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HORIZONTAL MOVEMENT OF PILE FOUNDATION DUE TO COMBINED LOADS

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ABSTRACT: The vertical loads of a structure are usually carried by pile foundations, but horizontal loads are dominant in some other structures. It is, however, necessary to note that combined loads are seldomly analyzed in simultaneity even though they work simultaneously on-site. This means the horizontal movement added due to the combined loads is not usually considered in construction. Therefore, this research was conducted to investigate and analyze the effect of combined loads at horizontal movement on a single pile and group pile foundations. The process was in three stages. The first was an analysis conducted through 2D-FEM Plaxis2D8.6, the second was an experimental test in the laboratory, and the third involved the analysis through 3D-FEM Plaxis3D Foundation1.1 for validation using soil data and loading test on several projects. The results showed the horizontal movement increased significantly up to the moment it averagely collapsed after reaching ((Pu.D)/(Hu. L.E)=$\pm 2.5 \times 10^{-6}$) for a single pile and ((Pu.D)/(Hu.L.E)=$\pm 0.745 \times 10^{-6}$) for group pile. This increment needs to be considered in the construction process and the additional horizontal movement due to the combined load also needs to be considered after the limits have been reached.

Keywords: Vertical-horizontal loads; Single-pile; Group-pile; Horizontal-movement

1. INTRODUCTION

The vertical loads of a structure are usually carried by pile foundations but the dominant loads in some other structures are horizontal. This makes it very important to calculate the horizontal loads in pile foundations [1]. It is important to note that combined loads are seldomly analyzed in simultaneity. This involves calculating the vertical load first to determine the vertical carrying capacity and vertical movement followed by the determination of the horizontal load to evaluate the horizontal bearing capacity and horizontal movement. Meanwhile, the two loads work simultaneously on-site [2]. These loading tests are, however, not usually conducted simultaneously in Indonesia and this leads to non-consideration of the additional horizontal movement due to the combined loads in the construction process as required by the ASTM D3966-07 [3]. Previous studies have reported the reduction of horizontal movement in pile foundation under combined loads due to vertical loads [4] while horizontal loading was discovered not to be causing any vertical movement but can increase the movement in combined loads [5]. A study also showed horizontal bearing reduced as the embedded part of the pile was decreased while the horizontal movement also reduced with an increase in the vertical load on the pile head [6]. Moreover, a three-dimensional finite element analysis was conducted to determine the influence of combined vertical and horizontal loads on homogeneous clay and sandy soils. The results showed a significant increase in the effect of vertical load on the horizontal bearing capacity in sandy soil and a slight decrease in clay soil, but a substantial influence was recorded for sandy soils, even for piles with 30D in length, and a less significant impact was found with clay soils for piles above 15D in length [7]. Another test conducted on poorly graded sand with the pile and loading varied also showed an increase in the horizontal bearing capacity as the vertical load was increased [8]. A numerical study analysis of pile-soil interactions subjected to vertical and horizontal loads simultaneously using LPILE, a finite element (FE) model with Abaqus/Cae and SAP 2000, also showed an increase in vertical load caused the induced bending moment and horizontal movement to reduce and this subsequently increased its capacity to withstand horizontal forces [9]. Another research also discovered that the influence of vertical loads on horizontal bearing capacity pile increased significantly in sandy soils but less significantly in loamy soils [10]. Vertical loads were also reported to have less effect on horizontal resistance in sandy soil, but the progression was observed to be increasing as the soil density increased [11,12]. Moreover, the influence of vertical load on horizontal bearing capacity significantly increased in sandy soils and slightly in clay soils while the square-shaped pile was found to have the ability to withstand 1.3 times more load than the round pile [13]. The numerical analysis also showed the effects of combined loads are beneficial, but the interactions were very complex, and depending on the load conditions, there is a possibility of a contrary effect on system rigidity and max load [14]. Limited experimental research also discovered that the application of a static vertical load has a minimal effect on the horizontal behavior of micropiles fixed in rigid clay soil [15]. Furthermore, some studies also provided evidence that horizontal loads reduced combined loads even though deflection was decreased by vertical loads due to their presence.

