LATERAL MOVEMENT OF PILE GROUP DUE TO EXCAVATION AND CONSTRUCTION LOADS
(*Case study*)

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Abstract: *This paper presents a numerical method for analyzing the behavior of pile groups under construction of installing piles and excavating conditions. The numerical modeling and the measured data from construction sites were used for analysis. In the case study, the results of the lateral movement of piles from numerical analyses are in good agreement with the measured data, with differences of around 7.2% and 1.6%. Each incidence and whole construction process were modeled to determine the effects of excavation and equipment loadings for installing piles on the lateral movement of piles and surrounding soil. With the improper construction procedures, the piles can be easily damaged during construction. To mitigate pile damages due to construction, a proposed construction procedure is presented in this study and recommended for use. With the proposed procedure, the lateral movement of pile groups can be greatly reduced by at least 80% and the pile damages will be eliminated.*

Keywords: *Lateral movement, pile group, soft soil, FE analysis.*

Tóm tắt: *Bài báo này trình bày phương pháp số để phân tích ứng xử của nhóm cọc trong điều kiện thi công hố đào và hạ cọc. Mô hình số và dữ liệu đo được từ hiện trường được sử dụng để phân tích. Trong nghiên cứu điển hình, kết quả chuyển dịch ngang của cọc từ các phân tích số rất phù hợp với dữ liệu đo thực tế, với sự khác biệt khoảng 7,2% và 1,6%. Mỗi sự cố và toàn bộ quá trình thi công được mô hình hóa để xác định ảnh hưởng của quá trình đào và tải thiết bị để hạ cọc đến chuyển dịch ngang của cọc và đất xung quanh. Với việc thi công không đúng quy trình, cọc có thể dễ bị hư hỏng trong quá trình thi công. Để giảm thiểu hư hại cọc do thi công, một quy trình xây dựng được đề xuất trình bày trong nghiên cứu này và được khuyến nghị sử dụng. Với quy trình đề xuất, chuyển dịch ngang của các nhóm cọc có thể giảm đáng kể ít nhất 80% và các hư hỏng của cọc sẽ được loại bỏ.*

1. Introduction

Soil movement is a big concern for engineers in the geotechnical engineering field. The effects of lateral movement are even more dangerous for substructures and existing buildings in these areas. The lateral movement of soil and other geo-structures due to adjacent excavation and/or loads has been studied widely. Loads may be permanent loads from superstructures or construction equipment acting during construction. The permanent adjacent loads are usually considered during the design process, but the loads during construction are often neglected or unforeseen. This can cause a lot of unexpected damages to the installed piles or structures nearby due to large soil movement. A single pile or pile group is strong under vertical loading but remains very weak under lateral loading or lateral movement. A number of limitations were identified as possible reasons behind the overestimation of the predicted deflections. Experiment tests including Peng et. al. (2010), Aland Sabbagh (2019), Sark et al. (2020) show the small lateral strength of pile under lateral loading and movement. The interactions between soil-pile, pile-pile in group, or pile cap have studied together with free and fixed head by AL and Hatem (2019). The behavior of piles or pile groups with free head under adjacent loads and excavation is more suitable with the conditions during construction sites and will be presented in detail in this paper.

Lateral movement of pile and soil or lateral deformation of piles under excavating is a complicated problem. The problem is more complicated if considering the loads of installing equipment acting together with excavation of adjacent areas. Not much data from full-scale tests were performed because of their cost and complicated instrumentation. Therefore, many studies used numerical analyses for simulating the tests or actual problems. The numerical analyses may use 2-D or 3-D simulations Kahyaoglu (2009), Peng (2010), Hirai (2016), Nguyen et al. (2020).

To understand more about this topic, a case study in this paper related to lateral deformation of pile groups under excavation and construction loads will present the measurement data of the pile damages from an actual construction site. It can be considered a full-scale test because it was measured at the time the failure condition was reached.

2. Measure data and FE Analysis

In this paper, the large lateral movement of pile groups due to excavation and construction loadings were simulated using the Finite Element (FE) method (Plaxis 2D). The FE results were compared with the actual lateral pile movement at the construction site.

Introduction to the project: The observed lateral movement of pile groups at a construction site will be present in this paper. The construction project is a Shopping Mall and housing Complex in a Southern Province of Vietnam. The proposed foundations are pile groups (PHC500A) with the pile diameter of 50 cm, and the average length of 48 m, material bearing capacity is 190T. The distribution of the pile group and the current damage of pile groups will be discussed in detail.

Soil conditions: The plan view of investigated borehole distribution and the soil profile with depths are shown in Figures 1 and 2.

