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THE EFFECT OF PILE DRIVING PROCESS ON STRESS AND STRAIN OF NEIGHBORING BUILDING'S FOUNDATIONS: AN APPLICATION IN VIETNAM

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ABSTRACT: The driving of pile into the ground is one of the important tasks of construction works and especially for new buildings in big city. Difficulties in driving piles for new construction will adversely affect the foundations of neighboring and adjacent building. This research proposes a measure to assess the state of conduct of the pile driving process using a nonlinear Finite Element Method (FEM). Manuscript using Plaxis 3D Foundation analysis software for an existing building with reinforced concrete pile foundation with foundation tower size 2.0 m x 2.0 m on 4 piles with a cross-section of 0.3 m x 0.3 m, length 10.0 m; foundation bearing a load of 1000 kN. Then press the reinforced concrete pile size 0.3 m x 0.3 m, pile length 10.0 m, pressing position 0.5 m from the edge of the existing foundation, pressure 500 kN. The results of the analysis showed the effect of the adjacent pile process to the stress and strain of the neighboring building foundation in cramped land for construction conditions. In order to provide solutions to overcome difficulties for the adjacent building be effective. The effective stress in the existing reinforced concrete pile foundation without adjacent is -273.7 kN/m^2, but when it is interlocked, it is -3490.0 kN/m^2. After pressing the piles, the horizontal displacement of the existing piles is 10.2 mm and a bending moment of 48.6 kNm occurs.

Keywords: Pile foundation, Adjacent pile, Stress, Strain, FEM.

1. INTRODUCTION

The construction of a new building near a previously built structure often encounters one of the following dangerous situations: deformation of existing house due to excavation of the foundation pit or nearby trenches, which cause dislocation of the soil at the bottom of the new foundation pit and the existing foundation pit; house deformation due to dynamic impact of construction machineries; deformation of the house due to groundwater drainage in the new foundation pit, which leads to the phenomenon of soil washing at the bottom of the old foundation or increment of the pressure of natural soil because there is no longer buoyant pressure of water that leads to further settlement; deformation of the old house on the friction pile when building near the new house on the raft foundation in the area adjacent to the new house where the pile is subjected to negative friction, the ground is subsided and the bearing capacity of the pile is reduced; deformation of existing houses from pouring materials near the house or leveling with artificial filling soil that damages the natural structure of the soil, especially when there is soft clay near the bottom of the foundation.

The characteristics of the state of stress-strain in the ground due to pile driving are shown as follows: Firstly, the interaction between the pile and the surrounding soil mass from when the pile driving starts until the construction is completed and put into use. At that time, the soil mass forms different stress-strain states at positions under the tip and around the pile. Physical and mechanical properties of the soil include saturation, strength and strain. Among which, the deformation plays an important role and affects the formation and change of stress-deformation state of the soil mass in the affected area in contact with the pile. Secondly, after the pressing of the piles, the soil starts to have excess pore water pressure, and when this pressure is dissipated, it will cause the stress - deformation state of the soil in the affected area to change over time. In saturated soil, the process of changing the stress in the soil will take place together with the consolidation process and dissipation of the water pressure in the pores, then the effective stress value increases over time and reach a stable value. Therefore, in order to quantify the stress-strain state of the soil mass interacting with the pile, it is necessary to consider two basic stages: the pile pressing phase and pile "resting" stage, and the pile working stage under loads. These two stages will influence each other and play an important role in forming the load-carrying capacity of the pile.

There have been many studies on the displacement of the soil in the adjacent structure due to the pile driving process and adverse effects on previously pressed piles. The studies are analyzed using aggregated data from a variety of sources, ranging from preliminary estimates of building displacements due to adjacent pile driving to measurements of ground displacement when driving single piles in laboratory models. Results showed that initial prediction of ground settlement due to adjacent pile driving has accurate results without explicitly modeling the interactions between pile and soil.

Chong M. K. (2013) studied the displacement of the soil due to the pile driving process in adjacent structure and the adverse effects on the piles that have previously been pressed [1]. Antonios V. et al. (2018) also did a field study in East Baton Rouge, Louisiana on the horizontal displacement of the ground soil when driving piles into soft clay gound [2]. Fatemeh V. et al. (2019) proposed a new numerical analysis method to estimate the load-displacement behavior and bearing capacity of piles driven in sandy soil using the results of CPT experiments [3].

Mandy K. (2009) studies on deformation and damage of adjacent structures due to deep excavation in soft soil [4]. The study focused on typical soil conditions in Netherland. The result of the study is a report on the general damage assessment process to adjacent structures due to deep excavation in soft soil. Yan X. et al. (2020) studied the influence of high-rise building loads on neighboring underground works [5]. The settlement of each surrounding soft soil layer was analyzed using the data of the gauge at the settlement monitoring station of the ground near the study area. Also, the settlement of the tunnel in the study area mainly depends on the deformation of the surrounding soil. Cesar S. and Andrew J. W. (2021) conducted a study on soil movement when piles were driven into clay [6]. The results showed that the initial prediction of ground settlement due to adjacent pile driving has accurate results without explicitly modeling the pile-soil interactions.

