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Numerical Investigation on the Effects of Deep Excavation on Adjacent Pile Groups Subjected to Inclined Loading

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***Abstract*—There is a growing demand for construction of high-rise buildings and infrastructures in large cities, which sometimes require deep excavations in the vicinity of pile foundations. In this study, a two-dimensional finite element analysis is used to gain insight into the response of pile groups adjacent to deep excavations in sand. The numerical code was verified by available experimental works, and a parametric study was performed on different working load combinations, excavation depth and supporting system. The results show that the simple two-dimensional plane strain model can accurately simulate the excavation induced changes on adjacent pile groups. It was found that further excavation than pile toe level and also inclined loading on adjacent pile group can severely affect the serviceability of the foundation.

***Keywords*—Deep excavation, pile group, inclined loading, lateral deformation.

I. INTRODUCTION

THE land in large cities is scarce, and usually, the choices for construction location are very limited. Considering this fact, it is also likely that the project site for high rise buildings and various infrastructures which normally require deep excavations, would be in the proximity of another building with pile foundation. This engineering challenge caused a lot of worries since deep excavation induces stress relief which results in adjacent soil and pile group deformation [1], [2].

Because of the importance of the matter, there have been a considerable number of studies investigating this subject. Comprehensive centrifuge tests, reported by [3]-[6], suggest that the excavations induce substantial deformations in the adjacent pile foundations and severely affect their bending moment. However, these changes reduce dramatically with increasing the distance of piles to excavation. Some other researchers used numerical simulations [7]-[10] to study the other aspects of this topic which were unable to consider in experimental works such as investigating the effects of pile length, supporting system, pile head fixity, etc. There are also some other studies which applied theoretical and analytical methods [11], [12].

Reviewing the literature provides a good insight into this engineering challenge; however, it is perceptible that there is still a paucity of information about some of the important aspects of this topic such as piles behaviour within a group subjected to various inclined working loads.

In this study, two-dimensional finite element analysis was used to investigate the behaviour of 2×n pile group adjacent to deep excavation in sand. The numerical code and the modeling procedure were verified by the centrifuge test reported by [3]. Various parameters were investigated including working load combinations, excavation depth, and supporting system.

II. VALIDATION OF TWO-DIMENSIONAL FINITE ELEMENT MODELING

The two dimensional finite element models used in this paper were verified by centrifuge test reported by [3]. Verification was conducted to examine whether the procedure used in the modeling of the pile group in two dimensional plane-strain model, soil and soil-pile interactions are appropriate to correctly predict the pile groups behaviour.

As a conventional method which is shown in Fig. 1, a 2D converted plate element is used to model piles, and their axial and bending stiffness were calculated per unit width so that it would be equivalent to actual pile rows properties. Fig. 2 shows the 2D plane strain simulation of test number G17 of the mentioned centrifuge test [3]. The soil used in the test was Toyoura sand with internal friction angle of 43, unit weight of 15.78 kN/m^3, dilation angle of 12 and a Young's modulus of 6z MPa, where z is the depth below ground surface in meters. The piles were a hollow square aluminium tube with a prototype bending stiffness of 2.5×10^5 kNm^2. The wall thickness was 3-mm aluminium plate which is equivalent to 24×10^3 kNm^2.

The computed maximum lateral displacement occurred at the top of piles with 3.16 mm and the maximum bending moment for front pile was calculated as 32.14 kN.m. The measured results in the experiments were 3.55 mm and 39.7 kN.m, respectively. With good accordance between computed and measured data, it can be concluded that this problem which is three dimensional in nature, can be converted into 2D plane strain modeling with acceptable error.

III. TWO-DIMENSIONAL NUMERICAL ANALYSIS

A two-dimensional numerical analysis was performed by using PLAXIS 2D software to study the behaviour of a pile

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group subjected to inclined loading adjacent to braced deep excavation. In this study, a typical excavation geometry that used in urban areas was used which is shown in Fig. 3. The final excavation depth (De) was adopted with a range of 15 m to 25 m meters, supported by 1 m thick and 40 m deep diaphragm wall which is braced by 4 m vertically and 8 m horizontally spaced struts. Steel pipes were used as struts in the analysis with an outer diameter of 500 mm, thickness of 25 mm and axial rigidity of 7.45×10^6 kN.