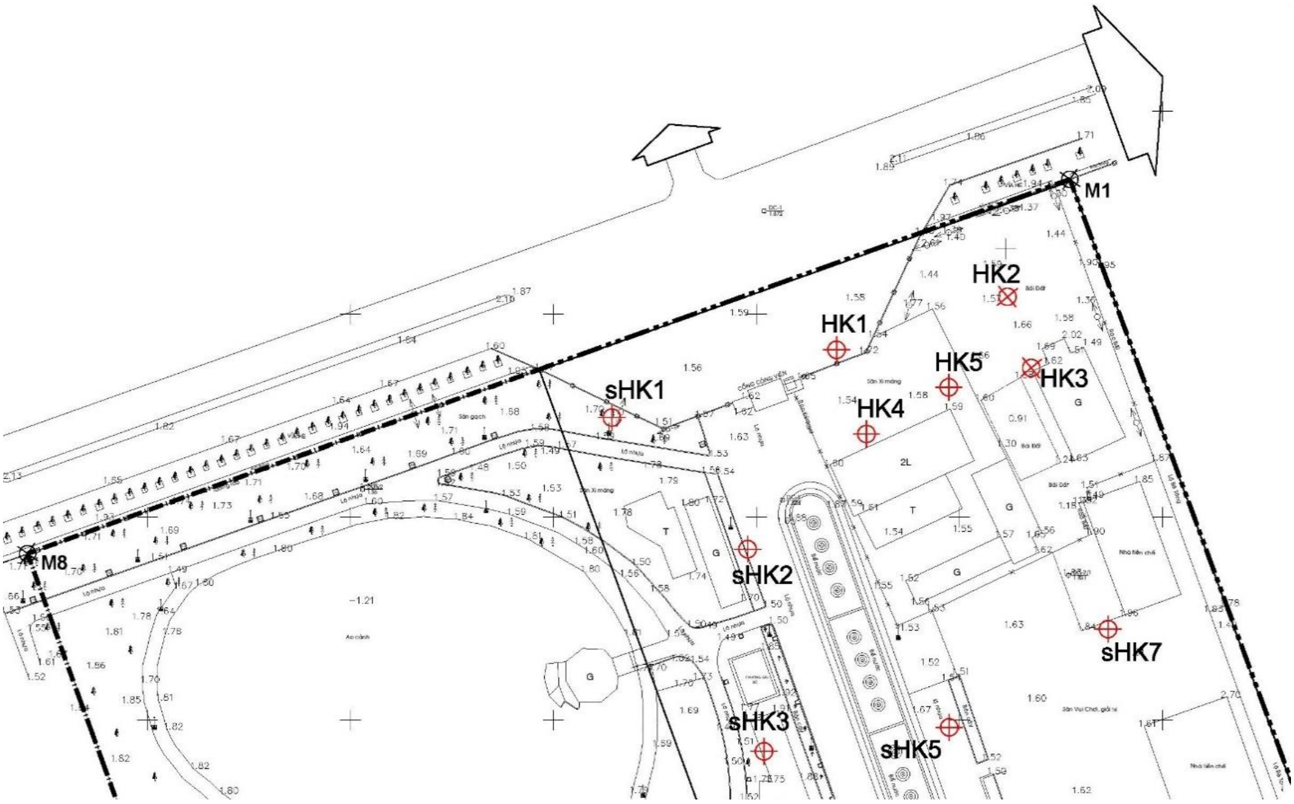

Figure 1. *Plan View of Boreholes*

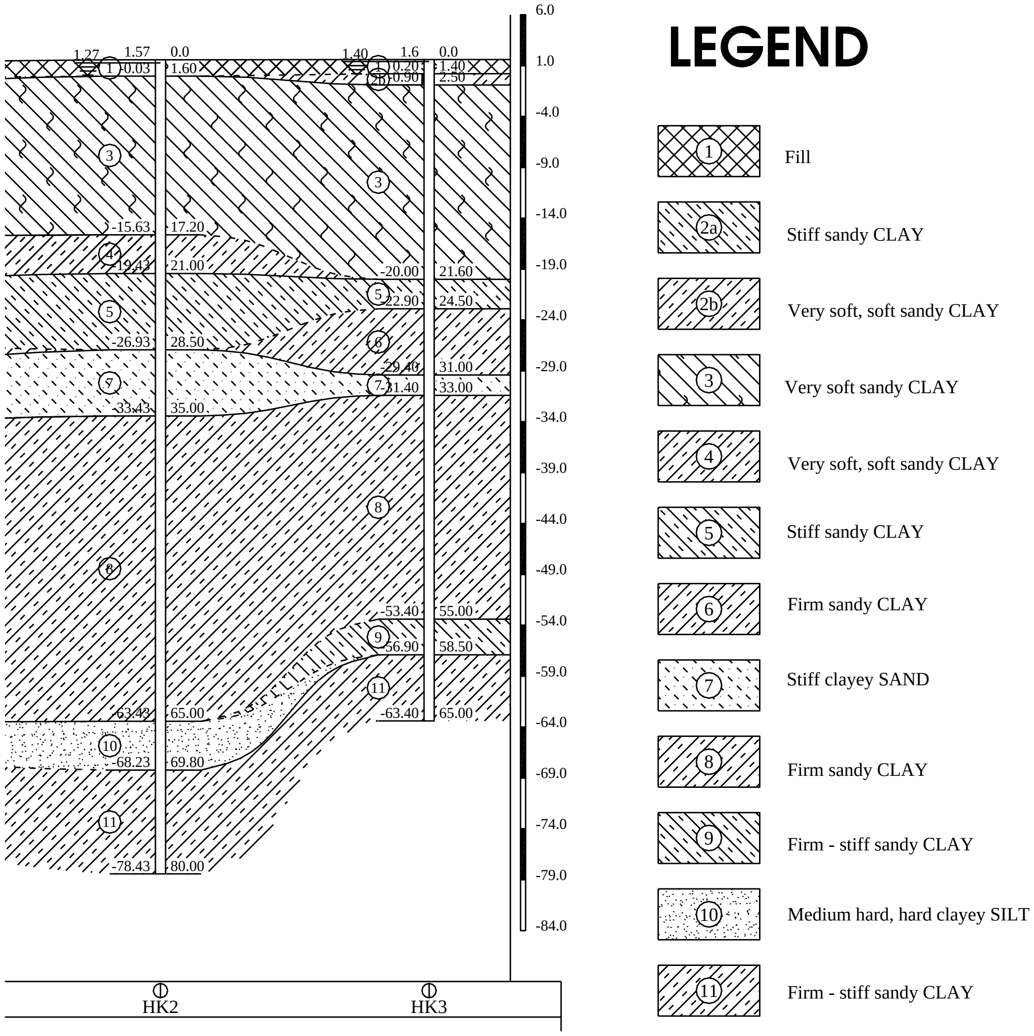

Figure 2. *Soil Profile*

Construction progress:

- Installation of testing piles began on December 14th 2019;
- Mass construction of pile installation started on January 8th 2020;
- Excavation of axes 2 and A-B (see Figure 3) on February 17th, 2020. Many piles were discovered tilted, especially at the pile groups 2B and 2C as shown in Table 1. The location of pile groups and pile numbers are shown in Figures 3 and 4. Figure 3 showed the direction of the lateral movement of piles for groups 2B and 2C. These pile groups have severe lateral movements. The maximum reached was 2.19m at pile group 2C.

