Influence of Wall Stiffness and Embedment Depth on Excavations Supported by Cantilever Walls

Muhammad Naseem Baig, Abdul Qudoos Khan, Jamal Ali

***Abstract*—**Ground deformations in deep excavations are affected by wall stiffness and pile embedment ratio. This paper presents the findings of a parametric study of a 64-ft deep excavation in mixed stiff soil conditions supported by cantilever pile wall. A series of finite element analysis has been carried out in Plaxis 2D by varying the pile embedment ratio and wall stiffness. It has been observed that maximum wall deflections decrease by increasing the embedment ratio up to 1.50; however, any further increase in pile length does not improve the performance of the wall. Similarly, increasing wall stiffness reduces the wall deformations and affects the deflection patterns of the wall. The finite element analysis results are compared with the field data of 25 case studies of cantilever walls. Analysis results fall within the range of normalized wall deflections of the 25 case studies. It has been concluded that deep excavations can be supported by cantilever walls provided the system stiffness is increased significantly.

***Keywords*—**Excavations, support systems, wall stiffness, cantilever walls.

I. Introduction

DEEP excavations are getting common due to overcrowding and limited spaces in major cities of the World. These excavations are supported by use of different excavation support systems especially where the excavation is close to adjacent infrastructure, e.g. buildings, buried services, piled foundations and major highways, etc. The ratio of embedment depth and stiffness of wall/pile for cantilever supported excavations is an important aspect in design of support system as it ensures safety against lateral movements as well as rotation about the base.

The effects of wall length on wall deflections and surface settlements for braced excavations in normally consolidated clays were studied by [1] by carrying out a series of finite element analysis. It was reported that the deflection shapes as well as the magnitude of deformations is affected by pile/wall length and embedment depth ratio. Similarly, a series of analysis for a multi pivoted excavation support system for the Suzhou subway station to determine the optimum embedment ratio was carried out by [2]. The authors concluded that increasing the embedment depth beyond a critical value does not result in any significant reduction in ground deformations. This paper presents the results of a parametric study carried out using Plaxis 2D for an existing excavation in Lahore, Pakistan. Influence of system stiffness and pile embedment were the focus of this study. The results were also compared with wall deflections from 25 case histories of excavations in similar soil conditions.

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II. Project Description

Information Technology (IT) Tower located in Gulberg Lahore consists of 28 floors including six basements and standing 200 ft above the ground surface is taken as the case study. The IT Tower site is approximately trapezoidal in shape with an average length of 230 ft and an average width of 160 ft and an excavation of 64 ft [3]. Two 46 ft wide roads are running on northern and eastern side of the tower; whereas single/double story residential buildings are located on the other two sides. The subsoil consists of an approximately 45 ft thick layer of silty clay in medium stiff to stiff in situ state underlain by silty fine sand till 200 ft depth. The clay layer is categorized as medium plastic with liquid limit (LL) varying from 31% to 38%. Based on SPT blow counts, the in situ consistency of silty sand is categorized as dense to very dense state [3].

III. Model Description

The finite element analysis was carried out using Plaxis 2D software. Plain strain conditions were simulated and fixed boundaries were modeled in horizontal and vertical directions. The lateral extent of the model was set equal to seven times the excavation depth from the end of the excavation to nullify the effects of boundary conditions on the computed results as suggested by [4] and [5]. Fifteen nodded triangular mesh elements with medium coarseness were used. The initial stresses were generated using K_o procedure and the water table was taken at a depth of 90 ft. Hardening soil (HS) model was used as the soil constitutive model to consider the changes in modulus for unloading and reloading conditions. The model parameters used for FEM simulation were derived from existing correlations [4]-[8] and are given in Table I. Linear elastic model was used to model the solider pile wall. Soil pile interaction was integrated in the analysis to account for friction/adhesion between concrete pile and soil. To include the effect of cracking in solider beams, the stiffness of concrete was reduced by 30%. This reduction in strength/ stiffness of the concrete or other materials is essential to model the inefficiencies that occur in the field while execution to predict deformations as close as possible to field values in [4] and [5]. The material input parameters of the solider piles are listed in Table II.

