavation.

1 Introduction

Construction works in urban areas have become a challenge to the construction industry. The lack of adequate space in the urban areas has compelled me to excavate deeper into the ground. With the recent upsurge in commercial/residential multi-storied buildings, there has been increasing requirements for car parking and other utilities.[21]. Unusual features of urban settings are insufficient space for equipment, restricted movements, foundation interaction, soil heterogeneity, and effects of changes in the water table. Structures in the close vicinity of excavations, the presence of underground obstructions, dense traffic state, and utilities have made excavations a difficult task to execute. The faces of the deep excavation cuts need to be protected by retention systems to keep the sides stable, minimize the excavation area, and to ensure that movements will not cause damage to neighboring structures or utilities in the surrounding ground.

Excavation support is a concern of extreme importance to construction safety due to the serious threat to life posed by a potential earth collapse. Large ground settlements often damage the adjacent buildings, which may result in a serious public safety issue. As per the Occupational Safety and Health Act (OSHA), all trenches exceeding 5 feet in depth need to be shored. Hence different deep excavation retention systems have to be constructed before the construction activities.

It has become necessary to check the effects of excavations on surrounding structures and the behavior of the retention system. To deal with such a situation, it is important to predict the behavior of such excavation well in advance. The prediction of ground movement and necessary measures to mitigate any adverse situation is of supreme importance before excavation to ensure the safety and serviceability of surrounding properties [24]. The nature of soils is complex and its behavior is affected by many factors, including the fact that initial stresses existing in the natural ground are anisotropic [12].

The excavations without any support create various risks due to the soil heterogeneity, presence of underground obstructions, presence of shallow groundwater table, dense traffic conditions. Excavation support provision depends on the type of soil, the excavation depth, foundation type to be built. The space near the excavation also to be considered for the provision of support systems. Some soil types may produce problems than other soil types during excavation. The one such soil type is sandy soil which is considered risky. This soil type cannot stand for some time after making the vertical cut. The variation in the moisture content of air and variation in the groundwater table may create the instability of the cuts. The earth collapse may occur in case of sandy soil due to the vibrations created by heavy machinery, material loads at the cuts, heavy traffic in urban areas and blasting process if any.

Compared to sandy soil the clayey soil creates fewer problems. Only in the case of soft clay, the large ground settlements were observed. In the case of silty soils, similar safeguards and support provision as sand has to be taken.

Hence there is a need for analysis of the designed retaining walls to predict the performance under varying soil conditions. The present study is directed towards the numerical analysis and prediction of the performance of braced excavation using geotechnical analysis tool PLAXIS 2D which works on the finite element method of analysis.

2 Literature Review

During the last few decades, from the literature, it can be revealed that many researchers have worked on deep excavations and simulated them using different finite element tools and soil constitutive models.

Whittle et al. (1993) described the use of finite-element analysis for modeling underground parking. The analysis considered both coupled flow and deformations of soil for the exact simulation of construction activities. The predictions were calculated and evaluated through comparison with field data, the results showed that reliable results can be obtained by the advanced method of analysis.

Charles et al. (1998) presented the results and the procedures of numerical analyses of a deep excavation using the nonlinear Brick model. The predicted results were compared with the complete record of the case study. The author has taken observed deflections and bending moments of the wall in a small quantity. Less than 0.3% of shear strains were developed near the site during the excavation. During wall installation, it was observed lateral stress reduction in the ground.

Chang et al. (2000) examined the three-dimensional movements of the wall and soil through field observations and finite element analyses. The results showed that the soil near the excavation zone tends to move towards the excavation area. It increases with an increase in excavation depth. Numerical studies showed that the ground movements can be predicted reasonably using three-dimensional finite element analysis.

Richard et al. (2006) demonstrated that three-dimensional finite element analysis can be effectively used to simulate actual excavation activities. Field observed horizontal movements and strut forces at the field were compared with predictions of FEA simulations. It was proved that the actual construction sequence and design can be done with this type of simulation.