Previous studies reported that vertical loads were able to reduce the horizontal movement caused by combined loads. The horizontal loads were also reported to have increased the vertical movement in combined loads, but early analysis conducted with 2D-FEM showed a new result. The horizontal movement at the pile head was observed to have increased significantly at a certain point up to the period of collapse due to the combining load. This was further proven by the preliminary modeling of a single pile foundation using the axisymmetric menu on the 2D Finite Element Method (2D-FEM) which consists of different loading directions including vertical, horizontal, and combination of both, variations of lengths and diameters of the pile, soil variations including soft, medium, dense, homogeneous, layered, and different ground-water table conditions including submerged and not submerged.

This research was conducted to continue the initial 2D-FEM research and investigate the effect of simultaneous loading on horizontal movement.

2. RESEARCH SIGNIFICANCE

This research is very important because combined loads are seldomly analyzed in simultaneity even though they work simultaneously on-site. This means the horizontal movement added due to the combined loads is usually not considered in the planning of pile foundation construction with a horizontal load that is quite influential so the results of this study can be used for consideration in the calculation and planning of the bearing capacity of the pile foundation.

3. METHODOLOGY

The process was divided into three stages with the first being a preliminary analysis conducted through the 2D Finite Element Method (2D-FEM) with Plaxis2D8.6 approach, the second was the laboratory model experimentation test, and the third was the analysis conducted using the 3D Finite Element Method (3D-FEM) with Plaxis3D Foundation1.1 approach based on the results of loading tests obtained from several field projects such as Citarum Bridge, Dompak Bridge, and Batang project.

3.1 Stage I, Analysis With 2D Finite Element Method (2D-FEM)

The preliminary analysis involved the modeling of a single pile foundation using the axisymmetric menu on 2D Finite Element Method (2D-FEM) Plaxis2D8.6 which consists of different loading directions such as vertical, horizontal, and combinations of both, variations of lengths and diameters of the pile, soil variations including soft, medium, dense, homogeneous, and layered. Loading direction and soil parameter variations used in this research are, however, presented in Table 1 and Table 2 respectively.

Table 1 Variation of the load in 2D-FEM

Type of soil	Pile Dimensions		Load (kN), until it collapses		
	D (m)	L (m)	H	V	C
Ts	0.65	17	to 600	to 12000	V+H
Ts	0.65	30	to 600	to 12000	V+H
Tm	0.65	22	to 600	to 12000	V+H
Tm	0.65	26	to 600	to 12000	V+H
Tm	0.65	30	to 600	to 12000	V+H
Td	0.6	17	to 600	to 12000	V+H

Note: Ts= Soft soil, Tm=Medium soil, Td=Hard soil, H=Horizontal loads, V=Vertical loads, C=Combined loads

3.2 Stage II, Laboratory Model Experimental Test

The model was a (1.5x1.5x1.2) m^3 test box filled with silty-sand soil obtained from Berbah District, Sleman City, Special Region of Yogyakarta, Indonesia. The pile foundations were modeled using steel bars with 0.5m and 0.6m lengths and 0.015m and 0.02m diameters, while group pile foundations (1x2) and (2x2), respectively with s=2.5D and s=3D presented in Fig. 1 and subjected to vertical, horizontal, and combined loads. The Laboratory Test model is presented in Fig. 2 Variations in foundations lengths and diameters and combined loads are indicated in Table 3.

3.3 Stage III, Analysis Using 3D Finite Element Method (3D-FEM)

The analysis conducted using the 3D Finite Element Method (3D-FEM) involves modeling a single pile foundation soil data from several field projects including Citarum Bridge, Dompak Bridge, and Batang Project. The variables used include vertical, horizontal, and combined loads as indicated in Table 4 and Table 5.

