UDC 624
DOI: 10.15587/1729-4061.2025.322258

IDENTIFYING LATERAL RESISTANCE BEHAVIOR OF SHORT PILE FOUNDATIONS IN LIQUEFACTION SOIL

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Currently, infrastructure development in earthquake-prone areas can overcome major challenges related to soil liquefaction phenomena, especially in areas with high earthquake intensity. This is a critical issue in foundation design, especially short pile foundations. One important aspect influencing the behavior of foundations in soil experiencing liquefaction is lateral resistance, which directly affects the stability and ability of the foundation to withstand lateral loads. The object of the study is to determine the lateral occupant behavior of short pile foundations with variations in vertical load, foundation depth, in liquid soil. This research was carried out with a series of tests on groups of rigid piles on sandy soil that received earthquake loads. The sand material used comes from Lumajang with a uniform density to ensure consistent soil conditions in each test. The length of the pile is determined based on the pile stiffness factor (T), with L values of 1T, 1.5T, and 2T. The vertical load applied to the pile is varied by 0.1Pu, 0.2Pu, and 0.3Pu, where Pu is the ultimate load of the pile. The research results show that pore water pressure fluctuations can be an indicator of significant liquefaction potential. Specifically, at a soil density of 20 %, the pore water pressure fluctuates in the range of 1 to 3 kPa and can reach Ru values close to or equal to 1. Another result is that the relationship between lateral deformation and lateral load in pile foundations shows an increase in linear load, and lateral deformation is not the only factor that influences the load resistance of piles. However, there are also factors such as soil conditions and the characteristics of the pile material itself

Keywords: lateral, resistance, short, pile, foundation, liquefaction, soil, group, deformation, vertical

Received 01.11.2024
Received in revised form 23.12.2024
Accepted 09.01.2025
Published 26.02.2025

How to Cite: *Alihudien, A., Munawir, A., Zaika, Y., Suryo, E. A. (2025). Identifying lateral resistance behavior of short pile foundations in liquefaction soil. Eastern-European Journal of Enterprise Technologies, 1 (7 (133)), 6–13. https://doi.org/10.15587/1729-4061.2025.322258*

1. Introduction

Currently, infrastructure development in earthquake-prone areas faces major challenges related to the phenomenon of soil liquefaction, especially in areas with high earthquake intensity. Liquefaction occurs when saturated soil loses strength due to earthquake vibrations, causing a significant reduction in the soil's bearing capacity. This is a critical issue for foundation design, especially short pile foundations, which are often used to support various structures such as bridges, piers, and retaining walls. One important aspect in understanding the behavior of foundations in liquefied soil is lateral resistance, which directly affects the stability and ability of the foundation to withstand lateral loads due to earthquake forces or ground pressure.

Research on the behavior of pile foundations under liquefaction soil conditions has become an important topic in the geotechnical field because of its significant impact on structural stability, especially in earthquake-prone areas. Several previous studies have contributed to the understanding of this aspect with various theoretical, experimental and numerical approaches. The liquefaction mechanisms in sand-saturated soils resulting from earthquake vibrations have been identified, which paved the way for further studies on how liquefaction affects structural elements such as pile foundations [1]. Subsequent research developed a method for evaluating soil-pile interactions during liquefaction, including the effect of increased pore pressure on lateral bearing capacity [2, 3]. Further, the importance of lateral deformation analysis in pile foundations was highlighted, emphasizing how foundation depth and soil conditions influence lateral response during and after liquefaction [4]. Numerical studies showed that the lateral behavior of pile foundations is strongly influenced by earthquake pressure and dynamic soil properties, but these results require validation through scale experiments [5]. Experimental research used a physical model to show that vertical loads on piles can significantly increase lateral deformation in soil conditions experiencing liquefaction [6]. These findings provide empirical evidence for the correlation between vertical load and lateral deformation, but do not address the influence of other parameters such as soil density and earthquake acceleration.

However, the lateral resistance of foundations in liquefied soil is still not fully understood, especially regarding the influence of parameters such as vertical load, foundation depth, soil density and earthquake acceleration. This lack of understanding can lead to inefficient or even structurally failed designs, with detrimental consequences both economically and for public safety. In addition, numerical approaches that are often used in analyzing foundation behavior under liquefaction conditions require empirical validation through small and large-scale experiments to ensure the accuracy of the results. Therefore, research that focuses on identifying the lateral resistance behavior of short pile foundations in liquefied soils becomes very relevant to address this technical challenge.

