The Study of Liquefaction Time Stages due to a Short Duration Shaking

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Abstract: During the 2006 Yogyakarta earthquake, liquefactions were massively found in Opak River, Yogyakarta, Indonesia. Learning from those events, an experimental study of liquefaction using shaking table was performed, especially to investigate the effect of short shaking duration to liquefaction potential. Several experimental tests were performed under varied accelerations (0.3g, 0.35g, and 0.4g) and vibration frequencies (1.4 Hz, 1.6 Hz, and 1.8 Hz), with a short shaking duration of 8 seconds. The liquefaction parameter used in this study was the excess pore water pressure ratio. The results revealed that liquefaction occurs in every loading criteria and the short shaking duration applied on each loading influences time stages of liquefaction, i.e. the liquefaction duration, the initial time of liquefaction, and the initial time of pore water pressure dissipation. In addition, the dynamic loads applied in a short duration influenced the maximum excess pore water pressure ratio.

Keywords: Liquefaction potential; excess pore water pressure; short shaking duration.

Introduction

It is known that Indonesia is vulnerable to earthquakes. During the last decade, several big earthquakes occurred in some provinces in Indonesia. Nangroe Aceh Darussalam earthquake in 2004, Bengkulu earthquakes in 2000 and 2007, Yogyakarta earthquake in 2006, and Padang earthquake in 2009, were some strong earthquake events that happened in the last decade.

Earthquakes did not only result in the damage to the buildings, but also triggered other hazards, such as landslides, ground movements, and liquefactions. Among those catastrophic events, liquefaction can be categorized as a unique phenomenon. This phenomenon is caused by the effective stress reduction due to the excess pore water pressure during an earthquake. According to Day [1], liquefaction may occur under an earthquake having a minimum Moment Magnitude (M_w) of 5 and Peak Ground Acceleration (PGA) of 0.1g.

The increase of seismic activities in Indonesia attracts Indonesian researchers to study earthquake and its impact, especially liquefaction.

Several Indonesian researchers studied the liquefaction phenomena in some areas, such as Hakam [2] for a case study in Padang, Misliniyati et al. [3], and Monalisa [4] for the case studies in Bengkulu, and Mase et al. [5] and Mase [6,7] for the case studies in Yogyakarta. Generally, those researchers focused on the analysis of liquefaction severity based on the site investigation data (Standard Penetration Test and Cone Penetration Test data), and were aiming to obtain a rough estimation of liquefaction vulnerability and as a preliminary study.

Yogyakarta Special Province is one of the vulnerable areas to undergo liquefaction in Indonesia. In 2006, liquefaction which was triggered by an earthquake with a magnitude of 6.3 M_w, occurred in the Southern Yogyakarta. Many liquefaction evidences including sand boils and lateral spreads, were found, especially along the riverbank of Opak River.

Liquefaction study in Yogyakarta was initiated by some researchers that conducted the preliminary analysis to draw the vulnerability map (Figure 1a). Yogatama and Fathani [8] studied liquefaction potential based using Liquefaction Potential Index (LPI) method [9]. Furthermore, Setiabudi [10] continued Yogatama and Fathani [8] study by using Liquefaction Severity Index (LSI) [11] method to draw the liquefaction vulnerability map in Yogyakarta (Figure 1b). Based on those maps, the preliminary studies showed that Southern Yogyakarta was generally categorized as the most vulnerable area to undergo liquefaction, especially along the riverbank of Opak River. The results also confirmed the actual liquefaction evidences in 2006, which were massively found along the riverbank of Opak River.

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Referring to both previous studies, Mase et al. [5] and Mase [6,7] conducted the experimental studies of soil liquefaction using shaking table. Those studies were performed to investigate the soil behaviour of the Southern Yogyakarta sand (i.e. Opak Imogiri sand [5,6] and Watu sand [7]) under various dynamic loads. The PGA values of 0.3g, 0.35g, and 0.4g were performed in the experimental tests. PGAs were considered based on the Indonesian Seismic Map [12]. In Mase et al. [5] study, all dynamic loads were simulated at a constant vibration frequency of 1.8 Hz for 32 seconds, whereas in Mase [6] the dynamic loads were also applied at the same vibration frequency, i.e. 1.8 Hz for 8, 16, and 32 seconds. In Mase [7] study, all dynamic loads were simulated at the various vibration frequencies of 1.4 to 1.8 Hz, for the various shaking durations of 8 to 32 seconds. In general, those studies concluded that all applied loads were possible to trigger liquefaction. Besides, the applied loads also affected the generated excess pore water pressure ratio and liquefaction duration. The excess pore water pressure ratio (r_u) become larger, when the earthquake load was increased. The increase of dynamic load also potentially extended the liquefaction duration.

