A SIMPLE SHAKING TABLE TEST TO MEASURE LIQUEFACTION POTENTIAL OF PRAMBANAN AREA, YOGYAKARTA, INDONESIA

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Abstract

This paper presents the experimental study of liquefaction potential for sandy soil in Prambanan Area, Yogyakarta, Indonesia, which underwent liquefaction due to the M_w 6.3 Jogja Earthquake on May 27, 2006. Shaking table tests considering the variation of acceleration and shaking duration were performed to investigate the liquefaction potential of sand. The liquefaction time stages including time to start liquefaction, time to start pore pressure dissipation, and liquefaction duration were observed. The percentage of liquefaction duration increase, the excess pore water pressure ratio and the required time to generate liquefaction, and the effect of applied acceleration to cyclic stress ratio, were also presented. The results showed that the sand could undergo liquefaction under the variation of dynamic load. The variation of dynamic load significantly influenced the time stages of liquefaction, the increase of liquefaction duration percentage and cyclic stress ratio. The results also exhibited that the larger applied acceleration and the longer shaking duration means the longer liquefaction duration and the larger liquefaction potential. In general, the result could bring the recommendation to the liquefaction countermeasure for Prambanan Area.

Keywords: Experimental study, Liquefaction time stages, Prambanan sand, Shaking table

Introduction

An earthquake with magnitude of 6.3, which was also known as the Jogja Earthquake, hit the Yogyakarta Special Province, Indonesia on May 27, 2006. This earthquake was triggered by the activity of Opak Fault Segment crossing northern to southern part of Yogyakarta Special Province (Figure 1) [1]. The earthquake resulted in the massive damage to the buildings and the historical temples. The earthquake also triggered liquefactions in several locations along the Opak Fault Segment (Figure 1) in the southern to eastern Yogyakarta Special Province [1]. One of the locations where the massive damage of the Jogja Earthquake found in 2006 was Prambanan Area (shown by the hatched red rectangle in Figure 1). The Prambanan area is located at the border of Yogyakarta Special Province and Klaten Regency, the Central Java Province. Suryolelono [2] mentioned that the Prambanan Temple had undergone major earthquakes as much as 16 times. Suryolelono [2] also reported that many temple stones were scattered around the temple yard because of the Jogja earthquake shaking. Liquefactions indications, such as sand boil and lateral spreading were also observed during the Jogja Earthquake [2].

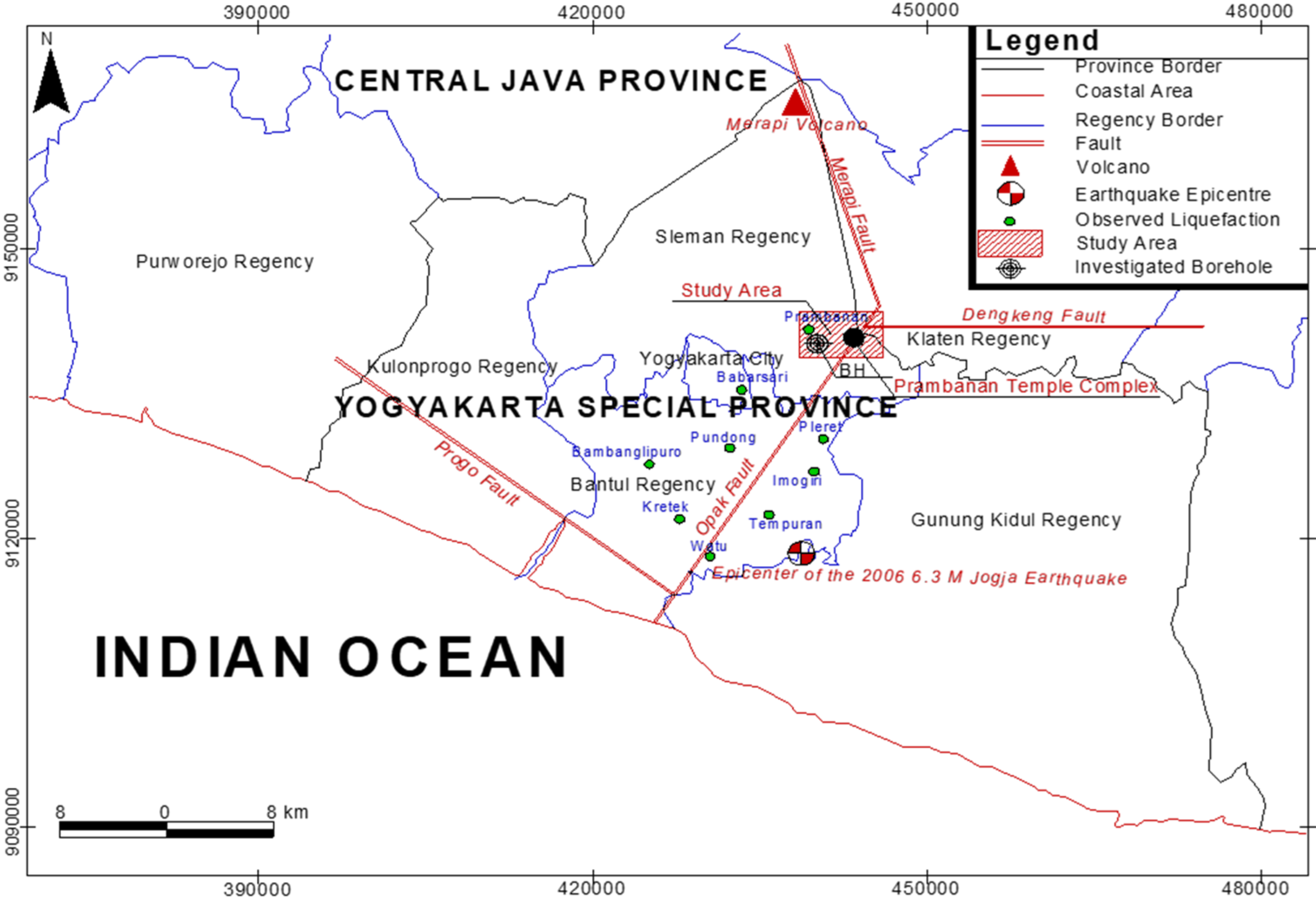


Figure 1. The locations of study area, active faults, and the earthquake epicenter in Yogyakarta (modified from [7])

Several researchers had performed the experimental studies of liquefaction during the Jogja Earthquake and its impacts. Mase et al. [3] and Mase [4, 5, and 6] performed the experimental study of liquefaction using shaking table, especially for the liquefied sandy soils in Imogiri and Watu (southern parts of Yogyakarta). In general, those previous studies were performed to investigate the liquefaction potential based on site investigation data and soil physical properties and to simulate sandy soils subjected to the horizontal excitation. However, experimental studies to inspect the liquefaction potential of sandy soils in the eastern part of Yogyakarta where many cultural heritages exist, has not been performed yet. Therefore, the study of liquefaction potential in the world heritage locations in Yogyakarta is very important.