2. Literature review and problem statement

Regarding the lateral behavior of pile foundations during the liquefaction process, researchers have conducted analytical research and laboratory tests. This study examines the behavior of pile foundations in liquefied soil using shaking tests [7], single or group of foundations, depth and diameter of foundations, pile foundation material, and roughness of pile foundation material on lateral resistance of pile foundations for uniform non-cohesive soil. However, an aspect that has not been explored in depth is the influence of interactions between piles in different soil conditions, such as cohesive soils or soils with high organic content, which may significantly influence the behavior and reliability of pile foundations. It has not been widely studied due to the complexity of simulating more heterogeneous and varied soil conditions in laboratory testing, as well as the challenges in translating such results into effective practical applications. The second researcher has developed research through experiments on the effects of vertical loads on piles [8]. One area that has received less attention is the influence of heterogeneous soil conditions on the behavior of piles when subjected to vertical loads. Most studies, including those conducted by these researchers, often use homogeneous soil models to simplify analysis. However, soil conditions are more complex, with layers that have different densities and compositions. This limitation can affect the validity and applicability of research findings, where variability in soil conditions can affect the safety of pile structures. The results showed an increase in lateral pile resistance of 49 % up to 107 % compared with no vertical load. In group pile installation, the effect of spacing and depth of piles and drilled piles has been researched and studied [9]. However, an aspect that remains less explored is the influence of soil-pile interactions on heterogeneous soil conditions. This is important because the uneven distribution of soil characteristics can significantly influence the behavior of piles when subjected to lateral loads. Limitations in modeling and field testing that are able to accurately represent complex and varied soil conditions are the main reason why this aspect has not been widely studied.

Some research has been carried out on the lateral behavior of pile foundations during the liquefaction process, including studying the behavior of pile foundations on liquefied soil using vibration tests, single or group foundations, depth and diameter of foundations, pile foundation materials, and the roughness of pile foundation materials against lateral resistance of non-universal pile foundations [10, 11]. However, an aspect that has not yet been explored in depth is the influence of interactions between piles in a wide group configuration on the lateral behavior during liquefaction. This has not been widely studied due to the complexity of accurately modeling interactions between piles under liquefaction conditions, which requires more sophisticated simulations and modeling to fully understand its effects. Apart from that, research has also been carried out on the development of the influence of vertical pile loads [12]. The research results showed an increase in lateral pile resistance by 49 % to 107 % compared to without vertical load. Apart from that, for the installation of group piles, the influence of the distance and depth of piles and drilled piles has been studied [13]. However, there are still aspects that have not been fully explored, especially regarding the influence of interactions between piles in a pile group on vertical load conditions. This aspect has not been widely studied due to the complexity in modeling dynamic interactions between piles, which requires a more in-depth analysis approach and the use of more sophisticated modeling technologies.

A study of the lateral behavior of pile foundations during the liquefaction process in liquid soil using vibration tests has been carried out [14, 15]. However, there are still aspects that have not been explored in depth. One area that has been under-researched is the influence of variations in liquefied soil density on the dynamic response of pile foundations. This is due to the difficulty in simulating accurate liquid soil conditions on a laboratory scale as well as the complexity in modeling soil-pile interactions, which are highly dependent on the local characteristics of the soil. The pile foundation used is a single pile with clamped piles. There is also a study of the lateral behavior of pile foundations using the shake table test [16, 17], but the parameters determined are not able to describe conditions in the field so the results need to be revalidated. In other research, observations have also been made on changes in the behavior of pile foundations in the soil during liquefaction [18, 19]. However, there are still aspects that have not been fully explored, especially those related to the long-term influence of liquefaction on stress distribution in the soil, which has an impact on the stability of pile foundations. Further research has not been conducted in this area possibly due to limitations in monitoring technologies that can accurately measure changes in soil conditions at significant depths and over long periods of time following liquefaction events. Other research also shows that there is a change in soil stiffness around the pile foundation, which is accompanied by changes in pore water pressure on lateral forces due to the liquefaction process [20]. However, a less explored aspect is the long-term influence of these changes in pore water pressure on the structural stability of pile foundations under different conditions of the hydrological cycle. This has not been studied in depth due to limitations in long-term simulations that require complex and accurate modeling to represent the dynamic interactions between soil structure and hydrological changes, which often involve unpredictable variables and complex interactions between geotechnical components. Changes in pore water pressure seem to be one of the factors that need to be taken into account, but the method used is to prepare an analysis with the assumption that when liquefaction occurs the soil is liquid so the lateral load must also be taken into account. The response to the lateral load of pile foundations in liquid soil is by creating a p-y curve [21]. However, the response of pile foundations to lateral loads in liquefied soil conditions remains poorly explored, especially in the development of accurate p-y curves. The lack of experimental data and analytical models that can predict the complex interactions between piles and liquid soil is the main reason why this aspect has not been widely studied.