Poulos H.G. (1964) had a study on the behavior of piles subjected to horizontal loads in the pile group [7]. Research results showed that the distribution of displacement, rotation and load in the group is largely influenced by the ratio of length, diameter, and relative flexibility of the pile. Pan Z. et al. (2021) analyzed the behavior of existing piles when driving adjacent piles in undrained clay [8]. The behavior of single pile is analyzed using existing theory and simulation method. Franza A. et al. (2021) investigated the interaction between soil-pile-structure caused by vertical loads and tunneling [9]. Model results for piles subjected to vertical loads compare well with the field and other analytical models to confirm the reliability of the model. Peng Z. et al. (2020) also studied the lateral behavior of existing single piles when there is invasion of adjacent piles in undrained clay when pressing piles [10]. The study used a two-stage analysis method to predict the behavior of the existing pile due to pressing adjacent piles. Mukhtiar A. S. et al. (2019) Analysis of pile behavior to the excavation of neighboring structures in soft clay [11]. The study showed that the pile behavior against excavation depends on the degree of formation of the excavation as well as the depth of the wall. Jiangwei S. et al. (2019) study the mechanism of stress transmission and settlement of piles due to deep excavation of adjacent structures in dry sand [12]. A three-dimensional numerical parameter study was carried out to investigate the stress transfer and settlement mechanisms of piles due to tunnel excavation by using the plastic sand model in centrifuge experiment.

Shuntaro T. et al. (2018) evaluated the critical behavior of the pile group by actual lateral load testing and numerical analysis method [13]. Charles. W. W. Ng et al. (2021) analyzed the performance of energy pile group with different pile spacing in clay [14]. Shakeel M. and Charles W. W. Ng (2018) studied the settlement and transmission of pile groups adjacent to deep excavations in soft soil [15] by using finite element model to study the influence of excavation depth, pile length, pile group position during excavation, stiffness of support system, soil condition and permeability, and working load. Jue W. et al. (2014) studied the influence of forced harmonic vibration piles on adjacent piles in multi-layer soil environment by double shear model based on Pasternak foundation and Timoshenko beam theory [16].

The above studies have presented the causes, formation mechanisms and principles for predicting problems when constructing piles for adjacent works. However, research on the interaction between piles, between piles and ground soil to the stress and deformation of adjacent building foundations has not been studied and analyzed in depth by the authors. This study aims to apply the finite element method to analyze the effect of pile pressing on the stress and deformation of adjacent foundations. The research results aim to propose a reasonable pile pressing plan for the geological conditions of My Tho city, Tien Giang province, Vietnam, and areas with similar geology.

2. RESEARCH SIGNIFICANCE

This research proposes a measure to assess the state of conduct of the pile driving process using a numerical simulation method. The results of the analysis showed the effect of the adjacent pile process on the stress and strain of the neighboring building foundation in cramped land for construction conditions in order to provide solutions to overcome difficulties for the adjacent building to be effective. The results of the research can help the company to design pile driving to anticipate possible technical problems. The deformation of stress and strain of the neighboring building foundations due to pile driving.

3. CURRENT STATE OF PILE FOUNDATION USAGE FOR CIVIL WORKS IN MY THO CITY

Currently, in My Tho City, many methods are used to construct reinforced concrete piles such as pressing with jacks, or using robots to press large centrifugal piles… The choice and usage of method depends on the site geology and project location [17]. In addition, it also depends on pile length and construction machinery and equipment. The process of pile driving at the construction site has many pressing options, with the following two as the most popular:

Option 1 is to dig a foundation pit to the top of the pile, then bring machinery and pressing equipment to drive the pile to the required depth. The advantage of the method is that it is convenient to dig the foundation pit, is not obstructed by the pile heads and does not have to press through the surface ground. The disadvantage is that in places with high groundwater level, it is difficult to dig the foundation pit first and then execute the pile pressing. When it rains during the process of pile driving, it is necessary to take measures to pump water out of the foundation pit. Moving construction machinery and equipment is also difficult. With a narrow construction site and existing works in the vicinity, the construction works following this option face many difficulties, and sometimes it is not even possible to proceed.

Option 2 is to proceed to leveling the ground to facilitate moving the press and transport equipment, then proceed to press the pile as required. Thus, to achieve the height of the top of the pile, it is necessary to press the pile into the ground. It is necessary to prepare sections of steel or reinforced concrete piles so that the piles can be pressed to the design depth. After pressing the piles, the workers can proceed to excavate the soil to construct the scaffolding and the pile bracing system. The advantages are, moving the pile pressing equipment and transporting the piles can all be done smoothly even when it rains, it does not depend on the groundwater level, and the construction speed is fast. The disadvantages are, it is necessary to add the lead piles to make negative press, the excavation of the foundation pit is difficult, much of which must be manually excavated, and the construction time is long because it is difficult to construct with heavy machineries.

Based on the advantages and disadvantages of the above two options, based on the construction site, the excavation plan for the foundation pit, we will choose the most suitable pile driving construction plan. However, option 2, combined with digging the foundation pit in the form of a pond, will combine many advantages to carry out effective construction. This adjacent construction work will affect the damage to the adjacent works when built. Therefore, it is necessary to analyze the position and depth of piles so that the construction process of pressing piles does not affect the quality of these works.

4. FEM MODEL ANALYSIS

4.1 Building structure

Carrying out the study in the conditions of the adjacent residential buildings in My Tho City with the data on the geological conditions and the foundation load of the adjacent works taken in accordance with the actual works. The location of the adjacent works (No. 39) on the construction site is shown in Fig. 1. In the plan, the existing buildings are buildings No. 38 and 40.

