Impact on pile behavior due to new adjacent excavations: A case study and numerical simulation

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ABSTRACT: Due to rapid urbanization and infrastructure development, new pit excavation is often a necessity in close proximity to existing structures. Movements caused by these deep excavations affect the behavior of existing adjacent piles and thus the nearby structures. To analyze the change in the behavior of the existing piles due to adjacent new excavations, numerical simulation is used in this study for which the finite element software PLAXIS 3D is applied. A group of three pile is analyzed using the Hardening soil constitutive model which considers the elasto-plastic behavior of soil. The naturally occurring multi-layered soil strata is used for which subsequent excavations on two adjacent sides of the pile cap is considered. The pile-soil interface is simulated to take into account the soil-structure interaction. It is observed that once excavation occurs on one side of a pile group, further excavation on another side of the same pile group has negligible effect. The analysis results can be used for similar type of soils in any region to predict existing pile behavior adjacent to new excavations.

Keywords: adjacent excavation, existing pile, numerical modelling, PLAXIS 3D.

1 INTRODUCTION

Utilization of underground space often leads to deep excavation which causes ground movements and change in stress of in-situ soil. Often these excavations are close to the foundation of existing structures, which generally are pile foundations. The behavior of pile foundation is affected by adjacent soil movement caused due to unloading effect from excavation. Thus it is a key challenge to figure out the changes in soil and pile characteristics due to adjacent new excavations.

Different researchers have tried to analyze the soil excavation – pile interaction mechanism. Liu et al. (2020) developed analytical solutions to figure out the excavation induced pile behavior. Li et al. (2019) and Goh et al. (2003) have presented full-scale instrumented field cases to study the behavior of an existing pile due to nearby excavation works. Numerical modelling studies have also been carried out by Shakeel and Ng (2018) to analyze the behavior of pile group near excavation. In most of the cases, the analysis is done with excavation on one side of the pile group.

The uniqueness of this study lies in the fact that it analyses the behavior of soil and pile when excavation is carried out consequently on two adjacent sides of a pile group. The existing pile group considered for this analysis is near to new excavations being executed for a Metro railway project in Taiwan; where, two subsequent excavations are carried out on two adjacent sides of the pile group. The effect of these two excavations are presented here.

2 NUMERICAL ANALYSIS

Three-dimensional numerical simulation is done using the commercially available finite element software PLAXIS 3D. Fig. 1 shows the excavation geometry used in the analysis. The final excavation depth for excavation side 1 is 24 m and that for excavation side 2 is 15 m. The supporting diaphragm walls are 1.2 m in thickness. Bottom up excavation method is adopted which is supported by struts spaced 5 m center-to-center horizontally. Buttress wall at 7.5 m spacing is placed only on excavation side 1.

A group of three piles connected by a pile cap is positioned 5 m from the face of diaphragm wall on first excavation side and 1.5 m from face of Diaphragm wall on second excavation side. The 1 m diameter piles are rigidly connected to the pile cap with 3 m center-to-center spacing among the piles. Length of each pile is 48 m. The pile cap is 1.5 m thick and located 1 m below the ground surface with a uniform surface load of 523 kN/m^2.

Numerical analysis is performed in two parts; first with only excavation side 1 and in the second part with both excavation side 1 and excavation side 2.