Table 1. *Pile Lateral Movement (measured at the site)*

No	Pile Group	Pile Number	Lateral Movement (m)		
			Dx	Dy	$\sqrt{DX^2 + DY^2}$
1	2C	P3.4	1.284	-0.194	1.298
		P3.1	1.553	-0.800	1.747
		P3.2	2.109	-0.591	2.190
		P3.3	1.385	-0.811	1.605
		P3.5	1.582	-0.775	1.762
		P3.6	1.592	-0.771	1.768
		P3.2a	2.184	-0.951	2.383

		Average Value			**1.822**
1	2B	CTH1	0.321	-0.093	0.334
		P3.7	0.547	-0.207	0.585
		P3.8	0.717	-0.143	0.731
		P3.8a	1.062	-0.337	1.114
		P3.9	0.574	-0.145	0.592
		P3.10	0.994	-0.215	1.017
		P3.11	1.423	-0.302	1.455
		P3.12	0.260	-0.077	0.271
		Average Value			**0.762**

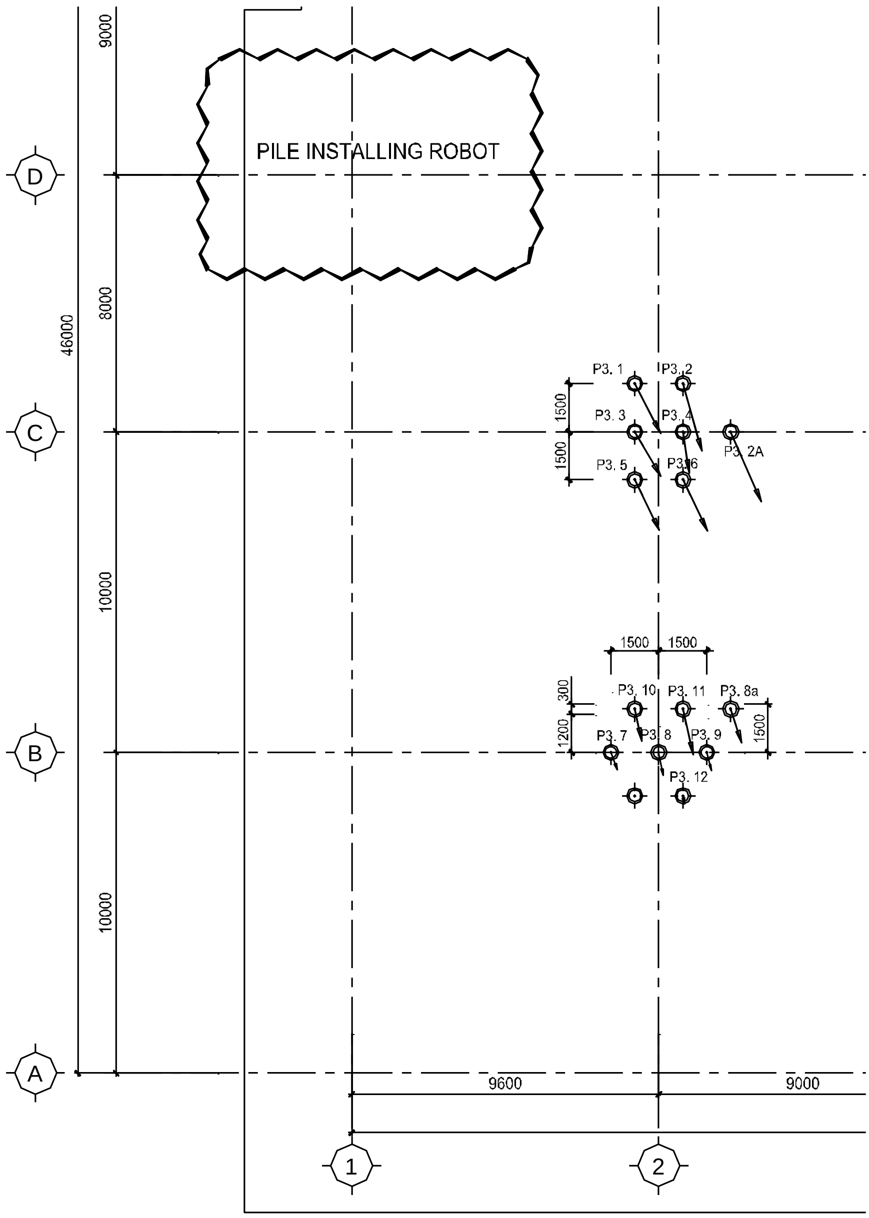

Figure 3. *Pile Distribution and Direction of Lateral Movement*

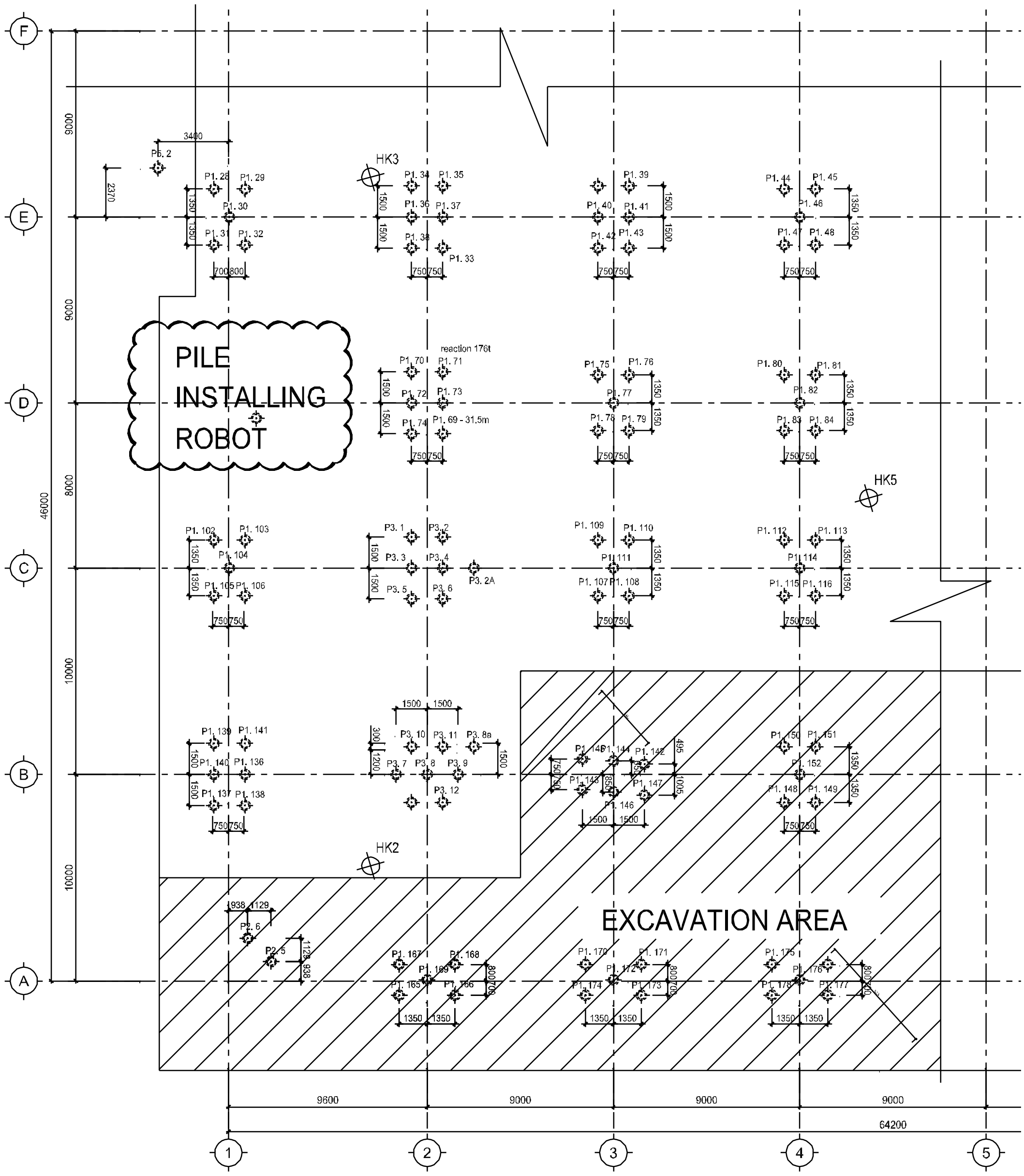

Figure 4. *Pile Distribution and Excavation Location on February 13-14th 2020 during pile installation at group 1D*

Construction procedure and measurement data:

During the discovery of the pile movement:

- Pile installation finished for group 2B on Jan 17th 2020 and 2C on Jan 13rd 2020;

- Excavation of axis A started on February 9th and finished on Feb 11th 2020;

- Exacavation of axis B3 to B6 on February 12nd 2020;