A 2×n elevated pile group was considered with center to center spacing of 4 m between piles which is equal to the distance between pile group to excavation. Piles considered to have 1 m diameter and 35 GPa Young's modulus same as retaining wall.

Only one half of the excavation was modeled because of geometrical symmetry. The adopted size was 80 m in width and 80 m in depth so that the effects of boundary conditions would be minimized. Water table was assumed beneath the bottom boundary and soil considered to be a sand reported by [13] which was modeled with hardening soil model given in Table I.

IV. Analysis of the Computed Results

A. Pile Group Bearing Capacity

The majority of the researches on this topic ignore the loadings acted on piles which seems to be impractical. As mentioned, the final goal of this paper is to examine the effects of different loading combinations on pile groups. Therefore, it is necessary to determine the pile group load carrying capacity. Ultimate bearing capacity of pile groups was analysed by the same software and also with conventional calculations, and the results were approximately the same with 1450 kN for each single pile. With a factor of safety of 3.0, the ultimate permissible vertical working load would be 968 kN acting on every 4 m out of plane dimension of pile cap. This vertical working load was applied on all of the models to better simulate the real conditions.

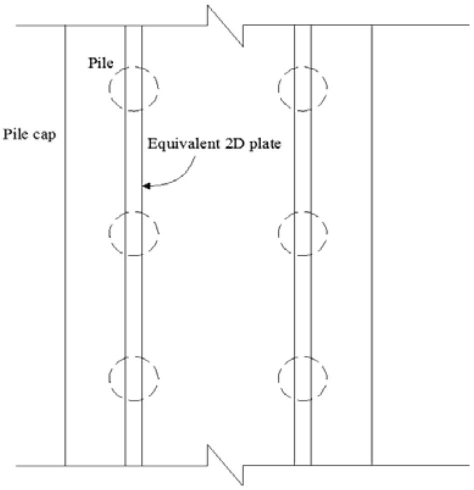

Fig. 1 Converting a pile group to 2D plane strain model

TABLE I
SAND PARAMETERS [13]

Parameter	Sand
E^{ref}_{50} (kN/m^2)	15000
E^{ref}_{oed} (kN/m^2)	15000
E^{ref}_{ur} (kN/m^2)	45000
Cohesion (kN/m^2)	1
Friction Angle	31.5
Poisson's Ratio	0.25
Soil Unit Weight (kN/m^3)	17.44
Strength Reduction Factor	0.8

