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Investigating Lateral Displacement of Pile Groups Under Construction Loads and Excavation - A Case Study

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ABSTRACT

Piles in weak soils are sensitive to adjacent excavation and construction loads. Excessive lateral displacement of piles during construction adds shear and bending moment to the piles. This is of great concern because these additional lateral loads are sometimes not accounted for when designing piles, and the horizontal bearing capacity as well as shear strength of the piles is low. This paper presents a case study of a recent project with severe pile damage and large soil displacement during construction due to the installation of piles and excavating foundation pits. With the improper construction procedures, the piles were severely damaged, and have almost no bearing capacity before the construction of the superstructure even begins. On-site measured data were used as inputs for numerical simulations, and analyses were carried out to study the behaviors of pile groups affected by construction activities. The simulation was for each construction activity/stage as well as the whole construction process to determine the effects of excavation and construction/equipment loadings used for installed piles. The effects on the lateral displacement of piles and surrounding soil were quantified. The results from finite element analysis on the lateral deformation of piles are in good agreement with the measured data, with differences of about 5% to 10%. Several construction procedures are recommended, with recommendations made to mitigate pile damages and large soil displacement due to construction. With the recommended procedures, the lateral deformation of pile groups can be greatly reduced by at least 90% and pile damages can be eliminated.

Keywords: Lateral displacement; pile group; soft soil; numerical simulation.

INTRODUCTION

Lateral displacement and deformation of piles under permanent loads and service loads are considered in design and construction of deep foundations with great attention. However, lateral displacement of piles or pile groups due to the installation process and excavation of foundation pits is sometimes not considered properly. The lateral bearing capacity of piles is small compared to vertical bearing capacity, therefore, whenever subjected to lateral displacement of soil due to adjacent excavation and/or adjacent loads the chance for piles to get damaged is high.

Structural and geotechnical failures as a result of large lateral displacements or excessive differential settlement are not uncommon. Large deformation and displacement of piles or pile groups are of concern for designers and contractors in the geotechnical engineering field. In some cases, large lateral deformation during pile installation can cause a reduction on pile lateral and vertical bearing capacity or even breakage of the piles before loads from super structures are applied on the piles.

The requirements of the maximum lateral deformation of the driven piles or drilled shaft were mentioned in current design manuals such as ASSHTO (2020) and FHWA (2018). The maximum lateral deformation at the top of shaft, based on the FHWA (2018) design guideline, does not exceed 1/2 inch.

Loads from soil displacement due to construction procedures are often neglected or difficult to predict during the design phase. Excessive soil displacement can cause unexpected damages to the installed piles or structures nearby. A pile or pile group can take large vertical loading but may fail under much smaller lateral load or lateral displacement, as showed in experimental tests conducted by Peng et al. (2010), Aland Sabbagh (2019), Sark et al. (2020). The interactions between soil-pile, pile-pile in group, or pile cap together with free head and fixed head have been studied by Al-Abdullah and Hatem (2019), Al-Abboodi and Sabbagh (2019). Free head condition is more suitable to study the behaviors of piles or pile groups under adjacent loads and excavation conditions during construction sites and will be used for this study.

Research on the pile displacement due to lateral displacement of soil adjacent to cut or fill slopes or excavations were conducted. *P-y* method is often used to analyze load-displacement relationship of piles as mentioned by Duncan et al. (1994); Ooi et al. (2004); Zhang et al. (2013). Methods to analyze the behaviors of a pile or pile groups under lateral soil displacement were discussed by Ooi et al. (2004). Lateral movement of soil and lateral deformation of piles under excavating is a complex problem. The problem becomes even more complex when considering the loads of installation equipment acting together with excavation of adjacent areas. Full-scale tests on this subject are high-cost and require complicated instrumentation. Other researchers conduct the studies using numerical method to simulate tests or actual problems using 2-D or 3-D simulations include Kahyaoglu (2009), Peng (2010), Hirai (2016), Nguyen et al. (2020). Taghavi et al. (2016) and Zhao et el. (2021) also used centrifuge tests to study this subject. However, these tests cannot fully describe the behaviors of the piles on site due to size and gravity effects.

This paper presents a case study related to lateral deformation of pile groups under excavation and construction loads with measured data of the damaged piles from a construction site. With the measurements collected at the time of failure, this case can be considered as a full-scale test. Analysis and discussions of the failure of the piles are presented, and numerical analysis was carried out to analyze the effects of construction procedures on pile head displacement under the in-situ condition. Plaxis 2D was used to simulate the pile groups and excavation slope from the project, and different construction scenarios were modeled and analyzed for recommendations on construction procedures.

SITE DESCRIPTIONS

The project is a shopping mall and housing complex in Bac Lieu, Vietnam. The plan view of the project, with the positions of boreholes HK2 and HK3 - the area with the observed large pile displacement and soil cracks - are in Figure 1. Soil profile presented in Figure 2 shows that the ground consists of approximately 10 intermittent different soil strata, with the top 20 m of *very* soft sandy clay layers, with shear strength as low as 12 kN/m^2, underlain by stiffer clay layers up to the depth of the boreholes of 60-70m. Ground water table was at depth of 0.5 m. Soil properties are presented in Table 1.

The recommended foundation is prestressed reinforced concrete piles with outer diameter of 500 mm, inner diameter of 350 mm, and average length of 48 m. The installing machine, model ZYC 800B with hydraulic jacks attached on the rigs were used for pile installation, has the total weight of about 400 tons and a base area of 14m x 8.56 m (length x width). Pile arrangement is shown in Figure 3. The base of pile caps is design to be at depth of 4m below the ground surface, therefore, soil excavation is needed for the construction of the pile cap was also about 4m below. During the excavation, water was drawn down to the depth of 4m.

