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Evaluation of dynamic earth pressure acting on pile foundation in liquefiable sand deposit by shaking table tests

Mintaek Yoo[1a] and Seongwon Hong*[2]

[1]Departemnt of Civil and Environmental Engineering, Gachon Univeristy,
1342, Seongnam-daero, Sujeong-gu, Seongnam-si, Gyeonggi-do, Republic of Korea
[2]Department of Safety Engineering, Korea National University of Transportation,
50 Daehak-ro, Chungju-si, Chungbuk 27469, Republic of Korea

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Abstract. In this study, a series of shaking table model tests were performed to evaluate the dynamic earth pressure acting on pile foundation during liquefaction. The dynamic earth pressure acting on piles were evaluated with depth and pile diameters comparing with excess pore water pressure, it means that the kinematic load effect plays a substantial role in dynamic pile behavior during liquefaction. The dynamic earth pressure acting on pile foundations with mass exhibited significant similarity to those without upper mass. Analyzing the non-fluctuating and fluctuating components of both excess pore water pressure and dynamic earth pressure revealed that the non-fluctuating component has a dominant influence. In case of non-fluctuating component, dynamic earth pressure is larger than excess porewater pressure at same depth, and the difference increased with depth and pile diameter. However, in the case of the fluctuating component, the earth pressure tended to be smaller than the excess pore water pressure as the depth increased. Based on the results of a series of studies, it can be concluded that the dynamic earth pressure acting on the pile foundation during liquefaction is applied up to 1.5 times the excess pore water pressure for the non-fluctuating component and 0.75 times the excess pore water pressure for the fluctuating component.

Keywords: dynamic behavior; dynamic earth pressure ; liquefaction; pile foundation; shaking table tests

1. Introduction

Infrastructures, such as bridge, embankment, pipeline and tunnels, can be damaged in an earthquake with significant socioeconomic consequences. In addition, Korean society experienced successive earthquakes of a magnitude exceeding 5.0 in the past 3 years resulting in increasing concerns about earthquake stability of urban infrastructures. Especially, liquefaction was firstly observed in Korea during Pohang earthquake(M5.4), therefore, public concerns about earthquake and liquefaction stability for major underground infra structures substantially increases.

Therefore, various preceded research performed on the behavior of pile foundation and geotechnical structure by earthquakes. Nguyen *et al.* conducted a study on the dynamic behavior analysis of quay structures during earthquakes. Nasiri *et al.* (2020) and Seyrek and Topçu(2022) evaluate the dynamic behavior of embankment dam during earthquake. The dynamic behavior of pipeline was evaluated by Yigit (2022). In addition, Yang *et al.* (2022), Kwon *et al.* (2020), Yoo *et al.* (2022), evaluate dynamic behavior underground railway structure and suggest risk assessment method. Yun and Han (2021), Shamsi *et al*. (2023) analyzed the dynamic behavior of a soil-pile interaction system during an earthquake, however, these researches could not consider liquefaction effects on pile foundation. The researches related to liquefaction were also conducted by many researchers. Ji *et al.* (2021) conducted the research about assessment of the potential risk of liquefaction that may occur due to the Pohang earthquake. In addition, Okamura *et al.* (2006) evaluated liquefied soil pressure on vertical walls by FEM model, and Yukio *et al.* (2003) suggested seismic soil-structure interaction model during liquefaction. Mehdi *et al.* (2021) evaluate soil-pile interaction behavior during liquefaction by FEM model. However, these researches only concentrate on dynamic behavior of geotechnical structures, such as occurred displacement or moment during liquefaction, and it cannot consider the dynamic earth pressure acting on geotechnical structure during liquefaction.

Due to reduction of soil resistance and dynamic earth pressure induced from ground displacement, pile foundation often cannot resist earthquake and failed when it was installed in liquefiable ground. Especially, many previous researches insist that the kinematic force component is more dominant factor for dynamic behavior of pile foundation during liquefaction due to significant ground movement. (Tokimatsu 2005, Yoo *et al.* 2017, Kwon and Yoo 2019) In that case, the dynamic earth pressure acting on pile foundation by kinematic force is very important factor for safety of pile foundation. However, despite a series of studies on the dynamic behavior of structures under earthquakes and liquefaction, there is a lack of research on the dynamic earth pressure acting on pile foundation during liquefaction.