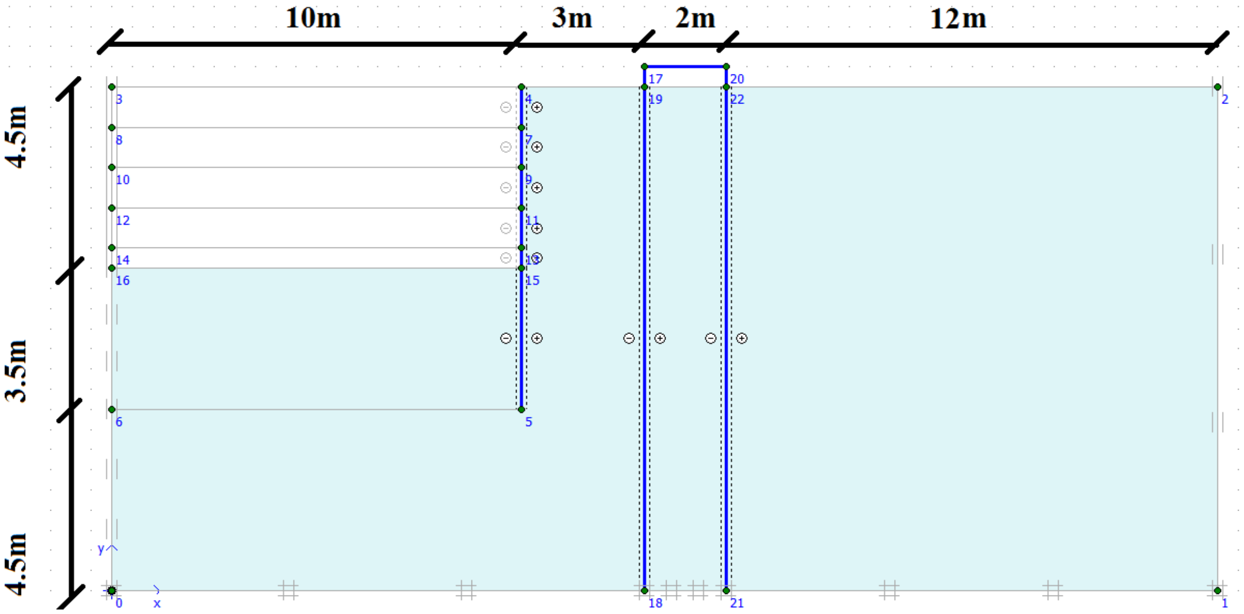

Fig. 2 The numerical validation model geometry for test number G17 [3]

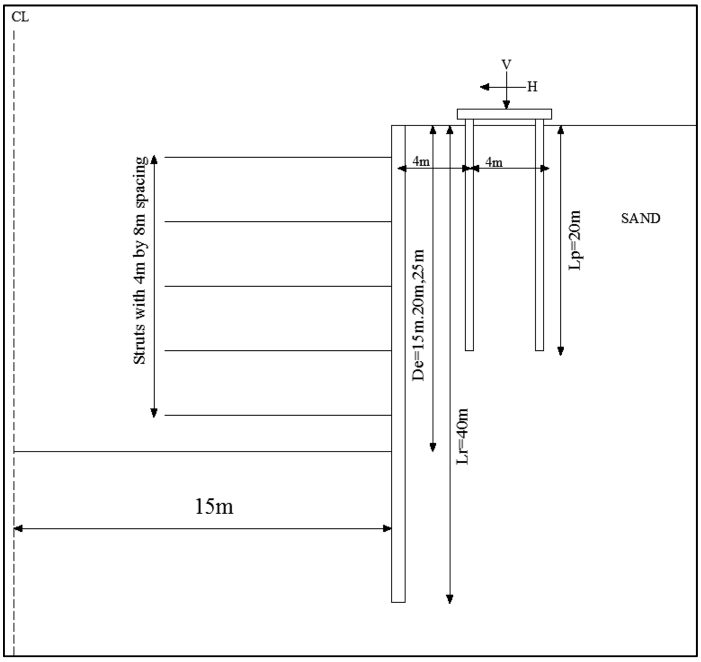

Fig. 3 Typical geometry of the models used in this study

B. *Effects of Excavation Depth*

Figs. 4 and 5 show excavation induced lateral deformation in front row and rear row piles respectively. It can be seen that the excavation until the pile toe level (De/Lp=1), causes a rather uniform lateral movement for front pile row toward retaining wall. Further excavations to beneath the pile toe level (De/Lp=1.25) increase lateral deformations considerably, especially at pile toe depth.

Lateral deformation for rear pile row increases with excavation depth, but they are generally less than front piles. The shape of lateral deformation diagram stays quite unchanged with more deformation for top of the piles rather that pile toe. This can be attributed to the fact that only the top of rear pile row stays in slip surface.