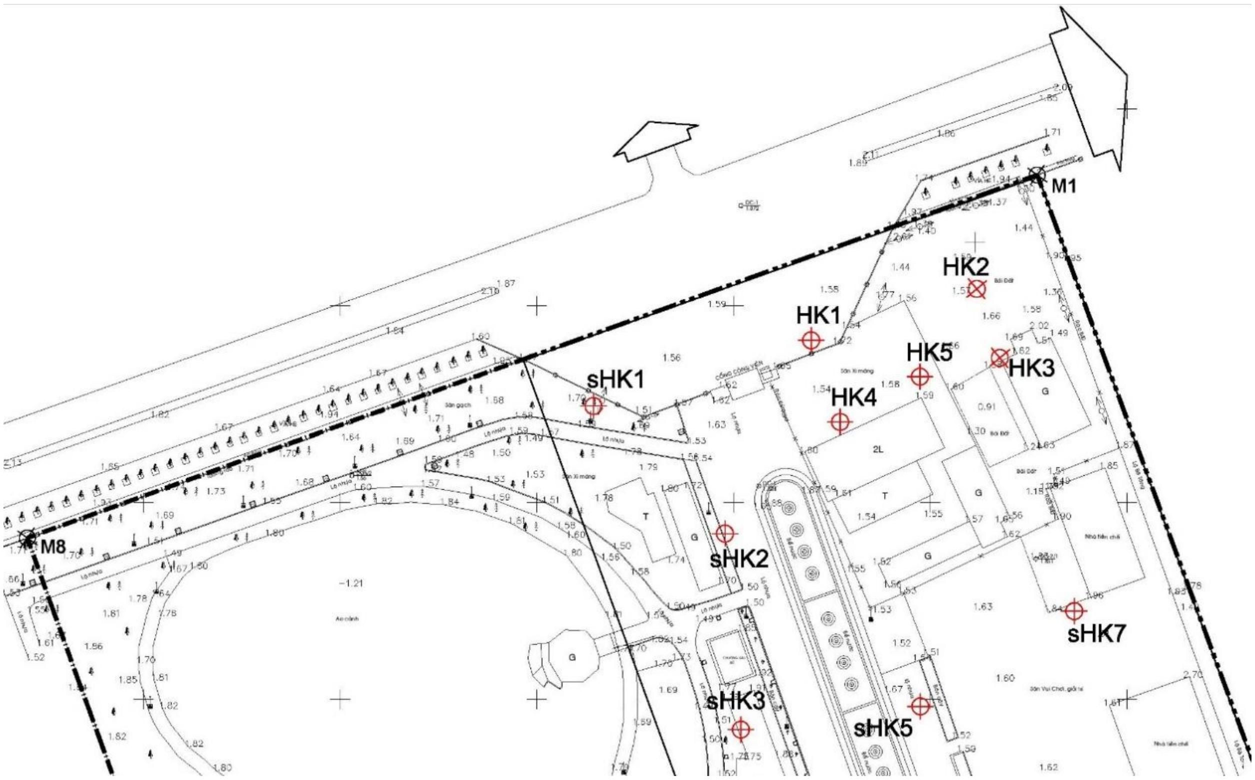

Figure 1. Plan view of boreholes

CONSTRUCTION PROCEDURE

Figure 3 shows the direction of the excavation and the installing machine route. Summarize of the construction stages are: 1) Pile installation Stage 1, with all piles in groups at Axes A, B and C were hydraulic jack installed. This stage was finished on Jan 17th 2020; 2) Pile installation Stage 2 and soil excavation, with piles in Axis D scheduled to be installed at the same time with excavation at Axis A. The excavation at Axis A was finished early Feb 2020. 3) Exacavation of Axis B was scheduled to finish on February 12^{nd} 2020, at the time the installing machine was installing piles at Axis D. Then large pile head displacement and failure were noticed and the construction paused.

FAILURE OBSERVATION AND MEASURED DATA

When area B2 was excavated, large lateral displacementss of pile head were noticed, especially pile groups B2 and C2 (on February 12, 2020) and measured data were recorded at the same day. At that time, the intalling machine was working at Axis D, and the excavating was almost done at Axis B. Most piles visibly leaned side way from the vertical positions, with the displacement of the pile heads up to 2.2 m. The large lateral displacement of piles and soil can be seen in Figures 4 and 5, with the measured data of the maximum lateral displacement of piles at groups B2 and C2 are shown in Table 2. Pile integrity test (PIT) was used to discover the crack locations along the piles. Most of the piles that have the head displacement of more than 1.6 m were cracked. The cracks were found at about 5.8 m from the top of the piles, or 8.8 m from the ground surface. The soil moved laterally, causing cracks on the road as shown in Figure 6. The combined effects of excavation and installing load near the piles could be the major cause of the large lateral pile displacement and soil movement.