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*Corresponding author, Associate Professor
E-mail: shong@ut.ac.kr
[a]Assistant Professor

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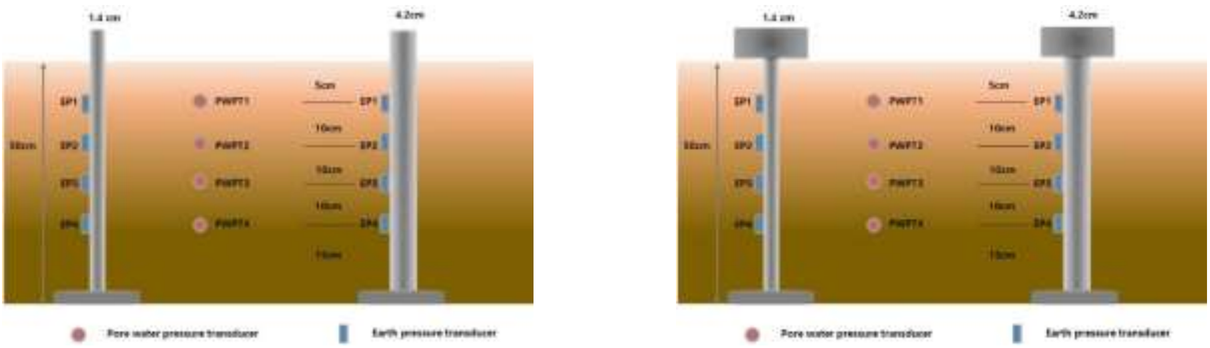


(a) Case 1 Test Section (b) Case 2 Test Section

Fig. 1 Schematic drawing of test section

In this study, a pile foundation was applied to investigate the dynamic behavior in a liquefiable sand deposit. Pile foundations significantly affect kinematic and initial force due to ground movement and are widely used for various structures. Therefore, in this research, a series of dynamic shaking table tests were conducted to evaluate the dynamic behavior of the pile foundation, and the relationship between inertial force and kinematic force during liquefaction was confirmed. Additionally, the dynamic earth pressure acting on the pile foundation during liquefaction was evaluated, and a quantitative method for assessing dynamic earth pressure was suggested.

2. Test set-up and programs

In this research, four dynamic model tests were conducted with upper mass of pile head and without upper mass. The dynamic earth pressure acting on piles are evaluated with same test conditions such as input acceleration, input frequency, and relative density of saturated sand. Based on a series of dynamic model tests on loose sand deposit, the effect of dynamic earth pressure acting on the pile foundation during liquefaction was evaluated.

Model soil is Jumoonjin sand, classified as SP by Unified Soil Classification System. Average particle size (D_{50}) is 0.57 mm, and Specific gravity (Gs) is 2.62. The detail properties of model soil are summarized in Table 1. To form the ground of the liquefiable layer, a sieve was installed on the soil box. Next, the model ground has to be made as loose as possible for constructing model ground under a low confining pressure. Loose sand ground was prepared using water sedimentation method. The liquefiable loose sand ground is formed using water by pouring the sand through a 1-mm sieve to reduce the dropping velocity.

The water table elevation coincided with that of the ground surface. The particles were slowly dropped into the water to create a composition similar to the formation principle of the sedimentary layer, and the Jumoonjin sand was saturated in water for 72 h. The model ground was formed at a relative density of 25%.

Table 1 Properties of model soil

Properties	Jumoonjin sand
USCS	SP
Effective grain size, D_{10}	0.38 mm
Average particle size, D_{50}	0.57 mm
Coefficient of uniformity, C_u	1.58
Specific gravity, Gs	2.62
Maximum dry unit weight, r_{max}	15.99 kN/m3
Minimum dry unit weight, r_{min}	13.05 kN/m3

Two model piles with 4.2 cm and 1.4 cm diameters are applied to dynamic model tests to investigate the effect of acting area of underground structure on dynamic earth pressure. Model piles were fabricated with aluminum pipe with length of 55 cm and young's modulus (E) of 67.82 GPa. In this study, the similitude ratio was not applied for specific prototype structure. 1 g shaking table test has limitation of not being able to reproduce the in-situ confining pressure, which means it cannot account for the nonlinearity of the ground. In addition, since this study is not aimed at a specific structure but analyzes the dynamic earth pressure during liquefaction acting on piles under various conditions, the study was conducted under model scale conditions.

Fig. 1. shows the schematic drawing of test section. The model piles were fixed at the bottom of the soil box and a concentrated mass of 5 kg was located 1.0 cm above the subsurface in case 2. Four earth pressure transducers were attached to model pile to measure dynamic earth pressure during liquefaction. In addition, pore water pressure transducers were also installed in the soil at the same depth at the same depth with earth pressure transducer. 5.0 cm of sponges are attached at both side of soil box for prevention from the interference of a reflected wave.

Test conditions are shown in Table 2. Liquefaction occurs when a relatively large repetitive load is applied continuously. Since the purpose of this study is to analyze the dynamic earth pressure acting on the pile foundation during liquefaction, a sine wave, which is not a realistic seismic wave but a continuous repetitive load, was used to efficiently generate liquefaction. The sine wave with input acceleration of 0.2 g and frequency of 10 Hz was applied for dynamic model tests as shown in Fig. 2.