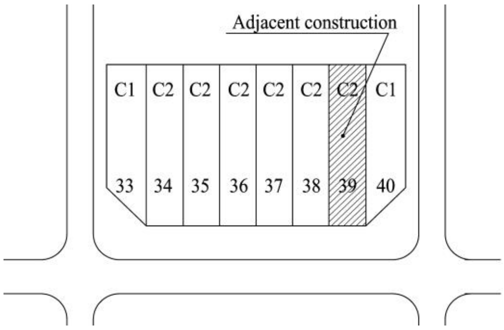

Fig. 1 Position of the adjacent construction work

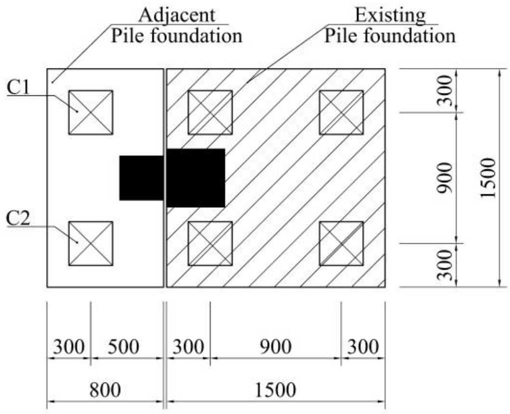

Fig. 2 Top view of the pile foundation

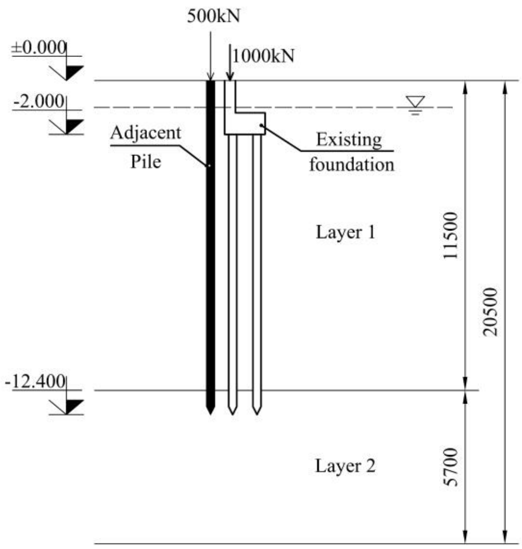

Fig. 3 Cross section of the pile foundation

The piles of the adjacent foundation include 2 reinforced concrete piles with a cross section of 0.3 m x 0.3 m, length of 11.5 m, which are pressed 0.5 m away from the existing foundation (Figs. 2 and 3).

4.2 Geological conditions

In general, due to the characteristics of the ground surface being young alluvium, which is rich in clay and organic mud, in terms of topography, the elevation is relatively low, in terms of engineering geology, the bearing capacity is not high, which makes it necessary to level and reinforce the ground for construction projects. In order to gain data on the properties of the site's natural soil, a 30 m borehole was drilled to survey and results of experiments to determine the physical parameters of the soil layers are shown in Table 1.

Table 1. Physical properties of the soil layers

Properties	Layer 1	Layer 2
Thick of layer (m)	11.5	5.7
Grain size distribution		
- Clay (%)	48.5	33.8
- Silt (%)	48.6	54.7
- Sand (%)	2.9	11.5
Water content, W (%)	127.0	23.5
Wet unit weight, γ_w (g/cm^3)	1.345	1.968
Density, γ_s(g/cm^3)	2.693	2.700
Liquid limit, LL (%)	87.1	41.0
Plastic limit, PL (%)	40.2	21.8
Plasticity index, I_P	46.9	19.2
Liquidity index, I_L (%)	1.85	0.09
Friction angle, φ (^{o})	$5^o23'$	$16^o45'$
Cohesion, c (kG/cm^2)	0.032	0.429

From the laboratory test results combined with the field survey results, the geotechnical structure of the construction site was assessed preliminary as follows: Layer 1 has an average thickness of 11.0 m, the soil condition was mainly organic, containing clay, molten clay, clay mud... The sedimentary layer was soft, with low load-bearing capacity and durability; Layer 2 was located below layer 1 with an average thickness of 6.0 m, mainly composed of clay, yellow-brown clay, blue clay, semi-hard clay. The deeper the depth, the better the soil condition.

4.3 Plaxis 3D Foundation Model

Plaxis 3D Foundation is a three-dimensional finite element program for analysis of foundation structures for constructions on land and at sea. Thanks to the application of technological advances, this program allows users to solve complex structural problems with simple input data. The results of the problem give us the values of stress, strain ... at each position in the foundation as well as the entire foundation. Modeling method of Plaxis 3D Foundation: Representation of construction site, simulation of soil layers, simulation of building structure, determination of material properties, meshing of elements (2D-3D), determination of elements calculation step.

The material characteristics of the soil layers and reinforced concrete piles in Plaxis 3D Foundation are calculated and shown in Tables 2 and 3.

