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IDENTIFICATION THE INFLUENCE OF INCREASED PORE WATER PRESSURE AND VERTICAL DEFORMATION UNDER THE INFLUENCE OF THE LIQUEFACTION

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This study examines how increase in pore water pressure weakens the sand foundation, triggers liquefaction and lateral shift. This is related to the interaction of pressure, density, depth, and load through experiments and simulations to increase the foundation design. Numerical analysis using UBC3D-PLM 3D plaxis, while experimental tests are carried out with a 2.2 kW electric motor-powered table. Experiment uses an acrylic ground box 0.5×1×1.5 m^3 which is strengthened by steel. The foundation model is in the form of a 2×2 pole group with four pillars and pile caps. The results of the study showed an increase in pore water pressure due to vertical and earthquake loads could trigger liquefaction and vertical deformation. Numerical analysis shows a surge in pressure in 20 seconds, in the case exceeding the 7.0 ratio, shows full liquefaction. The vibrating table experiment (relative density of 10 %) shows RU values close to 1, confirming the potential for liquefaction. Both experiments and simulations indicate rapid initial deformation before stabilization. Pore water pressure jumped to the critical level before stable, indicating the potential for full liquefaction. Non-linear vertical deformation confirms significant soil changes below the dynamic load. This study identifies the limit of the pressure ratio for partial and full liquefaction and soil response to vertical and seismic loads. The combination of numerical and experimental data allows the analysis of vertical deformation of foundation stability. This finding supports the design of earthquake resistant foundations and geotechnical risk assessment, although its application must consider soil conditions and limitations of numeric models, so it is necessary to be further calibration for prediction accuracy

***Keywords:** lateral resistance, group pile, sand soil, liquefaction, vertical load*

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1. Introduction

In recent decades, the phenomenon of soil location due to increased pore water pressure has become a serious concern in geotechnical engineering, especially in earthquake-prone areas. Many failures of the building foundation and infrastructure occur due to the loss of the carrying capacity of the soil caused by liquefaction, as seen in earthquakes in Palu (2018) and Niigata (1964). This condition is very dangerous because it can cause significant lateral deformation, resulting in a shift in structure, and in extreme cases, causing the collapse of the building. Therefore, research on increasing pore water pressure and its impact on liquefaction and lateral deformation is very important for understanding the mechanism of soil failure and developing a more effective mitigation strategy. The results of this study are needed in practice to increase the foundation design that is more resistant to liquefaction, so as to reduce the risk of structural damage and improve infrastructure safety in earthquake-prone areas.

In recent years, research on the liquidation and lateral deformation of the sand foundation has experienced significant development. Various studies have focused on factors such as earthquake acceleration, depth of foundation, and the effect of soil density in determining structural responses to liquefaction.

Therefore, further research is needed that not only evaluates the impact of pore water pressure on lateral deformation of sand foundation but also integrates other important factors in one comprehensive analysis model.

2. Literature review and problem statement

Numerous researches have demonstrated that lateral foundation transfer is made worse by an increase in earthquake acceleration; however, these studies do not account for the fluctuation of vertical loads that may impact the overall lateral stability [1, 2]. In addition, although the influence of the depth of the foundation has been reviewed, a study that integrates soil density in the analysis of liquefaction is still limited [3]. The main limitation in previous studies is the difficulty of simulating the accurate variation of soil density in the numerical model, as well as a lack of full-scale experiment that is able to isolate the effects of each parameter simultaneously [4, 5].

Furthermore, research using the centrifugation test has succeeded in showing the impact of earthquake acceleration on the lateral shift of pole foundation, but does not explore how variations in the depth of the foundation can mitigate this effect [6, 7]. In addition, the numerical model developed to assess the lateral performance of the pole foundation in liquefaction conditions has not yet considered a variety of vertical loads, although this aspect has the potential to affect the failure mechanism [8]. Studies that have been carried out on the effect of soil density on foundation stability also have not yet considered the variation of earthquake acceleration that can contribute to changes in pore water pressure during liquefaction [9].