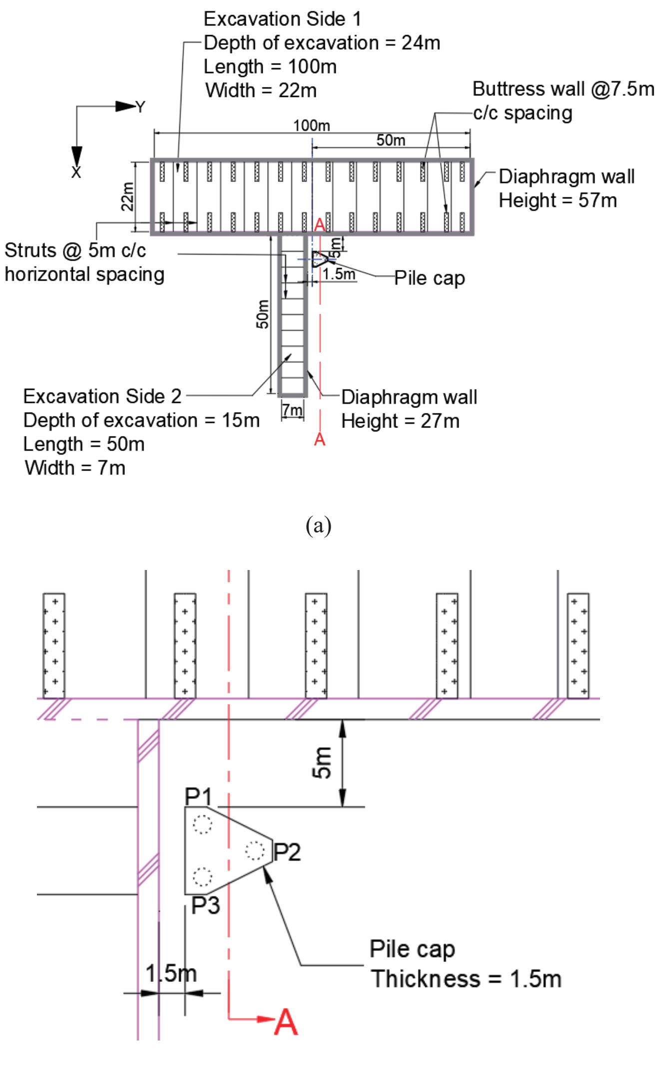

Fig. 1. Excavation geometry (a) plan and (b) enlarged view of pile cap area.

2.1 Finite element mesh

The naturally occurring multi-layered soil strata is considered in the analysis. Hardening soil model is used with calibrated soil properties from laboratory tests. Soil is modelled as 10-noded tetrahedral elements (PLAXIS 2020). The ground water level is 3 m below the ground surface. The properties used for the different soil layers are tabulated in Table 1.

Table 1: Soil properties for Hardening soil model.

Depth(m)	Soil type	ɣ(kN/m^3)	E_{ur}^{ref} (kPa)	E_{50}^{ref} (kPa)	E_{oed}^{ref} (kPa)
0~2.5	SF	18.84	27887	9296	13944
2.5~7.8	CL	17.66	30130	4184	2929
7.8~10	SM	18.76	50809	16936	25404
10~12.6	SM	18.76	59081	19694	29541
12.6~17.5	CL	18.02	16290	3694	2586
17.5~22.5	CL	17.81	17560	3263	2284
22.5~25	CL	17.81	22180	4456	3119
25~27	CL	17.81	15600	3469	2428
27~29.5	CL	18.41	12070	4060	2842
29.5~32	CL	18.41	21460	6061	4243
32~35.3	CL	18.41	13560	5767	4037
35.3~36.8	SM	19.33	33607	11202	16804
36.8~42.7	CL	19.16	18760	5681	3977
42.7~46.5	ML/SM	18.92	38233	12744	19116
46.5~70	GW	19	61980	20660	30990

Embedded beam type elements are used for pile. The properties used for pile in the analysis are shown in Table 2.

Parameter	Value
Unit weight, ɣ (kN/m^3)	25
Young's modulus, E (kPa)	13*10^6
Pile diameter, d_p (m)	1
Pile length, L_p (m)	48
Axial Skin resistance	Layer dependent
Maximum skin resistance, T_{max} (kN/m)	1*10^{12}
Maximum base resistance, B_{max} (kN)	1000

The generated finite element mess with medium coarseness factor is shown in Fig. 2. The number of nodes and soil elements generated are 602776 and 396875 respectively.