Research on liquefaction raises two problems, namely first, the behavior of pile foundations during liquefaction, and second, the method of estimating foundation lateral resistance [22]. In this research, there is still a lack of in-depth understanding of the interaction between pile foundation structures and soil experiencing liquefaction. This is mainly due to the complexity of the liquefaction phenomenon, which involves drastic changes in the mechanical properties of the soil in a short time. In addition, local geological conditions vary.

Based on the results of previous research, the parameters that influence the liquefaction of short group foundations have not been obtained in detail, especially those related to the influence of the lateral resistance of a group of rigid piles that receive vertical loads during soil embankment. So it is necessary to find a solution by carrying out further research in order to obtain more valid parameters regarding the influence of the lateral resistance of a group of rigid piles. The cause is the level of difficulty in modeling the lateral resistance of a group of small-scale rigid piles in the laboratory, not to mention the high implementation costs.

3. The aim and objectives of the study

This research aims to determine the lateral resistance behavior of short pile foundations with variations in vertical load, foundation depth, in liquid soil.

To achieve the aim, the following objectives were accomplished:

– to investigate the potential for liquefaction in vertical loads, foundation depth, soil density, and earthquake acceleration on the lateral resistance of pile foundations;

– to investigate the correlation between lateral deformation and lateral load that occur in pile foundations in liquefaction soil.

4. Materials and methods

The object of the study is the lateral occupant behavior of short pile foundations with variations in vertical load, foundation depth, in liquid soil.

This research was carried out with a series of tests on groups of rigid piles in sandy soil that received earthquake loads. The test was carried out using a shaking table. The shaking table is made of steel with dimensions of 1.5 m long, 1 m wide and 1.0 m high. The vibrating table moves in a horizontal direction on the provided rail, equipped with an accelerometer. To observe liquefaction behavior, 3 sensors were installed to observe the increase in pore water pressure (PWP), at different depths. Next, optical flow was installed on the top side to observe lateral deformation. Fig. 1 shows the experimental setup of this study.

The pile modeling uses a 2×2 pile group, which consists of 4 piles. The distance between pile caps is 2.5 pile diameters and the distance between piles and the outermost edge is 1.5 diameters. Fig. 2 shows the form of pile modeling in this research.

The soil box type uses the Rigid Container type, with dimensions of 1,500 mm long, 300 mm wide and 1,000 mm high. The ground box material is made of acrylic on all four sides with a thickness of 10 mm with steel reinforcement on each side, as seen in Fig. 3, 4.

The sampling is carried out based on locations with potential for liquefaction and methods of collection in disturbed conditions. Next, in the laboratory, a gradation test (ASTM D1140), specific gravity test (ASTM D854-14), and relative density test (ASTM D2049) are carried out. Soil characteristic test results can be seen in Table 1.