Apart from these various achievements, there are still gaps in understanding how pore water pressure, soil density, and interaction between lateral and vertical loads simultaneously affect the foundation deformation during liquefaction. The effect of vertical loads can increase or reduce lateral deformation depending on soil conditions, but the explicit relationship between this variable and the depth of the foundation is still not examined in depth [10, 11]. The main challenge in overcoming this gap is the limitations of experiments that are able to cover all these factors simultaneously. In addition, the role of pore water pressure in determining the stability of the foundation during the liquefaction has not specifically considers the effect of soil density on deformation mechanisms, which require a more sophisticated experimental approach to ensure the replication of realistic field conditions [12, 13].

Research on numerical analysis of earthquake acceleration effects, foundation depth, vertical load, and soil density on lateral resistance in disbursement conditions [14, 15]. The results showed the effect of earthquake acceleration, the depth of the foundation, vertical load, and soil density of lateral resistance. This is shown that these parameters have a significant effect on the stability of the foundation, but there are problems that have not been resolved related to dynamic interactions in heterogeneous soil conditions. This is due to difficulties in modeling the foundation-land interaction and the high cost of experimental research. The way to overcome this difficulty is through a numerical simulation approach [16]. But this also still produces uncertainty so it is advisable to conduct further studies of this parameter interaction comprehensively and realistically.

Research on the effect of earthquake acceleration variations on pore water pressure around the foundation of the sand soil [17, 18]. The results showed that the effect of earthquake acceleration variations on pore water pressure around the foundation of the sand soil. It is shown, that an increase in earthquake acceleration increases pore water pressure significantly, but there are problems that have not been resolved related to the complexity of the dynamic behavior of sand. This is caused by objective difficulties in the simulation of real conditions and the high cost of full-scale laboratory tests. This can be overcome by numerical modeling with small-scale experimental calibration [19]. But the numerical validation is still limited. So, it is recommended to conduct further studies on the effect of earthquake acceleration variations on pore water pressure around the foundation of the sand soil.

The effect of the vertical load on the lateral foundation response in sandy soil [20]. Shows, that the vertical load significantly affects the behavior of lateral foundation, but there are problems that have not been resolved related to the complexity of the foundation of the foundation in a combined load condition. This is possible difficulty in modeling heterogeneous soil conditions. How to overcome this difficulty can be with a numerical modeling approach or small-scale experiment in the laboratory, as this approach is used in [21]. However, numerical results still require further experimental validation. So, it is recommended to conduct further studies on the interaction of vertical and lateral loads in the foundation in sandy soils.

Increasing the depth of the foundation can increase stability and reduce lateral structural transfer during disbursement [22, 23]. Presenting the results of research on the effect of the depth of the foundation on structural stability during disbursement. Shown, that the depth of the larger foundation can increase stability and reduce lateral structural transfer. However, the problem has not been able to determine the depth of the optimal foundation due to objective difficulties in variations of soil conditions. How to overcome this difficulty can be through small scale testing [24]. However, the approach still needs further validation, so it is advisable to conduct an experimental study of effective foundation depth in soil disbursement conditions.

The use of element methods to model soil interaction in disbursement conditions for changes in soil pore pressure [25]. Presenting the results of research on the application of the element method to model soil interaction in disbursement conditions due to changes in soil pore pressure. It is shown that this method is quite effective in general, but there are problems that have not been resolved related to the accuracy of the prediction of pore pressure in extreme conditions. This may be due to objective difficulties in representing soil heterogeneous properties or the impossibility of direct experimental validation. This can be overcome through a combination of numerical simulations with limited laboratory testing. The approach is used in [26] but is still limited to certain soil conditions and does not cover a fairly extensive variation of the actual soil parameters. All of this shows that it is advisable to conduct further studies on numerical modeling soil pore pressure with wider soil parameter variations to increase the reliability of the element method to predict the interaction of soil-structures under disbursement conditions.

Increased soil density significantly increases the lateral carrying capacity of the foundation [27]. Presenting the results of research on increasing soil density which significantly increases the lateral carrying capacity of the foundation, but the problem is related to its application in various types and soil conditions. So that the difficulty is related to testing soil density in locations that are difficult to access, and the certainty of the consistency of soil density in all areas. Ways to overcome this by developing more efficient testing technology. This approach has been used in previous studies [28], but practical challenges still exist. Therefore, it is recommended to conduct further studies on techniques that can reduce costs and increase the effectiveness of the application of this method.