- On Febuary 13-14, 2020, installation equipment was place in area 1D. The settlement was very large and we could not install driven piles in this group, so an alternative solution of using bored pile was chosen.

On February 12nd 2020 while excavating area 2B, the large lateral movement of piles was discovered, especially at 2B and 2C. The differential level between the bottom of excavation at axis A and the ground level at 1D was about 4 m, it may be a major cause of large lateral pile and soil movement (see Figures 5 and 6).

Figure 5. *Pile movement at axis A during Excavation*

Figure 6. *Pile movement at axis A during Excavation and construction of pile cap*

Finite Element (FE) Analysis:

The FE modeling is shown in Figure 7. In this 2D analysis, the considered cross-section is from axis D to axis A and through the location of the installing equipment loading.

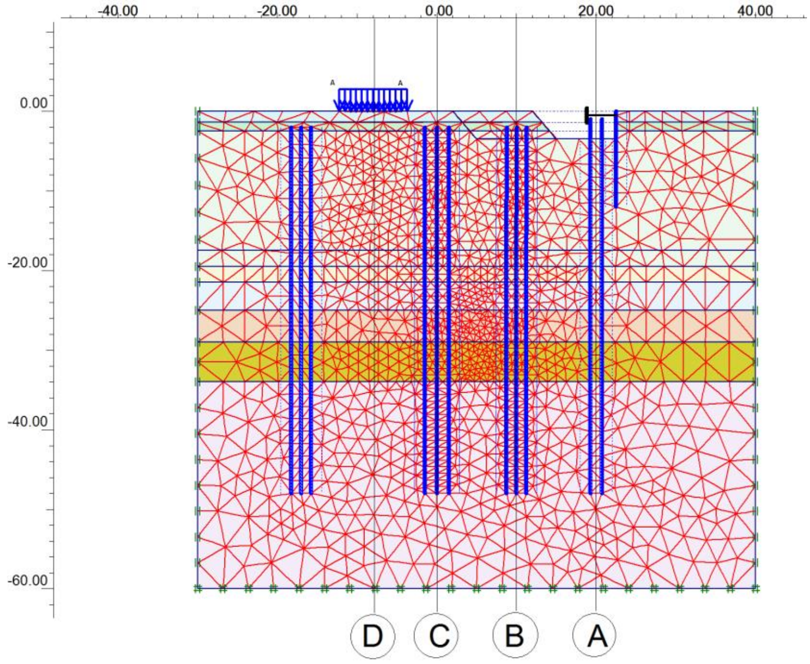

Figure 7. *FE Models*

Note: - Pile installing equipment at 1D (there is load acting on this location, but when considering the critical condition, there is no pile installed at 2D);

- During excavation and soil investigation, the water table is deeper than the bottom of excavation level and assumed at -5m;

- All stages of construction at the field were modeled using Plaxis 2D.