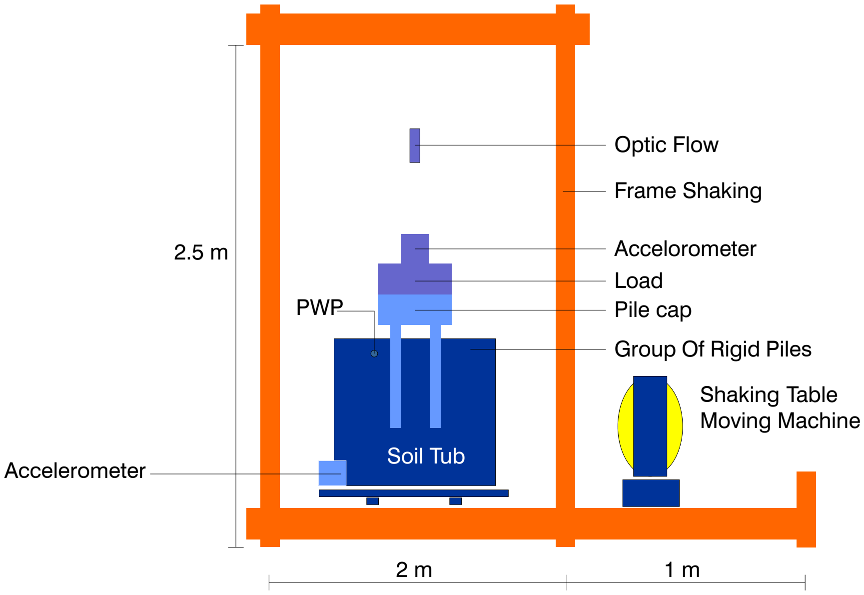

Fig. 1. Experimental setup

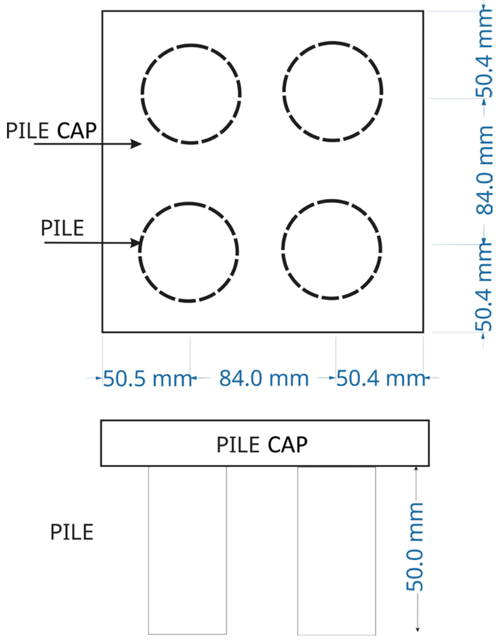

Fig. 2. Model of pile group

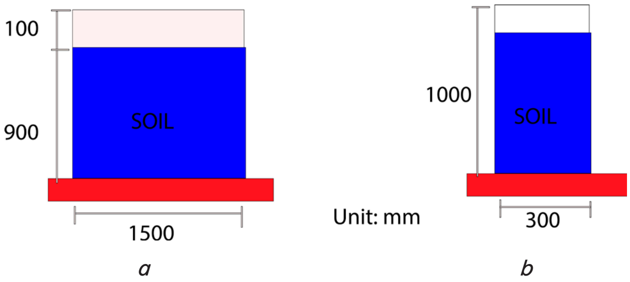

Fig. 3. Rigid container model: *a* – section of the earthquake acceleration direction; *b* – section perpendicular to the earthquake acceleration

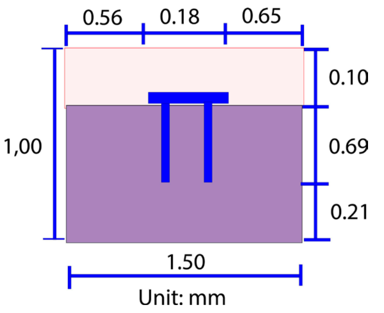

Fig. 4. Details of the rigid container model

Table 1 shows that sandy soil has a uniform gradation with low fine content and varying specific gravity values. Parameters such as C_u and C_c provide information about the grain size distribution, while $\gamma_{d\min}$ and $\gamma_{d\max}$ reflect the minimum and maximum dry density variations. These data provide a basis for understanding soil response to liquefaction and its influence on the behavior of short pile foundations.

The main hypothesis of the study is that fluctuations in pore water pressure in soil with relatively low density during vibration and vertical load can indicate liquefaction potential, which significantly affects the lateral resistance behavior and structural stability of pile foundations, and the lateral load increases with lateral deformation. However, there are other factors such as soil conditions and pile material characteristics that influence the load resistance of the foundation.

The assumptions used in this research include: the pile group configuration used in this research is a 2×2 square, with piles driven in uniform sandy soil, which has potential liquefaction characteristics. The sand soil used comes from Lumajang with a uniform density, while the piles used have a diameter of 3 cm.