Identification of critical parameters that affect the lateral behavior of the foundation in the soil that experienced the condition of disbursement [29]. Presenting the research results on the identification of critical parameters that affect the lateral behavior of the foundation in the soil that experienced the condition of disbursement. Research shows that soil density and disbursement depth affect the foundation stability. However, there are problems related to soil variability and measurement of accurate parameters in the field. This is due to the high experimental costs and limitations of equipment.

The solution for this can use computer simulations, as used in previous studies [30]. All of this shows the importance of further study of micro factors that affect the foundation stability in the condition of disbursement.

Several other studies also improve the specific aspects of the foundation and disbursement intentions. Increased vertical loads affect lateral deformation in sand soil [31]. Presenting the results of research that examines the effect of increased vertical load on lateral deformation in sand soils. The results showed an increase in vertical loads causing a significant lateral deformation, but unresolved problems related to this mechanism of interaction, may be caused by difficulties in accurate or high cost measurements for field testing. How to overcome this can use numerical simulations or laboratory models. This approach has been used before [32], but it is recommended to conduct further studies on the influence of other factors such as water content or soil density.

In addition, the evaluation of the performance of the basic reinforcement system to reduce the impact of disbursement conditions [33]. The results showed that an increase in vertical loads caused a significant increase in lateral deformation in sand soils, but there were unresolved problems related to the mechanism of interaction between vertical loads and sand soil characteristics. The possibility is related to the accuracy of the measurement of lateral deformation in field conditions, the impossibility of fundamental to replicate the original condition in experimentally, as well as the cost part in terms of testing. The way to overcome this difficulty can use numerical simulations or laboratory models with tighter control of variables [34]. This approach helps understand the contribution of soil improvement techniques to foundation stability during disbursement. However, further studies are needed to adjust the design with local soil conditions, especially the impact of variations in the geometric parameters of reinforcement on the performance of the foundation of the earthquake. The selection of the right method greatly affects structural resistance to deformation.

The combination of vertical and lateral loads to the foundation instability in the condition of disbursement [35]. Presenting the results of research on a combination of vertical and lateral loads to the instability of the foundation in the condition of disbursement. Research shows that the interaction of the two loads affects the stability of the foundation, but there are problems that have not been resolved related to accurate predictions of instability. This may be caused by objective difficulties in reproducing the condition of disbursement and high experimental costs. How to overcome this can use the numerical model [36]. However, this approach still has limitations. Therefore, it is recommended to conduct further studies on the effect of a combination of vertical and lateral loads on foundation instability.

Based on previous research there is still a gap in understanding the effect of disbursement on the deformation of the pole foundation in the sand soil. Research that studies variations simultaneously in earthquake acceleration, depth of foundation, vertical load, and soil density is still limited, with most research only focusing on one or two factors. In addition, despite numerical analysis with the element method until it is carried out well, the validation of the results with the shock table test is still minimal. Further research is needed to analyze the effects of these factors simultaneously and validate numerical simulation results with experimental data. This is important to increase the accuracy of the prediction of foundation deformation due to disbursement.

Although many studies have tried to understand the mechanism of liquefaction and lateral deformation in the sand foundation, there are still several recent research gaps that have not been completed as a whole. One of the main gaps is the lack of studies that explicitly integrate pore water pressure, soil density, and interactions between lateral and vertical loads in liquefaction conditions. Previous studies show that high pore water pressure can cause loss of soil carrying capacity and increase lateral foundation deformation, but the simultaneous effect of the soil density variable and the depth of the foundation on this phenomenon is still not examined in depth. In addition, previous research mostly used a numerical model or a limited scale laboratory test, which has limitations in replicating real conditions in the field. The numerical model developed has not been fully able to consider the combined effects of pore water pressure, earthquake acceleration, and vertical loads, so that the interpretation of the results still has limitations in describing the actual phenomenon in the field. In the experimental context, most studies only focus on the effects of earthquake acceleration or the depth of the foundation separately, without considering how these parameters interact with pore water pressure in influencing lateral deformation of sand foundation. Therefore, further studies are needed that develop an experimental and numerical approach that is more comprehensive to understand this mechanism of interaction in more detail.

3. The aim and objectives of the study

The aim of the study is to identifying the influence of increased pore water pressure on disbursement and vertical deformation of sand foundation. By understanding the effect of increased pore water pressure on the spread and vertical deformation of sand foundations, engineers can increase the strength of the foundation and reliability of building structures.