Table 2. Parameters of soil layers in the Plaxis model

Parameters	Symbol	Layer 1	Layer 2
Model	Model	MC	MC
Unsaturated unit weight (kN/m^3)	γ_{unsat}	13.45	19.68
Saturated unit weight (kN/m^3)	γ_{sat}	13.72	20.12
Young's modules (kN/m^2)	E	628.4	23074.4
Poisson's ratio (-)	ν	0.35	0.35
Cohesion (kN/m^2)	c_{ref}	3.20	42.90
Friction angle (^{o})	φ	$5^0 23'$	$16^0 45'$
Dilatancy angle (^{o})	ψ	0^0	0^0

Table 3. Parameters of reinforced concrete piles in Plaxis model

Parameters	Symbol	Layer 1
Unsaturated unit weight (kN/m^3)	γ_{unsat}	25
Young's modules (kN/m^2)	E	$29.2e^6$
Poisson's ratio (-)	ν	0.300

The calculation process in Plaxis 3D Foundation begins with the setup of the computational model. The computational model is a combination of boreholes and work planes (Figs 4 and 5).

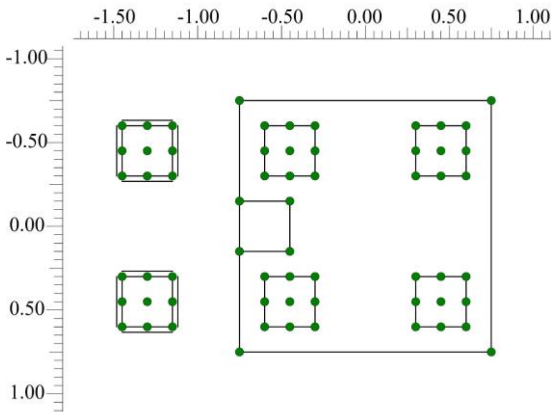

Fig. 4 FEM model in Plaxis 3D Foundation

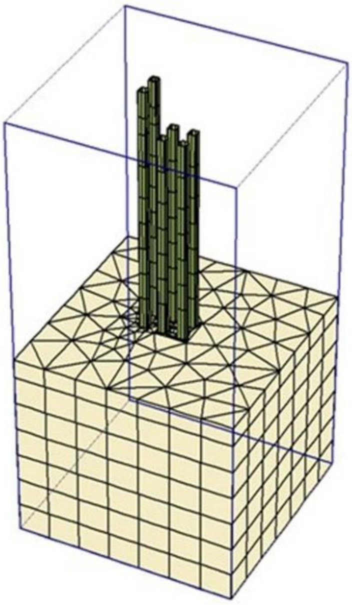

Fig. 5 Generated 3D Mesh

4.4. Work conditions

The simulation process for stress and strain analysis is carried out as shown in Table 4 and simulated as shown in Fig. 6 to Fig. 9.

Table 4. Calculation steps when driving piles in adjacent construction site

Phase	Task	Cal. type	Loading input
Initial	N/A	N/A	N/A
Phase 1	Press the C1 pile to a depth of 5.0 m	Plastic	Staged construction
Phase 2	Press the C1 pile to a depth of 10.0 m	Plastic	Staged construction
Phase 3	Press the C1 pile to a depth of 12.4 m	Plastic	Staged construction
Phase 4	Remove pressing load	Plastic	Staged construction
Phase 5	Press the C2 pile to a depth of 5.0 m	Plastic	Staged construction
Phase 6	Press the C2 pile to a depth of 10.0 m	Plastic	Staged construction
Phase 7	Press the C2 pile to a depth of 12.4 m	Plastic	Staged construction

The initial stage has reinforced concrete pile foundations of the existing works. The foundation tower is 2.0 m x 2.0 m in size and is placed on 4 piles with a cross section of 0.3 m x 0.3 m, with a length of 10.0 m. The foundation can withstand a load of 1000 kN.

Construction phase of 0.3 m x 0.3 m reinforced concrete pile with conditions for consideration and analysis: Number of piles: 1 pile and 2 piles; Pile tip depth: 5.0 m, 10.0 m and 12.4 m; Pressing position distance from the existing foundation edge: 0.5 m; Pressing force: 500 kN.

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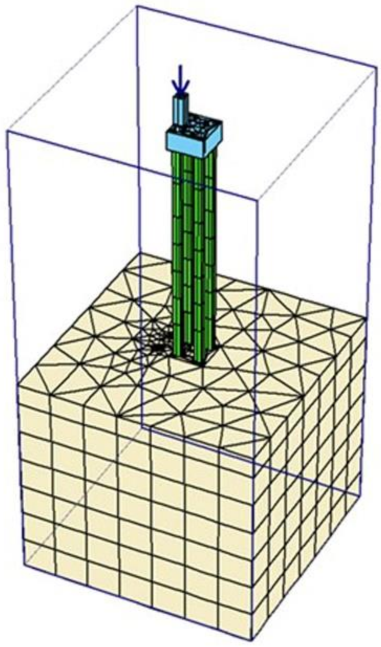