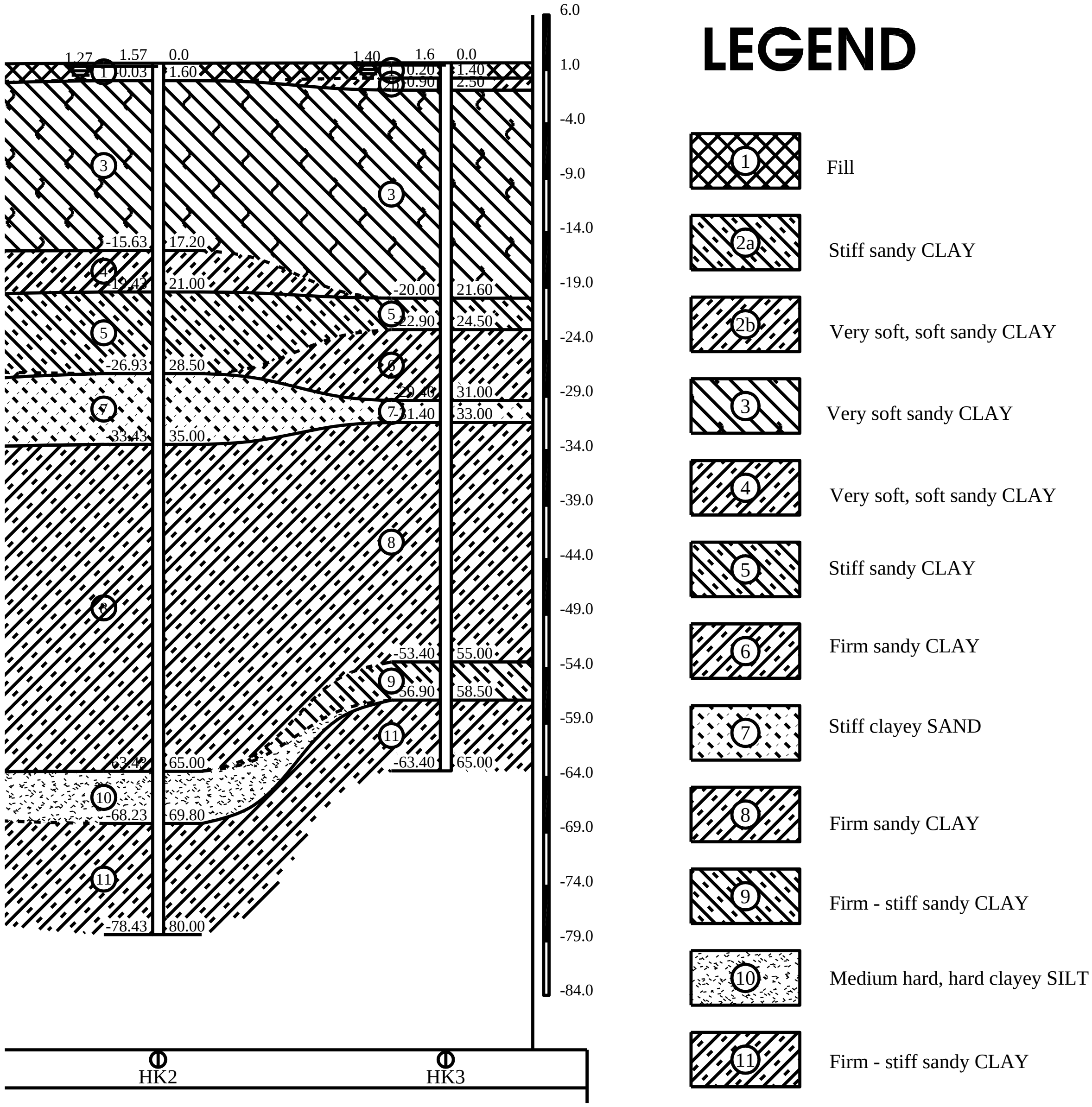

Figure 2. Soil profile at boreholes HK2 and HK3

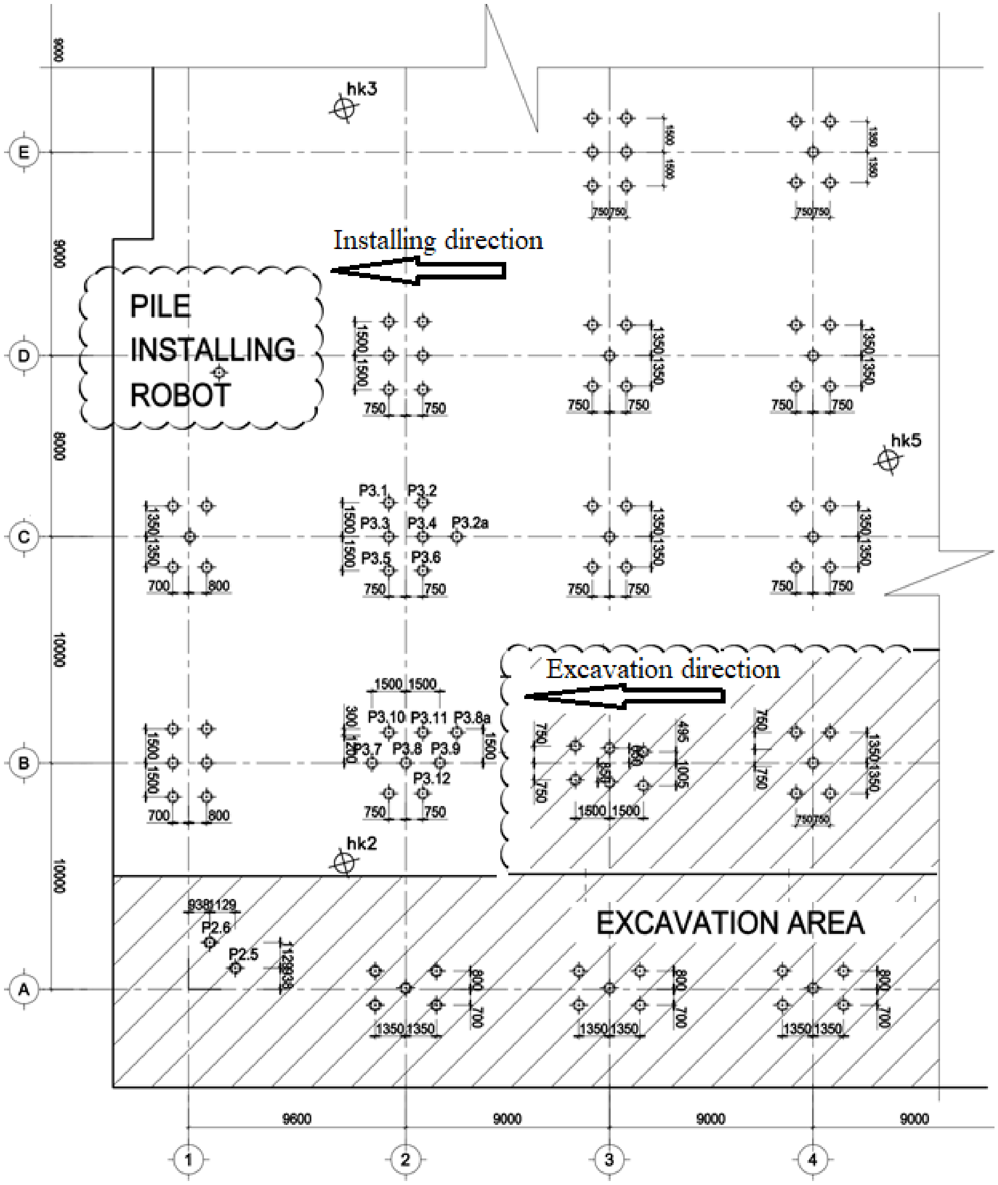

Figure 3. Pile arrangement and direction of excavation and installing machine

Figure 4. Pile displacement at Axis B during excavation

Figure 5. Pile displacement at Axis A during excavation

Figure 6. Road with soil cracks near the excavation

Table 1. Primary soil properties

Soil layer No	Top Fill	2a. Sandy Clay	3. Very soft clay	4. Sandy Clay, soft	5. Sandy Clay, stiff	6. Sandy Clay, stiff	7. Clayed Sand	8. Mix sandy clay and sand, very stiff
FE Soil Model	HM	HM	HM	HM	HM	HM	HM	HM
	Drained	Un-drained	Un-drained	Un-drained	Un-drained	Un-drained	Drained	Un-drained
γ_{unsat} (kN/m^3)	18.0	19.3	15.7	18.1	19.0	20.0	20.4	18.8
γ_{sat} (kN/m^3)	18.5	20.0	16.0	18.5	19.5	20.5	21.0	19.5
ν	0.30	0.495	0.495	0.495	0.495	0.495	0.3	0.495
E_{50}^{ref} (kN/m^2)	24000	13400	4800	9600	32560	26800	38320	47880
s_u (kN/m^2)		33.5	12	24	81.4	67		119.7
c_{ref} (kN/m^2)	5.00	-	-	-	-	-	15.6	-
Φ (deg)	26.0	-	-	-	-	-	21	-

Table 2. Measured pile lateral displacement

Pile Group	Row	Pile Number	Max Lateral Displacement (m)	Avg. Lateral Displacement
B2	Row 1	P3.10	1.017	1.195
		P3.11	1.455	
		P3.8a	1.114	
	Row 2 (middle row)	P3.7	0.585	0.636
		P3.8	0.731	
		P3.9	0.592	
	Row 3	T1	0.334	0.302
		P3.12	0.271	
		Average	0.762	
C2	Row 1	P3.1	1.747	
		P3.2	2.190	
	Row 2	P3.3	1.605	1.451
		P3.4	1.298	
		P3.2a	N/A	
	Row 3	P3.5	1.62	
		P3.6	1.768	
		Average	1.604	