Table 2 Variations of soil parameters and elements in 2D-FEM

Name/symbol	Ts	Tm		Td				Pile
	Lyr 1	Lyr 1	Lyr 2	Lyr 1	Lyr 2	Lyr 3	Lyr 4	
Material Model	MC	MC	MC	MC	MC	MC	MC	LE
Material Condition	D	D	D	D	D	D	D	NP
Dry Volume Weight (kN/m^3)	16.50	16	17	11.86	12.22	12,.86	13.57	24
Saturated Volume Weight (kN/m^3)	20	20	21	17.50	18.03	17.67	17.83	
Modulus Young', E (kN/m^2)	8×10^4	1.2×10^5	1.2×10^5	1.6×10^6	1.6×10^6	1.6×10^6	1.6×10^6	25.33
Poisson Ratio,u	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Cohesion, c (kN/m^2)	1	1	1	2.05	2.30	0.05	0.02	
Shear strength ∅ (°)	31	30	33	30	30	35	40	
interface, R_{inter}	1	1	0.70	0.40	0.35	0.70	0.70	

Note: D=Drained, NP=Nonporous, MC=Mohr Coulomb, LE=Linear Elastic, Ts= Soft soil, T3=Medium soil, T6=Hard soil, γ_k*=Dry unit weight,* γ_{sat}*=Saturated unit weight, E= Elasticity modulus; NP=NonPorous*

Table 3 Variation of loads in the laboratory experiment

Type of pile	Pile Dimensions		Pile distance	Load (kN) (until collapsed)		
	D (cm)	L (cm)	s (cm)	H	V	C
Single pile	2	60		0 - 7000	0 – 37500	V + (2000 – 5000)
	1.5	50		0 - 6500	0 – 25000	V + (1500 – 2500)
				0 - 14000	0 - 80000	V + (9000)
Group Pile	2	60	2.5D & 3D	0 - 14000	0 - 75000	V + (7000)
(1x2)	1.5	50	2.5D & 3D	0 - 19000	0 - 130000	V + (13000 – 14000)
				0 - 19000	0 - 105000	V + (8000)
Group Pile	2	60	2.5D & 3D	0 - 7000	0 – 37500	V + (2000 – 5000)
(2x2)	1.5	50	2.5D & 3D	0 - 6500	0 – 25000	V + (1500 – 2500)

Note: D=Diameter, L=Length, s=Distance, H=Horizontal loads, V=Vertical loads, C=Combined loads

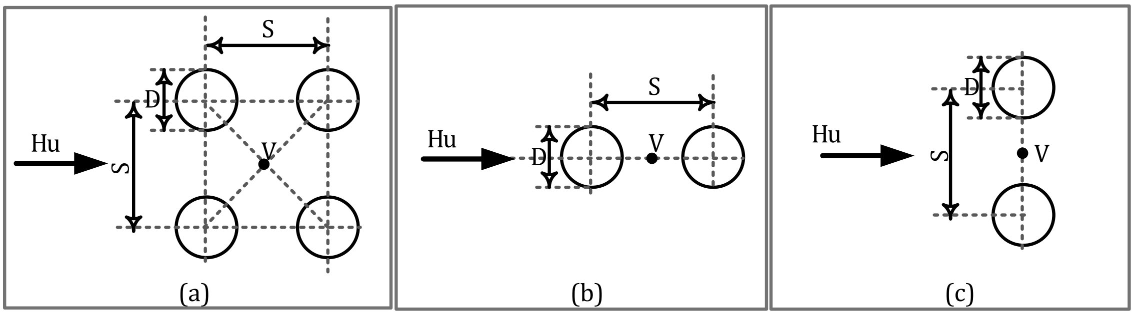

Fig. 1 The arrangement of the group pile. a) (2x2), b) (2x1), c) (1x2)