Table 1

Soil sample properties

No.	Parameter	Value
1	Effective diameter D_{10} (mm)	0.18
2	Average diameter D_{50} (mm)	0.3
3	D_{60} (mm)	0.35
4	Uniformity coefficient C_u	1.94
5	Coefficient of gradation C_c	1.43
6	Fines content (%)	0.12
7	PI	NP
8	$g_{d\min}$, t/m^3	1.379
9	$g_{d\max}$, t/m^3	1.74
10	$e_{\min}$	0.618
11	$e_{\max}$	0.104

This research simplifies the analysis by using groups of 2×2 square piles in uniform sandy soil from Lumajang, 3 cm pile diameter with varying lengths (1*T*, 1.5*T*, 2*T*), and vertical loads (0.1*Pu*, 0.2*Pu*, 0.3*Pu*). Tests were carried out with a steel vibrating table measuring 1.5×1×1 m and an acrylic Rigid Container type soil box (1,500×300×1,000 mm). Pore water pressure was monitored with three sensors, and lateral deformation was recorded using transducers. Laboratory scale simulations as well as homogeneous soil assumptions were applied to overcome cost and technological limitations, providing a basis for further research.

5. Results of research on the lateral resistance behavior of short pile foundations in liquefaction soil

5. 1. Potential for liquefaction in vertical loads, foundation depth, soil density, and earthquake acceleration on the lateral resistance of pile foundations

Test results on soil variations with a relative density of 10 %. Vibration with an amplitude of 15 mm and a frequency of 1 Hz, a vertical load of 0.1 Qu, and a foundation depth of 0.22 m. The potential for liquefaction can be seen in the time history of excessive pore water pressure readings in the soil as shown in Fig. 5. This graph shows the presence of liquefaction when vibrations occur in the soil, where the Ru value is approximately equal to 1.

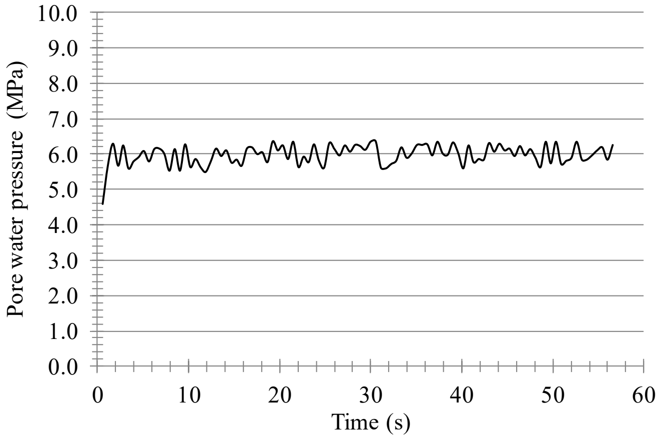

Fig. 5. Time history of pore water pressure readings in the soil

Fig. 5 shows the time history of pore water pressure measured in kilopascals (kPa) for 60 seconds. Tests were carried out on soil with a relative density of 10 %, subjected to vibration with an amplitude of 15 mm and a frequency of 1 Hz. In addition, a vertical load is applied equivalent to 0.1 times the ultimate load (Qu), with a foundation depth set at 0.22 meters.

The fluctuating lines indicate changes in pore water pressure throughout the duration of the test. Observing the behavior of pore water pressure over time helps assess how soil structure responds to dynamic loading conditions. The recorded pressure ranged from 5 to 7 kPa, which shows how the pressure increases and fluctuates under constant vibration and load.

Meanwhile, the test results were on soil variations with a relative density of 20 %. Vibration with an amplitude of 15 mm and a frequency of 1 Hz, a vertical load of 0.2 Qu, and a foundation depth of 0.22 m, as shown in Fig. 6.

Fig. 6 illustrates the time history of excess pore water pressure, measured in kilopascals (kPa), for a duration of 60 seconds with a relative density of 20 %, vibration with an amplitude of 15 mm and a frequency of 1 Hz, a vertical load of 0.2 times the ultimate load capacity (Qu), and the foundation depth is 0.22 meters. Test results show excessive pore water pressure fluctuations, generally ranging between 1 and 3 kPa. These fluctuations indicate the response of the soil to cyclic loading conditions, which is important for understanding the dynamics of pore water pressure buildup and dissipation.

Meanwhile, the test results were on soil variations with a relative density of 30 %. Vibration with an amplitude of 15 mm and a frequency of 1 Hz, a vertical load of 0.3 Qu, as shown in Fig. 7.