FINITE ELMENT ANALYSIS

Plaxis 2D software was used to model two pile groups B2 and C2 and the excavation from this project to find pile head displacements and compare them with the measured data. Global stability analysis was carried out using "c-phi reduction" function from Plaxis to find the factor safety of the excavation and compared with what was observed at the site. The area along Axis 2 (Figure 3) was modeled as shown in Figure 7. Soil properties of all soil layers input in the model are in Table 1. For the 2D model, all input data for piles were used as shown in Table 3. Stages of construction at the field were modeled using "phases" in Plaxis to account for time factor.

Table 3. Equivalent pile properties

No.	**Pile**	**EA** [kN/m]	**EI** [kNm²/m]	**w** [kN/m/m]	**ν** [-]
1	Pile D500 S = 1.5m	3.469E6	4.511E4	0.916	0.15
2	Pile D500 S = 1.35m	3.854E6	5.012E4	1.018	0.15

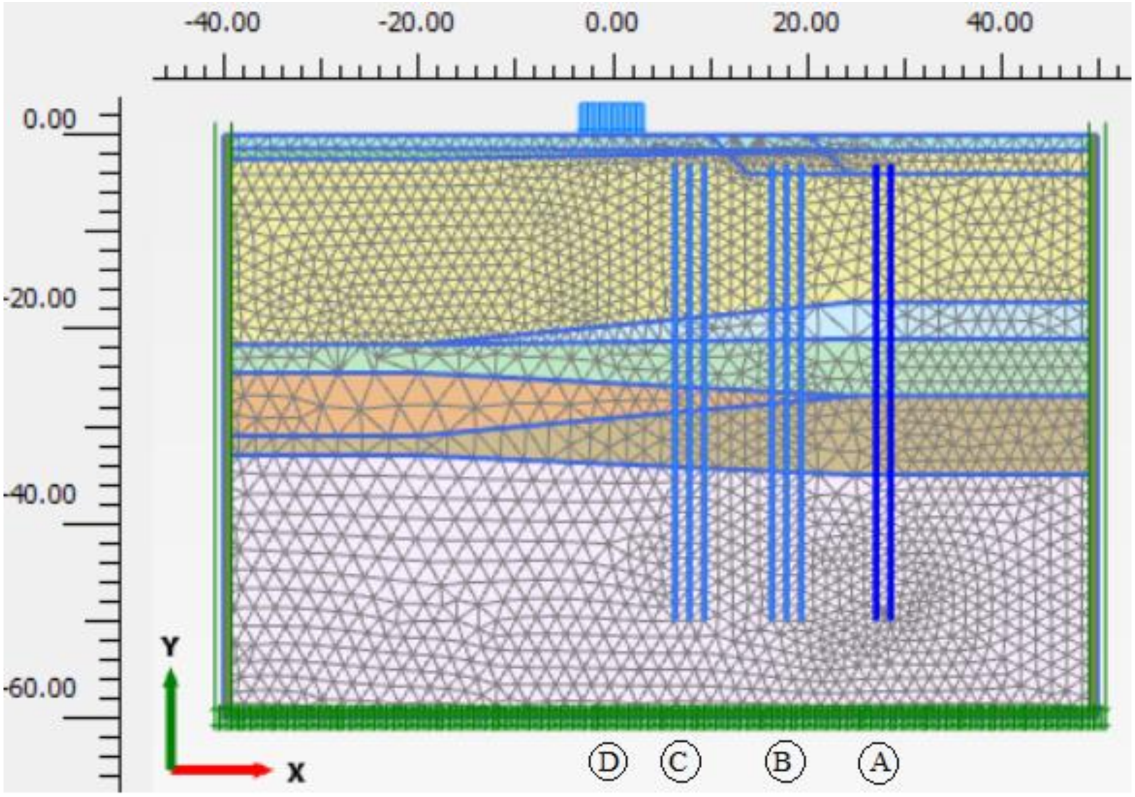

Figure 7. The FE model of piles, excavation, and installing machine load

Loading and soil condition: The equivalent load from the pile-installing machine is 32.7 kN/m^2 as calculated from a total load of about 400 tons acting on the base area of 14 m x 8.56 m. The soil profile of borings HK2 and HK3 used for the FE analyses are shown in Figure 2. The pile heads were about 3.0 m below the ground surface. During excavation at Axes A and B, the water table was lowered to the bottom of excavation at 4.0 m below the ground surface.