Table 4 Variation of soil parameters and elements in 3D-FEM

Project	Depth (m)	Material model / condition	μ	R	Gs	w	γb	γk	γsat	Parameters of soil	
						%	kN/m^3	kN/m^3	kN/m^3	$\varnothing^o$	c kN/m^2
Batang Project	1to8	MC/D	0.3	0.6	2.6	40	16.6	11.86	17.50	25.0	2.05
	8to12	MC/D	0.3	0.6	2.6	35	16.5	12.22	18.03	25.0	2.30
	12to20	MC/D	0.3	0.6	2.7	40	18.0	12.86	17.67	30.0	0.05
	20to30	MC/D	0.3	0.6	2.7	40	19.0	13.57	17.83	35.0	0.02
Dompak Bridge	1to6	MC/D	0.3	0.6	2.5	20	15.5	12.92	19.62	15.0	2.20
	6to12	MC/D	0.3	0.6	2.5	20	15.8	13.17	19.62	20.0	2.10
	12to22	MC/D	0.3	0.6	2.7	20	16.6	13.83	20.39	25.0	0.05
	22to34	MC/D	0.3	0.6	2.7	20	19.5	16.25	20.64	35.0	0.02
Citarum Bridge	0to1	MC/D	0.3	0.6	2.5	20	15.5	12.92	19.62	15.0	2.20
	1to4	MC/D	0.3	0.6	2.5	20	15.8	13.17	19.62	17.0	3.00
	4to14	MC/D	0.3	0.6	2.7	20	19.7	16.42	20.64	35.0	0.02
	14to60	MC/D	0.3	0.6	2.6	20	17.6	14.67	20.14	35.0	0.02

Note: Gs=Specific gravity, w=Water content, c=Cohesion, γ_b= Unit weight, γ_k=Dry unit weight, γ_{sat}=Saturated unit weight, D=Drained, MC=Mohr Coulomb, μ=Poisson ratio, R= interfac.

Table 5 Variation of the load in 3D-FEM

Project /	Pile Dimensions		Pile distance	Load (kN) (Until collapsed)		
Type of pile	D (m)	L (m)	s (cm)	H	V	C
Single pile						
Citarum Bridge	1.2	20		0 - 330	0 - 7700	V + (100)
Dompak Bridge	1	18		0 - 275	0 - 7200	V + (100)
Batang Project	0.6	17		0 - 370	0 - 7000	V + (170)
				0 - 1900	0 - 45000	V + (700)
Group Pile (1x2)				0 - 2500	0 - 60000	V + (500)
Citarum Bridge	1.2	20	2.5D & 3D	0 - 2500	0 - 30000	V + (500)
Dompak Bridge	1	18	2.5D & 3D	0 - 3500	0 - 90000	V + (1200)
Batang Project	0.6	17	2.5D & 3D	0 - 4000	0 - 90000	V + (1500)
				0 - 4000	0 - 80000	V + (1000)
Group Pile (2x2)				0 - 330	0 - 7700	V + (100)
Citarum Bridge	1.2	20	2.5D & 3D	0 - 275	0 - 7200	V + (100)
Dompak Bridge	1	18	2.5D & 3D	0 - 370	0 - 7000	V + (170)
Batang Project	0.6	17	2.5D & 3D	0 - 1900	0 - 45000	V + (700)

Note: D=Diameter, L=Length, s=Distance, H=Horizontal loads, V=Vertical loads, C=Combined loads

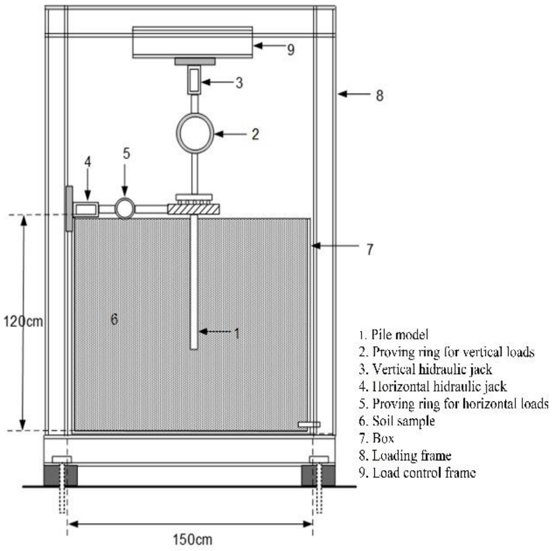

Fig. 2 Laboratory test model

4. RESULTS

The research results obtained from the 3-stage analysis as described above will be presented in the following subsections:

4.1 Analysis Using 2D Finite Element Method (2D-FEM)

This preliminary analysis showed the horizontal movement at the head of the pile due to combined loads is presented in Fig. 3 Horizontal movement at the head of the pile using 2D-FEM. The horizontal movement at the head of the pile was observed to have increased significantly at a certain point at an average value of ((Pu.D)/(Hu.L.E)=±2.5x10^{-6}) and the increment was continuous to the moment it collapsed, if the comparison has reached that point, it is necessary to take into account the added horizontal movement in the pile foundation design.

4.2 Laboratory Model Experimental Test of Single Pile

The results of the experimental tests conducted on the laboratory scale models, the horizontal movement at the head of a single pile due to the combination of loads are indicated in Fig. 4 Horizontal movement at the head of a single pile using laboratory test, was discovered to be almost like the 2D-FEM analysis. This is indicated by the significant increase at a certain point with an average value of ((Pu.D)/(Hu.L.E)=±2.5x10^{-6}), the increment was continuous to the moment it collapsed, if the comparison has reached that point, it is necessary to take into account the added horizontal movement in the pile foundation design.

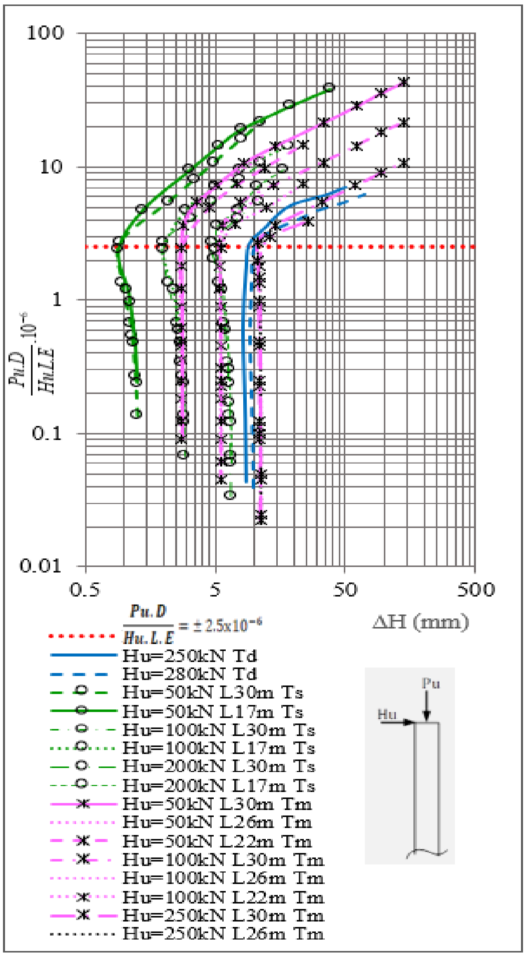

Fig. 3 Horizontal movement at the head of the pile using 2D-FEM

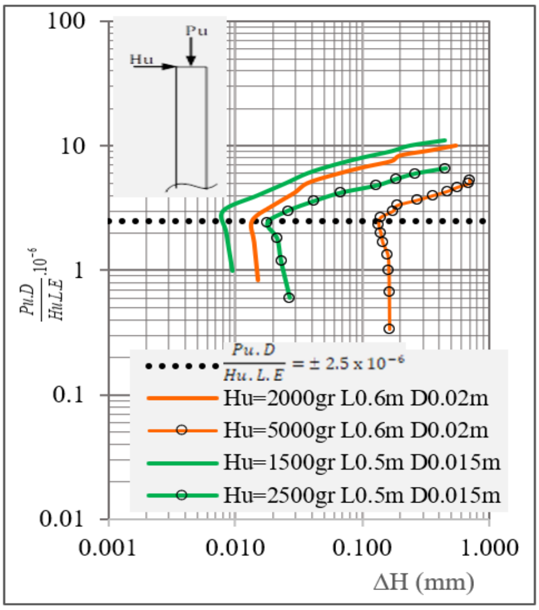

Fig. 4 Horizontal movement at the head of a single pile using laboratory test

4.3 Laboratory Model Experimental Test of Group Pile