Several studies on physical modelling of soil liquefaction using shaking table had been presented by several researchers. Varghese and Latha [7] conducted shaking table test to investigate the various factors influencing liquefaction potential on poorly graded sand. Otsubo et al. [8] performed several shaking table tests to investigate the performance of the recycled backfill materials as the mitigation effort of soil liquefaction during the 2011 Tohoku Earthquake. Banerjee et al. [9] conducted shaking table test to examine the liquefaction potential of Kasai River Sand in India. Unni et al. [10] examined the reliability of 1D-Shaking table test for liquefaction studies. Moss et al. [11] conducted shaking table test to investigate the large-scale liquefaction on post-liquefaction. In general, those previous studies had reached the conclusion that the use of shaking table test is appropriate to model liquefaction. Those previous studies also mentioned that the prediction resulted from shaking table test is generally consistent with numerical modelling and field evidence. Therefore, the shaking table tests for liquefaction studies are widely implemented around the world.

An experimental liquefaction study of liquefaction using simple shaking table is performed to observe dynamic behaviour of Prambanan sand during the Jogja Earthquake. The tests were considering dynamic loads, such as acceleration, vibrational frequency, and shaking duration. In general, this study is expected to describe the liquefaction potential for sandy soils in Prambanan Area. This study is also addressed to the local engineers to consider the liquefaction impact in Prambanan Area.

Prambanan Sand Properties

Figure 2 presents the general geological condition of study area. It can be observed that the study area is dominated by sandy soils, especially for first 15 m depth. Furthermore, rock materials composed of sandstones and breccia are found up to 30 m depth. Several studies performed by Mase [4], Yogatama and Fathani [12], and Pramumijoyo and Sudarno [13] reported that loose sandy soils at shallow depth in the Prambanan temple region was extruded out during the Jogja Earthquake. Those sand layers were indicated as saturated sand layers composed of loose to medium sands. In Figure 2, those layers are found at depth of 0.4 to 3 m depth. In this study, the experimental test was focused on that shallow sand layers [2]. First, the soil samples were collected from the sites and tested in the soil mechanics laboratory. Furthermore, tests of physical properties were performed. The summary of physical properties of sample are presented in Table 1. Based on Unified Soil Classification System (USCS), sandy soil of Prambanan Site is classified as SP or poorly graded sand. Relative density (R_D) of the soil is about 26%, whereas the degree of saturation (S) is about 78%. Grain size distribution is presented in Figure 3. The grain size distribution of sample is also compared to the criterion of preliminary investigation for liquefaction. In this study, the criterion of grain size distribution for liquefiable sands proposed by Tsuchida [14] is used to examine the liquefaction vulnerability on soil sample. The grain size distribution of Prambanan sand is also compared to some liquefiable sands from other locations in Yogyakarta Special Province, such as Watu sand [4] and Imogiri sand [5]. Based on the criterion, SP of Prambanan is categorized as the most liquefiable sand. Generally, grain size distribution of SP layer is similar to Watu Sand [5] and Imogiri Sand [4] which also underwent liquefaction during the Jogja Earthquake.

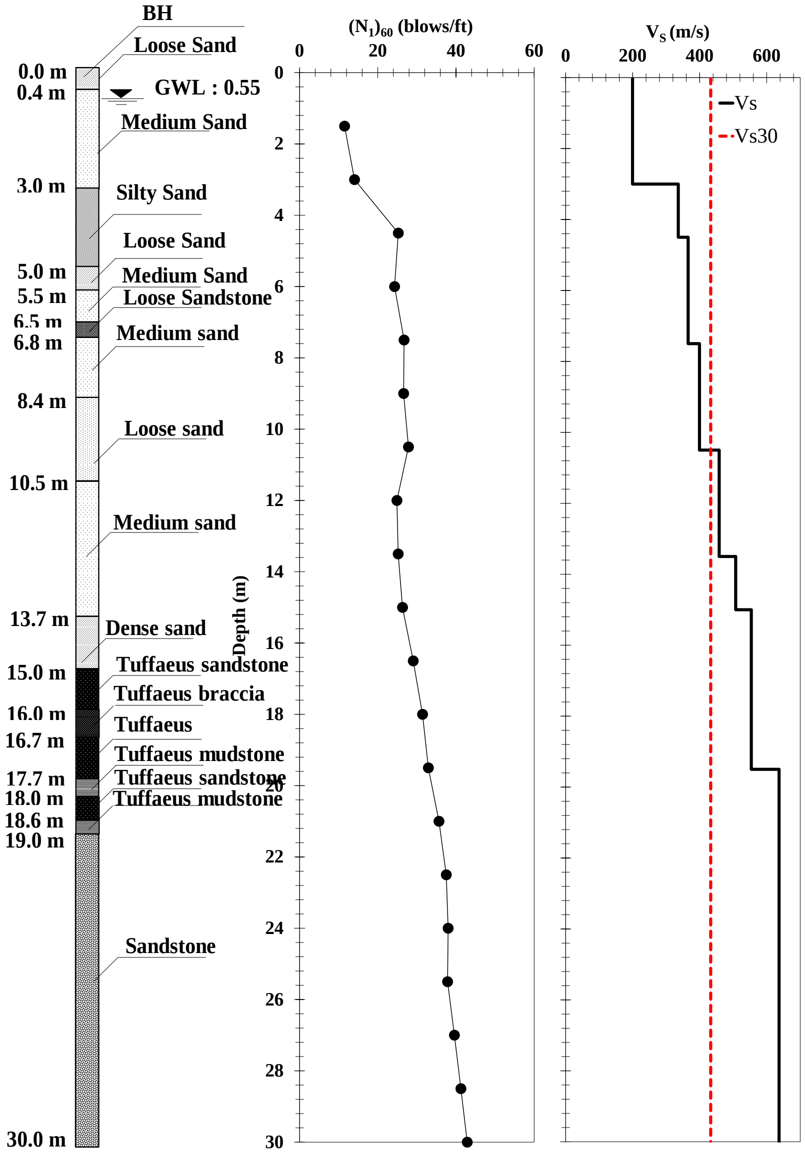


Figure 2. Geological condition of Prambanan area (modified from Suryolelono [2])

Experimental Methods

The test procedure to model liquefaction using shaking table machine had been presented by several researchers, such as Varghese and Latha [7], Otsubo et al. [8], Banerjee et al. [9], Unni et al. [10], Moss et al. [11], Pathak et al. [15], and Singh et al. [16]. In general, the physical model of liquefaction using shaking table consisted of some equipment, such as actuator to release the kinetic energy, sample container, roller to demonstrate harmonic motion, and measurement sensors (accelerometers and pressure transducers). In line with those previous studies, this study also adopted the test procedures from those previous studied that had been successfully implemented to physically model liquefaction.