Fig. 6 Initial state existing foundation

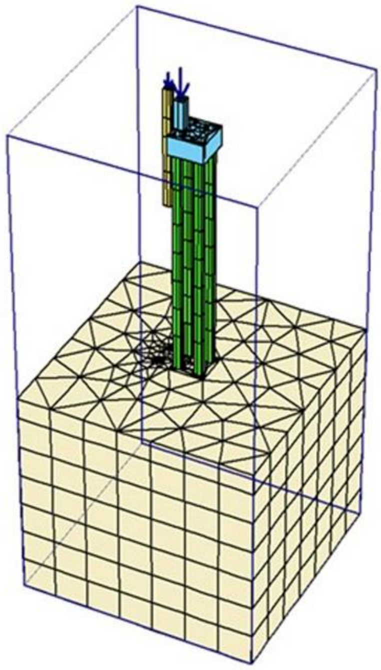


Fig. 7 Phase 1-Press the C1 pile to a depth of 5.0 m

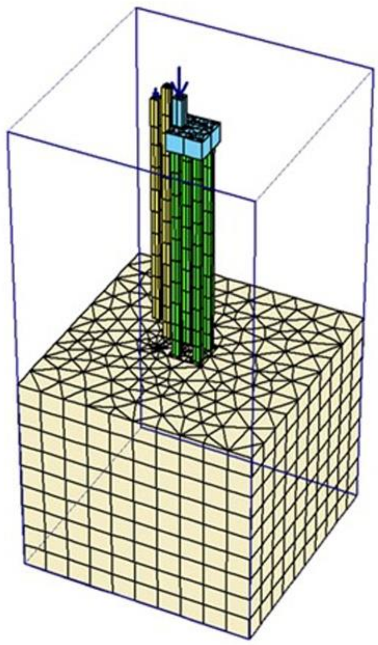


Fig. 8 Phase 6-Press the C2 pile to a depth of 10.0 m

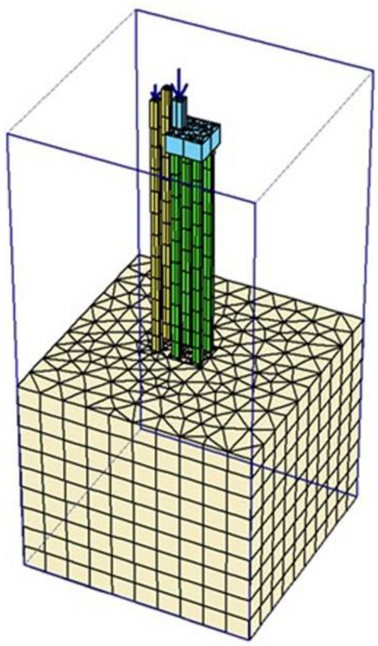
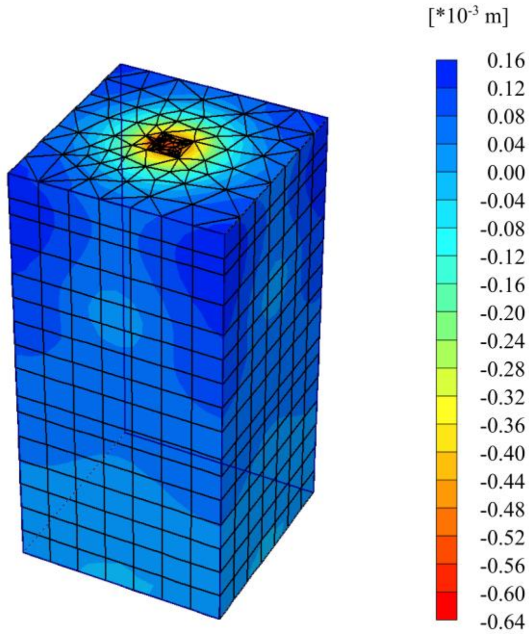


Fig. 9 Phase 7-Press the C2 pile to a depth of 12.4 m

5. RESULTS AND DISCUSSION

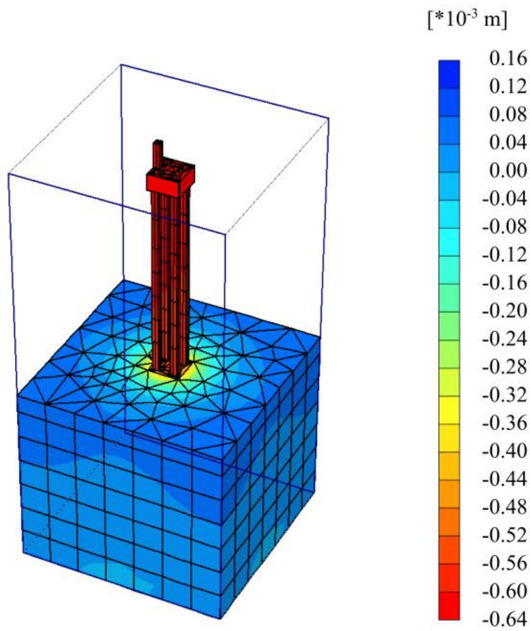
The vertical displacement and effective stress distribution of the ground-foundation system and in the existing reinforced concrete piles are shown in Fig. 10 to Fig. 13. The analysis results show that when the existing structure is working under normal conditions, i.e. without any interlocked construction work, the vertical displacement of the foundation system, which is mainly the stable foundation, the vertical displacement is very small, U_y= -0,6 mm; The effective stress at the pile foot of the pile foundation is -273,7 kN/m^2.