Bin-Chen Benson Hsiung (2008) explored a case study of excavation in the sand completely. The author conducted a numerical analysis to evaluate the effects of soil plasticity, soil–wall interface, and creep. The use of small strain parameters in an elastic-perfect plastic model was shown from the back analysis. It was observed that excavation- induced seepage effects on vertical displacements in little amount.

Ma et al. (2011) presented a case study of an excavation retained by soil-nail supported deeply mixed (DM) wall (DMSNW) in the soft deposit of Shanghai, China. The soft deposit in Shanghai is Quaternary sediment. It has silt content and clay content of about 50% and 40% respectively. This deposit has very low strength and very high sensitivity. Usually, soil-nail supported DM wall is adopted when the excavation depth is less than 6 m. A two-dimension finite element method (2D-FEM) was conducted. The results calculated DM wall displacements were compared with the site measured value. The obtained results show that FEM analysis is an effective way to predict the displacement and internal force of nails.

Brian et al. (2013) designed deep excavation for the Shangri-La hotel and luxury condominium tower in downtown Toronto with eight levels of underground structure, four extending into the shale bedrock. The site, confined on three sides by City streets. Author adopted a modeling and monitoring program for where risks due to excessive movements were greatest. The FLAC modeling of predicted rock movement provided good results. The predicted results were in good insight with actual movements

Ching et al. (2013) proposed an anisotropic elastoplastic bounding surface model with a non-associative flow rule. This model can describe realistically the behavior of various types of cohesive soils. The study demonstrates the use of this model in the FEA of deep excavation. The PLAXIS was used by the author for comparison with the measurements obtained at the case study site.

Subha et al. (2013) discussed a numerical model to assess the design parameters which affect the wall behavior for a braced excavation. The results obtained from the numerical study were in close agreement with field data. The best possible result was obtained among all the combinations studied. Based on the results of this numerical study a design guideline was also presented.

Bhatkar et al. (2016) studied the nature of surface settlement and wall deformation in soft soil for deep excavation. For the provision of the basement, this excavation was carried out. The numerical analysis predicts the soil behavior during excavation. The wall displacements were measured during construction. The predicted deformation was fairly high. The conclusion was done as the numerical analyses predict the results effectively.

Richard et al. (1988) took a case study of an internally braced deep excavation in soft clay for a pump station at a sewage treatment plant in Milwaukee, Wisconsin. The design was influenced by the hydrostatic blow out at the bottom of the excavation and limited site area. It was a necessity to limit ground deformation to protect present structures and utilities. Construction monitoring was done with slope inclinometers to measure the horizontal deflection of the support system and piezometers were used to measure hydrostatic pressure in a confined aquifer. Measured horizontal deformations of the excavation support system were more compared to the predicted deformations.

Murthy et al. (2010) discussed a few case studies of protection systems for deep excavation. The different techniques are to be employed such as soil nailing with touch piles or micro piles if the basement excavations were taken close to the existing structure. The nailing system can reduce the earth's pressure on the permanent retaining wall by carefully planning and designing. The author concluded that the grouted nailed and driven nailed protection schemes and anchored touch piles for deep excavation are the feasible and economical options in urban areas with restricted space all round.

Gandhi (2011) described common methods adopted for deep excavation. Also, the author described the common problems faced while executing the excavation and remedial measures that can be adopted. Usually, excavations up to a depth of 15-20m are very common for most of the projects. The property lines are the edge of a busy street with heavy traffic which makes the excavation and construction challenges. Few case studies were described as typical problems during excavation.

Ahmed et al. (2016) presented three case studies in which shoring was used. For various scenarios of loading, adjacent structures, subsoil conditions, environmental constraints, equipment, and technical expertise availability different deep excavation support types were explained. Pile wall systems were presented as relevant solutions.

In the present study numerical analysis of braced and unbraced excavation was carried out with Varying Depth of embedment in terms of ratios of the depth of embedment and depth of excavation. An attempt is made to find an effective D_b/D_e ratio for two different soil profiles.