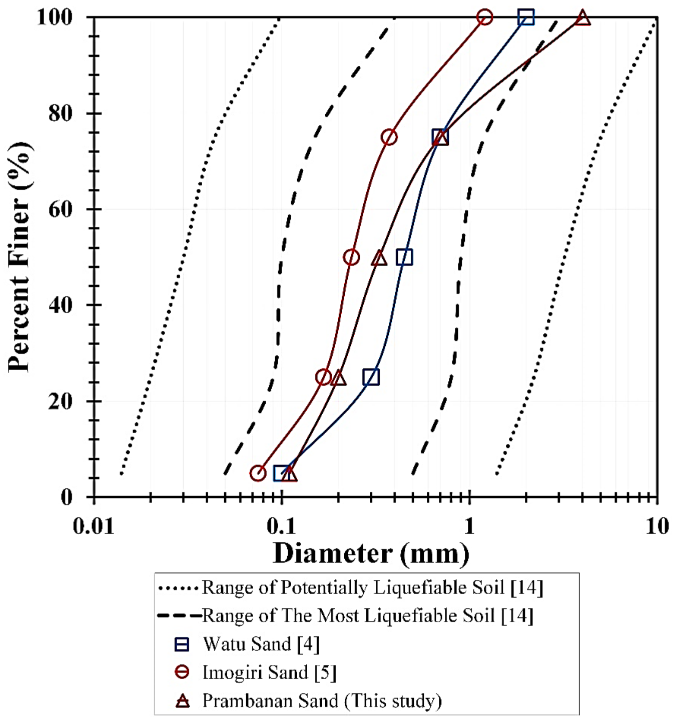


Figure 3. Grain size distribution for Prambanan sand to other Yogyakarta Sands

Table 1. Physical Properties of Loose Sandy Soils in Prambanan Site

Physical Properties	Notation	Value	Unit
Soil Classification (USCS)	SP	-	-
Uniformity Coefficient	C_u	3.82	-
Curvature Coefficient	C_c	1.58	-
Moisture Water Content	w	25	%
Bulk Density	γ_b	16.40	kN/m^3
Dry Density	γ_d	13.12	kN/m^3
Saturated Density	γ_{sat}	18.67	kN/m^3
Specific Gravity	G_s	2.68	-
Maximum Void ratio	e_{maks}	0.97	-
Minimum Void ratio	e_{min}	0.54	-
Degree of Saturation	S	78	%
Relative Density	R_D	26	%

The scheme of shaking table machine used in this study is presented in Figure 4. The machine had a rigid platform for the soil sample container, with the maximum capacity of 2 tons. The shaking table was horizontally driven by roller at base of shaking table that has been transmitted by actuator. The motion is modelled as harmonic motion. Therefore, the motion applied in this experiment was sinusoidal motion. The maximum applied vibrational frequency was 5.5 Hz, whereas the maximum applied acceleration was 12.5 m/s2 or 1.25g

($g \approx 9.81$ m/s^2). The container used in this study is a drum sized 60 cm in diameter and 80 cm in height. Container was equipped by a circular plate to cover the top of soil sample during test. To ensure no movement at container during dynamic loading, several stiffener plates were installed. A pressure head was also installed to ensure there is no seepage at the container. Pore pressure transducer was installed at the height side of container. This sensor is also connected to personal computer and data acquisition.

For the sample preparation, several steps were performed. Firstly, the distillation water was filled into the container until reaching 10 cm in height. Next, the sand which had been filtered using the sieve filter of 2 mm was poured into the container. Air bubbles appeared from the sample void due to the sand pouring was removed. The previous steps were repeated until the required sample height (i.e. about 60 cm) was reached. Furthermore, sample in the container was left for at least 2 hours to ensure that sample was totally saturated. For the last preparation step, to ensure that no drainage path exists during pore pressure generation, a circular plate was put on the soil deposit.

To determine initial condition, initial pore pressure (u_o) and initial effective stress (σ_v') were measured. Afterwards, the shaking table machine was driven corresponding to the dynamic loads listed in Table 2. In this study, dynamic load variables that included acceleration, vibrational frequency, and shaking duration, were considered. Fathani et al. [17] mentioned that the epicentre of the Jogja Earthquake in 2006 was located at Southern Opak Fault, i.e. about 10 km from Prambanan site. Fathani et al. [17] also predicted that the estimated ground acceleration on the study area was observed to vary from 0.3 to 0.4g [5 and 17]. Therefore, the acceleration of shaking table machine was simply varied to be 3 m/s^2, 3.5 m/s^2 and 4 m/s^2. The constant vibrational frequency of 1.4 Hz was applied based on study of Kusumawardhani et al. [18] (since the strong earthquakes triggering liquefaction had the vibrational frequency of 0.5 to 2.5 Hz). Chang and Krinitszky [19] mentioned that for the earthquakes with magnitudes ranging from 6 to 7 occurred within 10 km radius of epicentre, the effective shaking durations were observed to vary from 16 to 32 seconds. In line with the study area, this recommendation was acceptable with the condition of study area, since it is located within radius of 10 km from the rupture of Jogja earthquake. Therefore, the shaking duration variations of dynamic tests were varied to be 16, 24 and 32 seconds. Excess pore water pressure was measured by pore pressure transducer installed at height of 30 cm from the bottom of container. The pore pressure measurement was performed when the dynamic load was executed up to the next 60 seconds. In this study, excess pore water pressure ratio or r_u is used as liquefaction parameter. The formulation of r_u is expressed in the following,

$$r_u = \frac{\Delta u}{\sigma_v^{'}} \tag{1}$$

where, Δu is excess pore water pressure and $\sigma_v^{'}$ is initial effective stress.

Liquefaction could occur when r_u is more than or equal to one. This parameter is also used in several studies, such as Varghese and Latha [7], Haeri et al. [20], and Takahashi et al. [21]. Observations to the time history of r_u, the initial time to generate liquefaction, the initial time of pore pressure dissipation, the liquefaction duration, and the maximum values of excess pore water pressure ratio are presented in this study. The results are also compared with the previous studies performed in the different areas, which also experienced liquefaction during the Jogja Earthquake in 2006. In addition, the effect of acceleration to cyclic stress ratio (*CSR*) obtained from the experiments are presented. The *CSR* curve is also compared to several *CSR* curves of sandy soils from some previous studies.