Soil properties: All soil layers in the model can be seen in Table 1.

Table 2. *Soil Properties*

Soil layer No	Top Fill	2a. Sandy Clay	3. Clay Loam		4. Sandy Clay	5. Sandy Clay	6. Sandy Clay	7. Clayed Sand	8. Mix sandy clay and sand
FE Soil Model	HM	HM	HM		HM	HM	HM	HM	HM
	Drained	Un-drained	Un-drained		Un-drained	Un-drained	Un-drained	Un-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	0.32	0.34		0.32	0.32	0.3	0.3	0.3
E_{50}^{ref} (kN/m^2)	12000	36590	1120		8100	56425	20000	65000	15560
E_{OED}^{ref} (kN/m^2)	16150	10680	3310		6200	15120	11000	15880	9350
s_u (kN/m^2)		34.0	0.6 set 2.0		5.9	42.5	14.1	27.8	11.3
c_{ref} (kN/m^2)	5.00								
Φ (degree)	26.0								
R_{inter}	0.9	0.75	0.70		0.75	0.75	0.70	0.85	0.75
Top Soil Level (m)	0	-1.5	-2.75		-19.5	-21.5	-25	-29	-34

Pile properties: The models for piles are showed in Table 3.

Table 3. *Equivalent Pile Properties*

No.	**Pile**	**EA** [kN/m]	**EI** [kNm²/m]	**w** [kN/m/m]	**ν** [-]	**Mp** [kNm/m]	**Np** [kN/m]
1	Pile D500 S = 1.35m	2.27E+6	5.0E+4	1.1	0.15	1E15	1E15
2	Pile D500 S = 1.5m	2.05E+6	5.4E+4	1.0	0.15	1E15	1E15

Loading condition: At the critical condition, there are two external loads at the field (1) a pile installing machine at area 1D and (2) an excavator at axis A (for the critical condition, assume the excavator was gone after excavating axes A and B, and only the pile installing machine was still at work). The equivalent load from the pile-installing machine is 35.9 kN/m^2 as calculated from a total load of 430 tons/ base area LxW of 14m x 8.56 m.

Construction stages: Five stages of construction at the construction site are modeled stage by stage, including the initial stage as shown in Table 4.

Table 4. *Modelling Construction Stages*

No	**Stage Model**	**Modelling Analysis**	**Time** (day)	**Note**
Initial	0	N/A	0	-
Stage 1	1	Plastic analysis	-	Installation of Pile D500
Stage 2	2	Plastic analysis	-	Excavation at axis A
Stage 3	3	Plastic analysis	-	Pile installation loading (Robot) (35,9 kN/m^2)
Stage 4	4	Plastic analysis	-	Excavation at axis B

3. Results and Analyses

All stages of construction at the construction site are modeled in the FE analysis (using Hardening Model HM for soil as showed in Table 1). The soil and pile displacement results of the critical stage 4 after excavating is showed in Figure 8.

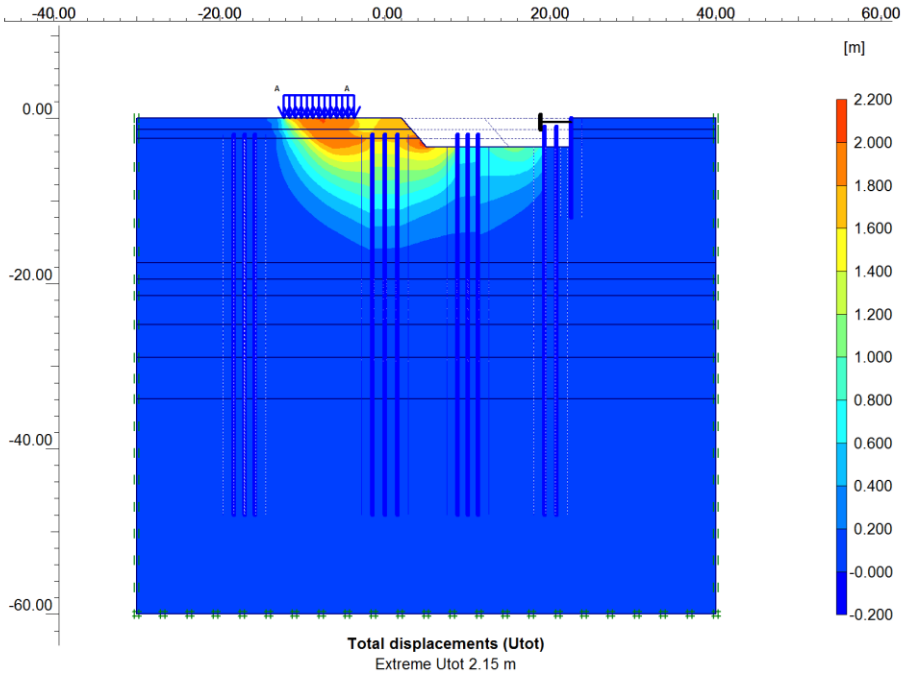

Figure 8. *Total displacement after excavation of axis B*

The maximum lateral movements of piles in group B and C are showed in Figures 9 and 10.