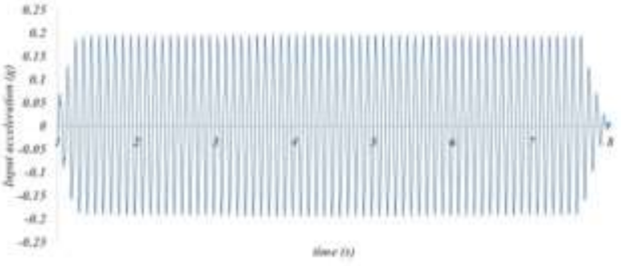


Fig. 2 Input acceleration time history

Table 2 Test program

R_D*	45%	60%	75%
Weight per unit volume (γ) (kN/m^3)	14.6	15.8	16.4
Angle of internal friction (ϕ)	34^o	36^o	38^o
Elasticity modulus (E) (MPa)	32	52	63
Specific Gravity (G_s)	2.65		
Soil Class (USCS)**	poorly graded sands (SP)		

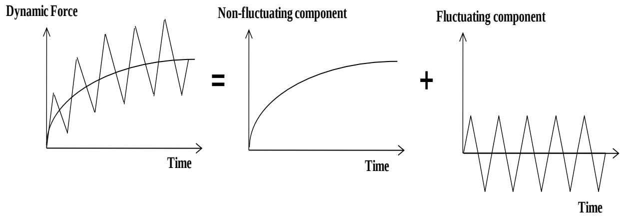


Fig. 3 Division of fluctuating and non-fluctuating components (Kim *et al*. 2004)

3. Test results

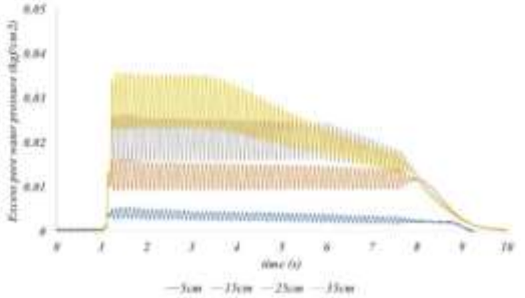
3.1 Load components acting on pile foundation

As shown in Fig. 3, Kim *et al*. (2004) and Han (2006) suggested that dynamic earth pressure acting on a quay wall and pile foundation can be divided into fluctuating component and non-fluctuating component.

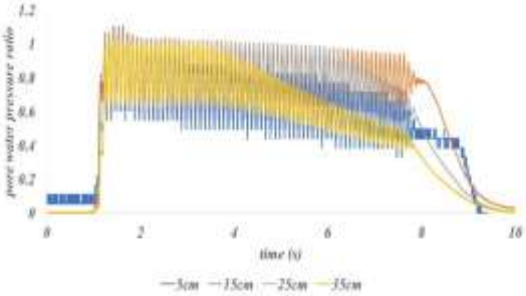
In this research, the analyzing method separating the earth pressure and excess pore water pressure into two components is also performed. To divide the dynamic earth pressure acting on pile foundation by fluctuating component and non-fluctuating component, frequency filtering method was used. The band pass filtering and low-pass filtering method was used for dividing fluctuating and non-fluctuating component. Band pass filtering frequency for fluctuating component is 2 hz – 30 hz and low-pass filtering for non-fluctuating component is 2 hz.

3.2 Excess pore water pressure results

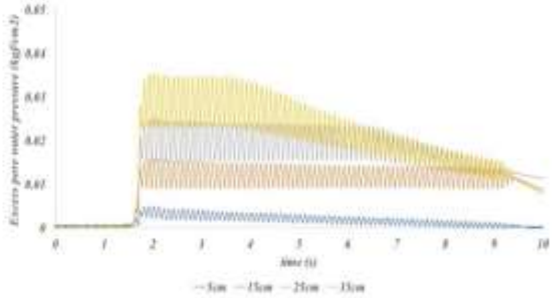
Fig. 4 shows the excess pore water pressure and excess pore water pressure ratio during an earthquake. As shown in the figures, the excess pore water pressure ratio reaches 1.0 both case 1 and 2, therefore, it means that liquefaction occurred in both cases. In addition, the results of excess pore water pressure are significantly similar in both cases, which shows ground movement during liquefaction is also similar in both cases.



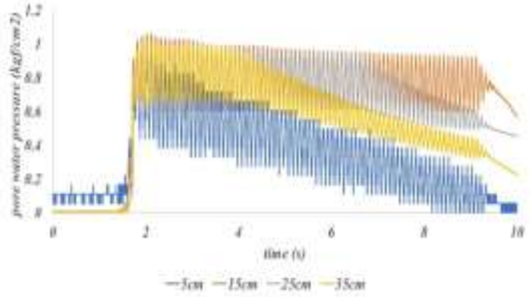
(a) Excess pore water pressure time history (case 1)



(b) Excess pore water pressure ratio time history (case 1)



(c) Excess pore water pressure time history (case 2)