Vertical displacements, U_y

Extreme value = -0.6 mm

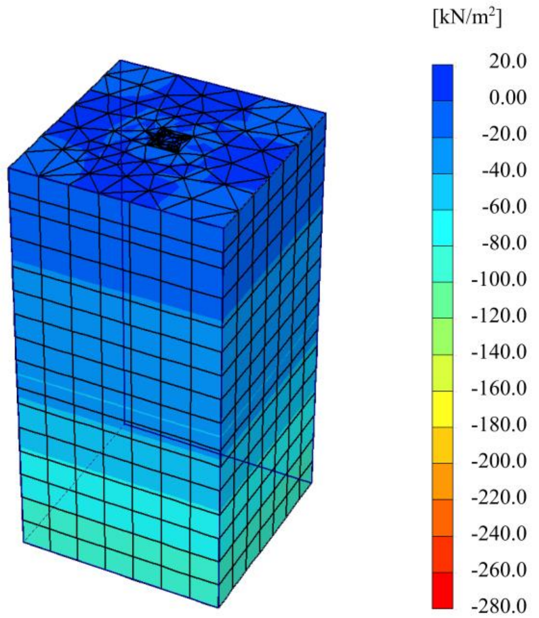
Fig. 10 Vertical displacement of the existing floor-foundation system



Vertical displacements, U_y

Extreme value = -0.6 mm

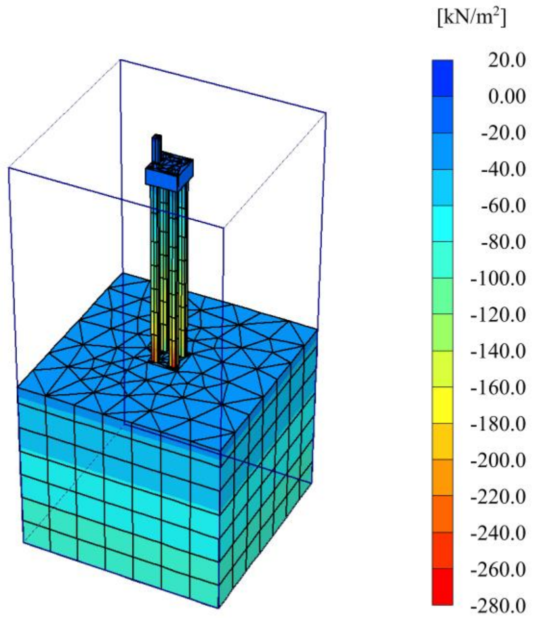
Fig. 11 Vertical displacement of the existing reinforced concrete pile foundation



Effective mean stresses, p'

Extreme value = -273.7 kN/m^2

Fig. 12 Effective stress distribution in the existing ground-foundation system

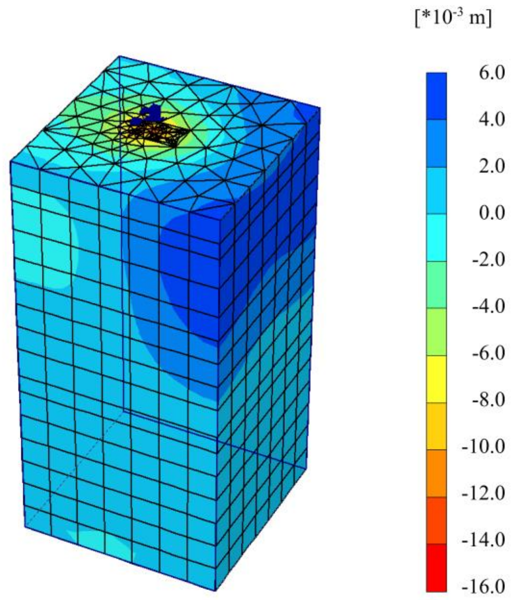


Effective mean stresses, p'

Extreme value = -273.7 kN/m^2

Fig. 13 Effective stress distribution in the existing reinforced concrete pile foundation

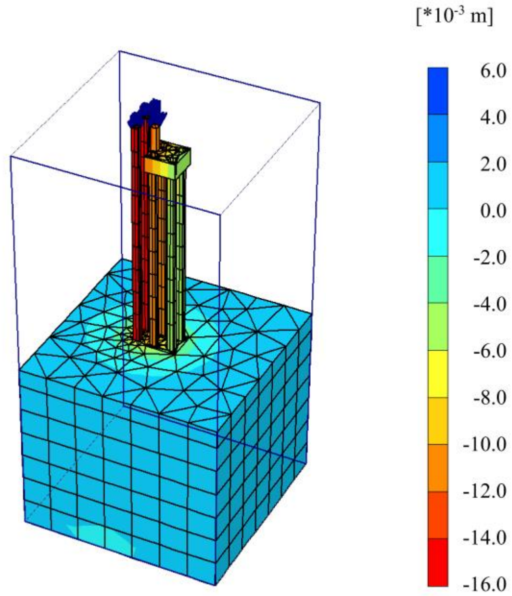
Vertical displacement and effective stress distribution of the floor-foundation system and in the existing reinforced concrete piles when the pile is pressed are shown in Fig. 14 to Fig. 17. Vertical displacement of the floor-foundation system has an increase of U_y = 15.9 mm, mainly caused by the pile pressing work, which occurs at the pressed piles. The vertical displacement of the existing foundation does not increase. This is true in theory because piles will affect the horizontal displacement for the existing building foundation system. The results of this horizontal displacement simulation are shown in Fig. 18.