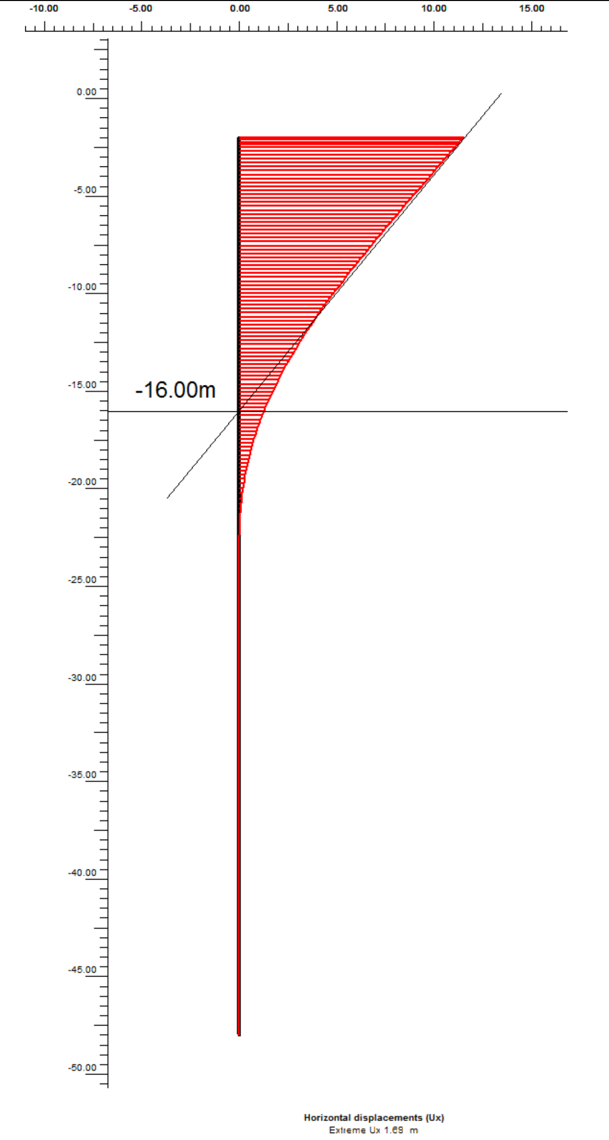

Figure 9. *Maximum lateral movement of pile in group C (U_{xmax} = 169cm)*

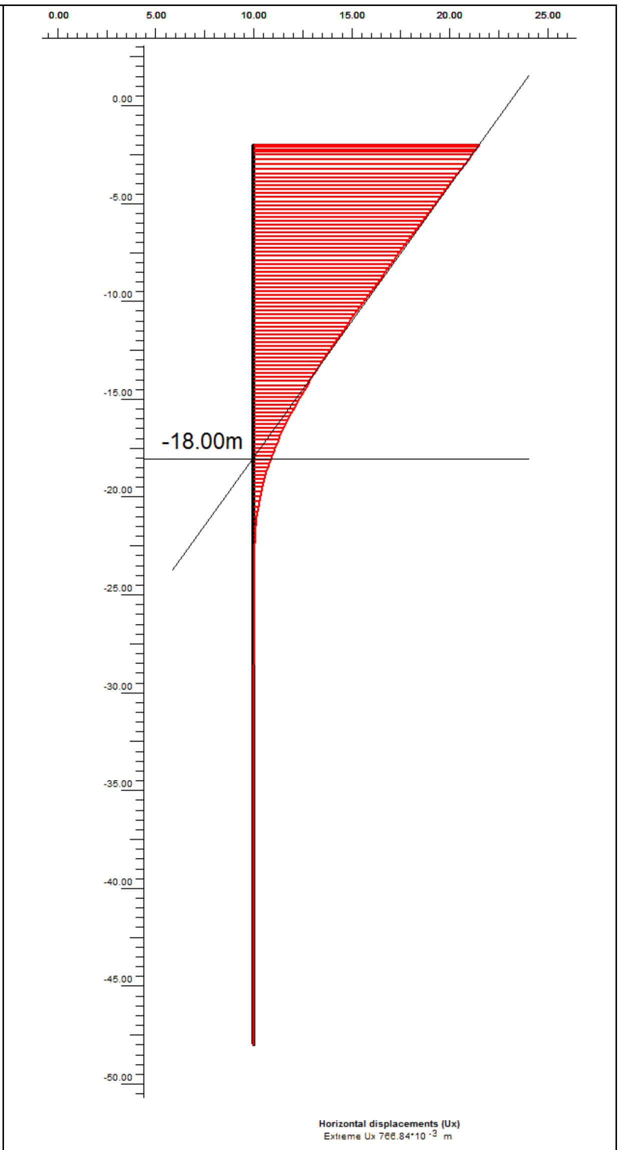

Figure 10. *Maximum lateral movement of pile in group B (U_{xmax} = 76,7cm)*

Note that the piles shown are broken in Plaxis when reaching the maximum material strength (bending moment or shear) due to the large lateral movement.

From the numerical analyses, piles at B and C groups were bent starting at the depth of -18m and -16m correspondingly, while the measured data at the construction site show that the depth of the maximum pile bending moment is about 5.5m from the pile head. Therefore, the geometry method can be used to determine the actual location of the starting bend from the measured data, and compared with the numerical results (see Figure 10 and Table 5).