Table 2. Dynamic loads applied for shaking table tests

Test Reference Number	Acceleration (*a*) (m/s^2)	Vibration Frequency (*f*) (Hz)	Shaking Duration (seconds)
1	3.0		16
2	3.0		24
3	3.0		32
4	3.5		16
5	3.5	1.4	24
6	3.5		32
7	4.0		16
8	4.0		24
9	4.0		32

Figure 4. Schematic of shaking table machine used in this study (courtesy of Cultural Heritage Preservation of Prambanan Temple in Yogyakarta Indonesia)

Results and Discussions

Excess Pore Water Pressure

The time history of r_u for each test is presented in Figures 5 to 7. Figure 5 shows time history of r_u for the dynamic load of 3 m/s^2. For the dynamic loads of 3.5 m/s^2 and 4.0 m/s^2, the interpretations are shown in Figures 6 and 7, respectively. r_u significantly increases within 5 seconds and exceeds the threshold of liquefaction ($r_u \approx 1$). Generally, shaking duration and acceleration tend to influence the liquefaction. A larger acceleration and a longer shaking duration could generate a higher r_u maximum ($r_u max$). This observation is also consistent with several studies performed by Mase [5 and 6], Varghese and Latha [7] and Singh et al. [16]. Based on the results, both longer shaking duration and larger acceleration could influence the time stages of liquefaction, such as initial time to generate liquefaction, time to start dissipation, and liquefaction duration.

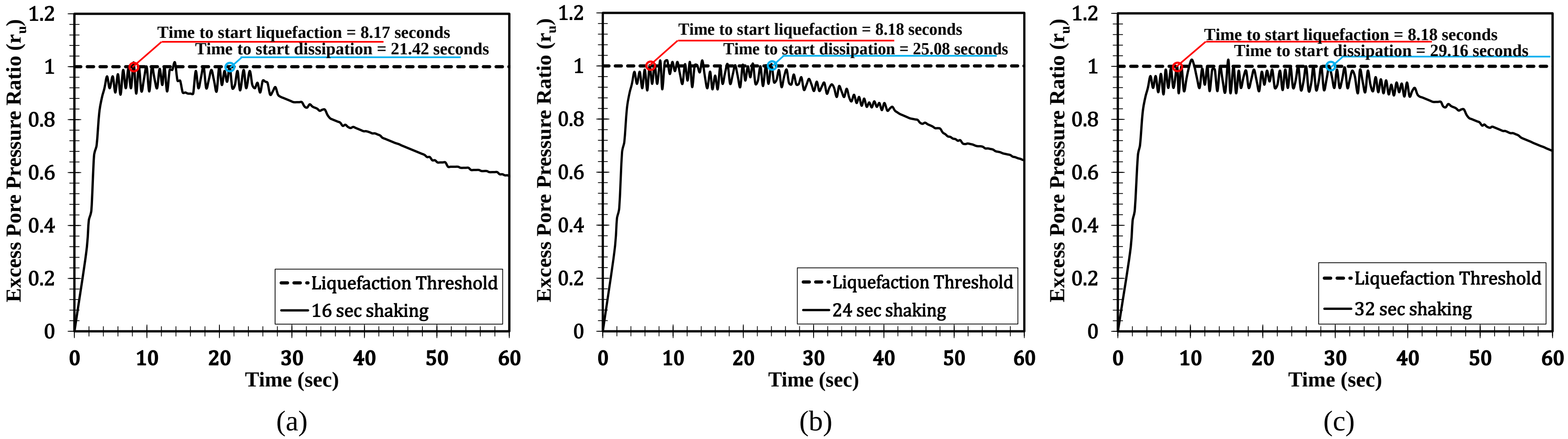
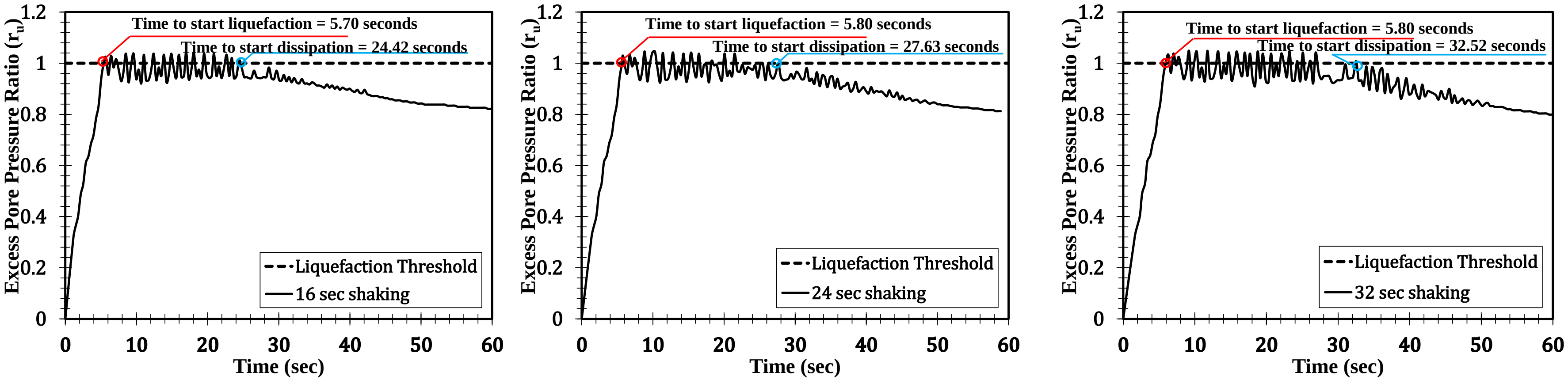
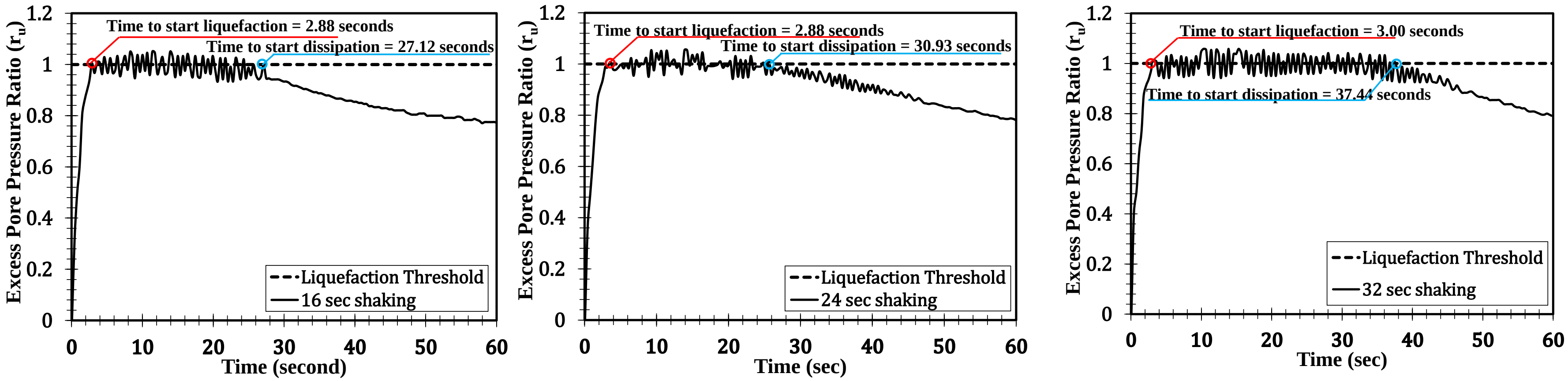