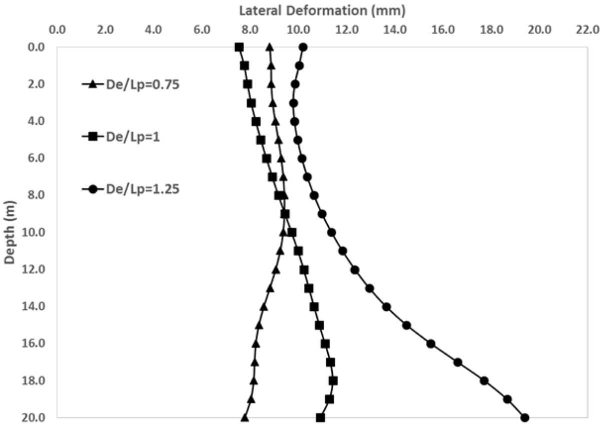

Fig. 4 Effects of final excavation depth on front pile row lateral deformation

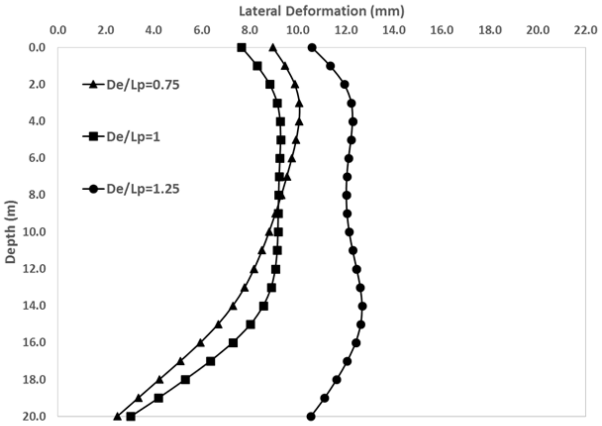

Fig. 5 Effects of final excavation depth on rear pile row lateral deformation

Figs. 6 and 7 show excavation induced bending moments in front row and rear row piles, respectively. It can be seen that the excavation in the vicinity of pile group can change the bending moment of piles dramatically. Maximum bending moment controls the structural design of piles and required steel reinforcement. The maximum induced bending moment is at pile head level for front piles, but it occurs at shallow depth (2 m) for rear piles. Induced bending moments increase by excavation depth.

C. *Effects of Inclined Loading*

It happens rarely that only vertical loads act on a pile group. In order to investigate the effects of simultaneous horizontal and vertical loading (inclined loading) on pile groups in the vicinity of excavations, three proportions (0.05, 0.10, and 0.15) of working vertical load (V) applied as horizontal load (H) which are a reasonable loading combination for piles [14]. The excavation depth is kept at the same level as pile toe (De/Lp=1) to only consider the changes caused by additional horizontal loading.

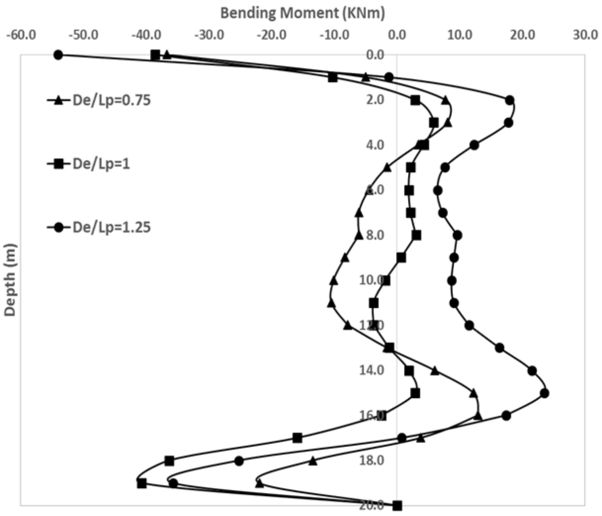

Fig. 6 Effects of final excavation depth on front pile row bending moment

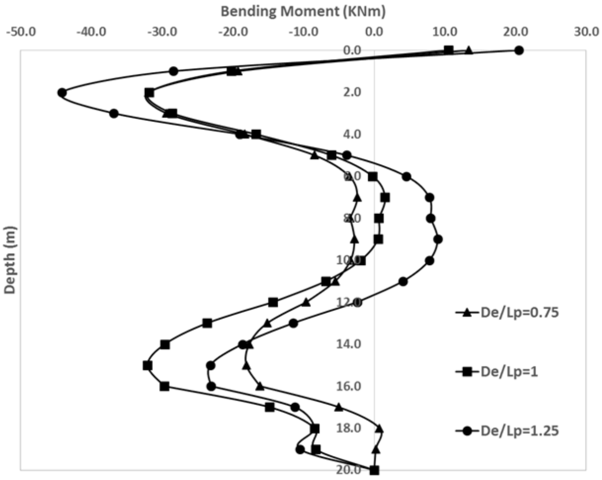

Fig. 7 Effects of final excavation depth on rear pile row bending moment

Figs. 8 and 9 show excavation induced lateral deformations in front row and rear row piles respectively. As it was expected, imposing additional horizontal loading, increases lateral deformation of piles specially at pile head and generally upper half of piles. These changes are the most profound when 15% of vertical working load imposed as horizontal load, increasing the head lateral deformation by 80% for both front and rear pile rows.

Figs. 10 and 11 show excavation induced bending moments in front row and rear row piles respectively. Additional horizontal loading mostly affects the bending moment at upper half of the piles. For front pile row, imposing 15% of vertical working load as horizontal load causes 125% increase in bending moment which should be noted in the structural design of the piles.