Vertical displacements, U_y

Extreme value = -15.9 mm

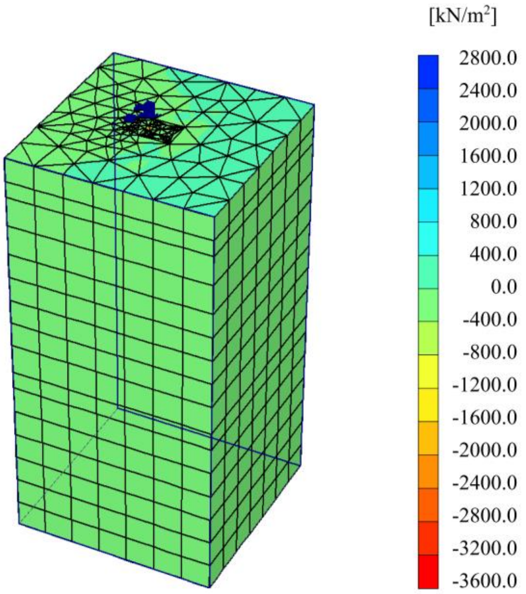
Fig. 14 Vertical displacement of the ground-foundation system when pressing piles for adjacent construction



Vertical displacements, U_y

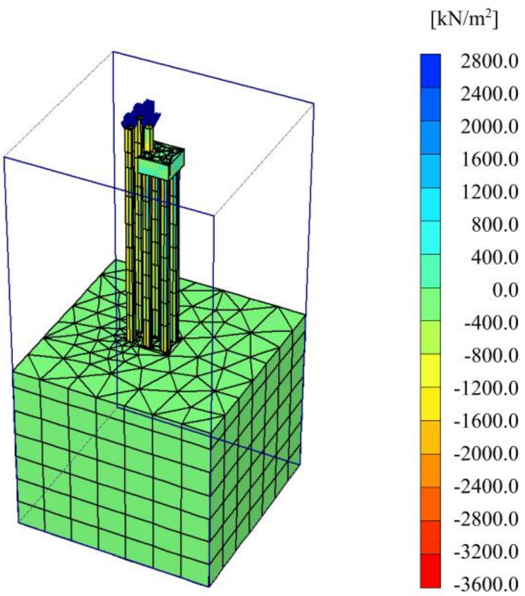
Extreme value = -15.9 mm

Fig. 15 Vertical displacement of reinforced concrete pile foundation



Effective mean stresses, p'
Extreme value = -3490.0 kN/m^2

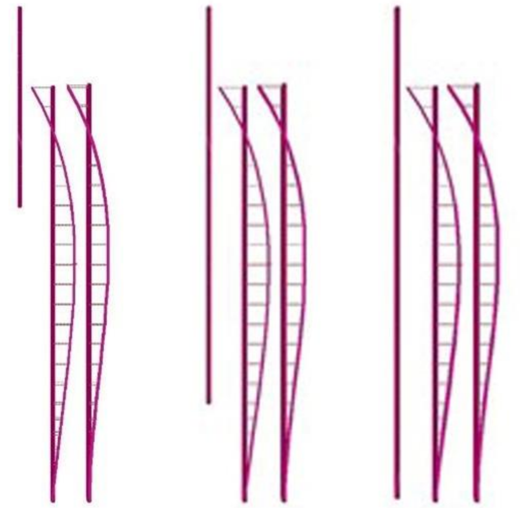
Fig. 16 Effective stress distribution in the ground-foundation system



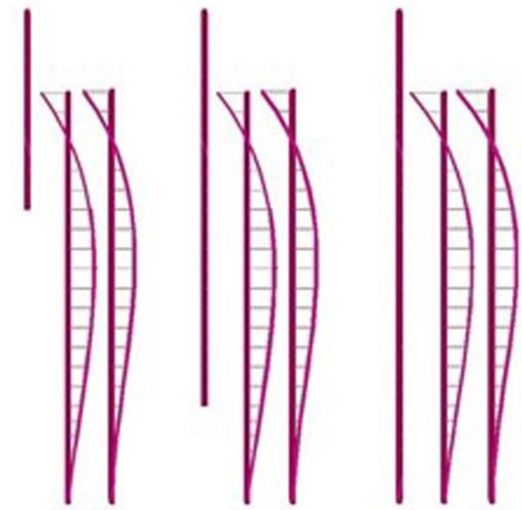
Effective mean stresses, p'
Extreme value = -3490.0 kN/m^2

Fig. 17 Effective stress distribution in reinforced concrete pile foundation

The process of pressing piles will cause the surrounding soil mass to be destroyed and displaced due to the displacement of the pile. When pressing the pile into the ground, the soil around the pile tends to displace horizontal. Fig. 18 shows that when pressing the first pile section C1, the depth of the pile tip reaches 5.0 m (Phase 1), the piles begin to affect the piles of the existing building's foundation with horizontal displacement U_x= 5.4 mm. This horizontal displacement also increases when the pile tip reaches depths of 10.0 m and 12.4 m, respectively, with horizontal displacements U_x= 9.6 mm (Phase 2) and U_x= 10.2 mm (Phase 3). After pressing the pile C1 segment, the press is unloaded to move to a new position to press the C2 pile segment, the horizontal displacement of the existing pile is also analyzed at the C2 pile tip when the pressing depth is 5.0 m, 10.0 m and 12.4 m. The pressing of C2 pile into the ground has made the ground more compact because the C2 pile continues to occupy the place and causes horizontal displacement of the ground and at the same time affects the existing foundation-foundation system, transverse displacement. The maximum value of the pile reaches the value U_x= 10.2 mm (Phase 7) when the pile tip C2 reaches the design height.