Finite Element simulation of field conditions for different scenarios:

Pile head displacements: The FE analyses were carried out for four cases corresponding to four loading and construction phases at the field:

Case 1: The application of only the installation machine load of 32 kPa at Axis D without excavating at Axis A or B to see the effect of the installing load on the installed piles (Figure 8a).

Case 2: Excavation at Axis A area without any loads (Figure 8b).

Case 3: Excavation at Axes A and B area without any loads (Figure 8c)

Case 4: Combination of both installing load and excavation at both Axes A and B (Figure 8d).

Results and discussion:

Case 1 was analyzed to understand the effects of the installation equipment load only, without excavating the surrounding soil, the model shown in Figure 8a was used to determine the displacement of piles and surrounding soil. The resulting displacement of typical piles at group B2 and C2 are presented in Figure 9. The simulation results show that the maximum lateral displacement of the pile heads at groups B2 and C2 are as small as 0.009 m and 0.012 m, correspondingly. These displacements are acceptable, and these values are less than 1.5% of the measured maximum displacement of the pile heads at the site, which are 0.636 m and 1.451 m respectively, which were caused by both pile installation equipment load and the excavation.

Case 2 and Case 3 were analyzed to find the effects of excavation only. It was found that the lateral displacement of piles due to excavation at axes A and/or B is relatively large, the maximum lateral displacement of pile heads at groups B2 and C2 are 0.174 m and 0.212 m, correspondingly. These values are much larger than what obtained from Case 1, showing that the effect of excavation is larger than that of installing load. The simulated pile head displacements are about 15% to 27% of the maximum measured data at the field.

Case 4 is to examine the combination effects of both installing load and excavation. This case models the actual activities at the site with the pile head displacements that were recorded. For both groups B2 and C2, good agreement was found between the simulation data and the measured data for pile head displacements. The difference between simulated and measured data is about 5% to 10%. In the field, several piles were collapsed. PIT was used and the location of detected cracks of piles in group C2 are at about 8.8m from the ground surface. The piles were broken because maximum material strength (bending moment or shear) was reached due to the large lateral displacement. From the numerical analyses, piles in groups B and C have the maximum bending moment at the depth of 18.0 m from the ground surface (Figure 10). The maximum shear stress was at the depth of 9.5 m. It is possible that the piles failed by shear, since 9.5 m is at the depth close to the crack locations of 8.8m. All FE results of four cases and comparison were summarized in Table 4 and Figure 9. Note that the comparisons were made on piles that are not damaged or cracked, because displacements after failure cannot be predicted.

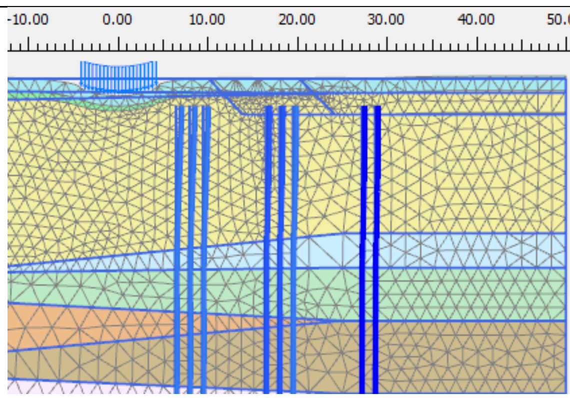

Figure 8a. Case 1

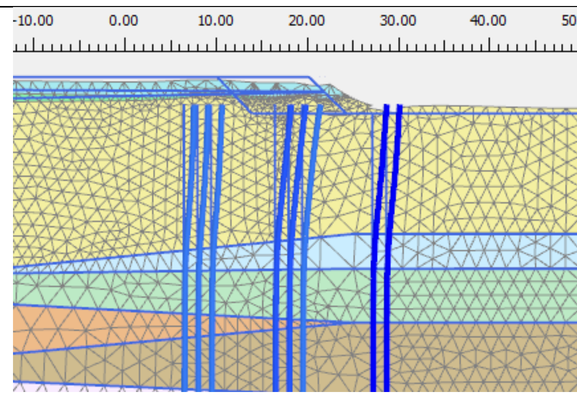

Figure 8b. Case 2

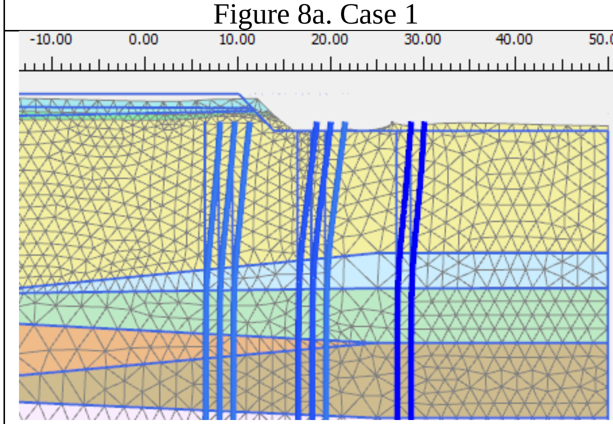

Figure 8c. Case 3

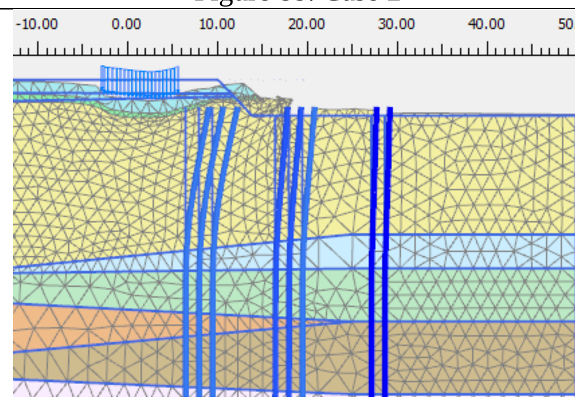

Figure 8d. Case 4

Figure 8. Deformed mesh for 4 cases

Table 4. FE Results and Comparison with the Measured Data

Pile Group	Pile Row	Maximum Lateral Displacement Dx(m) at the pile top					
		Case 1	**Case 2**	**Case 3**	**Case 4**	**Measure data**	**Difference (%)**
B2	Row 1 (front)	0.0091	0.177	0.209	0.706		
	Row 2 (middle)	0.0087	0.188	0.212	0.703	**0.636**	**-10 %**
	Row 3	0.0084	0.199	0.216	0.701		
C2	Row 1 (front)	0.0125	0.111	0.165	1.342		
	Row 2 (middle)	0.0121	0.115	0.174	1.368	**1.451**	**5.7%**
	Row 3 (rear)	0.0114	0.119	0.184	1.419		