To achieve this aim, the following objectives are achieved:

– numerical analysis of liquefaction due to earthquakes and the effects of vertical loads on lateral foundation resistance;

– experiment validation with using a shaking table.

4. Materials and methods

The object of the study is the behavior of sand foundation to increase pore water pressure and vertical deformation due to the effect of liquefaction. This study is to examine the impact of an increase in pore water pressure on the phenomenon of liquefaction and vertical deformation of the sand foundation, based on the identified identification gap. By taking into account changes in soil density, foundation depth, and lateral and vertical load interactions, this study will specifically investigate the connection between pore water pressure and vertical deformation.

In order to better understand the mechanism of liquefaction and how it affects foundation stability, this work combined experimental testing with numerical analysis. It is anticipated that the findings of this study will aid in the creation of a more successful risk mitigation plan and serve as a guide for designing foundations and plans that are more resilient to liquefaction in seismically active regions.

The soil used in this study is the sand land from Puger-Jember Indonesia Beach. This study uses numerical and experimental analysis methods. Lateral resistance analysis is seen from the amount of vertical deformation that occurs in the pile cap. Numerical analysis uses the final element method with 3D UBC3D-PLM plaxis software, while experiment uses a shaking table system that is driven by an electric motor power 2.2 kW with a speed of 1420 rpm to produce sinusoidal motion as input motion. The mechanism of motion is supported by two pulleys, which are arranged to move the crankshaft, resulting in vibrations that are in accordance with the specified parameter. To control the speed and frequency of input motion, the inverter (VFD) SHZK ZK880-3KW is used, with 380 V input specifications 3-phase ±15 % (47–65 Hz) and 380V output ±15 % (47–65 Hz) 6.8a, with a frequency range of 0–600 Hz and a capacity of 3KW/4HP. Fig. 1 shows the position of the test of the test soil on the shaking table.

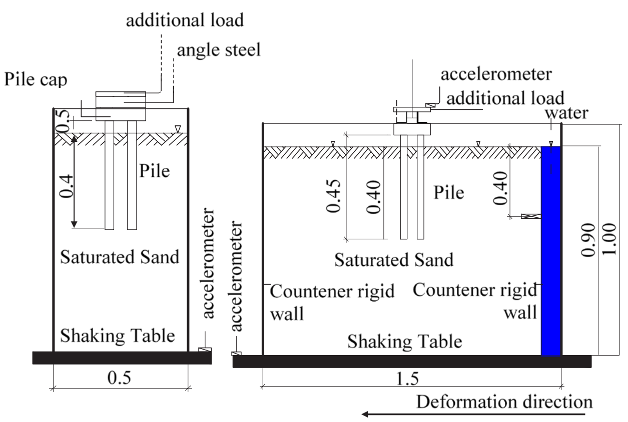

Fig. 1. Position of soil box and foundation and sensor placement

The place where the land tested uses a land box measuring 0.5×1×1.5 m^3, placed on the shaking table using the Rigid Container type. The ground box is made of acrylic with a thickness of 10 mm on all four sides and is strengthened with steel material on each side connection. To get accurate experimental data, several sensors are used, namely optical flow sensors, accelerometers, and PWP sensors. The optical flow sensor functions to measure vertical and lateral deformation, which is installed above the foundation model. Accelerometer is used to obtain vibrational acceleration data, with sensors placed above the shaking table and above the foundation model. Meanwhile, the PWP sensor is used to measure the increase in pore water pressure in the soil when the shaking table is vibrated, with the sensor placed at a depth of 40 cm from the ground.

The characteristics of the soil properties can be seen in Table 1.

Table 1

Characteristics of soil samples

No.	Parameter	Standard	Value
1	Effective diameter D_{10}	ASTM D422	0.18
2	Average diameter D_{50}	ASTM D422	0.3
3	Diameter D_{30}	ASTM D422	0.18
4	Diameter D_{60}	ASTM D422	0.35
5	Uniformity coefficient C_u	ASTM D422	1.94
6	Coefficient of gradation C_c	ASTM D422	1.43
7	Fines contend	ASTM D1140	0.12
8	PI	ASTM D4318	NP
9	$\gamma_{d\min}$	ASTM D854	1.379
10	$\gamma_{d\max}$	ASTM D854	1.74
11	$e_{\min}$	ASTM D4254	0.618
12	$e_{\max}$	ASTM D4254	0.104