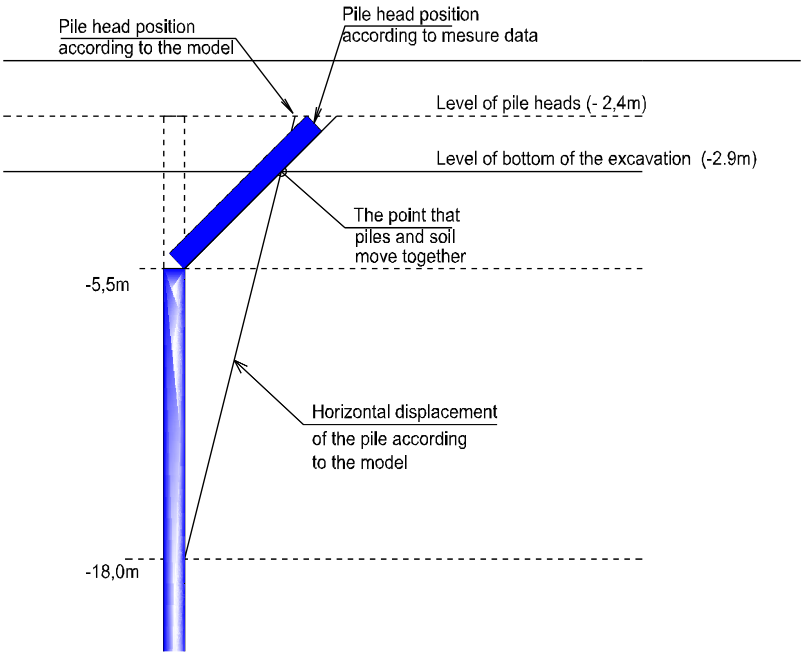

Figure 10. *Diagram to determine the actual lateral movements of piles*

Table 5. *Comparison of lateral movement between measured data and numerical results*

Lateral movement of piles	**Pile group 2B**	**Pile group 2C**
Plaxis results	81,7 cm	179,3 cm
Average lateral movement from measured data	76,2 cm	182,2 cm
Difference	7,2%	-1,6%

Further Analyses: It is clearly shown that the lateral movement of the pile group was very large due to the construction procedures at this site. The lateral deformation of piles caused by (1) loads of pile installing equipment and (2) rapidly excavated some areas nearby the installed piles will be analyzed separately to figure out the effects of each incidence. In addition, the complex soil condition in this construction site is another key problem causing the large lateral soil movement. To evaluate the effects of each incident, several analyses were conducted. Figure 11 shows the modeling to determine the movement of piles and soil surrounding under the installation equipment load without excavating the local areas. With this model, the only effect of pile installing equipment load on the lateral movement of soil and piles is considered. Figure 12 shows the deformation of typical piles at group 2B and 2C due to the pile installing equipment load.

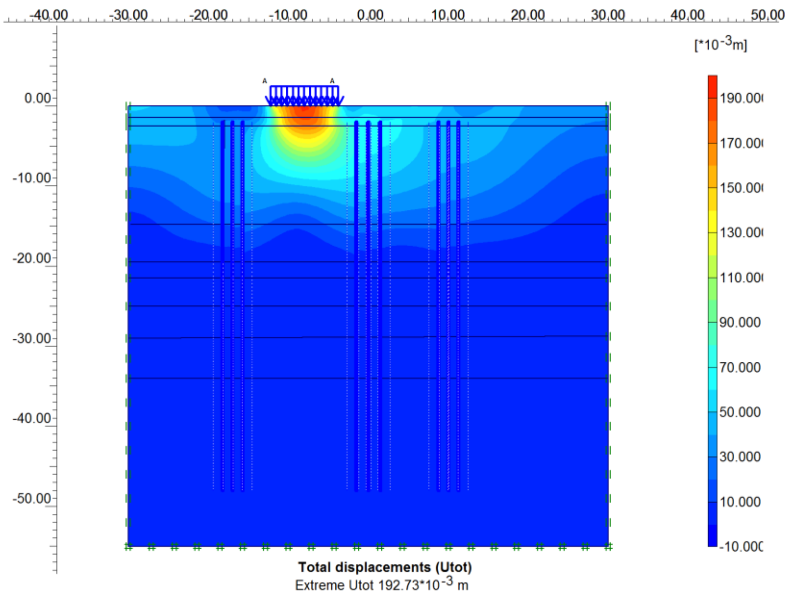

Figure 11. *Modeling pile installation with out excavating*

The numerical results show that the maximum lateral movement deformation of the pile head at groups 2B and 2C are 46 mm and 67 mm, correspondingly. The deformation is acceptable, and this value is about 10% of the maximum movement of the pile heads (462mm and 1822mm). This is due to both the effects of the pile installing equipment load and the excavation. It also shows the importance of the construction procedures.

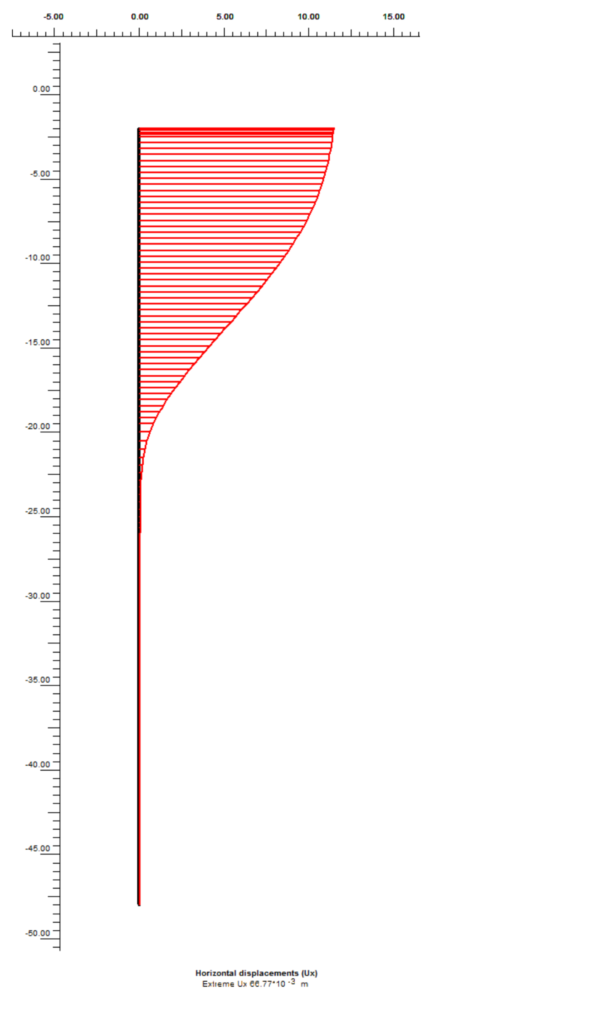

Figure 12a. *Deformation of typical pile at group C (U_{xmax} = 67 mm) (Not to scale)*