Another possible scenario analyzed was to excavate soil in layers and tiers, after pile installation. The thickness of each excavated soil layer should be small to minimize the effects on the installed piles. Excavation by layers and tiers can reduce the lateral earth pressure acting on piles. Four excavation layers of 1m thick with 2 tiers were modeled to see how the pile displacements reduce. Excavation with two tiers extending 10 m from the pile edge are modeled as shown in Figure 11. For this scenario, the lateral displacement also reduced significantly, down to 0.068m for pile group B2 and 0.105m for pile group C2 (Figure12), which equal to 8.5% and 7.1% of the measured displacement at the site. In practice, two or more tiers of excavation may help alleviate the lateral displacement of piles.

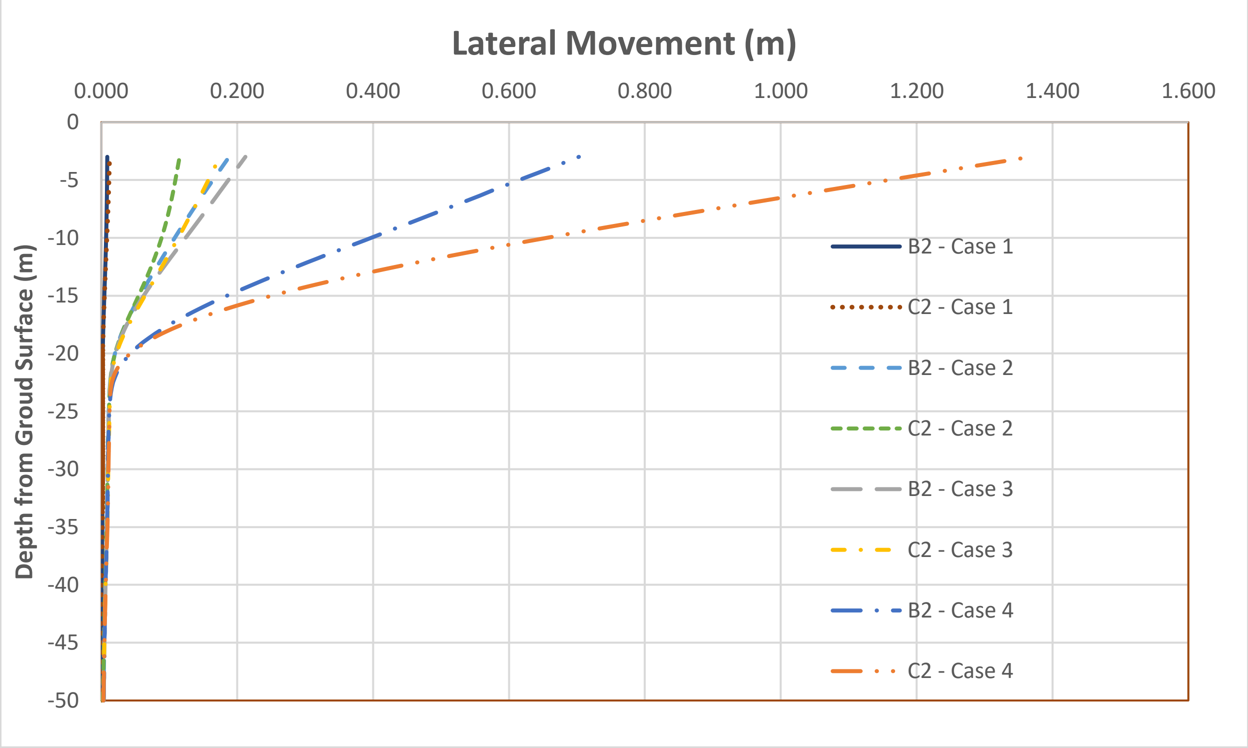

Figure 9. Lateral displacement of pile groups B2 and C2. Case 4 has largest displacements.

Global stability of the excavation: The configuration of the excavation with installed piles and loads are shown in Figure 8 with the excavation slope of 45 degrees, and depth of 4 m. To determine the factor of safety of the slope due to the excavation, the "C-phi reduction" function from Plaxis was used. With the installing load of 32 kPa, the excavation slope reached near critical condition, with the calculated factor of safety of 1.02. When the load increased to the actual value of 32.7 kPa, the soil collapsed, and FS should be less than 1.0. The simulation results matched with what was observed at the site, when soil moved laterally and the roads around the excavation show cracks as shown in Figure 6.