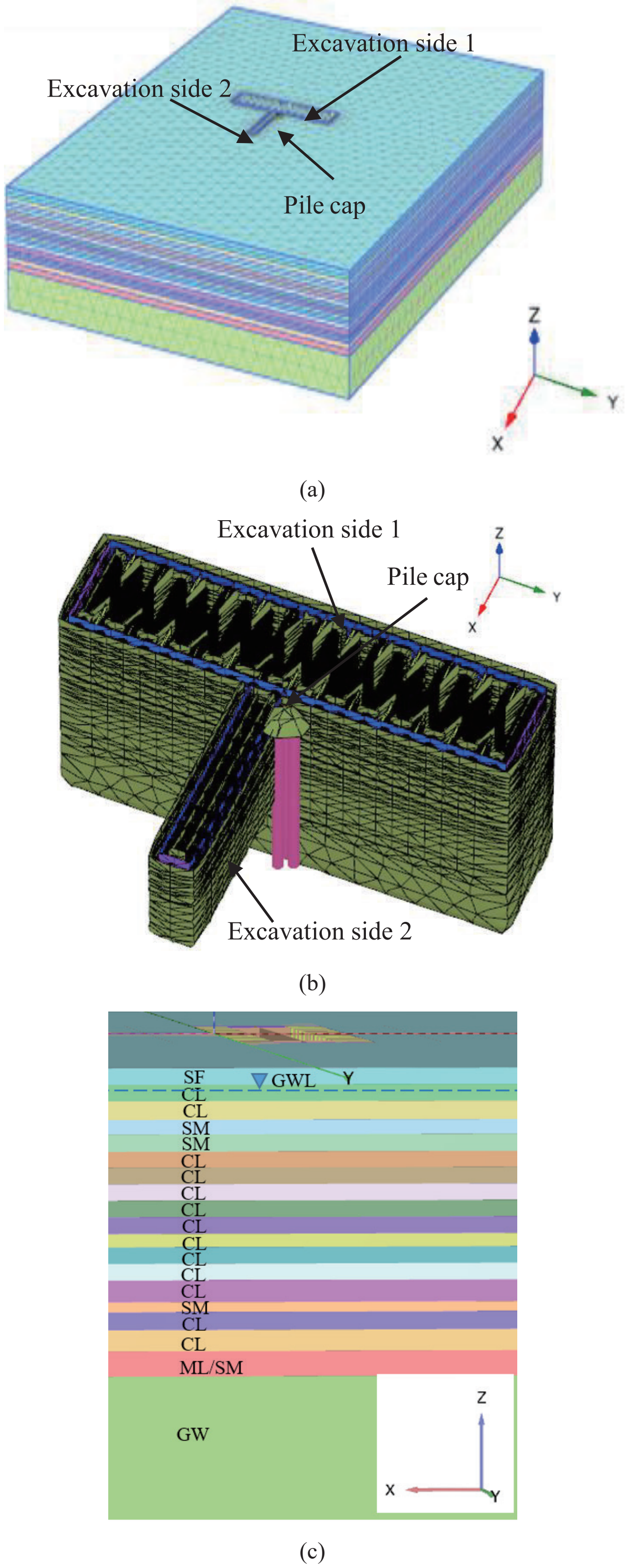

Fig. 2. Generated finite element mesh (a) 3-D view, (b) enlarged area near excavation and pile group and (c) soil layers.

2.2 Boundary conditions

For the displacement boundary condition, all the vertical sides are normally fixed, the base is fully fixed while the top is free to move in any direction. Hydraulically, no flow is allowed through the bottom surface. All the vertical sides and the top are open to allow water flow through them.

2.3 Steps for numerical modelling

In this study, the pile cap along with the piles is first positioned in the desired location and is subjected to working load before performing any excavation. Any excess pore water pressure generated due to the application of the working load is allowed to dissipate. Diaphragm wall along with the buttress walls are installed on the excavation side 1, followed by the steps shown in Table 3 to perform bottom up excavation. As excavation proceeds struts are positioned 70 cm above the excavated level in each stage. When excavation reaches the final stage of 24 m below GL, the excavation on side 1 is complete. Then the second side is excavated in the same way as the first up to -15 m. On the second excavation side, there is no buttress wall; only struts are placed 70 cm above each excavation level.

Table 3. Numerical modelling steps.

Steps	Description
1	Initial stress condition is established using k_0=1-sinφ'
2	Pile cap and piles are activated
3	Working load is applied on the pile
4	Excess pore water pressure generated due to the working load is allowed to dissipate
5	Diaphragm wall and buttress wall on excavation side 1 are activated
6	Excavation is done up to -3.7 m GL on 1st side
7	1st layer of Strut is installed 70 cm above the excavated level on 1st side
8	Steps 6 and 7 are repeated up to -24 m excavation depth
9	Diaphragm walls on excavation side 2 are activated
10	Excavation is done up to -3.7 m GL on 2nd side
11	1st layer of Strut is installed 70 cm above the excavated level on 2nd side
12	Steps 10 and 11 are repeated up to -15 m excavation depth

3 INTERPRETATION OF RESULTS

Fig. 3 shows the ground settlement curve for up to a distance of 100 m from the face of the diaphragm wall on excavation side 1. The section line is through the center of the pile cap, Section A-A shown in Fig. 1 and 1 m below the ground surface. As can be seen from Fig. 3, without any excavation, when only the working load is acting on the pile cap, the settlement of pile cap center is only 14.86 mm. When only side 1 is excavated, there is a considerable amount of settlement of 18.62 mm. The increase in settlement is almost 25.3% when one side excavation is carried out as compared to no excavation. In contrast to this, when second side is excavated after the first one, the settlement at pile cap center is 19.53 mm; which is only 4.9% of the increase due to the first side excavation.