TABLE I
SOIL PROPERTIES USED IN ANALYSIS FOR HS MODEL

Parameter	Silty Clay	Silty Sand
Depth, ft	0 - 45	45 - 120
Behavior	Undrained	Drained
γ (pcf)	121	125
SPT Navg	27	33
Φ' (degree)	26	35
Ψ (degree)	0	5
c_u (psf)	2350	0
v	0.20	0.20
E^{ref}_{50} (psf)	3.415×10^5	6.6×10^5
E^{ref}_{oed} (psf)	2.39×10^6	9.9×10^5
E^{ref}_{ur} (psf)	1.025×10^6	1.98×10^6
p^{ref} (psf)	2000	2000
m	0.80	0.50
K_o	0.56	0.43
R_{int}	0.90	0.62

TABLE II
MATERIAL PROPERTIES OF EXCAVATION SUPPORT SYSTEM

Soldier Pile	
Diameter, d (ft)	2
c/c spacing (ft)	3.5
0.7E (psf)	3.15 x 108
A (ft2/ft)	0.897
I (ft4/ft)	0.224
w (lb/ft/ft)	26.01
v	0.15

IV. INFLUENCE OF PILE EMBEDMENT

The embedment ratio “H/He” is defined as the ratio of pile length (H) to the depth of excavation (He). This ratio has a significant effect on the factor of safety and is therefore an important factor for deformation characteristics in soft clays. Finite element analysis was carried out to study the effects of pile length for excavations supported by cantilever piles in mixed soil conditions (clay deposits underlain by silty sand). The analyses were carried out for embedment ratios “H/He” of 1.25, 1.50, 1.75 and 2.0 keeping other factors i.e. stiffness of structural members and soil properties as constant. The normalized wall deflections are presented in Fig. 1. It is observed that increasing pile length reduces the magnitude of deflections up to an embedment ratio of 1.50. Beyond this ratio there is no significant reduction in wall deflections. Also increasing the pile embedment increases the factor of safety; however, it does not improve the performance of wall. Therefore, it is important to carry out a series of analysis by varying penetration depth to determine the threshold penetration depth to economize the design. These analysis results are in line with the findings of [2]. They proposed that the optimum embedment ratio for Suzhou Subway City station was in the range of 1.65 to 1.80 and further increase in embedment did not result in enhanced performance of the support system.

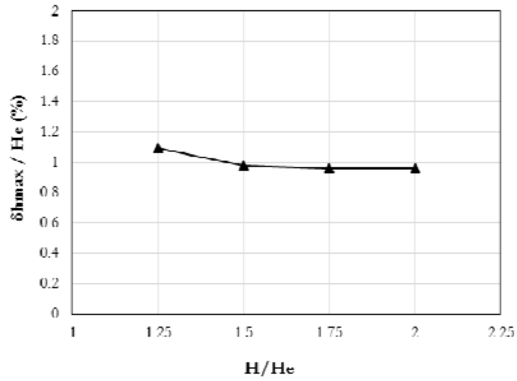


Fig. 1 Effect of pile embedment on deformation characteristics

V. INFLUENCE OF PILE EMBEDMENT

The bending stiffness of a wall is one important factor in affecting the magnitude of wall deformations. The results of finite element analysis from studies of [7] and [9] for braced excavations suggests that the reduction in δ_{Hmax}/H_e is more pronounced when stiffer diaphragm walls were analyzed keeping other factors constant (thickness of clay layer and depth of hard stratum). The stiffness of the solider pile was varied between 0.5 to 25 times the actual stiffness value, to study the effects on cantilever walls. The FEA results are shown in Fig. 2. The maximum lateral wall deflection for actual stiffness is predicted to be 196 mm and may be on higher side. The deformations decreased from 196 mm to 101 mm when system stiffness was increased by 25 times. Large lateral deformations may be attributed to (a) the depth of excavation i.e.,19.5 m and (b) low system stiffness “EI”. FEA results from Fig. 2 also suggest that the system stiffness not only affects the magnitude of wall deformations but also the deflection shape; i.e., as the system stiffness increases, the location of point of maximum wall deflection moves closer to the surface. The point of maximum wall deflections is represented by the dashed line in Fig. 2.