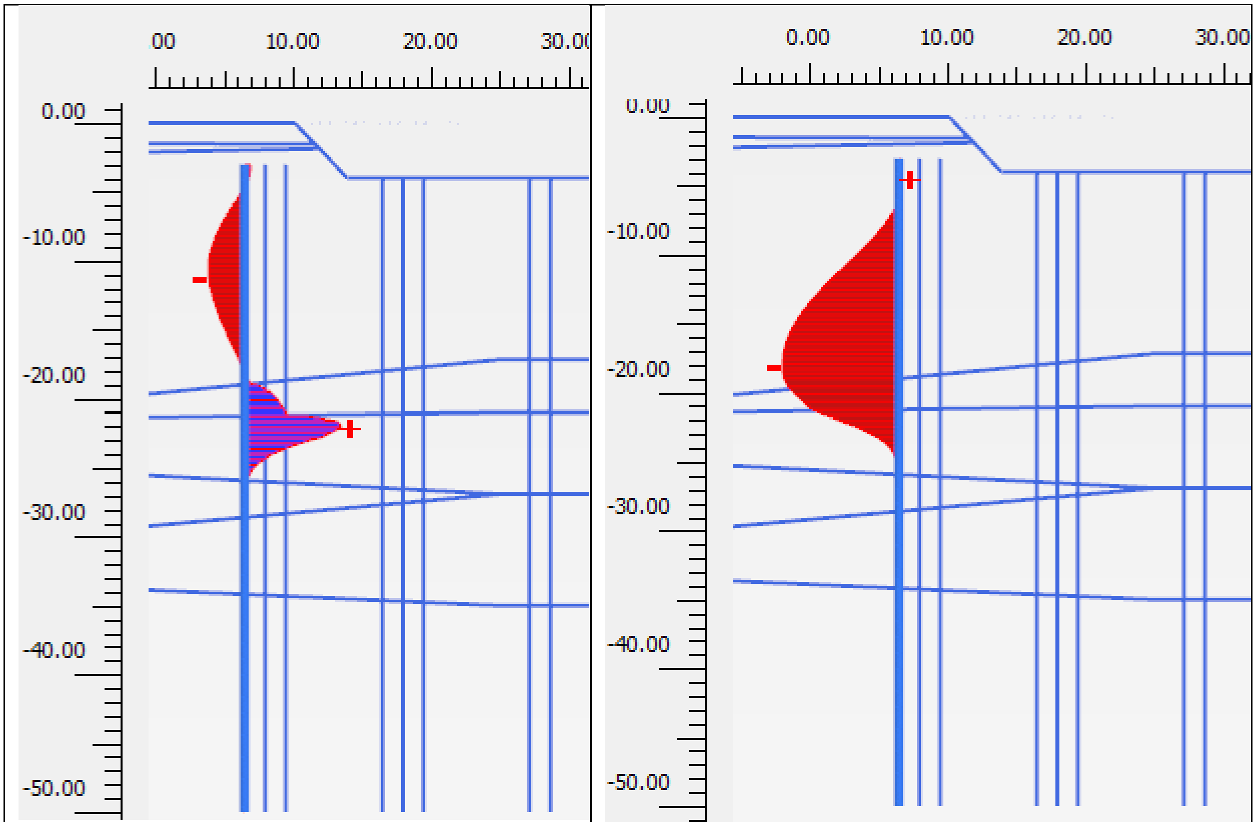

Figure 10a. Shear stress at pile row 1 in group C2 (Q_{max} = 140kN/m)	Figure 10b. Bending Moment at pile row 1 in group C2 (M_{xmax} = 423 kN m/m)

Figure 10. Internal stress profile of piles row1 at Group C2 for case 4

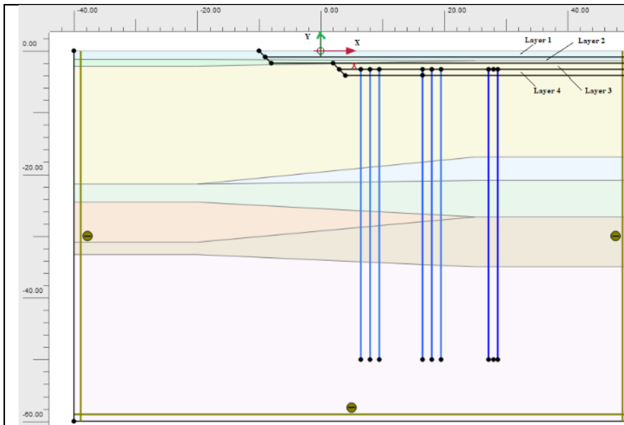

Figure 11a. Recommended model

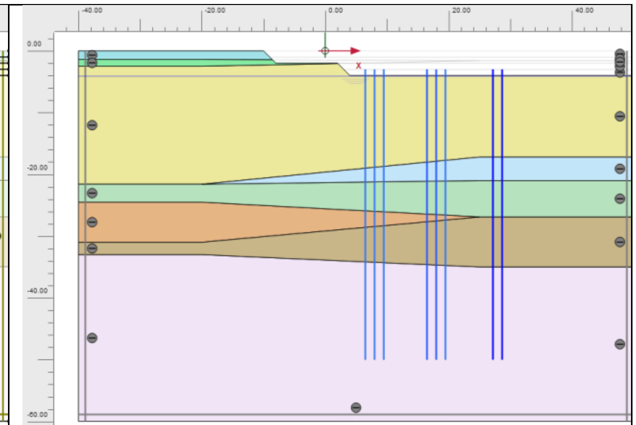

Figure 11b. Excavation steps with 4 layers

Figure 11. FE model for recommended construction procedure.

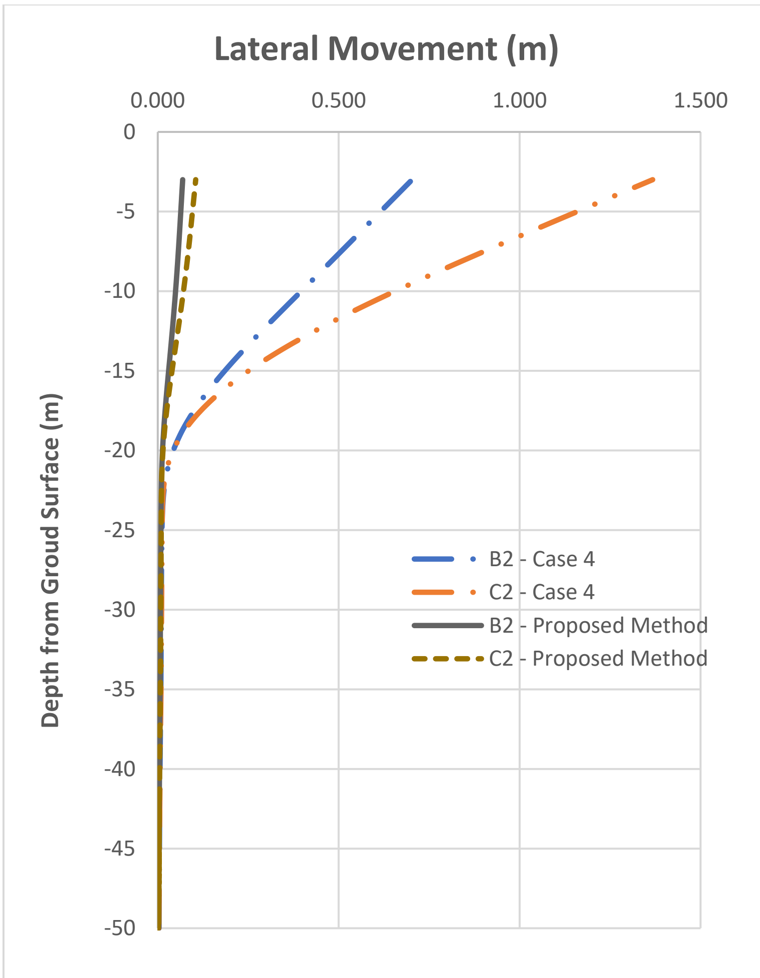

Figure 12. Comparisons of pile lateral displacement of recommended and used procedures