3 Modeling and Parametric Studies

Deep excavations certainly result in deformations of nearby ground and settlement of ground surface. In the present study, a soil profile was considered consisting of 5 layers. The soil profile consisted of soil layers in which soil stiffness increased with depth. The two soil profiles are described in the Table. 1. The depths of excavation (D_e) were considered 5m, 10m, and 15m. With various excavation depths, the embedded depths (D_b) of the wall were varied to study their influence on lateral wall displacement, ground surface settlement.

Table 1. Description of Soil Profile 1 and Related Soil Parameters

Depth below ground level (m)	Description of Soil	Unit weight of soil (kN/m^3)	C' (kPa)	Φ' (degree)	SPT N-Value
0 – 3	Soil 1	15.8	1	30	5
3 - 7	Soil 2	16	1	32	10
7 – 17	Soil 3	16.5	1	33	15
17 – 27	Soil 4	16.8	1	34	30
27 - 50	Soil 5	17	1	35	40

For the numerical simulation of deep excavation, the excavation problem was analyzed numerically using the finite element method. The two-dimensional program PLAXIS is used in this study. In this study plane, the strain Mohr-Coulomb Model and 15 node triangular elements were selected to model soil layers and other volume clusters. All the phases were calculated as plastic analysis.

The deep excavation of width 20m was considered. The effect of excavation was aimed to study up to 200m from both the walls. The geometry of the model is shown in Fig. 1 and the boundary and mesh of the model are shown in Fig. 2. the horizontal boundary of the mesh was set at 50m below ground level. Both the vertical boundaries are set at 200m on either side of the wall. Both the vertical and horizontal movements were restrained along the bottom boundary and only horizontal movements were restrained along the vertical boundaries.

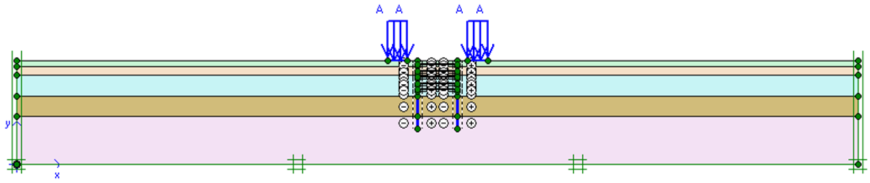

Fig. 1. Typical model showing geometry of model (De=15m, Db/De=1.2).

The diaphragm wall of 1m thickness was provided to retain the surrounding soil and these are modeled as plate elements with flexural stiffness (E_A) 2.5 x 10^7 kN/m and flexural rigidity (EI) 2.083 x 10^6 kN m^2/m. Deep excavation supports are influenced by adjacent structures. Hence in this analysis uniformly distributed load of 20 kN/m^2 was considered at a distance of 5m from the wall and for the span of 10m to simulate the adjacent structures. The lateral struts were provided to reduce lateral wall displacements. The struts used were of uniform properties flexural stiffness (E_A) 4.374 x 10^6 kN and are placed at a horizontal distance of 4.5m.

The construction of the diaphragm wall was simulated similarly to the construction sequences as staged construction. Calculation type is plastic for all the phases of calculations. The nodes along the length of diaphragm walls were defined to obtain load-displacement curves.

The depths of excavation (De) were considered 5m, 10m, and 15m. With various excavation depths, the embedded depths (Db) of the wall were varied to study their influence on lateral wall displacement, ground surface settlement. The depths of embedment were varied as a ratio of Db/De 0.4, 0.8, 1.2, and 1.6.