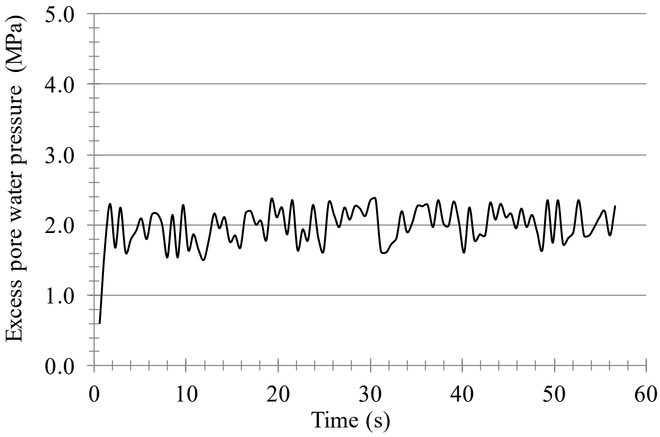

Fig. 6. Time history of excess pore water pressure

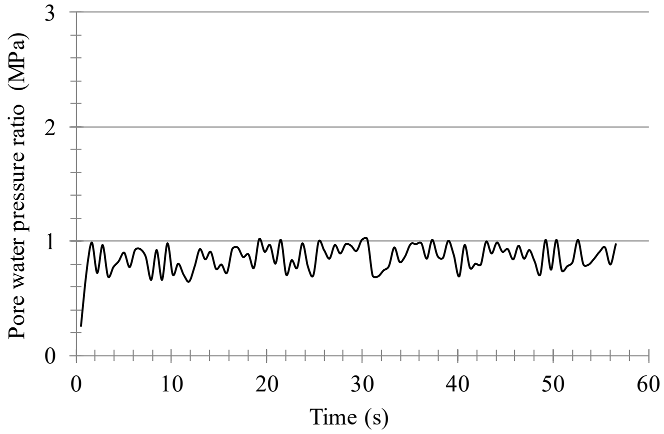

Fig. 7. Time history of excess pore water pressure ratio

Fig. 7 shows the pore water pressure ratio over a time span of 60 seconds, under soil test conditions involving a relative density of 30 %, vibration with an amplitude of 15 mm and a frequency of 1 Hz, a vertical load equivalent to 0.3 times the ultimate load (*Qu*), and a depth of foundation 0.22 meters.

The line on the graph fluctuates around a value typically below 1.0, with some peaks slightly above this mark, indicating the dynamic response of pore pressure to the applied loading and vibration conditions. A ratio of 1.0 or greater may indicate that excess pore pressure equals or exceeds the initial hydrostatic pressure, which is a critical condition for soil liquefaction.

This behavior indicates a fluctuating but largely controlled pore water pressure ratio, indicating that although the soil experiences pressure increases due to applied loads and vibrations, it may not consistently reach levels typically associated with immediate liquefaction risk, especially considering that the ratio generally remains below 1.0. This is an important indicator when assessing soil stability and liquefaction potential in seismically active areas.

5. 2. Correlation between lateral deformation and lateral load that occur in pile foundations in liquefaction soil

Fig. 8 shows the lateral resistance of pile foundations under dynamic test conditions. The data points, which fluctuate significantly over the recorded time, show a response to cyclic or dynamic loading that simulates seismic effects.

The line spike indicates a moment of significant lateral force exertion on the pile foundation. These patterns are critical to understanding the stiffness and damping properties of soil-pile systems during and after simulated liquefaction conditions.

Variations in amplitude and frequency of spikes may represent different behavior of soil pile systems under continuous or varying loads. A higher surge may indicate greater lateral resistance at a given time, indicating a moment at which the pile effectively resists lateral forces, perhaps due to soil density around the pile or a temporary increase in pile-soil friction.

Fig. 9 illustrates the relationship between the amount of lateral load (in Newtons) and the corresponding lateral deformation (in centimeters) observed in laboratory tests. The data points are spread across the plot with a general trend showing that as lateral deformation increases, so does the lateral load, although not evenly across the data points.

The trend line equation ($y=0.4936x^{0.91}$) shows a linear relationship, where the load increases by approximately 0.4936 N for every centimeter of deformation, with an initial load of 91 N if no deformation occurs. The coefficient of determination ($R^2=0.4548$) shows a moderate correlation, which implies that although lateral deformation is a significant determining factor of lateral load, lateral deformation is not the only factor that influences the load resistance of piles.