Table 2

Characteristics of foundation structure

Parameter	Unit	Value
Pile cap		
Thick	M	0.05
Modulus of elasticity	kN/m^2	21,019,039
Unit weight	kN/m^3	24
Pile foundation		
Foundation type	Circular tube	
Diameter	M	0.0336
thick	M	2.600E-3
Modulus of elasticity	kN/m^2	200,000,000
Unit weight	kN/m^3	78.50
Shear modulus	kN/m^2	80,000,000

Table 3

Soil characteristics for modeling

Parameter	Unit	R_D 10 %	R_D 20 %	R_D 30 %
γ_{unsat}	kN/m^3	18.951	19.173	19.382
γ_{sat}	kN/m^3	18.951	19.173	19.382
ϕ	–	32.19	34.37	36.56
E_{ref}	kN/m^2	2,970.5	4,132	5,485
E_{oed}	kN/m^2	3,998	5,562	7,384
G	kN/m^2	1,442	1,589	2,110
$K_{w.ref/n}$	kN/m^2	114×10^3	154×10^3	205×10^3

The research process begins with the manufacture and assembly of the group pile foundation, which is designed using the 2×2 pile group configuration, consisting of four piles. The model of the pile group used in the study, in this modeling, the dimensions of the pile cap are determined based on the distance approach between the piles, which is 2.5 times the diameter of the pile, while the distance from the pile to the outer edge is set at 1.5 times diameter of the pile.

Procedure experimental validation using shaking table test:

– prepare a sand foundation model (0.5×1×1.5 m^3 acrylic ground box) and install pile groups (2×2 configuration);

– compact sand to a relative density of 10 %, 20 %, and 30 % to simulate varying soil densities;

– apply vertical and lateral loads using an electric motor-driven shaking table (2.2 kW, 1420 rpm);

– use optical flow sensors, accelerometers, and pore water pressure (PWP) sensors to measure deformation and liquefaction onset;

– record data on excess pore water pressure, RU values, and lateral foundation movement.

5. Result of impact pore pressure on sand foundation settlement and lateral deformation

5. 1. Numerical analysis results on liquefaction from earthquakes and vertical load

Fig. 2 shows the variation of the ratio of pore water pressure (in kPa) to time (in seconds) in a study, it is most likely related to soil behavior or porous material in a dynamic condition. Data shows the fluctuations in the increase in pore water pressure at first, reaching its peak in about 40 seconds, then stable with smaller oscillations after about 60 seconds.

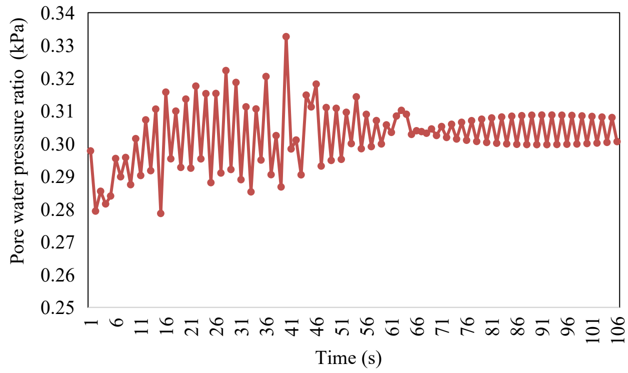

Fig. 2. Numerical analysis results in excess pore water pressure

This trend can indicate the effect of compaction, consolidation, or other cyclic phenomena that occur in the test sample during the experiment. The increase in water pressure pores will reduce the effective voltage. The liquefaction degree can be observed by observing the ratio value of the ratio of pore water tension increases with an effective voltage commonly referred to as pore water pressure ratio (RU).

Fig. 3 shows changes in excess water pressure (excess pore water pressure) in units of KPA on time (in seconds). Initially, excessive pore pressure was at about 3 kPa with small fluctuations, then decreased in about 40–50 seconds, which was followed by a sudden surge before returning to a more stable trend after 60 seconds. After this point, pressure tends to increase slightly and becomes more stable. This pattern indicates the possibility of changes in soil or material conditions due to external loads, such as liquefaction or liquefaction cycles that affect the distribution of water pressure in the system.