3.1 Soil Profile

The Soil Profile is described in Table. 1 is considered for analysis. For different depth of excavation, the parametric study was carried out. The depth of each excavation for different depth of excavation and the position of struts are described in Table. 2

Table 2. Description of Excavation stage and stage-wise depth of excavation

	Excavation Stages		Position of Struts	
The total depth of Excavation (m)	Excavation Stage	Depth of excavation from GL (m)	Excavation Stage	Depth of excavation from GL (m)
5 m	Excavation 1	0-3	Strut 1	1.5
	Excavation 2	3-5	Strut 2	3.5
10 m	Excavation 1	0-3	Strut 1	2
	Excavation 2	3-6	Strut 2	5
	Excavation 3	6-10	Strut 3	8
15m	Excavation 1	0-3	Strut 1	8
	Excavation 2	3-6	Strut 2	5
	Excavation 3	6-9	Strut 3	8
	Excavation 4	9-12	Strut 4	11
	Excavation 5	12-15	Strut 5	14

3.2 Parametric study for soil profile

Variation of lateral wall displacement with depth. The behavior of the wall for lateral displacement was analyzed for different excavation depths. Also, the effect of embedment was analyzed by the varying depth of embedment in the ratios of D_b/D_e as 0.4, 0.8, 1.2, and 1.6.

From Fig. 3, 4, and 5 it has been observed that for all depth of excavation the lateral wall movement at the ground surface is nearly the same. At D_e=5m the maximum lateral displacement was observed for D_b/D_e = 0.8. At D_e =10m the lateral wall displacement for D_b/D_e =0.4 was observed maximum due to less depth of embedment. D_b/D_e = 0.8 can be an effective ratio as all other higher ratios produce the same maximum lateral displacement of the wall. At D_e =15m all the ratios produce the same maximum lateral displacement of the wall. Hence in this case D_b/D_e = 0.4 can be effective. But the maximum lateral displacement of the wall increases as the depth of excavation increases.

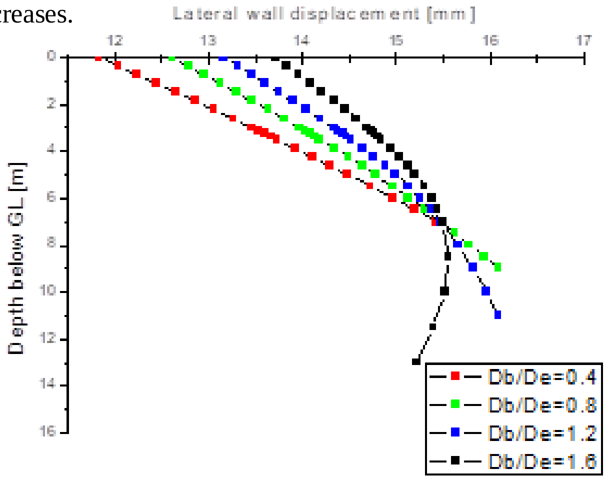

Fig. 3. variation of Lateral wall displacement with Depth below GL for D_e=5m

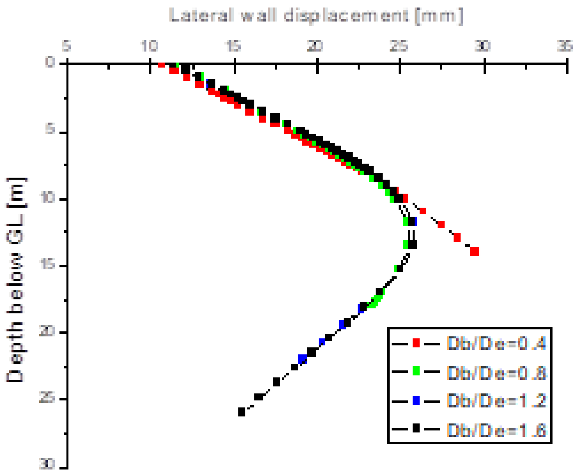

Fig. 4. variation of Lateral wall displacement with Depth below GL for D_e=10m

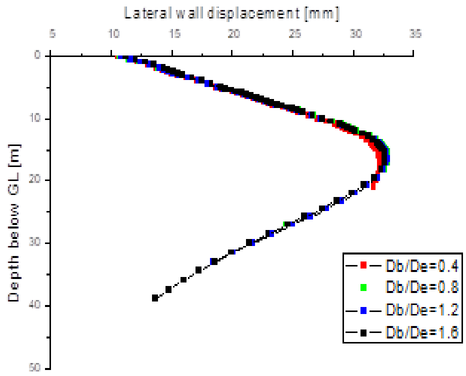

Fig. 5. variation of Lateral wall displacement with Depth below GL for D_e=15m.