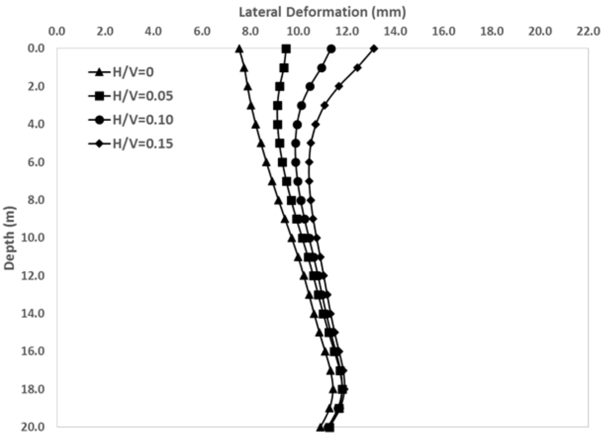

Fig. 8 Effects of inclined loading on front pile row lateral deformation

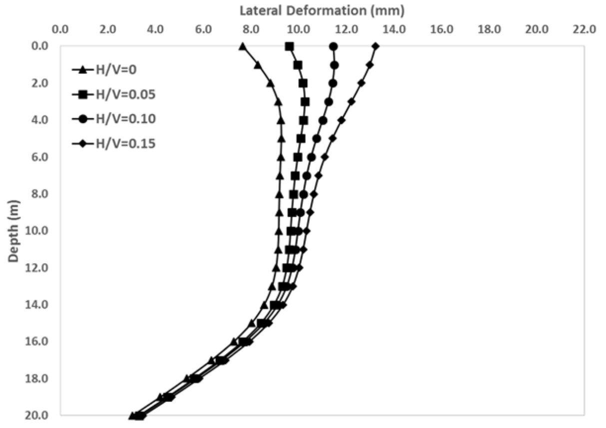

Fig. 9 Effects of inclined loading on rear pile row lateral deformation

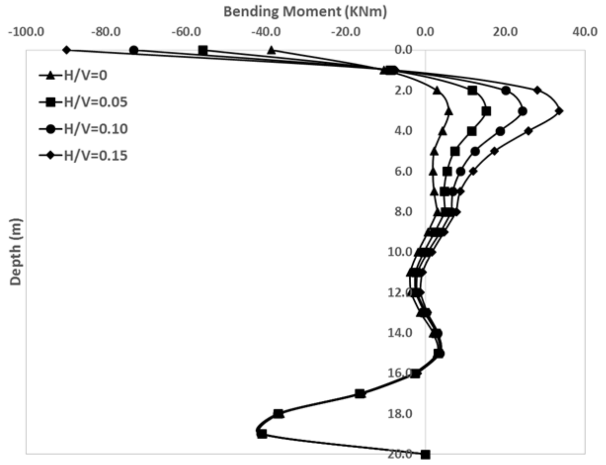

Fig. 10 Effects of inclined loading on front pile row bending moment

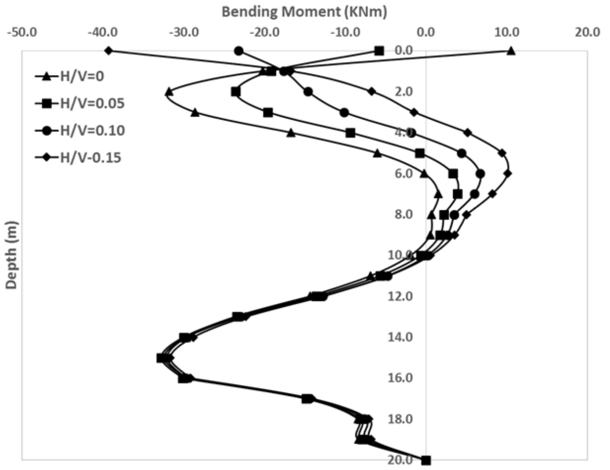

Fig. 11 Effects of inclined loading on rear pile row bending moment

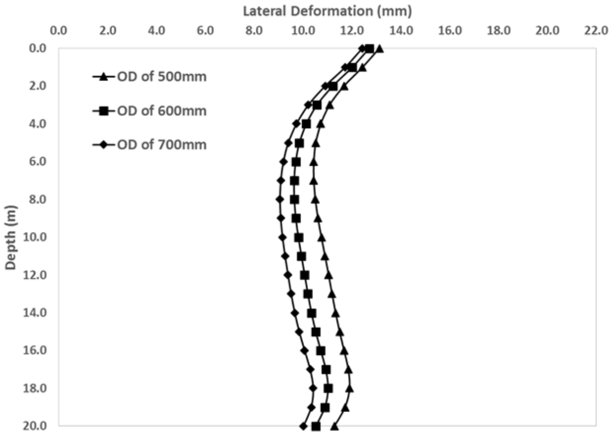

Fig. 12 Effects of supporting system rigidity on front pile row lateral deformation