Mase [13] investigated the effect of grain size distribution and cyclic load to the liquefaction potential of Opak River sandy soil. According to the result, the required PGA to trigger liquefaction would be larger, with the relative density (R_d). Moreover, the cyclic load also increased the liquefaction potential. Due to the increase of cyclic load, the possibility of liquefaction would also become larger. The minimum PGA of 0.1g was capable to trigger liquefaction for sandy soil having relative density of about 30%.

In general, the previous studies were focused on reporting the earthquake impacts and interpreting the liquefaction potential by the empirical approaches and the general experimental studies. Basic information achieved from those previous studies, was the rough estimates of liquefaction susceptibility in Southern Yogyakarta. However, the detail description of the soil behaviour for Opak River riverbank, especially under a constant short duration, applied for various vibration frequencies, was still not achieved in those previous studies.

The objective of this study is to present the dynamic testing of soil liquefaction during a short shaking duration. The excess pore water pressure during the excitation is investigated. Several time stages of liquefaction (time to generate liquefaction, time to start dissipation, and liquefaction duration) are studied. In addition, the maximum excess pore water pressure ratio ($r_u$max) during the excitation is observed. Generally, this study is expected to better understand soil liquefaction phenomenon and contribute to liquefaction study in Indonesia.

Physical Properties of Soil Sample

Sand taken from Opak River riverbank (shown by red rectangle in Figure 1) in Imogiri, Southern Yogyakarta, was used for all dynamic tests. Table 1 presents the physical properties of the tested soil. In general, the soil sample is categorized as the poorly graded sand (SP). It is shown by the values of uniformity coefficient (C_u of 2.32) and curvature coefficient (C_c of 0.81), which do not meet the well graded criteria, ($C_u \geq 6$ and $1.5 \leq C_c \leq 3$). The soil sample is also categorized as loose sand, which is indicated by the relative density of less than 33% (the maximum limit of relative density for loose sand). Furthermore, the grain size distribution graph and other standard graphs of liquefaction investigation are matched in Figure 2 [14]. The comparison is addressed to obtain the rough estimation of liquefaction susceptibility. In Figure 2, the grain size distribution is compared to two vulnerability ranges of grain size, i.e. the potentially liquefiable soil (blue dotted lines) and the most potentially liquefiable soil (red dashed lines). In general, the grain sizes distribution of the sample is categorised as the most potentially liquefiable soil. It can be concluded that the riverbank sand of Opak River might be liquefied during the 2006 earthquake.

Test Set Up

The experimental tests were conducted on a shaking table equipment which belongs to Balai Pelestarian Cagar Budaya (BPCB) (Cultural Heritage Preservation Agency) of the Prambanan Temple Complex, Yogyakarta. The shaking table consisted of rigid platform, where the container was placed. The shaking table is horizontally driven by a dynamic actuator with maximum vibration frequency of 1.8 Hz. The test container was a drum with diameter of 60 cm and height of 80 cm. In this container, the sample was prepared. The container is equipped by pore pressure transducer, which was installed on the container side at 30 m height from the bottom of container. The whole test set up is presented in Figure 3. The shaking table can produce the steady state vibration, which models one dimensional harmonic excitation. The maximum amplitude of horizontal acceleration which can be performed is up to 1.25g.

Sample Preparation and Test Procedure

Sample preparation was initiated by pouring a certain quantity of water into the container. Firstly, the water was poured to fill the container up to 10 cm high. Secondly, the container was filled by sand, using a metal sieve with a mesh of 2 mm. During the sample pouring, air bubbles appearing from the