Variation of vertical settlement along with the horizontal distance from the wall. From Fig. 6, 7, and 8 it has been observed that for all the D_b/D_e ratio the maximum vertical settlement of 12 mm, 16mm, 20mm for D_e =5m, 10m, 15m was observed respectively.

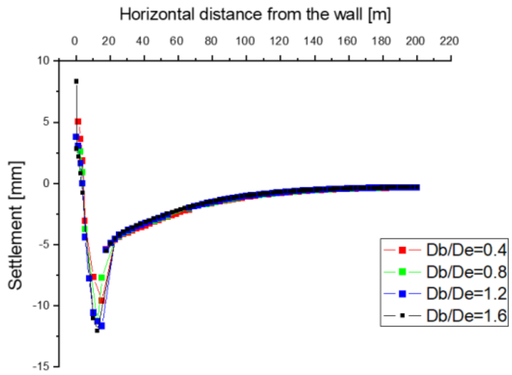

Fig. 6. Variation of vertical settlement with horizontal distance from the wall for D_e=5m.

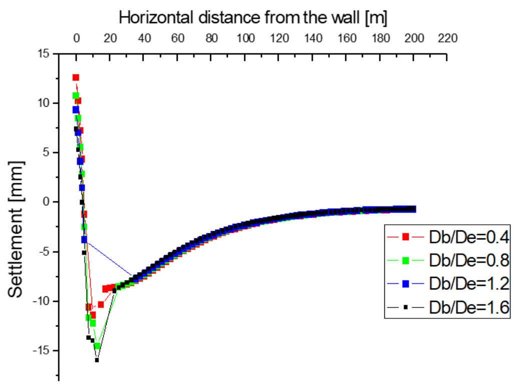

Fig. 7. Variation of vertical settlement with horizontal distance from the wall for D_e=10m.

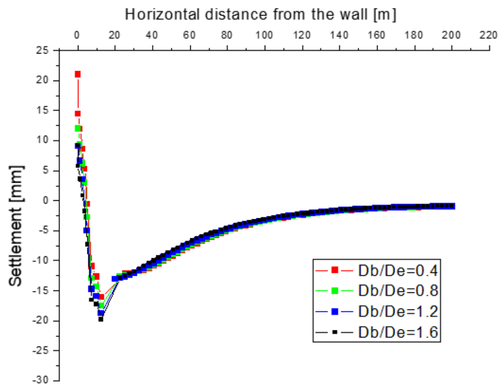

Fig. 8. Variation of vertical settlement with horizontal distance from the wall for D_e=15m.

The influence of ground settlement was up to a horizontal distance of 30m for all depth of excavation. Later the vertical settlement goes on reducing and finally reduces to nearly zero at a distance of 200m. In this soil profile the ground settlement was affected by the depth of excavation the embedment of the wall does not have any influence on the ground settlement. The provision of lateral struts has reduced the vertical settlement by 6mm, 44mm, 95mm for D_e=5m, 10m, 15m respectively.

The behavior of the wall at different excavation stages. The behavior of the wall at different excavation stages was analyzed for different excavation depths. Also, the effect of embedment at each stage was analyzed by the varying depth of embedment in the ratios of D_b/D_e as 0.4, 0.8, 1.2 and 1.6