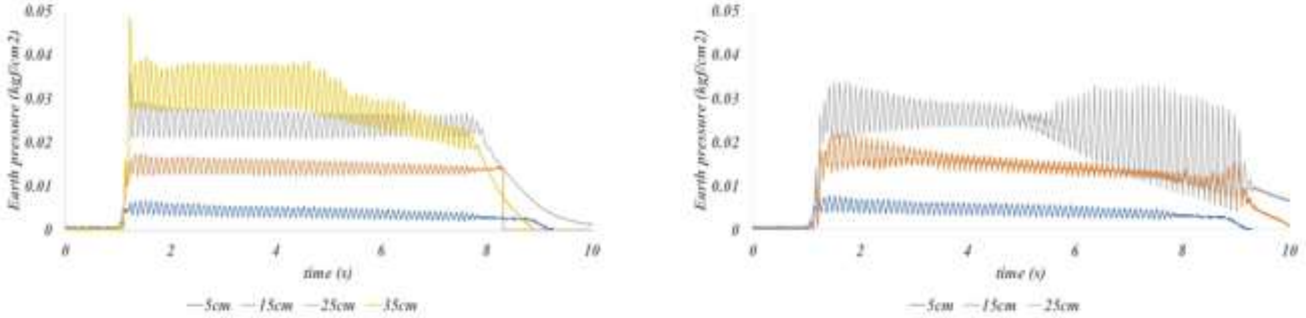


(d) Excess pore water pressure ratio time history (case 2)

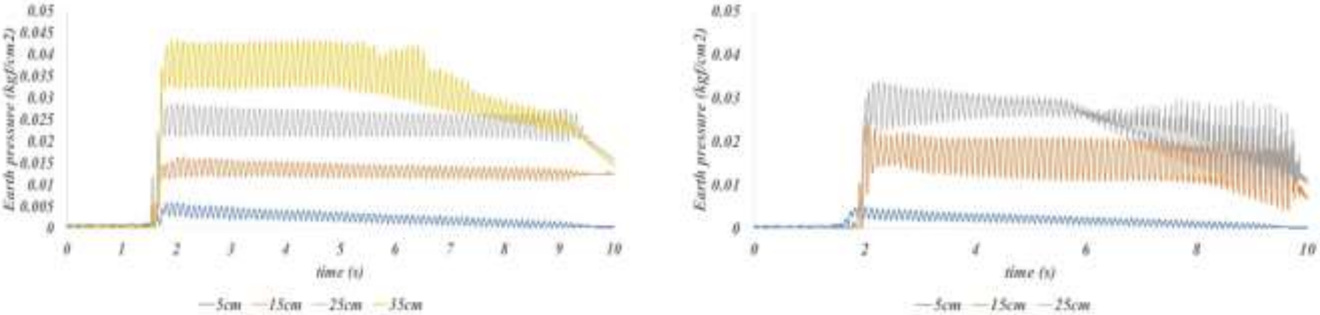
Fig. 4 Excess pore water pressure results

Fig. 5 shows the measured dynamic earth pressure in the pile foundation during liquefaction. The earth pressure transducer in 35 cm depth with the 4.2 cm diameter pile cannot measure due to instrumentation problem. By comparing Figs. 4 and 5, the excess pore water pressure and the dynamic earth pressure shows similar tendency.

Therefore, it can be confirmed that the dynamic earth pressure acting on the underground structure is closely related to the excess pore water pressure during liquefaction. In addition, the dynamic earth pressure acting on pile foundation with mass is significantly similar to that without upper mass. It means that the kinematic load effect



(a) Earth pressure (Case 1-1) (b) Earth pressure (Case 1-2)



(c) Earth pressure (Case 2-1) (d) Earth pressure (Case 2-2)

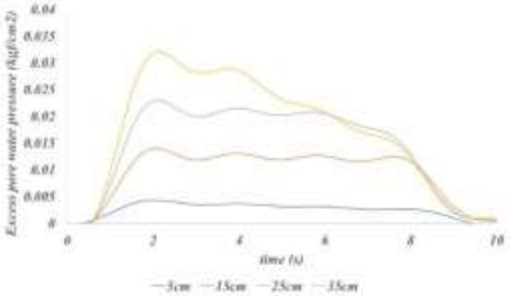
Fig. 5 Dynamic earth pressure results

has a significant influence on dynamic pile behavior, and the inertial force effect is not an important factor for dynamic pile behavior during liquefaction.

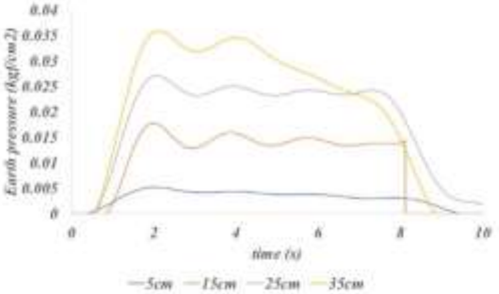
3.3 Analysis on Non-fluctuating components

Fig. 6 and 7 shows non-fluctuating component of excess pore water pressure and dynamic earth pressure for case 1. As shown in the figure, the non-fluctuating component is a dominant factor in both excess pore water pressure and dynamic earth pressure. In addition, the non-fluctuating component of dynamic earth pressure in shallow depth is almost identical to that of excess pore water pressure, however the non-fluctuating component of dynamic earth pressure is observed higher than that of excess pore water pressure as depth increased. In addition, the difference between dynamic earth pressure and excess porewater pressure increased with the diameter of the pile foundation. It means that the pile stiffness and the area of acting on earth pressure have also an effect on dynamic earth pressure.