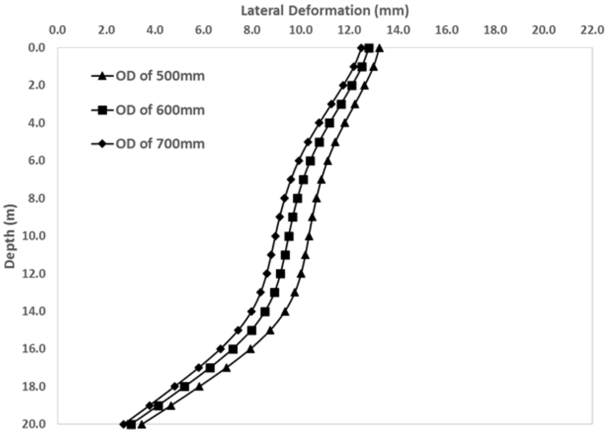

Fig. 13 Effects of supporting system rigidity on rear pile row lateral deformation

D. Effects of Supporting System Rigidity

In order to examine the contribution of supporting system in minimizing the lateral deformations in pile groups, two additional options for struts were investigated with outer diameter of 600 mm and 700 mm and the thickness of 25 mm which results in the axial rigidity of 9.03×10^6 kN and 10.50×10^6 kN, respectively. It was assumed that 15% of vertical working load acts as horizontal load on pile group. The excavation depth is kept at the same level as pile toe level (De/Lp=1).

Figs. 12-15 show the effects of supporting system stiffness on piles lateral deformation and bending moment, respectively. It can be seen that increasing struts rigidity has minimal influence on decreasing group piles lateral deformation and bending moment.

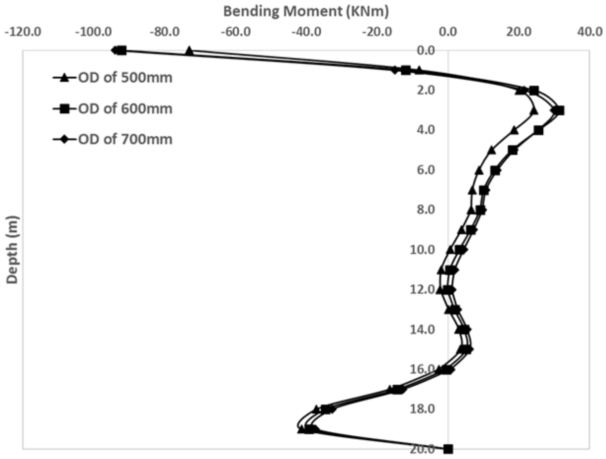

Fig. 14 Effects of supporting system rigidity on front pile row bending moment

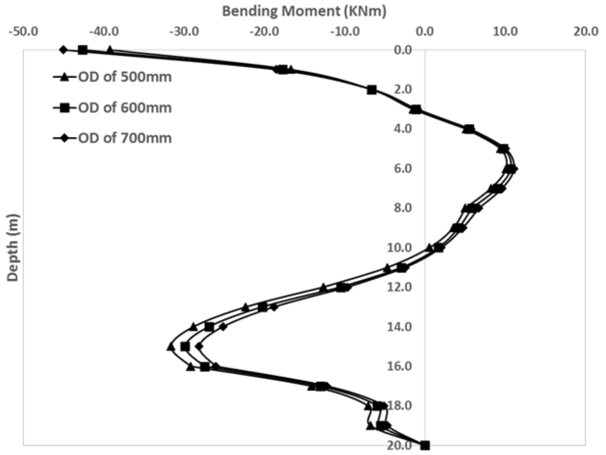

Fig. 15 Effects of supporting system rigidity on rear pile row bending moment

V. CONCLUSION

This paper investigated the effects of constructing a deep excavation in the vicinity of a pile group subjected to inclined loading by using a validated two-dimensional finite element code. Based on the assumed geometrical configurations and soil parameters, the following conclusions can be drawn.