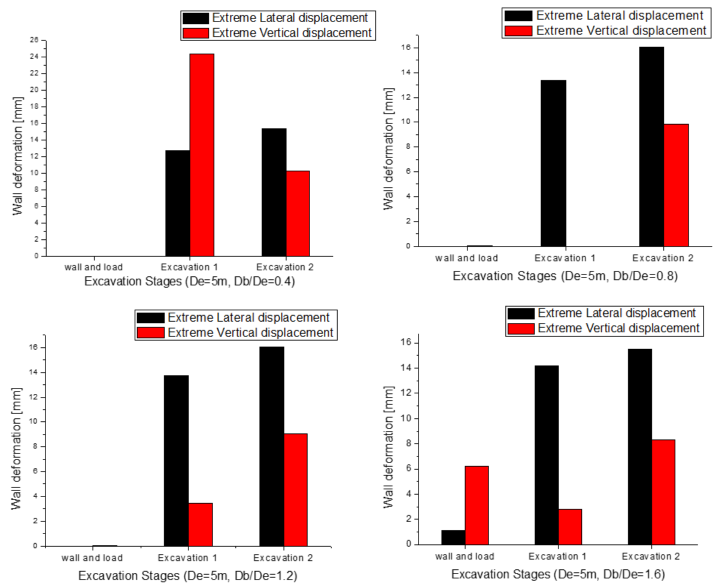

Fig. 9. The behavior of Wall at different Excavation Stages (D_e =5m, D_b/D_e=0.4, 0.8, 1.2, and 1.6)

For D_b/D_e = 0.4, 0.8, 1.2 at the initial stage no extreme lateral and extreme vertical displacements were found. In D_b/D_e =1.6 due to the effects of wall installation, the displacements were observed.

From fig. 9, at Excavation Stage I in all the D_b/D_e ratios the extreme lateral displacement was found nearly equal. But extreme vertical displacement at D_b/D_e =0.4 was observed maximum and the extreme lateral displacement for Db/De =0.4, 0.8, 1.2 were observed the same whereas extreme vertical displacements were negligible.