Figure 5. Excess pore water pressure ratio due to acceleration of 3.0 m/s^2 (a) 16 seconds shaking duration, (b) 24 seconds shaking duration and (c) 32 seconds shaking duration



(a) (b) (c)

Figure 6. Excess pore water pressure ratio due to acceleration of 3.5 m/s^2 (a) 16 seconds shaking duration, (b) 24 seconds shaking duration and (c) 32 seconds shaking duration



(a) (b) (c)

Figure 7. Excess pore water pressure ratio due to acceleration of 4 m/s^2 (a) 16 seconds shaking duration, (b) 24 seconds shaking duration and (c) 32 seconds shaking duration

Liquefaction Time Stages

Figure 8 presents initial time to generate liquefaction. In general, initial time of liquefaction for Prambanan Sand depends on the applied dynamic load. A larger applied acceleration means a shorter initial time to generate liquefaction. This is because a larger energy generated from a larger acceleration could yield much amount of excess pore water pressure. This also could exceed the initial effective stress shortly. However, initial time to generate liquefaction is not significantly influenced by the shaking duration. The same acceleration applied at the different shaking vibration tends to generate same initial time to generate liquefaction. The results are also compared with previous studies performed by Mase [4] (Imogiri sand) and Mase [5] (Watu sand). It can be seen that for each applied acceleration (3 m/s^2 (0.3g), 3.5 m/s^2 (0.35g), and 4.0 m/s^2 (0.4g)), initial time to generate liquefaction for Prambanan sand is longer than both compared sands. This may be caused by the soil properties, such as grain size characteristic and D_{50} of sands. Both coefficients of uniformity (C_u) and coefficient of curvature for Watu sands are 3.4 and 1.4, respectively. For Imogiri sand, both coefficients are 1.75 and 0.875, respectively, whereas both coefficients of Prambanan sand are 3.82 and 1.58, respectively. D_{50} of Prambanan sand is about 0.35 mm, whereas for Watu and Imogiri sands are 0.34 and 0.3, respectively. According to Mase et al. [22], Ishibashi [23], Aydan et al. [24], and Pathak and Purandare [25], sands with $C_u \leq 2$ and $D_{50} \approx 0.2$ mm are categorized as the most liquefiable sands. In addition, Lee and Seed [26] noted that the higher relative density could provide the higher soil resistance, which means that the liquefaction potential tends to decrease. The finding also shows that both Watu and Imogiri sands are easier to undergo liquefaction than the Prambanan Sand. The results also show that the vibrational frequency could influence initial time to generate liquefaction. A larger vibrational frequency applied to Imogiri sand, i.e. 1.8 Hz tends to shorten time to generate liquefaction compared to both Prambanan and Watu Sands.

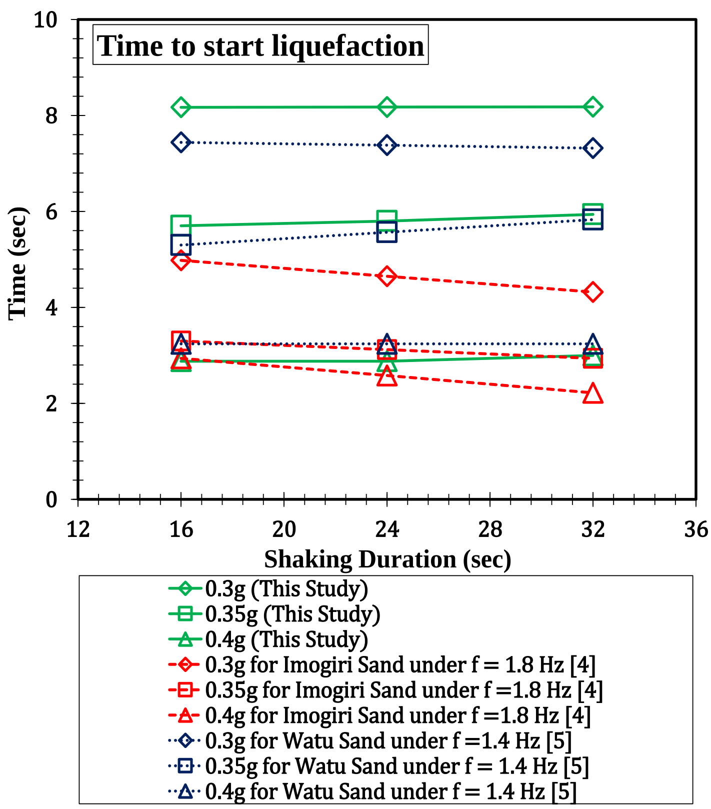


Figure 8. Time to start liquefaction

Figure 9 presents time to start dissipation of pore water pressure for Prambanan sand. Time to start dissipation is significantly influenced by shaking duration and acceleration. A larger acceleration performed in a longer duration could generate a longer time to start dissipation. This is because a larger acceleration applied for a longer shaking duration could maintain excess pore pressure temporarily concentrated at the liquefaction threshold ($r_u \approx 1$). A larger acceleration could also generate a shorter time to generate liquefaction. If it was applied for a longer time, pore pressure would accumulate at the threshold condition. It is able to be dissipated after the load was stopped. However, when the loading is stopped, pore pressure is not directly dissipated. It may be caused by the remained harmonic motion from the applied acceleration which still slowly generates a pore pressure at liquefaction threshold. Therefore, the initial time for pore pressure dissipation is also getting longer. Time to start dissipation for Prambanan sand also shows the similar tendency to both Imogiri and Watu Sands. Acceleration and shaking duration could affect initial time to dissipate. Time to start dissipation of pore water pressure of Prambanan sand is also shorter than Imogiri Sand, but longer than Watu Sand. This may be caused by the soil properties of sands, as previously elaborated. Imogiri sand was tested under a larger vibrational frequency (1.8 Hz) compared to Prambanan sand (1.4 Hz). A larger vibrational frequency tends to generate much amount of excess pore water pressure than a smaller one. Soil granules had snuggled each other after the dynamic loading. It may cause pore pressure to be not easily dissipated. Therefore, time to start dissipation is longer [27].