1. Excavation induces considerable changes on adjacent pile group, especially when the final excavation depth exceeds

the pile toe level.

2. Nearby pile row moves quite uniformly toward excavation until the excavation depth passes pile toe level where high lateral deformations occur which should be considered in retaining wall designing. Distant pile row is generally less affected by the excavation.
3. With increasing the excavation depth, additional bending moment imposed on piles which should be considered in structural designing of piles.
4. Inclined loading induces additional lateral deformations and bending moment for pile groups in the vicinity of excavation. simultaneous vertical and horizontal loading, mostly affect the upper half of piles and can cause structural damage to piles and serviceability problems by severe lateral deformation.
5. Increasing the axial stiffness of supporting system is not an effective counter measure for reducing lateral deformations and excavation induced bending moments for adjacent pile groups.

REFERENCES

[1] W. D. Goh aTC, Wong KS, Teh CI, “Pile responce adjacent to braced excavation,” J. Geotech. geoenvironmental Eng., 2003.

[2] H. I. Finno RJ, Lawrence SA, Allawh NF, “Analysis of Performance of Pile Groups Adjacent to Deep Excavations,” J. Geotech. Eng., 1991.

[3] D. E. L. Ong, C. F. Leung, and Y. K. Chow, “Behavior of Pile Groups Subject to Excavation-Induced Soil Movement in Very Soft Clay,” J. Geotech. Geoenvironmental Eng., vol. 135, no. 10, pp. 1462–1474, 2009.

[4] C. F. L. K. L. R. F. S. and Y. K. Chow, “Behavior of pile subject to excavation-induced soil movement,” J. Geotech. Geoenvironmental Eng., vol. 126, no. 11, pp. 947–954, 2000.

[5] 2 and R. F. Shen C. F. Leung, 1 Y. K. Chow, “Behavior Of Pile Subject To Excavation-Induced Soil Movement,” J. Geotech. Geoenvironmental Eng., no. November, 2000.

[6] C. F. Leung, D. E. Ong, and Y. K. Chow, “Pile Behavior Due to Excavation-Induced Soil Movement in Clay. II: Collapsed Wall,” J. Geotech. Geoenvironmental Eng., vol. 132, no. 1, pp. 45–53, 2006.

[7] J. Chai, S. Shen, W. Ding, H. Zhu, and J. Carter, “Numerical investigation of the failure of a building in Shanghai, China,” Comput. Geotech., vol. 55, no. 7, pp. 482–493, 2014.

[8] D. S. Liyanapathirana and R. Nishanthan, “Influence of deep excavation induced ground movements on adjacent piles,” Tunn. Undergr. Sp. Technol., vol. 52, pp. 168–181, 2016.

[9] M. Shakeel and C. W. W. Ng, “Settlement and load transfer mechanism of a pile group adjacent to a deep excavation in soft clay,” Comput. Geotech., no. December 2016, pp. 0–1, 2017.

[10] and C. T. G. M.R. Karim, S.-C.R. Lo, “Behaviour of piles subjected to passive loading due to embankment construction,” Can. Geotech. J., 2014.

[11] P. D. 1. R. J. M. and F. A. F. V. T. Mandy Korff, “Pile-Soil Interaction and Settlement Effects Induced by Deep Excavations,” J. Geotech. Geoenvironmental Eng., 2016.

[12] R. Zhang, J. Zheng, H. Pu, and L. Zhang, “Analysis of excavation-induced responses of loaded pile foundations considering unloading effect,” Tunn. Undergr. Sp. Technol., vol. 26, no. 2, pp. 320–335, 2011.

[13] M. El Sawwaf, “Experimental and Numerical Study of Eccentrically Loaded Strip Footings Resting on Reinforced Sand,” J. Geotech. Geoenvironmental Eng., vol. 135, no. 10, pp. 1509–1518, 2009.

[14] E. Conte, A. Troncone, and M. Vena, “Behaviour of flexible piles subjected to inclined loads,” Comput. Geotech., vol. 69, pp. 199–209, 2015.