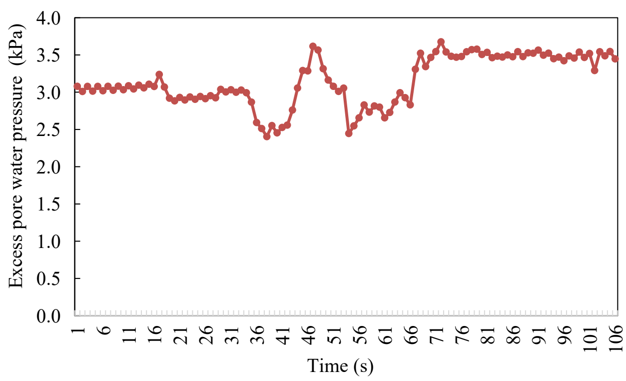

Fig. 3. Time history of excess pore water pressure ratio

Fig. 4 shows vertical deformation (in mm) against time (in seconds), which is most likely the result of testing compression or compaction of a material. Initially, there was a rapid increase in vertical deformation to around 0.2 mm, which then slowed down and approached stable conditions. After the initial phase, deformation continues to grow slowly with a very small increase trend until the end of the test. This pattern indicates that the material undergoes significant deformation at the beginning of the load is applied, but then tends to reach a consolidation state with a slight additional change over time.

Fig. 4 shows the vertical deformation to time. This illustrates the growth of non-linear deformation, where there is a significant increase. In addition, it shows that vertical deformation increases rapidly in the first few seconds before it tends to be stable or experience growth slowing. The difference in the value of this deformation can be caused by variations of soil conditions, loads applied, or characteristics of pore water pressure.

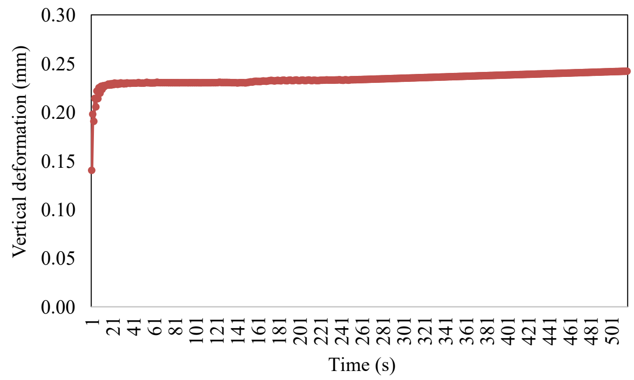

Fig. 4. Time histories vertical foundation deformation

5. 2. Validation of experimental results with using a shaking table

Experiment as validation using soil with a relative density of 10 %. Vibration with an amplitude of 15 mm and a frequency of 1 Hz, vertical load 0.1 Qu, and a depth of 0.22 m foundation.

Fig. 5 shows excessive water pressure in the experiment (blue line) fluctuates between 0.5 kPa to about 2.5 kPa, with significant variations at all times. Initially, the pressure increased from about 0.5 kPa to about 1.5 kPa in the first 10 seconds, then fluctuating ranging from 1.5 kPa to 2.5 kPa until the end of the experiment. Conversely, numerical analysis (orange line) shows an initial pressure of around 3.0 kPa, relatively stable for about 40 seconds, then experience a surge of up to around 3.6 kPa in about 50 seconds, before returning to the range of 3.2–3.5 kPa for the remaining experimental time.

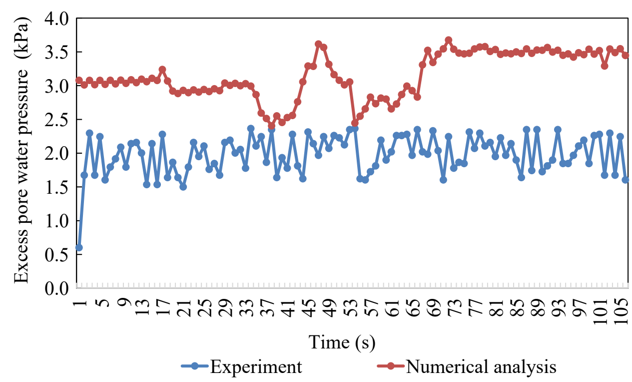

Fig. 5. History of excessive water pressure time

It can be seen that the results of numerical analysis generally give a higher pore pressure value than the experimental results. The average pressure in experiments ranges from 1.5–2.2 kPa, while in numerical analysis it is higher, which is around 3.0–3.5 kPa. This difference can be caused by assumptions in the numerical model that may not fully reflect the real conditions of the material or experimental limits. In addition, higher fluctuations in experimental data show the effect of external factors such as material heterogeneity, test equipment instability, or countless drainage effects in numerical modeling. Therefore, to increase the accuracy of the numerical model, calibration needs to be done by considering these factors so that the prediction of pore water pressure is more in accordance with the experimental results.