RECOMMENDED CONSTRUCTION PROCEDURES

Piles in weak soils are sensitive to adjacent excavation and lateral loads. Excessive lateral displacement of piles during construction add shear and bending moment to the piles, which is dangerous because the additional lateral loads are sometimes not accounted for when designing piles, and the horizontal bearing capacity as well as shear strength of piles is low. After understanding the effects of installing load, excavation, and combination of both load and excavation near the installed piles, it is clearly recognized that the construction procedure is of critical importance. For this type of project, recommended construction procedures are as follows:

Procedure 1: Excavate the soil first for all areas, then install piles. This reduces almost all lateral displacement of installed piles. This is the optimum solution.

Procedure 2: Install all piles first, then excavate soils for the whole foundation area by layers of less than 1m each (Figure 11). The thickness of each excavation layer should be determined based on the specific soil conditions and the adjacent structures at the construction site. This procedure can eliminate collapse or damage of piles and reduce over 90% of the excessive lateral displacement of the piles (Figure 12).

Procedure 3: In case of construction time restrictions, when pile installation and excavation need to proceed at the same time, keep the distance between the pile installation equipment and the edge of the excavation greater than two times the excavation depth. The distance should be determined based on soil conditions and adjacent loads or equipment, types of excavation, etc. The excavation slope should be far enough at least 5m from the piles to reduce the excessive lateral displacements of the installed piles. If there is no space for excavation slope, sheet piles can also be used but it is costly.

CONCLUSION

This paper presents a case study, which can also be considered as a full-scale test, on the effects of construction procedures on lateral pile displacement and soil movement. Four cases with different loading and excavation scenarios were modeled using Plaxis to understand the individual or combined effects of loading and excavation. The results from numerical analyses are in good agreement with the measured data, with accurate prediction of factor of safety for global stability of excavation slopes, and with the differences of around 5% to 10% for lateral displacement of the pile heads. Recommendations were made for construction procedures, which can be applied for similar projects of this type with weak soil conditions, to reduce the risk of failure or/and the excessive lateral displacement of piles before subjected to actual loads from superstructures. The recommended procedures can mitigate more than 90% the pile head displacement that can cause pile damages during construction. A specific construction procedure must be planed and designed carefully to reduce unnecessary damages.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO) (2020), LRFD Bridge Design Specifications.

Al-Abboodi, I. and Sabbagh, T.T. (2019). *Numerical Modelling of Passively Loaded Pile Groups*, Geotechnical and Geological Engineering Journal, Springer, 37, 2747–2761.

Al-Abdullah, S.F.I. and Hatem, M.K. (2019). *Behavior of Free and Fixed Headed Piles Subjected to Lateral Soil Displacement*, Ferrari A., Laloui L. (eds) Energy Geotechnics. SEG 2018. Springer Series in Geomechanics and Geoengineering, Springer, 67-74.

Duncan, J. M., Evans, L. T., and Ooi, P. S. K. (1994). *Lateral load analysis of single piles and drilled shafts*, Journal of Geotechnical Engineering, 120(6), 1018–1033.

Federal Highway Administration (FHWA) (2018). *Drilled Shafts: Construction Procedures and LRFD Design Methods*, FHWA-NHI 18-024.
Hirai, H. (2016). *Analysis of piles subjected to lateral soil displacements using a three-dimensional displacement approach*, International Journal for Numerical Analysis Methods in Geomechanics, 40, 235–268.
Kahyaoglu, M. R., Imancli, G., Ozturk, A.U., Kayalar, A. S. (2009). *Computational 3D finite element analyses of model passive piles*, Computational Material Science 46, Issue 1, pp:193–202.
Nguyen, N. T., Tran, D. H., and Hoang, D. H. (2020). *Report on verification of pile installation at Complex center in Bac Lieu*, Vietnam Institute for Building Science and Technology, Hanoi, Vietnam.
Ooi, P. S. K., Chang, B. K. F., and Wang, S. (2004). *Simplified Lateral Load Analyses of Fixed-Head Piles and Pile Groups*, Journal of Geotechnical and Geoenvironment Engineering, Vol. 130, No. 11, November 1, 2004.
Peng, J.R., Rouainia M., and Clarke, B.G. (2010). *Finite element analysis of laterally loaded fin piles*, Computers and Structures Journal, 88 (2010) 1239–1247.
Plaxis PV (2016). *Geotechnical Software Manual*.
Sakr, M.A., Azzam W.A., Wahba M.A. (2020). *Model study on the performance of single-finned piles in clay under lateral load*, Arabian Journal of Geosciences, (2020) 13:172.
Taghavi, A., Muraleetharan, K., Miller, G., and Cerato, A., (2016). *Centrifuge Modeling of Laterally Loaded Pile Groups in Improved Soft Clay*, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 142, Issue 4.
Zhang, L., Zhao, M., and Zou, X., (2013). *Elastic-Plastic Solutions for Laterally Loaded Piles in Layered Soils*, Journal of Engineering Mechanics, Vol. 139, Issue 11 (November 2013) https://doi.org/10.1061/(ASCE)EM.1943-7889.0000580.
Zhao, R., Leung, A. K., Knappett, J., and Robinson, S., (2021). *Nonlinear Lateral Response of RC Pile in Sand: Centrifuge and Numerical Modeling*, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 147, Issue 6 (June 2021).