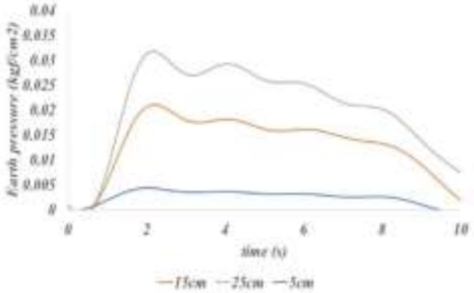
Fig 8 shows the maximum dynamic earth pressure acting on pile foundation and excess pore water pressure of non-fluctuating component with depth. As shown in figure, dynamic earth pressure acting on pile foundation is larger than excess porewater pressure at same depth, and the difference increased with depth and pile diameter. The reason why the difference increases with depth is due to the effect of pile displacement. As the depth increases, the pile displacement decreases and the resistance against dynamic earth pressure also increases. Therefore, larger dynamic earth pressure acing on pile foundation. This can also be explained by the phenomenon that the dynamic earth pressure increases as the pile diameter increases.



(a) Non-fluctuating component of excess pore water pressure (case 1)

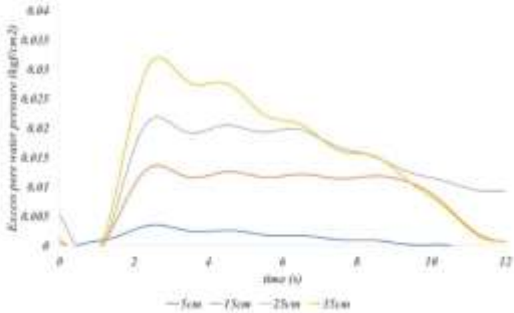


(b) Non-fluctuating component of earth pressure (Case 1-1)

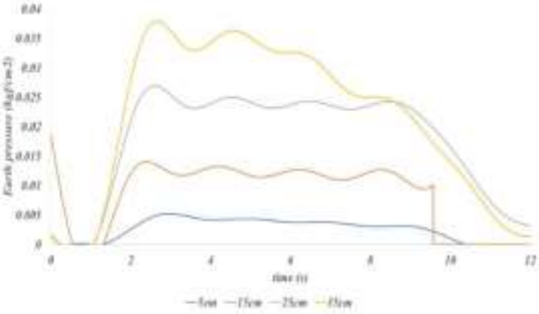


(c) Non-fluctuating component of earth pressure (Case 1-2)

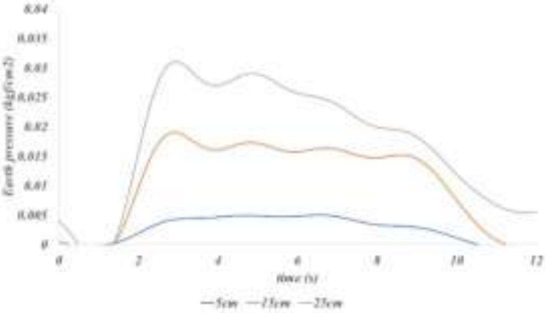
Fig. 6 Non-fluctuating component (Case 1)



(a) Non-fluctuating component of excess pore water pressure (case 2)



(b) Non-fluctuating component of earth pressure (Case 2-1)



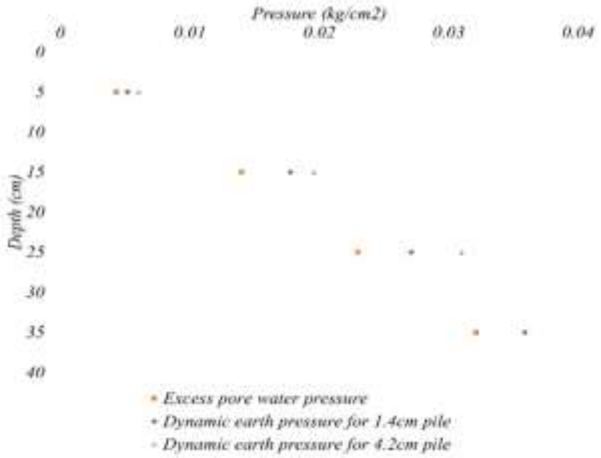
(c) Non-fluctuating component of earth pressure (Case 2-2)

Fig. 7 Non-fluctuating component (Case 2)