sample were removed. The previous steps were continuously repeated until the sample height reached the required level (in this study, the required height of sample was 60 cm). After the required height, i.e. 60 cm, was reached, it was left for at least two hours to ensure that the sample was totally saturated. After this step, the water overlaying the sample was removed. For the last step, the circular plate was put on the soil deposit to ensure that there was no drainage path when the pore water pressure built up. Prior to testing, the initial pore water pressure was also measured.
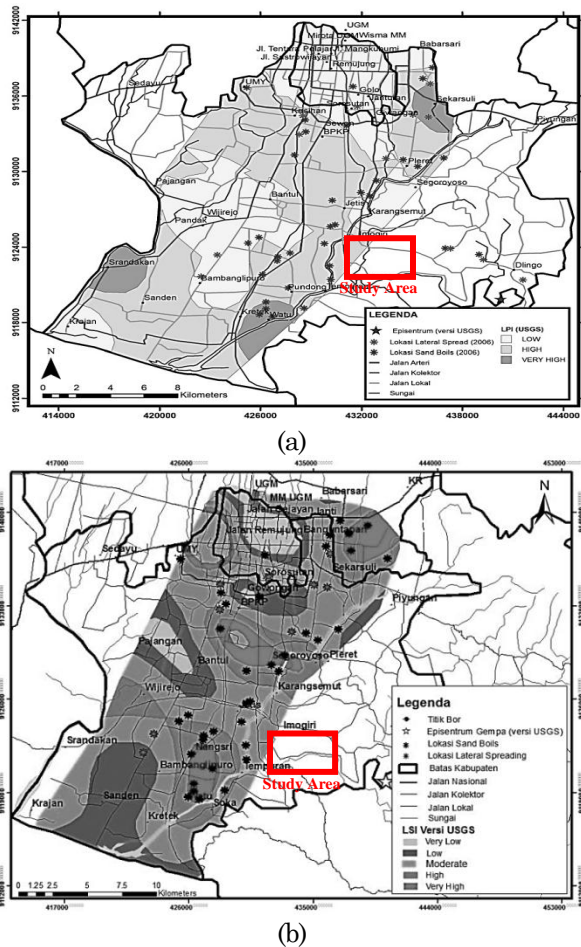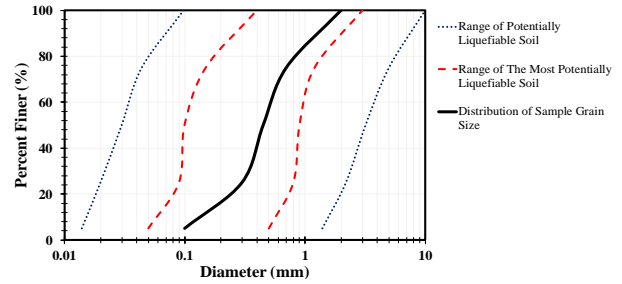

Figure 2. Grain Size Distribution of Soil Sample in Opak River Imogiri Compared to Vulnerable Criteria [14]

Tests were performed on the saturated sandy soil at different accelerations with different vibration frequencies. All tests were conducted at a shaking duration of 8 seconds, which was addressed to study the effect of short shaking duration to the liquefaction stages. The selected acceleration levels were based on Mase [13] and Fathani et al. [15] studies, which investigated PGA distribution in Yogyakarta due to the 2006 earthquake. The variation of dynamic test in this study is presented in Table 2.

In this study, excess pore water pressure during each test was continuously recorded up to 60 seconds. The liquefaction threshold was determined when the excess pore water pressure ratio (r_u) was equal or more than one. The liquefaction threshold was based on Casagrande [16] concept, which was also adopted by several researchers, such as Mase et al. [5], Mase [6,7], Gupta [17] and Singh et al. [18], in studying liquefaction potential using the shaking table.

Result and Discussion

The main output of the test was excess pore water pressure time history. Furthermore, excess pore water pressure was correlated with some liquefaction stages that included the initial time of liquefaction, the initial time of pore water pressure dissipation, and the liquefaction duration. Besides, $r_u$max during the excitation was also analysed. In these following sections, the observed points are discussed.

(a)

(b)

Figure 1. Liquefaction Susceptibility Map in Yogyakarta Special Province and Bantul Regency, (a) Based on LPI [8], and (b) Based on LSI [10]

Table 1. Physical Properties of Sample

Physical Properties	Notation	Value	Unit
Uniformity Coefficient	C_u	2.32	-
Curvature Coefficient	C_c	0.81	-
Moisture Water Content	w	23.00	%
Bulk Density	γ_b	16.40	kN/m^3
Dry Density	γ_d	14.10	kN/m^3
Saturated Density	γ_{sat}	18.00	kN/m^3
Specific Gravity	G_s	2.70	-
Maximum Void ratio	e_{maks}	0.99	-
Minimum Void ratio	e_{min}	0.58	-
Degree of Saturation	S	68.00	%
Relative Density	R_D	26.00	%