The maximum wall deflections are normalized with depth of excavation and are shown in Fig. 3. The results suggest that if the wall stiffness is increased by 25 times, the lateral deformations have decreased by 94%. The normalized lateral deflection δ_{Hmax}/H_e reduced from 1.0% to 0.50% as the bending stiffness was increased from 143 MNm^2/m to 3575 MNm^2/m. Like other support systems, stiffness is an important parameter for controlling lateral deformations for cantilever supported excavations. Increasing system stiffness up to 1500 MNm^2/m reduces wall movements significantly but further increase in stiffness does not affect the wall deflections as represented in Fig. 3, where the deformation curve becomes almost flat at EI values greater than 1500 MNm^2/m. For cantilever piles, wall deformations are dependent on system stiffness in stiff soil conditions. These results are in contradiction to the findings of [10] and [11] for braced excavations in which the authors suggested that the system stiffness has less effect on maximum lateral deformations in stiff soil conditions.

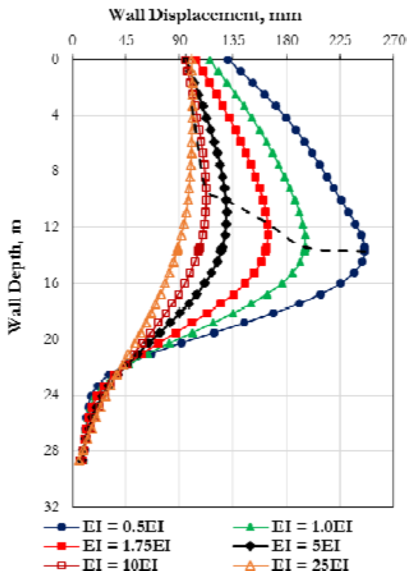


Fig. 2 Wall displacements plots for cantilever supported excavations

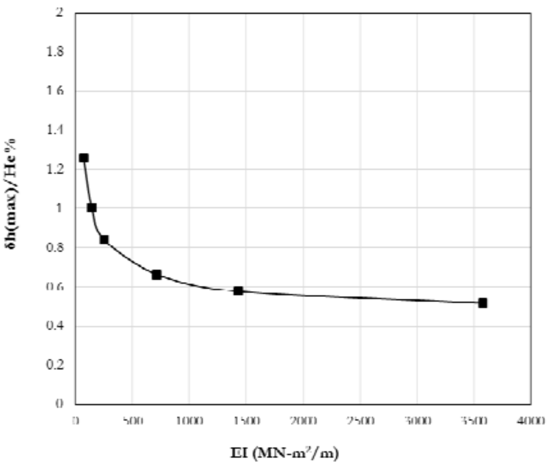
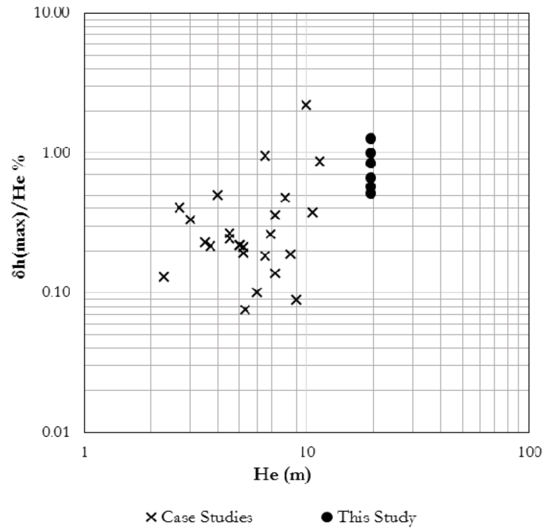


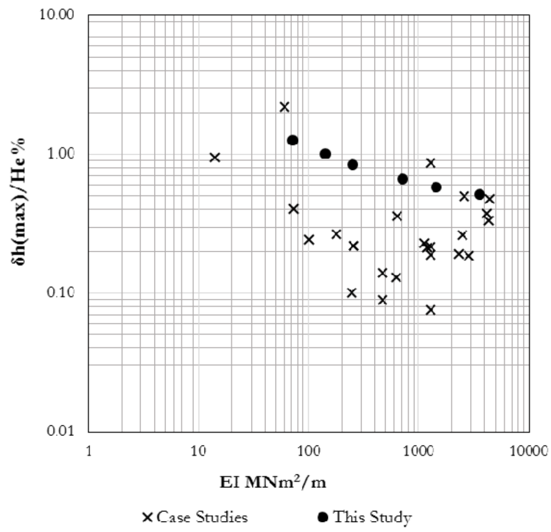
Fig. 3 Influence of wall stiffness on deformation behavior