Fig. 6 shows the ratio of pore water pressure ratios (in kPa) between experimental results (blue lines) and numeric analysis (red line) to time (in seconds). From the experimental results, the pore water pressure ratio undergoes significant fluctuations with a range of values between 0.6 to 1.0 kPa, while the results of numerical analysis show a much more stable trend with a relatively constant value around 0.3 kPa over the testing time. At the beginning of the experiment, the experimental results showed a rapid increase from about 0.3 kPa to 0.7 kPa in the first few seconds, then experience fluctuations ranging from 0.6 to 1.0 kPa until the end of the experiment. Conversely, the results of numerical analysis remain in a much lower range, without experiencing significant surges or fluctuations.

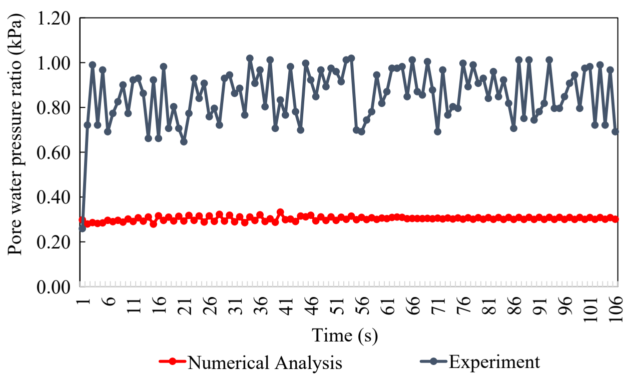

Fig. 6. History of excessive water pressure ratio

This is also seen that there are quite striking differences between the results of the experiment and numerical analysis. The experimental value is almost two to three times higher than the numerical results, especially after the first 10 seconds of testing. High fluctuations in experimental data can indicate external factors such as imperfections in test materials, water pore drainage effects, or instability in the testing system. Conversely, numerical analysis that shows lower and stable results indicates that the numerical model may not capture the full complexity of experimental conditions, including material variability and pore water flow dynamics. Therefore, it is necessary to improve the parameters in numerical modeling to be more in accordance with the real conditions and approach the results of the experiment.

Fig. 7 shows the ratio of vertical deformation (in mm) to the time (in seconds) between the experimental results (blue lines) and numeric analysis (red line). The experimental results showed significant fluctuations with oscillating deformation between –0.3 mm to 0.3 mm, while the results of numerical analysis showed much more stable deformation with a value that was almost constant at around 0.2 mm after the beginning of the experiment. In the early stages, deformation in experiments experienced a rapid increase from 0 mm to around 0.2 mm, but then began to show a substantial oscillation pattern, while in numerical analysis, deformation increased slightly at first and then remained stable around 0.2 mm throughout the experiment.

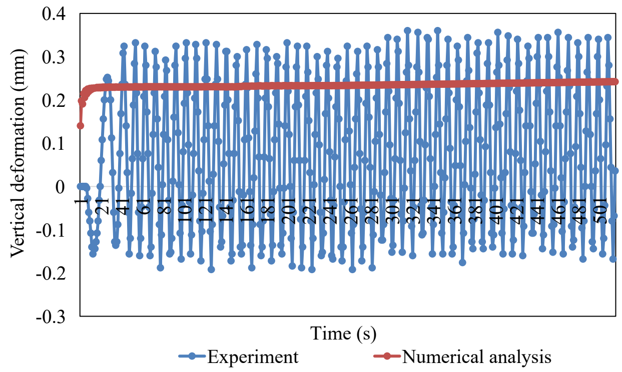

Fig. 7. History of time reading time of vertical deformation in the pile plate

The difference between experimental results and numerical analysis is very striking, especially in terms of data stability. The experimental results show large fluctuations, which can be caused by external factors such as imperfections in the test equipment, material instability, or variations in the load given. Conversely, a more stable numerical result shows that the analysis model used does not capture the actual dynamic effects in experiments. The deformation range in experiments ranges from –0.3 mm to 0.3 mm, whereas in the numerical model it remains constant at 0.2 mm, shows that the numerical model may be too idealized and lacks the oscillation effect that appears in real conditions. Therefore, improvements are needed in numerical modeling to make it more accurate in representing experimental conditions, for example by considering the effects of instability or non-linear factors in deformation analysis.