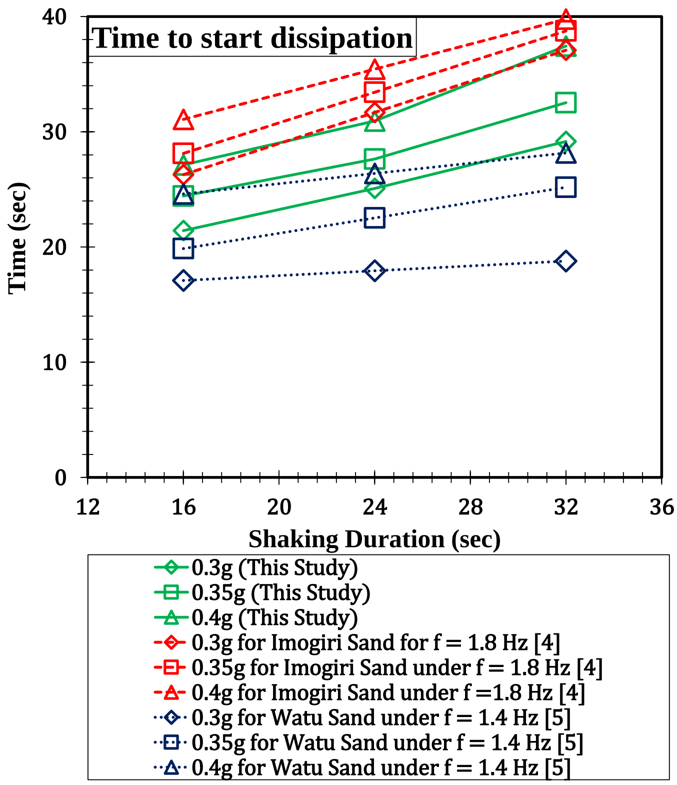


Figure 9. Time to start dissipation

Liquefaction duration for Prambanan Sand is presented in Figure 10. Liquefaction duration is defined as the difference between time to generate liquefaction and time to start dissipation. Liquefaction duration is influenced by shaking duration and applied acceleration. A shorter initial time to generate liquefaction and a longer time to start dissipation mean a longer duration of liquefaction. Both time stages depend on applied acceleration and shaking duration, so does liquefaction duration. Comparison to previous studies is also presented in Figure 10. The tendency of liquefaction duration for the Prambanan sand and both compared sands is generally consistent. However, liquefaction duration of Prambanan sand is shorter than Imogiri sand, but longer than Watu sand.

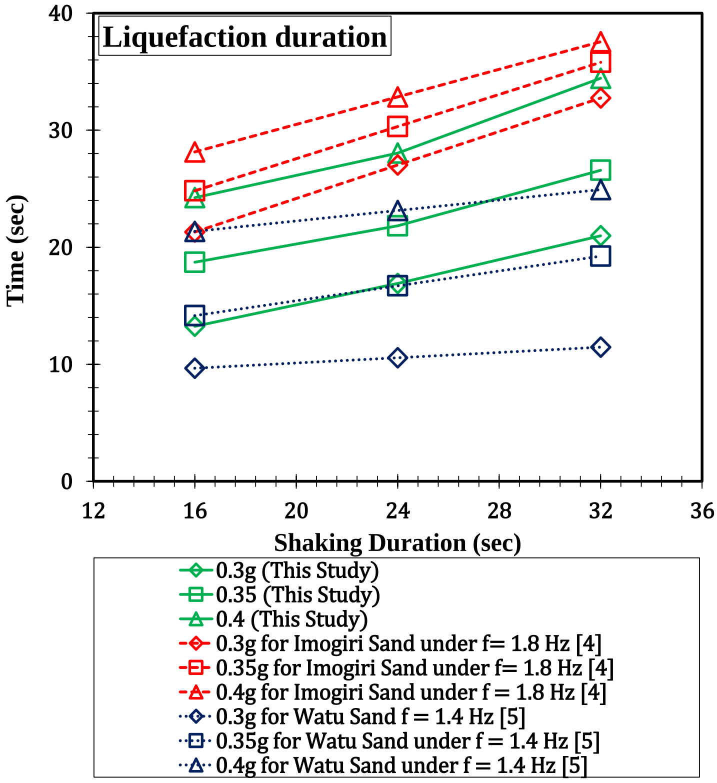


Figure 10. Liquefaction duration

Soil properties which influenced initial time to generate liquefaction and time to start dissipation, would certainly influence liquefaction duration. As presented in previous paragraph, liquefaction duration is influenced by shaking duration and applied acceleration. In this study, the percentage of liquefaction duration or D_{Liq} is simply estimated from this following equation,

$$D_{Liq}(\%) = \left(\frac{D_{Liq(t)} - D_{Liq(i)}}{D_{Liq(i)}} \right) \times 100\% \qquad (2)$$

where, $D_{Liq(t)}$ is the current test and $D_{Liq(i)}$ is the initial test

Figure 11 presents the interpretation of the increase of liquefaction duration (%). In general, the increase of liquefaction duration varies from 29 to 83%. The increase of liquefaction duration is influenced by the applied acceleration. A larger acceleration means a larger increase of liquefaction duration percentage. The increase percentage of liquefaction duration for Prambanan sand is larger than Imogiri sand, but smaller than Watu sand. This is due to the fact that liquefaction duration is influenced by applied dynamic load and soil properties. The increase of acceleration could result in a larger percentage of liquefaction duration increase. It is because of the difference between liquefaction duration due to the applied loads. The vibrational frequency also plays important role in increasing of liquefaction duration. A larger vibrational frequency applied to Imogiri sand tends to result in a smaller percentage of liquefaction duration increase than a smaller frequency as applied on Watu and Prambanan Sand. It indicates no significant different of liquefaction duration due to the acceleration applied for each shaking duration. Both Prambanan and Imogiri sands shows similar tendency in which a longer shaking duration results in a smaller increase.