VI. Comparison with Case Histories

Reference [12] analyzed data of 296 case studies of deep excavations in stiff soil conditions. Field measurements data of 25 cantilever wall/pile case histories taken from [12] have been used to compare results from finite element analysis. The normalized maximum wall deformations for FEA are compared with case studies and shown in Fig. 4 (a). The maximum lateral deformations for 10 m deep excavation in San Francisco were reported to be 220 mm. An 11.5 m deep excavation in Salzburg yielded maximum wall deformation equal to 100 mm. From Fig. 4 (a), the ratio $\delta_{Hmax}/H_e = 0.84\%$ falls within the upper bound values of case studies for tangent pile walls. Field data from three case studies have δ_{Hmax}/H_e more than 0.84%. The plot between wall stiffness and normalized wall deflections are shown in Fig. 4 (b). It is observed that the trend of wall deflections from FEA is like that of reported case histories.



(a)



(b)

Fig. 4 Comparison of FEA results with case studies

VII. Conclusion

A parametric study was carried out by changing the stiffness and embedment depth of 64 ft deep excavation supported by cantilever pile/wall. Finite element analysis results led to the following conclusions:

- Pile embedment ratio affects the maximum wall movements. Maximum wall deflections decrease by increasing embedment ratio up to 1.50; however, any further increase in pile length does not improve the performance of wall.
- The wall deformations are dependent upon the stiffness of wall/pile. The maximum lateral deformation has decreased by 94% by increasing the system stiffness by 25 times.
- A stiff system such as secant pile or tangent pile wall can reduce lateral deformations to a significant extent for cantilever supported excavations.

- The system stiffness not only affects the magnitude of wall deformations but also the shape of deflection as well as the point of maximum deflection.

Published data indicates that cantilever supported excavations are used for shallow depths. If deep excavations are to be supported by cantilever walls then high system stiffness shall be required.

REFERENCES

[1] Hashash, Y. M. A., and Whittle, A. J. (1996). “Ground movement prediction for deep excavations in soft clay.” J. Geotech. Engrg., 122(6),474–486.

[2] Gao, X., Liu, S., and Zhang, S. (2014) Ratio of Embedded Depth of Multi-Pivots Retaining Walls to Excavation Depth in Suzhou Subway Stations in China. Tunneling and Underground Construction: pp. 246-255.

[3] Kibria, S., Saeed, S. and Akbar, A. (2010), “A Comparative Study of Pile-Anchor Support System for Deep Excavations in Lahore,” Proceeding of the International Conference on Geotechnical Engineering, Lahore, 5-6 November 2010, pp. 121-128.

[4] Khoiri, M. and Ou, C. Y. (2013), “Evaluation of deformation parameter for deep excavation in sand through case histories”, Computers and Geotechnics, Vol. 47, pp. 57–67.

[5] Hsiung, B. C. and Dao, S. D. (2014), “Evaluation of Constitutive Soil Models for Predicting Movements Caused by a Deep Excavation in Sands”, Electronic Journal of Geotechnical Engineering, Vol. 19, pp. 17325-17344.

[6] Schanz, T. and Vermeer, P. A. (1998) “On the stiffness of sands”, Geotechnique 48, pp-383-387.

[7] Schanz, T., Vermeer, P. A. and Bonnier, P. G. (1999), “The hardening soil model: formulation and verification”, Beyond 2000 in computational geotechnics, 281-296.

[8] Phien-wej, N., Humza, M. and Aye, Z. Z. (2011), “Numerical modeling of diaphragm wall behavior in Bangkok soil using hardening soil model”, Proceedings of the 7th International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, pp-715-722.

[9] Wong, K. S., and Broms, B. B. (1989). “Lateral wall deflections of braced excavations in clay.” J. Geotech. Engg., 115(6), 853–870.

[10] Clough, G. W., and O’Rourke, T. D. (1990). “Construction induced movements of in situ walls.” Proc., Design and Performance of Earth Retaining Structure, Geotechnical Special Publication No. 25, ASCE, New York, 439–470.

[11] Bryson L. and Zapata-Medina D. (2012), Method for Estimating System Stiffness for Excavation Support Walls” J. Geotech. Geoenviron. Eng. Vol. 138, No. 9, 1104-1115.

[12] Long, M. (2001). “Database for retaining wall and ground movements due to deep excavations.” J. Geotech. Geoenviron. Eng., 127(3), 203–224.