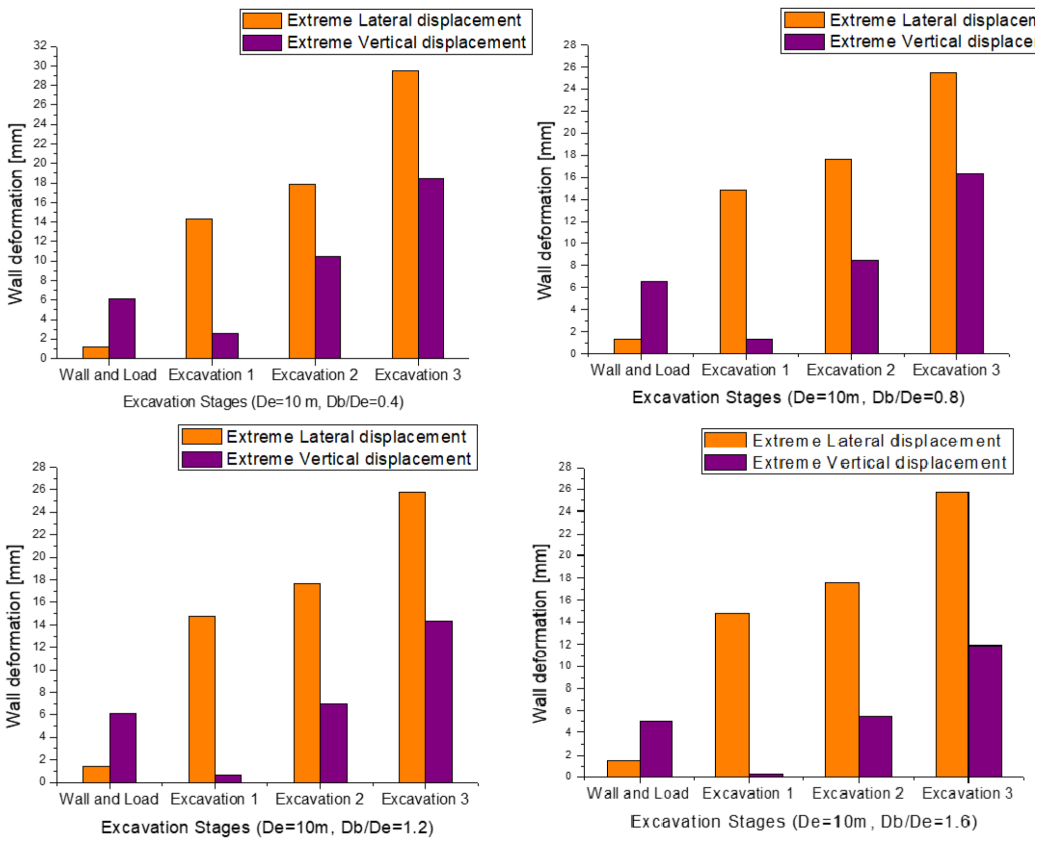

Fig. 10. Behaviour of Wall at different Excavation Stages (D_e =10m, D_b/D_e =0.4, 0.8, 1.2, 1.6)

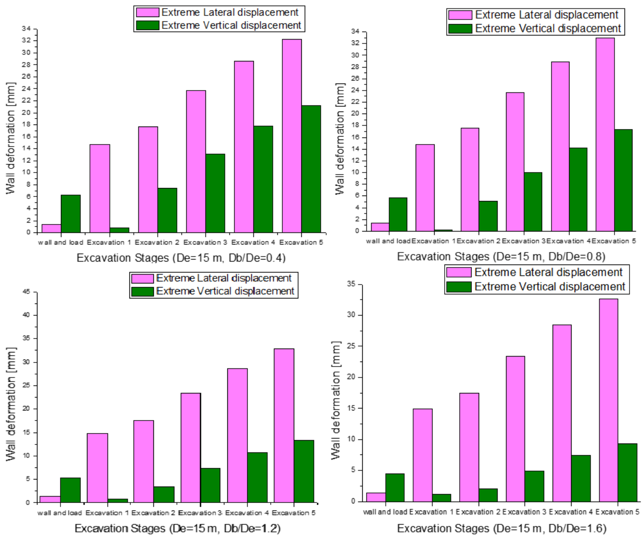

Fig. 11. Behaviour of Wall at different Excavation Stages (D_e =15m, D_b/D_e =0.4, 0.8, 1.2, 1.6)

From fig. 10, at Excavation Stage II the extreme lateral displacement was reduced in D_b/D_e of 0.8, 1.2, and 1.6. and also, vertical displacement reduced in D_b/D_e = 1.2, 1.6 compared to other lower ratios, and the extreme lateral displacement for D_b/D_e =0.4, 0.8, 1.2 were observed the same but extreme vertical displacements were reduced for an increase in D_b/D_e ratio. At the initial stage i.e. wall and load extreme lateral displacement and extreme vertical displacement were observed the same in D_b/D_e ratios.

From fig. 11, at Excavation Stage III the extreme lateral displacement and extreme vertical displacements were reduced for an increase in D_b/D_e ratio. At the initial stage i.e. wall and load extreme lateral displacement and extreme vertical displacement were observed the same in D_b/D_e of 0.4, 0.8, and 1.2, 1.6.

At Excavation Stages I, II, extreme lateral displacement and extreme vertical displacement were observed same in D_b/D_e of 0.4, 0.8 and 1.2, 1.6 and for excavation stage III, IV and V extreme lateral displacement and extreme vertical displacement were found reduced with increase in D_b/D_e ratio.

5 Conclusions

1 As the depth of excavation increases, the lateral wall displacement also increases.
2 The increase in soil stiffness exerts more lateral pressure on the wall.
3 From the observations D_b/D_e = 0.8 can be effective ratio. The variations of the vertical settlement of the ground with horizontal distance from the wall were found nearly equal due to the increased stiffness of soil.
4 In the case of D_e =5m, the lateral wall displacements were found increased in increase with D_b/D_e ratio but a decrease in vertical displacement.

5 In the case of D_e =10m and 15m, both the lateral wall displacements and vertical displacement keep increasing with the increase in depth of excavation.

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