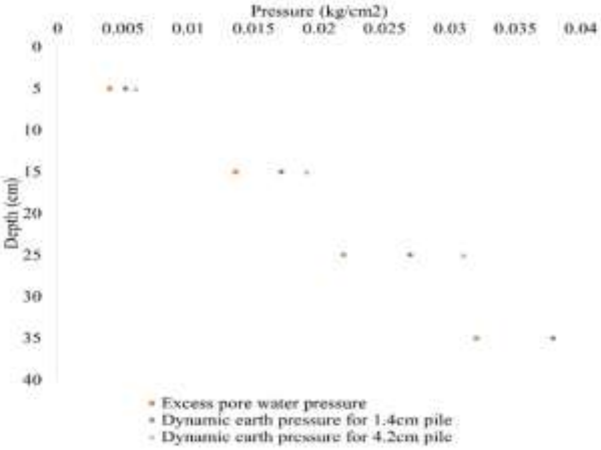
3.4 Analysis on fluctuating components

Fig. 9 and 10 demonstrates fluctuating component of excess pore water pressure and dynamic earth pressure for cases 1. As shown in the figure, the fluctuating components are smaller than the non-fluctuating components both excess pore water pressure and dynamic earth pressure. This result indicates that the kinematic load effect of fluctuating component is less than that of non-fluctuating component. In addition, the fluctuating component of dynamic earth pressure in shallow depth is also almost identical to that of excess pore water pressure. However, in the case of the fluctuating component, the earth pressure tended to be smaller than the excess pore water pressure as the depth increased.

Fig 11 shows the maximum dynamic earth pressure acting on pile foundation and excess pore water pressure of fluctuating component with depth. As shown in figure, dynamic earth pressure acting on pile foundation shows similar value at shallow depth, however, dynamic earth pressure is smaller than excess porewater pressure with increasing depth. In addition, the difference in the dynamic earth pressure of the fluctuating component by pile diameter was not significant.



(a) Without mass case (Case 1)

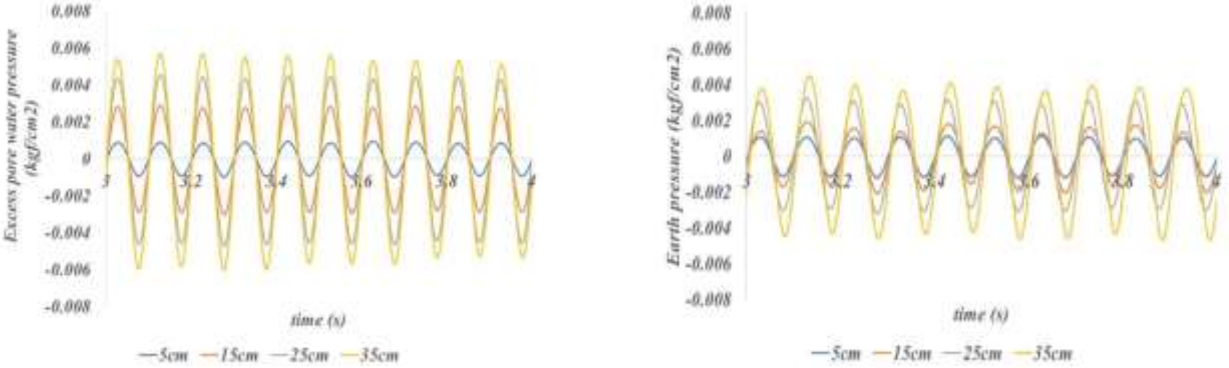


(b) Without mass case (Case 2)

Fig. 8 Maximum dynamic earth pressure and excess pore water pressure of non-fluctuating component with depth

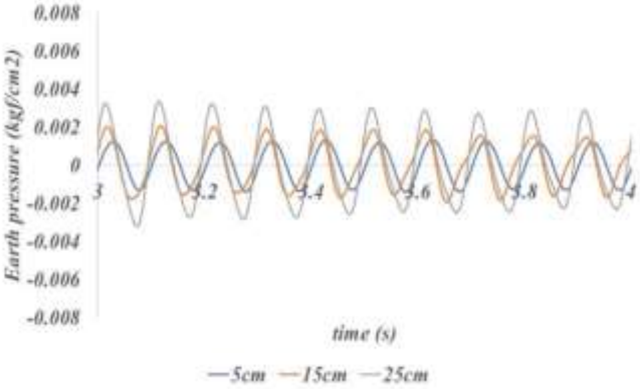
4. Discussions

Based on a series of dynamic model tests, the relationship between excess porewater pressure and dynamic earth pressure have been analyzed. The non-fluctuating component acting on the pile foundation is larger than the excess pore water pressure, while the fluctuating component is smaller than the excess pore water pressure. In case of the non-fluctuating component, it is believed to be the effect of ground movement during liquefaction. When liquefaction occurs, the ground shows strain softening behavior, which causes lateral ground movement. This ground movement is applied to the pile foundation, resulting in a measured dynamic soil pressure higher than the excess pore water pressure. However, this ground movement has almost a non-fluctuating component and does not appear to have affected the fluctuating component. In the case of the fluctuating component, it is not almost affected by ground movement, however, the stiffness of the pile is larger than that of ground, so the dynamic earth pressure is observed smaller than the excess pore water pressure.