The horizontal movement at the group pile foundation caused by the combined loads is presented in Fig. 5 for the (1x2) arrangement and presented in Fig. 6 for the (2x2) arrangement. The horizontal movement at the head of the group pile was found to have increased significantly at a certain point at an average value of ((Pu.D)/(Hu.L.E)=±0.799x10^{-6}) for the (1x2) arrangement and ((Pu.D)/(Hu.L.E)=±0.746x10^{-6}) for the (2x2) arrangement.

4.4 Analysis using 3D Finite Element Method (3D-FEM) of Single Pile

The horizontal movement at the group pile foundation caused by the combined loads is presented in Fig. 7 Horizontal movement at the head of a single pile using 3D-FEM was to be almost like the results of the 2D-FEM analysis. It also confirmed the findings from the laboratory experiment that the horizontal movement at the single pile head increased significantly at a certain point with an average value ((Pu.D)/(Hu.L.E)=±2.5x10^{-6}) and the increment was continuous to the moment it collapsed.

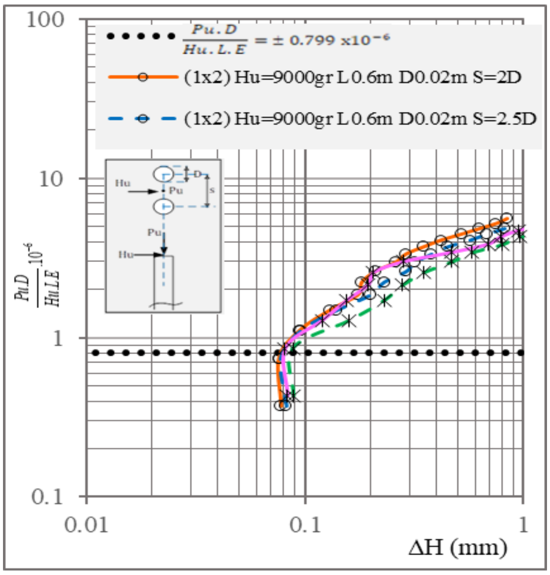

Fig. 5 Horizontal movement at the head of the group pile using laboratory tests for the (1x2) arrangement.

4.5 Analysis using 3D Finite Element Method (3D-FEM) of Group Pile

The horizontal movement at the head of the group pile Citarum bridge, Dompak bridge, and Batang project are indicated in Fig. 8 and Fig. 9. The results were observed to be almost the same as the findings of the experimental laboratory model which showed the horizontal movement at the pile head to be very significant at a certain point and increased substantially at some point. The values for each of the projects analyzed are presented as follow:

Citarum Bridge (3D-FEM),
(± 0.798x10^{-6}) for the (1x2) arrangement
(± 0.748x10^{-6}) for the (2x2) arrangement
Dompak Bridge (3D-FEM),
(± 0.734x10^{-6}) for the (1x2) arrangement
(± 0.815x10^{-6}) for the (2x2) arrangement
Batang Project (3D-FEM),
(± 0.659x10^{-6}) for the (1x2) arrangement
(± 0.659x10^{-6}) for the (2x2) arrangement