The settlement along the depth through the pile cap center is shown in Fig. 4. In this case also, when side 1 is excavated there is a considerable amount of change in the settlement as compared to the one prior to excavation. But when side 2 is excavated, the change is negligible compared to the first one. At a depth of 24 m below ground surface (the final excavation depth of side 1) and 15 m (the final excavation depth of side 2), the settlement values are shown in Table 4. The increase in settlement at -24 m is 68.7% due to side 1 excavation and only 8.3% due to another excavation on side 2. Similarly, at 15 m depth below GL, the increase in settlement due to side 1 is 51.7% and that due to both side excavation is 6.2% as compared to side 1. Table 5 shows the increase in settlement due to excavation on one side as compared to settlement without any excavation; and also increase in settlement due to second side excavation as compared to first side.

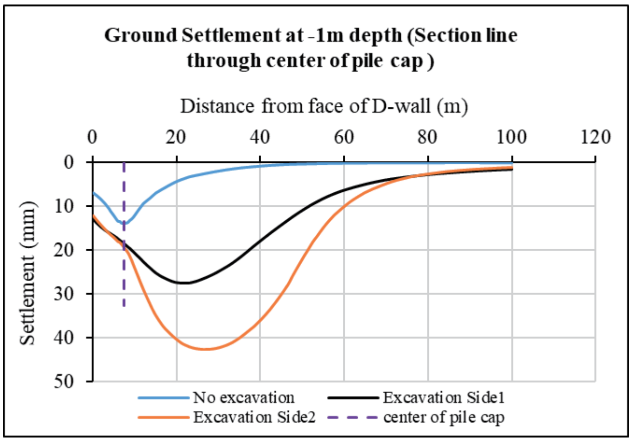

Fig. 3. Ground settlement curve.

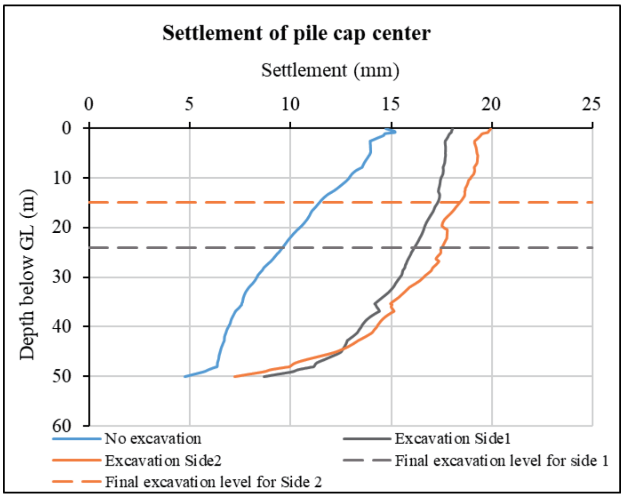

Fig. 4. Settlement along depth through pile cap center.

Table 4: Settlement values at pile cap center.

Case type	Settlement (mm)	
	At -24 m	At -15 m
No excavation	9.57	11.40
Excavation only on side 1	16.14	17.30
Excavation on two adjacent sides	17.48	18.38

Table 5: Settlement increase at pile cap center.

Case type	Settlement increase (%)		
	At -1 m	At -15 m	At -24 m
Increase from no excavation to excavation on side 1	22	51.7	68.7
Increase from excavation on side 1 to excavation on both sides	9	6.2	8.3

4 CONCLUSIONS

Because of unloading due to excavation, there is a change in the settlement of the adjacent soil. When one side of an existing pile cap is already excavated, then further excavation on another side does not have much influence on the settlement of pile cap. Also, in this case study, the side 1 excavation is deeper compared to side 2 and the deeper one has more influence on the pile cap. If the side 2 would have been deeper than side 1, then the excavation with major influence still needs to be studied.

Also, for Hardening soil model, plastic calculation does not take time into account even though time interval can be specified (PLAXIS 2020). Hence this study cannot interpret the change in ground deformation with time. If 3-D coupled consolidation analysis is carried out it can give a better understanding of the time profile of ground deformation.

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