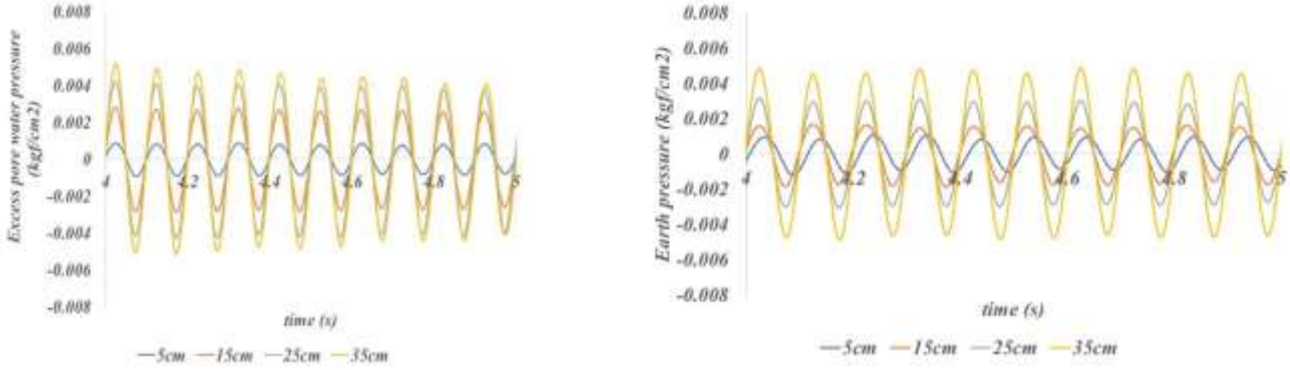
(a) Fluctuating component of excess pore water pressure (Case 1)

(b) Fluctuating component of earth pressure (Case 1-1)



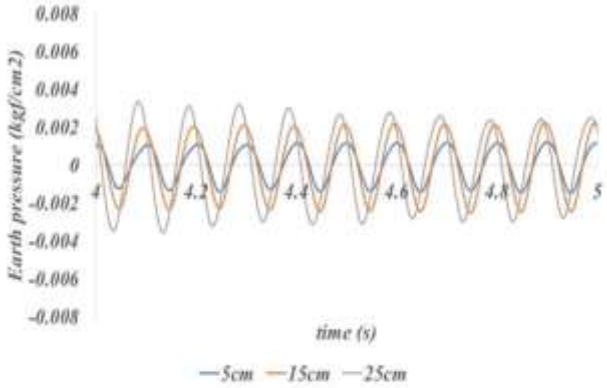
(c) Fluctuating component of earth pressure (Case 1-2)

Fig. 9 Non-fluctuating component (Case 1)



(a) Fluctuating component of excess pore water pressure (Case 2)

(b) Fluctuating component of earth pressure (Case 2-1)



(c) Fluctuating component of earth pressure (Case 2-2)

Fig. 10 Non-fluctuating component (Case 2)

Table 3 Lateral pressure value up to depth of 25 cm

	Without mass case (Case 1)		With mass case (Case 2)	
	Non-fluctuating component	Fluctuating component	Non-fluctuating component	Fluctuating component
Excess pore water pressure	0.2874	0.0624	0.276	0.063
Dynamic earth pressure (D=1.4 cm)	0.3524	0.0462	0.345	0.045
Dynamic earth pressure (D=4.2 cm)	0.3803	0.0470	0.391	0.048

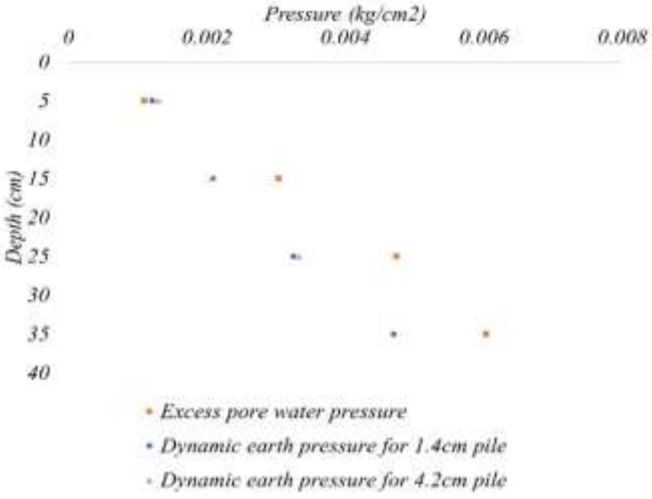
Table 4 Normalized dynamic earth pressure

	Without mass case (Case 1)		With mass case (Case 2)	
	Non-fluctuating component	Fluctuating component	Non-fluctuating component	Fluctuating component
Pile diameter = 0	1	1	1	1
Pile diameter = 1.4 cm	1.27	0.74	1.25	0.72
Pile diameter = 4.2 cm	1.38	0.75	1.41	0.76