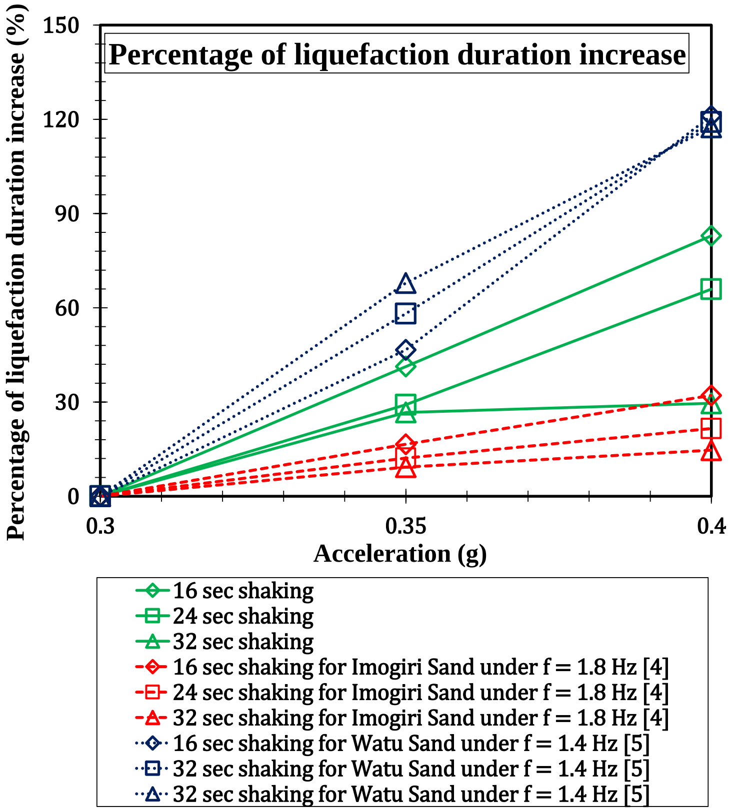


Figure 11. Percentage of liquefaction duration increase

Overall, it can be simply estimated that the combination of a larger acceleration and a longer shaking duration could increase the liquefaction potential and influence the liquefaction time stages. Basically, a larger acceleration means a large energy. A larger energy applied for longer duration would increase the liquefaction potential. In line with this, the liquefaction time stages also depend on the dynamic load. It can be concluded that the applied acceleration and the shaking duration strongly influence the liquefaction potential and liquefaction time stages. This observation is also generally consistent with several studies performed by Mase [5 and 6], Varghese and Latha [7], and Singh et al. [16]. The comparison also lead to the effect of vibrational frequency to liquefaction potential. A larger vibrational frequency could produce a faster harmonic motion. A larger acceleration applied under a longer shaking duration and a larger vibrational frequency would result in a larger liquefaction potential. Therefore, a vibrational frequency and a shaking duration certainly also influence the liquefaction time stage. This observation is also consistent with several studies performed by Mase [5 and 6], Varghese and Latha [7], and Singh et al. [16].

Cyclic Stress Ratio (*CSR*)

In the shaking table test, the cyclic stress ratio (*CSR*) is a parameter reflecting cyclic stress resulted due to the dynamic loading. *CSR* are estimated based on these following equations,

$$CSR = \frac{\tau_h}{\sigma_v'} \quad (3)$$

$$\tau_h = \frac{W}{g} a_{\max} \quad (4)$$

where, *CSR* is cyclic stress ratio, τ_h is the cyclic shear stress, *W* is total pressure exerted at the base, *g* is gravity acceleration, a_{max} is the maximum acceleration of the uniform cyclic motion. The number of cycles (N_{liq}) is required for liquefaction resistance curve. The formulation of N_{Liq} is expressed below,

$$N_{Liq} = \frac{\text{Initial time to generate liquefaction}}{T} \quad (5)$$

$$T = \frac{1}{f} \quad (6)$$

where, N_{liq} is number of cycles to generate initial liquefaction and *T* is period of vibrational shaking, and *f* is the vibrational frequency.

Figure 12 presents the interpretation between *CSR* against required time to generate $r_u max$. A longer time to generate $r_u max$ is required for a larger *CSR*. To generate a larger $r_u max$ under a larger acceleration, the required time would be shorter. A longer shaking duration tends to results in a longer required time to generate $r_u max$. Acceleration applied at a longer time could result in a larger amount of pore pressure. A larger generated pore pressure means a larger excess pore water pressure ratio. However, no significant time gap is required to generate liquefaction for each shaking duration. It is because soil would be compacted and generated pore water pressure would insignificantly increase during shaking.

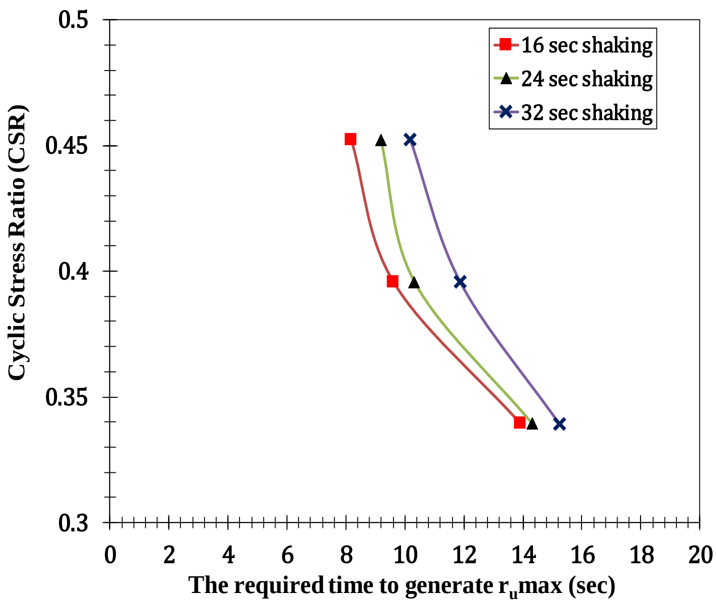


Figure 12. Time to generate $r_u max$ versus *CSR*

Figure 13 presents $r_u max$ interpretation against *CSR*. It can be observed that a larger *CSR* means a larger applied acceleration and a larger applied acceleration means a larger energy to produce ground shaking. It can be concluded that a larger applied acceleration could generate a larger $r_u max$. In addition, a longer shaking duration potentially resulted in a larger $r_u max$. It is due to the fact that a larger acceleration applied for a longer duration would result in a large amount of pore pressure.