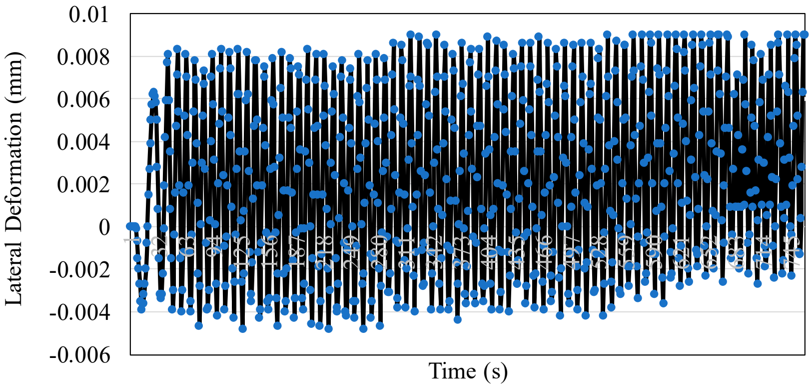

Fig. 8. Time history of lateral deformation readings on the pile cap

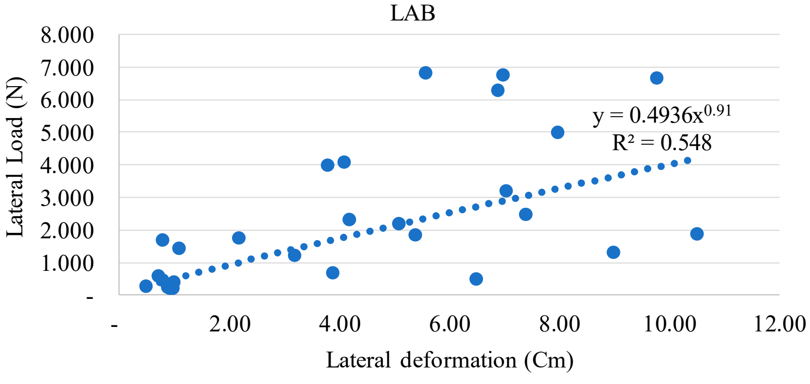

Fig. 9. Correlation of lateral deformation and lateral load

The behavior of pile foundations in liquefiable soil is complex due to the reduction in soil stiffness and strength due to earthquake forces. This graph helps quantify the lateral resistance created by short piles, which is critical in designing foundations capable of withstanding dynamic and potentially damaging forces during an earthquake.

6. Discussion of the research results on the lateral resistance behavior of short pile foundations in liquefaction soil

Fig. 5 shows changes in pore water pressure in soil with a relative density of 10 % subjected to vibration and vertical loading providing important insights into soil behavior under conditions close to construction and geotechnical reality. In infrastructure design in earthquake-prone areas or where the soil must support heavy dynamic loads. Vibrations with an amplitude of 15 mm and a frequency of 1 Hz imitate seismic conditions, causing soil particles to move and rearrange, which increases pore water pressure due to rapid changes in pore volume. Low relative density indicates that the soil has a lot of pore space that can be filled or emptied by water, so that the response to vertical loads and vibrations becomes more complex and dynamic. The addition of a vertical load equivalent to 0.1 times the ultimate load (Qu) adds a static element to the resulting stress dynamics, increasing the complexity of the interaction between vertical and horizontal loads and how this affects overall structural stability.

Fig. 6 shows the excess pore water pressure for 60 seconds in soil with a relative density of 20 %, vibration with an amplitude of 15 mm and a frequency of 1 Hz, and a vertical load of 0.2 times the ultimate load capacity (*Qu*) with a foundation depth of 0.22 meters, describes how soil behaves under conditions similar to those encountered during seismic activity or other vibrations caused by human activity. Meanwhile, excess pore water pressure that fluctuates between 1 and 3 kPa is a direct indicator of the soil response to cyclic loading. These fluctuations indicate that the soil is not completely consolidated and is still able to adapt to changing load conditions. This is relevant in the context of understanding how soil will behave during earthquakes or other loads that cause rapid and intense movement in the soil. This research helps in evaluating risks such as liquefaction, where soil loses its strength and turns into a liquid-like state due to a rapid increase in pore water pressure.