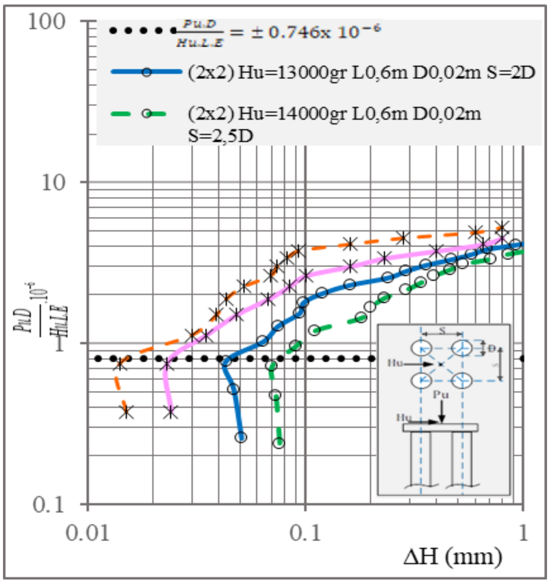

Fig. 6 Horizontal movement at the head of the group pile using laboratory tests for the (2x2) arrangement

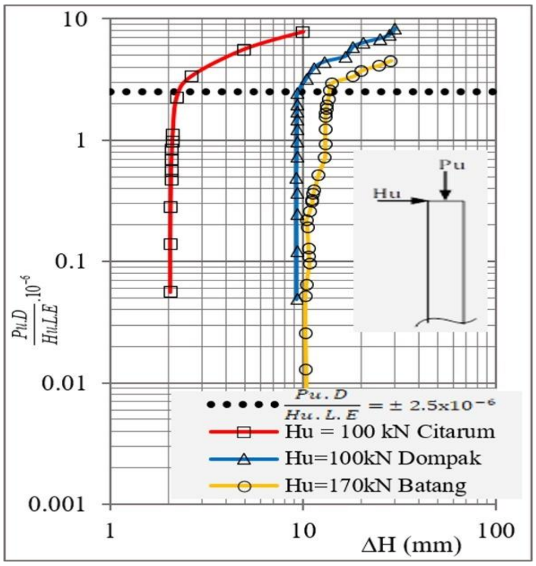

Fig. **7** Horizontal movement at the head of a single pile using 3D-FEM

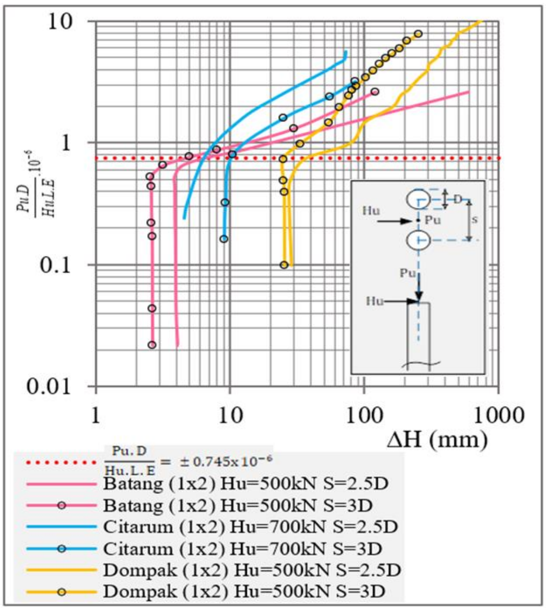

Fig. 8 Horizontal movement at the head of the group pile using 3D-FEM for the (1x2) arrangement