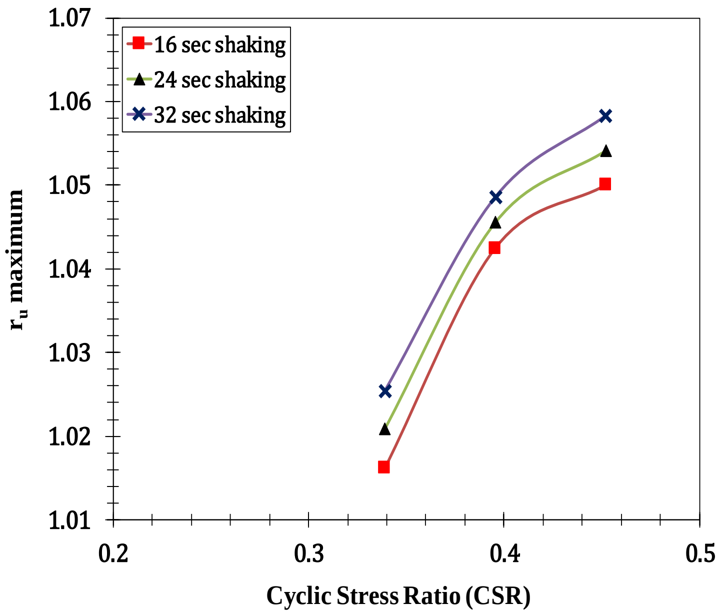


Figure 13. *CSR* versus $r_u max$

Figure 14 shows liquefaction resistance curve of Prambanan sand compared to several previous studies. The comparison is presented to observe the liquefaction resistance tendency on liquefiable sandy soils. Besides, the comparison is addressed to observe the liquefaction resistance corresponding to physical model dimension. The liquefaction resistance for Prambanan Sand is generally higher than compared sands. It indicates that a greater number of cycles is required to generate liquefaction under the similar *CSR*. It could be also due to ratio of length to height of the sample which affects *CSR* considerably as well as number of cycles to generate liquefaction. This effect is also known as the confinement effect of sample box, which was also reported by several studies performed by Yoshimi [28], Whitman [29], and [30], and Emery et al. [31]. O-hara and Suzuoka [32] considered the ratio of length to height for the sample was about 3.4:1, whereas DeAlba et al. [33] and Finn et al. [34] were 22.5:1 and 10.3:1, respectively. Compared to those ratios' values, the ratio of length to height for Prambanan sand sample is generally smaller, i.e. 1:1. The cyclic stress ratio increases with the decrease in the ratio of length to height of sample. Because of the increase of *CSR*, the number of cycles required to generate liquefaction also increases [15]. A higher vibrational frequency is therefore required to be applied to obtain specific variation of *CSR* and number of cycles to generate the liquefaction [15].

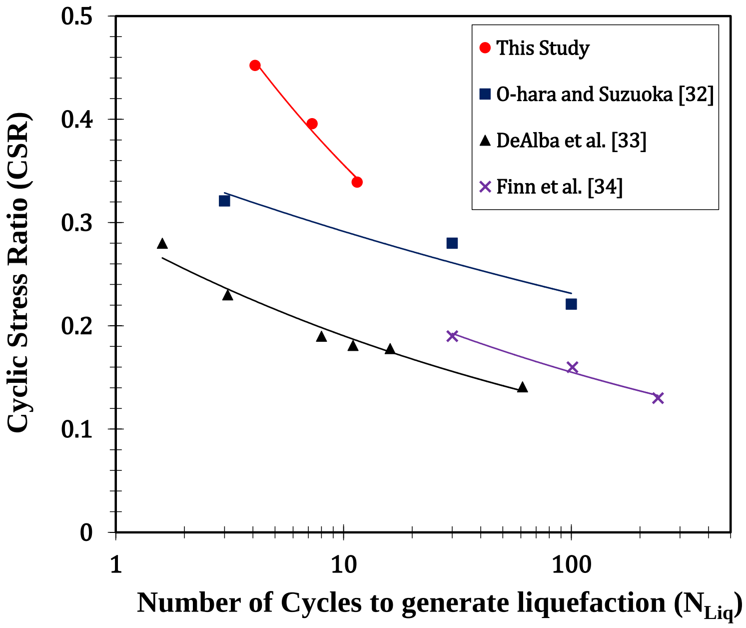


Figure 14. *CSR* vs N_{liq} and the comparison to previous studies

Recommendation for Liquefaction Countermeasure

In line with the experimental result, it is observed that sandy soil classified as SP at depth of 0.4 to 3.0 m is very vulnerable to undergo liquefaction. This sand layer is found at shallow depth with relatively shallow ground water level. At this depth range, shallow to medium foundation for buildings is placed. It means that the liquefaction countermeasure should be addressed for soil layer supporting foundation. Liquefaction is strongly depending on soil shear strength. The larger soil strength means the larger liquefaction resistance. Therefore, the concern on ground improvement to increase soil shear strength as the effort for liquefaction countermeasure is required. For shallow depth, Tani et al. [35] mentioned that several ground improvement methods, such as compaction, solidification, and drainage can be adopted as liquefaction countermeasures. Tani et al. [35] also mentioned that solidification method could be the most suitable method among other methods. The solidification method is generally conducted by compaction grouting. This method is addressed to increase the shear strength of liquefiable layers. Tani et al. [35] mentioned that this method is also applicable for both new and existing buildings. Several researchers, such as Orense [36], Han et al. [37], and Badanagki et al. [38] had presented the use of solidification method and also concluded that the performance of solidification method had been verified experimentally and numerically. This method seems to be reasonably implemented as liquefaction countermeasure in study area.

Conclusions

This study presents an experimental study to Prambanan sand which underwent liquefaction during the Jogja earthquake in 2006. Some observations, including the liquefaction time stages, the maximum excess pore water pressure ratio, and *CSR* versus the number of cycles to generate liquefaction are presented in this study. Several concluding remarks from this study are:

1. The site investigation results reveal that at the shallow depth in Prambanan Area is dominated by loose sandy soils, which was indicated to undergo liquefaction during the Jogja Earthquake. The shaking table experiment results exhibit that Prambanan sand could undergo the liquefaction under the simulated acceleration and shaking duration. It is confirmed by the excess pore water pressure ratio exceeding one. The results also confirmed that the first sand layer of Prambanan area could undergo liquefactions, which were found during the Jogja Earthquake in 2006.
2. The liquefaction time stages including the time to start liquefaction, the time to start dissipation, the liquefaction duration are significantly influenced by the applied acceleration and shaking duration. In addition, both parameters also influence the $r_u max$ and the required time to generate it as well as the cyclic stress ratio for Prambanan Sand. Generally, the results of this study are consistent with those of previous studies performed in Yogyakarta Special Province.
3. The cyclic resistance of Prambanan sand exhibit the same tendency to the compared sands, where the number of cycles to generate liquefaction increase with the increase of *CSR*. In general, the cyclic resistance of liquefaction for Prambanan sand is slightly higher than compared sands. The ratio of length to height could be the reason why *CSR* and the number of cycles to generate liquefaction are larger. The results also confirms the effect of length to height ratio to the cyclic resistance, which were performed in the previous studies.
4. The result of this study could bring a recommendation to consider the effect of liquefaction in Yogyakarta Special Province in general and Prambanan Temple in particular. Since the liquefiable layer is found at shallow depth, a solidification method can be the option as liquefaction countermeasures. The design of countermeasure can be formulated referring to this study and presented in the further study.

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