6. Discussion of impact of liquefaction on pile foundation

The results highlight the crucial role of pore water pressure in soil stability, evident in the analyzed data. Fig. 2, 5 compare experimental and numerical analyses, showing greater pressure variation in experiments due to dynamic grain redistribution, altering micro volume and affecting pressure distribution. Vibration compacts sand grains over time, reducing pore space, increasing pore water pressure, and decreasing effective stress. However, in real conditions, drainage and pore water pressure dissipation occur, preventing linear pressure buildup and causing fluctuations.

Numerical results show higher initial pressure with minimal fluctuations before the 40th second, likely due to simplified assumptions such as material homogeneity, ideal boundary conditions, and neglected drainage effects. Around the 50th second, a pressure surge appears in the model due to controlled external force responses, differing from experimental conditions.

Vibrations shift sand grains, redistributing pressure within the soil-water system. Initially, trapped water raises pore water pressure, but over time, compaction either increases or decreases pressure based on drainage efficiency. Limited drainage leads to rising pressure and potential liquefaction, while effective drainage keeps pressure fluctuating within a lower range, as seen in experiments.

Fig. 3, 6 reveal significant differences in pore water pressure ratios. Experimental vibrations redistribute sand grains, modifying pore structure and creating non-uniform pressure increases. Large fluctuations indicate cycles of compaction and pressure release due to dynamic sand-water interactions. Drainage and material heterogeneity further contribute to complex pressure variations, unlike the stable, lower pressure seen in the numerical model, which oversimplifies real conditions.

Fig. 4, 7 show notable differences in vertical deformation. Experiments exhibit large oscillations due to non-uniform compaction and dynamic pore water pressure release, highlighting cycles of compression and expansion caused by recurring vibrations. Deformation is non-linear, influenced by interactions between external forces, pore water pressure, and grain redistribution. In contrast, the numerical model, assuming homogeneous material and rigid boundary conditions, shows stable deformation without capturing real oscillation effects.

This study underscores the interplay between vibration, sand compaction, and pore water pressure. In the early stages, vibrations cause grain redistribution and increased pressure, leading to rapid deformation. As compaction cycles continue, deformation becomes unstable, showing large oscillations. In idealized conditions, without drainage and redistribution effects, deformation remains stable, as reflected in the numerical model. To enhance numerical accuracy, incorporating non-linear effects, drainage, and material variability is crucial to better reflect real experimental behavior.

This study has several restrictions, including limited observation time for 60 seconds, without considering the long-term effects or recurring load cycles. Environmental conditions are considered constant, without taking into account external factors such as temperature, rainfall, or seismic activity. This study was also conducted on a laboratory scale, which may not fully reflect field conditions.

Weaknesses of pore water pressure analysis only focus on external loads, without discussing long-term drainage mechanisms or full disbursement. The difference in results between numerical and experimental analysis is caused by variations in measurement points and limitations of numerical simulation. In the future, increased accuracy of modeling and use of additional sensors can increase the validity of the results.

Further research can explore various types of soil, load conditions, and more complex soil models, although there are challenges in maintaining uniform experimental conditions and processing numerical data that require high resources.

7. Conclusions

1. Increased pore water pressure (ΔU) causes an effective voltage decrease (σ_0'), which results in a reduced carrying capacity of the soil and increased risk of deformation in the foundation. When pore water pressure ratio (Ru) exceeds 0.9, the soil experiences full liquefaction, which is characterized by the loss of soil shear power and its inability to withstand structural burden.

2. Pore water pressure ratio (Ru) value is close to 1, which confirms the occurrence of liquefaction on the sand tested. The impact of this phenomenon can be seen in the maximum vertical deformation recorded at 0.006 m, which is consistent with the results of numeric analysis, thus proving the validity of the approach used in this study. In addition, the test shows that the foundation is collapse after the vibrational load is applied, according to the prediction of numeric analysis.

Conflict of interest

The authors stated that they did not have a conflict of interest in connection with this research, both financial, personalor other, which could influence the research and the results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

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

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