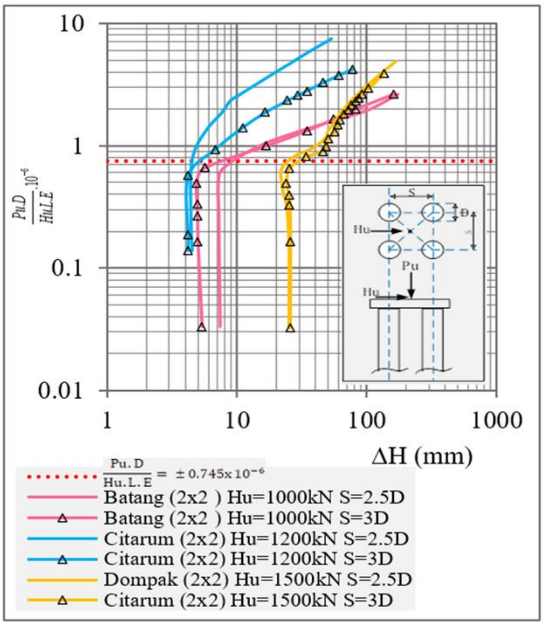

Fig. 9 Horizontal movement at the head of the group pile using 3D-FEM for the (2x2) arrangement

5. DISCUSSION

Previous studies reported horizontal movement to have reduced as the vertical load on the pile head increased [6] and the same was also observed from a test conducted on poorly graded sand with the pile and loading varied [8]. Another study showed the influence of vertical loads on the horizontal bearing capacity of piles increased significantly in sandy soils but less significantly in loamy soils [10]. Moreover, vertical loads have been reported to reduce horizontal movement caused by horizontal loads which further increased vertical movement in combined loads. The preliminary research conducted using 2D-FEM analysis showed something similar to previous research, however, this preliminary research shows something new that the horizontal movement at a single pile head was observed to have increased significantly at an average value of $((Pu.D)/(Hu.L.E) \geq \pm 2.5x10^{-6})$ therefore, further research will be investigating the analysis and experimental laboratory, the effect of horizontal movement on pile foundation, as the effect of combined loads, using a 3D-scale experiment in the laboratory as well as modeling through 3D-FEM analysis using loading test data obtained from several field projects. This research focused on both single pile and pile groups arranged at (1x2) and (2x2).

The single pile test results for the laboratory experiment tests and the 3D-FEM analysis were observed to be almost similar to those obtained from the 2D-FEM analysis with the horizontal deflection recorded to have increased significantly at an average value of $((Pu.D)/(Hu.L.E) \geq \pm 2.5x10^{-6})$ up to the period of collapse due to vertical load. Meanwhile, the increment recorded for the group pile was at an average value of $((Pu.D)/(Hu.L.E) \geq \pm 0.745x10^{-6})$, if the comparison has reached that point, it is necessary to take into account the added horizontal movement in calculating and planning pile foundation bearing capacity.

Moreover, the layered soil was observed to have different young and shear modulus values and this means the horizontal movement added was not linear. Further research is, therefore, required to determine the average curvature of the line and the curve equation for the increase in horizontal movement to estimate the horizontal movement added.

6. CONCLUSION

This research focused on investigating the effect of combined loads on the horizontal movement of single and group pile foundations through analyses and laboratory experiments. It was also used to determine the relationship to be used as a reference to analyze additional horizontal movement on single and group pile foundations. A preliminary 2D-FEM analysis was first conducted and this was followed by the laboratory experiment and further validated with a 3D-FEM model using loading test data from several field projects.

The results from the experiments and 3D-FEM modeling were observed not to be much different from those obtained from the 2D-FEM for single pile foundation that on average $((Pu.D)/(Hu.L.E) \geq \pm 2.5x10^{-6})$. The horizontal movement was observed to have increased significantly due to the combined load and this needs to be considered in planning the pile foundation. The group pile foundations were recorded to have ((Pu.D)/(Hu.L.E)≥±0.745x10^{-6}) and if the comparison has reached that point, it is necessary to take into account the added horizontal movement in calculating and planning pile foundation bearing capacity.

The research was conducted by laboratory experiment and by computer analysis due to cost limitations, it would be better if this research was continued with full-scale models to be verified through further studies to obtain satisfactory results

7. ACKNOWLEDGMENTS

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