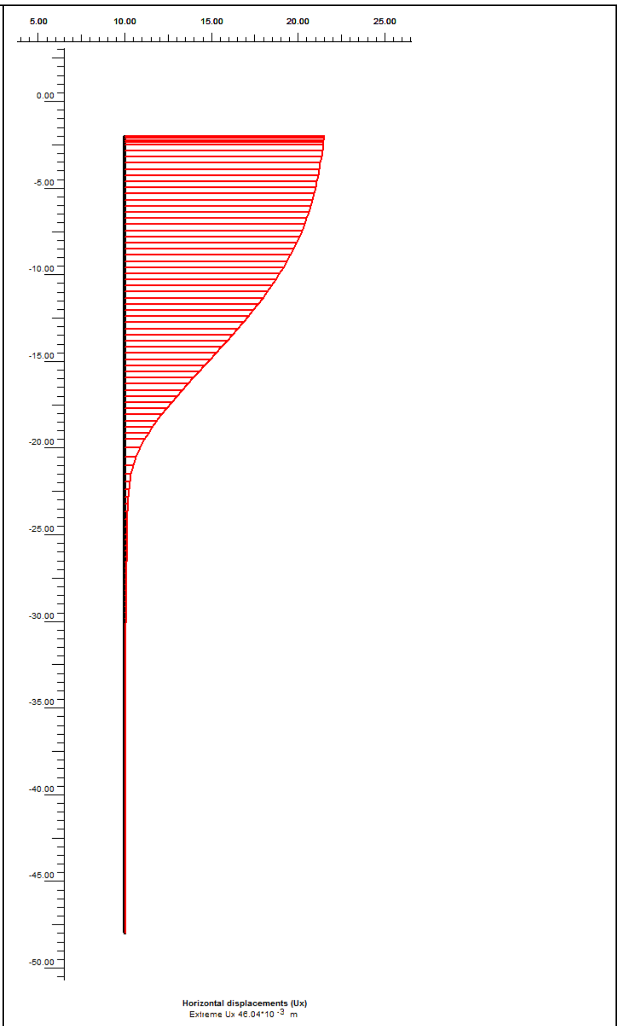

Figure 12b. *Deformation of typical pile at group B (U_{xmax} = 4,6 cm)*

4. Recommendations

Based on the results from the numerical analyses above, it can be recognized that the construction procedure in the construction site is very important to the movement of surrounding soil, especially the lateral movement of soil with the installed piles. If it is not considered seriously, the damages of installed piles may happen as shown in this case study. The study presents a proposed construction procedure to reduce the damage of piles or extremely lateral movement during construction. The proposed procedure can be used for many projects, such as installing piles in weak soil conditions and using heavy pile installing machines along with the adjacent excavation. A proposed construction procedure for this study is as follows:

1. The best way to reduce almost all lateral movement of installed piles are to do excavation first for all areas before installing piles.

2. If the method above cannot be performed, the following procedure can be used to mitigate the installed pile damages by over 80%:

- Locate the installing piles for the project;

- Perform mass construction of pile installation using one block of the project or whole project;

- The excavation steps:

+ Excavate the whole block (including all pile group within one building) with many layers. The thickness of each soil layer should be less than 0.5m;

+ After completely excavating the first layer for whole building, continuously excavate the second layer and repeat until the maximum required depth of the excavation is reached;

+ The accurate thickness of each excavated soil layer should be determined based on the specific soil conditions and the adjacent structures at the construction site;

- In case, the continuous construction is used, keep the minimum distance of the loads from the pile installing equipment to the nearest edge of the excavation is greater than (a) two times the excavation depth, in combination with (b) two times of the excavation width.

The reasonable or actual distance should be determined based on the information from the construction site such as soil conditions, value and area of adjacent loads or equipment, types of excavation, etc.

5. Conclusions

Based on the measured data from the construction site and the numerical analyses, we reach several important conclusions:

- The results of the lateral movement of piles from numerical analyses are in good agreement with the measured data at the construction site, with the differences of around 7.2% and 1.6%;

- The large movement of soil and piles in groups 2B and 2C is due to the unreasonable construction procedure used in the project. Lateral soil movement in weak soil areas is very sensitive to the adjacent excavation or acting loads nearby (such as construction equipment);

- The large lateral deformation of piles in many other projects in with the soil conditions closed to this project or under the thick soft soil layers and using the same construction procedure may have the same pile damage as discussed in the study (group 2B and 2C);

- To reduce the time spent in the construction site, the continuous method can be used (but the damage of the pile under construction must be avoided and the lateral deformation should be small enough to meet the requirements).

- For similar projects, a specific construction procedure should be made and followed strictly. A detailed construction measure of each work should be considered over all projects to reduce unnecessary damages.

- The proposed construction procedure in this study can be used to mitigate almost all (or at least greater than 90%) of the damages during construction.

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Ngày nhận bài: *16/7/2020.*

Ngày nhận bài sửa lần cuối: *03/9/2020.*

Chuyển dịch ngang của nhóm cọc do tải phân bố trên bề mặt và thi công hố đào
(nghiên cứu điển hình)

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