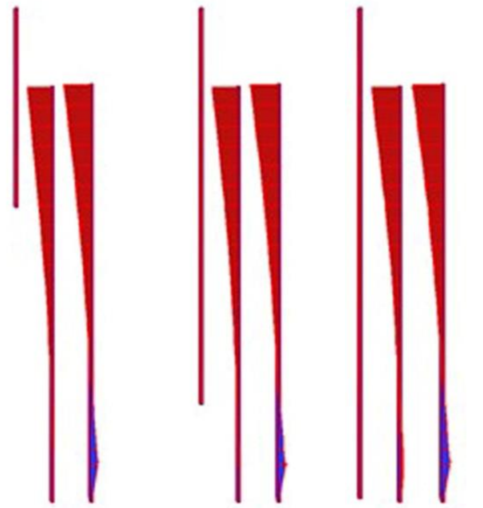


a) Phase 1 u_{xmax}=5.4 mm | b) Phase 2 u_{xmax}= 6.5 mm | c) Phase 3 u_{xmax}= 7.8 mm



d) Phase 5 u_{xmax}=8.4 mm | e) Phase 6 u_{xmax}= 9.6 mm | f) Phase 7 u_{xmax}= 10.2 mm

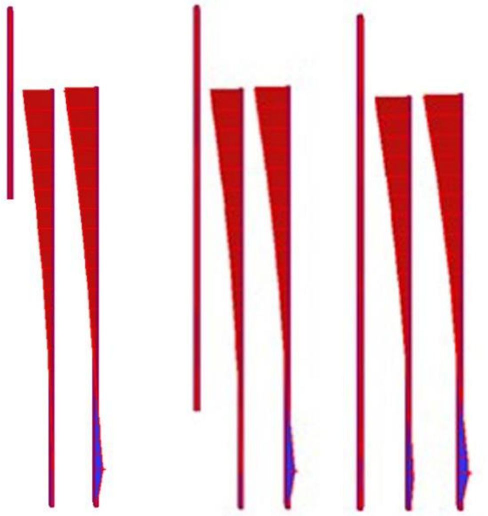
Fig. 18 Horizontal displacement changes when pressing piles for adjacent construction



a) Phase 1 M_{3max}= 9.5 kNm M_{3min}= -42.7 kNm

b) Phase 2 M_{3max}= 9.6 kNm M_{3min}= -43.7 kNm

c) Phase 3 M_{3max}= 10.7 kNm M_{3min}= -45.4 kNm



d) Phase 5 M_{3max}= 9.1 kNm M_{3min}= -46.5 kNm

e) Phase 6 M_{3max}= 9.3 kNm M_{3min}= -47.1 kNm

f) Phase 7 M_{3max}= 10.7 kNm M_{3min}= -48.6 kNm

Fig. 19 Change in stress of piles when pressing piles for adjacent construction

Simulation results also show the increase in bending moment in the piles of the existing foundation from Fig. 19a to Fig. 19f during the pressing of C1 and C2 piles. The positive torque value increased from 9.5 kNm to 10.7 kNm, the negative torque value increased from 42.7 kNm when the C1 pile tip reached a depth of 5.0 m, to 48.6 kNm when the C2 pile tip reached high design level 12.4 m.

The appearance of bending moment in the pile will be detrimental to the pile such as cracking, which then causes seepage and corrosion in the pile over time. If the difference between positive and negative moments is large, which can break the pile and collapse the structure.

When the pile is pressed into the soil, due to soil compression through the load acting on the pile head, the excess pore water pressure around and under the pile tip increases. During pile pressing, the largest residual pore water pressure is observed in the area around the pile tip. When the residual pore water pressure is large at the pile tip, the effective isotropic compressive stress is small, the shear resistance of the soil within the pile tip is small so pile pressing will be easier if it is done continuously.

After pressing to the design depth, the pile is allowed to rest, during this time the pore water pressure gradually dissipates. The underlying soil layer has a large permeability coefficient, so the excess pore water pressure dissipates almost completely. The area around the piles in the soft clay layer has a small permeability coefficient, so the time to stop permeable consolidation is longer.

6. CONCLUSIONS

By using finite element method, it is possible to simulate the construction process of pile pressing in adjacent construction works. The analysis results show that there has been an influence of the pile-pressing construction process on the stress and deformation of the foundation of the neighboring works. With the research goal of overcoming the situation of house construction affecting adjacent houses, the selection of foundation solutions is not enough, but it is necessary to have construction solutions that do not affect neighboring works, the research results show that:

When the adjacent construction work is not present, the vertical displacement of reinforced concrete pile foundation of existing works is 0.6 mm, but when pressing interlocked reinforced concrete pile with size 0.3 m x 0.3 m, pile length 10.0 m, position at 0.5 m from the edge of the existing foundation, this displacement is up to 15.9 mm and smaller allow displacement in Vietnamese standard. The effective stress in the existing reinforced concrete pile foundation without adjacent is -273.7 kN/m^2, but when it is interlocked, it is -3490.0 kN/m^2. After pressing the two pile segments C1 and C2, the horizontal displacement of the existing piles is 10.2 mm and a bending moment of 48.6 kNm occurs.

The construction plan for pressing reinforced concrete piles 0.5 m from the edge of the existing foundation for the My Tho city area in the study will help investor, design consultant, and construction quality management agency choose more suitable construction technology, machines and equipment when handling the foundation in narrow ground conditions.

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