Fig. 7 shows that understanding the behavior of pore water pressure is essential for evaluating the structural stability of soils under dynamic loading conditions such as earthquakes. A pore water pressure ratio that approaches or exceeds 1.0 indicates that the pore water pressure resulting from the test is equal to or exceeds the initial hydrostatic pressure of the soil. This is a critical condition that can trigger liquefaction, where the soil loses significant strength and stiffness, potentially leading to major structural failure. Therefore, this data is invaluable in designing foundations capable of withstanding seismic loads by taking into account possible liquefaction events and implementing appropriate mitigation measures. Meanwhile, fluctuations in the pore water pressure ratio in the tests reflect the dynamic response of the soil to changes in mechanical pressure due to vertical loads and vibrations. The physics behind this phenomenon is related to how energy from loads and vibrations is transferred into the soil, resulting in increased pressure in the water-filled pores. This pressure, if it reaches or exceeds a critical condition, can reduce the effective pressure supporting the soil, thereby increasing the risk of liquefaction. However, the graph shows that most of the time, this ratio remains below 1.0, indicating that despite increased pressure, the soil as a whole is still able to maintain a stable condition and does not consistently show an immediate risk of liquefaction.

Fig. 8 shows that there are spikes in the graph line indicating moments when significant lateral forces are applied to the pile foundation. This surge may occur due to sudden loading or due to changes in soil conditions, such as during liquefaction. During liquefaction, the soil loses its stiffness and strength so that the response of the soil pile system becomes critical for analysis to understand the stiffness and damping capacity of the structure. It also appears that variations in the amplitude and frequency of these surges can also provide varying load conditions affecting the ground pile system. A higher spike in the graph may indicate that there is a moment where the pile foundation has greater lateral resistance – perhaps due to a higher density of soil around the pile or increased friction between the pile and the soil supporting it. This shows the effectiveness of the pile in resisting lateral forces, which is crucial to ensure the stability and safety of the structure during seismic events.

Fig. 9 shows a linear increase in lateral load proportional to deformation indicating a largely elastic behavior, however, the fact that the coefficient of determination is not very high indicates that the system is also affected by non-elastic factors such as friction between soil particles and material plasticity. The behavior of pile foundations in liquefiable soils becomes more complex because the soil loses its stiffness under seismic conditions, which can change the load distribution and the way the load is transmitted into the soil. This underlines the importance of considering dynamic effects such as vibration and earthquake forces when designing foundations that can withstand not only static but also dynamic loads.

This research has several limitations set to ensure focus and clarity in the analysis of the lateral resistance behavior of short pile foundations in liquefied soil. First, the pile group configuration used is a 2×2 square, which was chosen to represent a common formation in practical applications such as bridges or small piers. These piles are driven in uniform sandy soil, which has potential liquefaction characteristics, so that the research results can specifically describe the response of the foundation to soil conditions relevant to the liquefaction phenomenon. The sand material used comes from Lumajang with a uniform density to ensure consistent soil conditions in each test. The length of the pile is determined based on the pile stiffness factor (T), with L values of $1T$, $1.5T$, and $2T$. This length variation aims to evaluate the effect of foundation depth on lateral resistance, so that it can provide insight into optimizing foundation design in various soil conditions. The vertical load applied to the pile is varied by $0.1Pu$, $0.2Pu$, and $0.3Pu$, where Pu is the ultimate load of the pile.

For further research, it is recommended to pay attention to several critical aspects that have the potential to influence the stability and effectiveness of pile foundations. First, the influence of the diameter of the pile foundation is very important because it can have a significant impact on the bearing capacity and load distribution. Second, the type of long pile foundation must be considered because different types of foundations offer different strengths and flexibility depending on the geotechnical conditions of the site. Third, soil conditions with inhomogeneous layers require more in-depth analysis because this heterogeneity can cause unpredictable behavior in terms of load transfer and structural stability. Fourth, taking into account the water content or saturation level of the soil is crucial, considering that these properties greatly influence the cohesion and load capacity of the soil.

7. Conclusions

1. Tests on soils with relative densities of 10 % and 20 % show that fluctuating pore water pressure during vibration (with an amplitude of 15 mm and a frequency of 1 Hz) and vertical loads indicates the potential for liquefaction. Pore water pressure fluctuations, which are in the range of 1 to 3 kPa at 20 % density, and reach Ru values close to or equal to 1, indicate an increase in pressure that could indicate liquefaction.

2. Correlation between lateral deformation and lateral load, lateral load increases as lateral deformation increases. However, the R^2 value of 0.4548 indicates that there are other factors besides lateral deformation that influence the pile load resistance, such as soil conditions and the characteristics of the pile material itself.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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