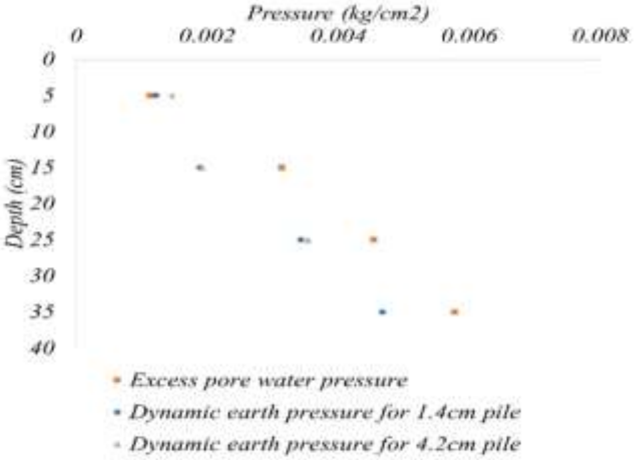
For quantitative analysis, the sum of the lateral pressures up to 25 cm, where the instrumentation was operated normally, is shown in Table 3. The sum of lateral pressures was calculated by linearly interpolating the magnitude of the maximum measured pressure by depth. The magnitude of lateral pressure of the fluctuating component is 12 to 22% of that of the non-fluctuating component, we can confirm that the non-fluctuating component is dominant factor in later pressure both excess pore water pressure and dynamic earth pressure during liquefaction.

Table 4 shows the results of normalizing the dynamic earth pressure acting on the pile to the excess pore water pressure. However, the pile diameter of 0 is the case where only the ground exists, so the value 1 is applied. The results show that the non-fluctuating component of the dynamic earth pressure acting on the pile increases nonlinearly, and the fluctuating component shows a value of 75% of the excess pore water pressure regardless of the pile diameter.

In order to calculate the maximum value of the non-fluctuating component of the normalized dynamic earth pressure, a hyperbolic fitting was performed as shown in Fig. 12. An initial slope of 0.3 and maximum value of 1.6 was obtained by hyperbolic function. These values are means that the dynamic earth pressure increased with pile diameter and up to 1.6 times the excess pore water pressure. Based on the results of a series of studies, it can be concluded that the dynamic earth pressure acting on the pile foundation during liquefaction is applied up to 1.6 times the excess pore water pressure for the non-fluctuating component and 0.75 times the excess pore water pressure for the fluctuating component. This result contributes to quantifying the magnitude of the dynamic earth pressure acting on the pile foundation during liquefaction as a ratio to the excess pore water pressure. In general, the magnitude of excess pore water pressure of non-fluctuating component is similar with the magnitude of confining pressure in the ground, and this conclusion can be used to infer the dynamic earth pressure acting on pile foundations during liquefaction. This is expected to be used for understanding the dynamic behavior of pile foundations during liquefaction and as a basis for seismic design.



(a) Without mass case (Case 1)



(b) Without mass case (Case 2)

Fig. 11 Maximum dynamic earth pressure and excess pore water pressure of fluctuating component with depth

However, this research was conducted by 1 g shaker table test, which cannot reproduce in-situ confining pressures, and the pile diameter conditions have significant difference from those used in in-situ condition. Therefore,

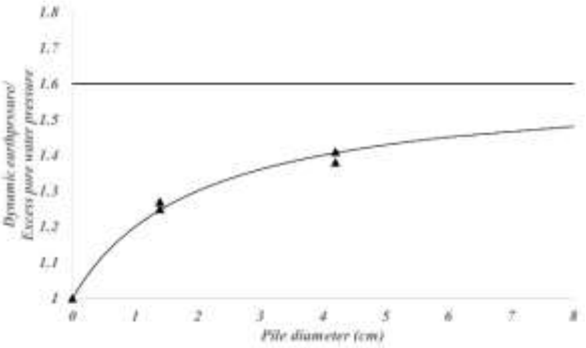


Fig 12. Normalized non-fluctuating component with pile diameter

for the results of this study to be applied quantitatively, additional research on evaluation of dynamic earth pressure is necessary via dynamic centrifuge tests and numerical analysis. In addition, further studies on various pile diameter also could be conducted in order to derive effective results that can be applied to various field conditions.

5. Conclusions

In this study, a series of dynamic model tests were conducted to evaluate the dynamic earth pressure acting on the pile during liquefaction.

(1) The dynamic earth pressure and excess pore water pressure displayed a similar trend. This observation indicates that the excess pore water pressure significantly affects the dynamic earth pressure acting on pile foundation.

(2) The dynamic earth pressure acting on pile foundations with mass exhibited significant similarity to those without upper mass. This implies that the kinematic load effect plays a substantial role in dynamic pile behavior, while the inertial force effect is not a significant factor during liquefaction.

(3) Analyzing the non-fluctuating and fluctuating components of both excess pore water pressure and dynamic earth pressure revealed that the non-fluctuating component has a dominant influence. In case of non-fluctuating component, dynamic earth pressure is larger than excess porewater pressure at same depth, and the difference increased with depth and pile diameter. However, in the case of the fluctuating component, the earth pressure tended to be smaller than the excess pore water pressure as the depth increased.

(4) Based on the results of a series of studies, it can be concluded that the dynamic earth pressure acting on the pile foundation during liquefaction is applied up to 1.5 times the excess pore water pressure for the non-fluctuating component and 0.75 times the excess pore water pressure for the fluctuating component.

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