Figure 3. Shaking Table at BPCB Prambanan Temple

The Excess Pore Water Pressure (r_u) Ratio Time History

Figure 4 presents the excess pore water pressure ratio time history on each test. In general, the conducted tests show that the soil deposit may undergo liquefaction. It can be seen from the excess pore water pressure ratio exceeding the liquefaction threshold (r_u = 1). As presented in Figure 4, the applied accelerations and frequencies at a short shaking duration influence the excess pore water pressure ratio. The larger energy tends to generate the larger amount of excess pore water pressure, which absolutely reduces the initial soil effective stress. Once the soil effective stress decreases to zero, then liquefaction happens. Considering these results, it can be concluded that the sandy soil of Opak River, Imogiri, is vulnerable to undergo liquefaction. The result is also consistent with Yogatama and Fathani [8] and Fathani et al. [15] studies, which concluded that based on empirical analysis, the considered PGAs (0.3g to 0.4g) were capable of triggering liquefaction in Opak River Area.

Table 2. Design of Dynamic Loading

PGA (g)	Frequency (Hz)	Shaking Duration (Seconds)
0.30	1.4	8
0.30	1.6	8
0.30	1.8	8
0.35	1.4	8
0.35	1.6	8
0.35	1.8	8
0.40	1.4	8
0.40	1.6	8
0.40	1.8	8

The Initial Time of Liquefaction

The initial time of liquefaction (build-up of lique-faction) is presented in Figure 5. In general, the increase of vibration frequency and PGA results in the shorter initial time of liquefaction and vice versa. As previously mentioned, both vibration frequency and PGA are possible to influence the liquefaction potential. This can be seen by the smallest dynamic load performed in this study (i.e., PGA of 0.3g and *f* of 1.4 Hz), which is able to trigger liquefaction within 7 seconds. Referring to this result, it can be predicted that the other lower dynamic loads may not have potential to trigger liquefaction within 8 seconds shaking duration. However, this prediction still needs to be further investigated by other experi-mental study.
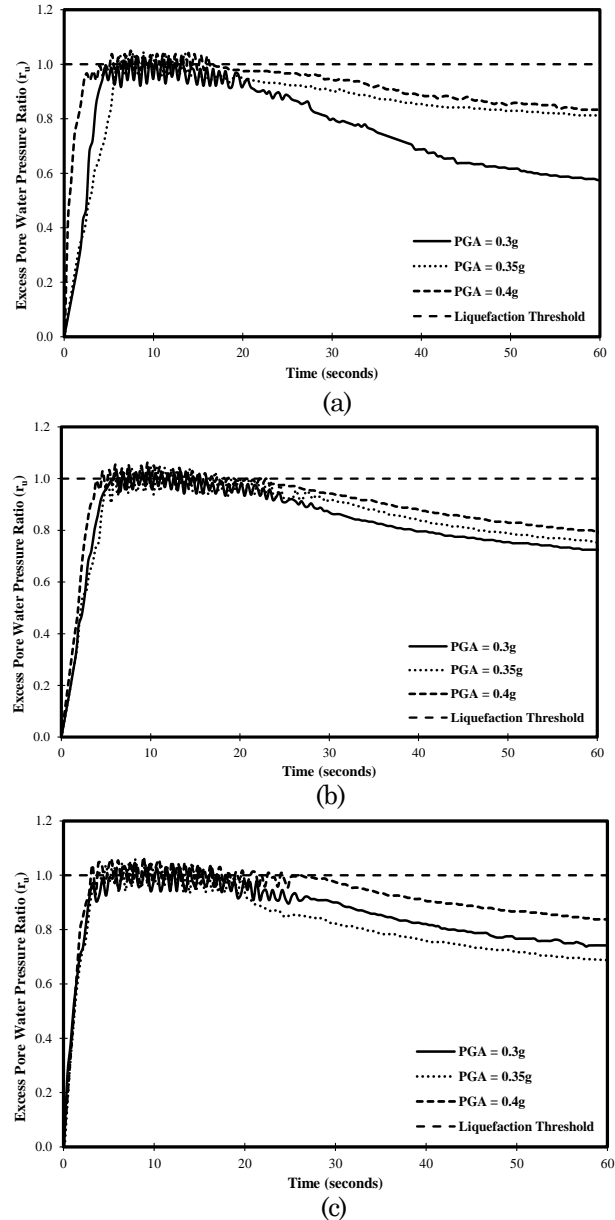

(a)

(b)

(c)

Figure 4. Interpretation of Excess Pore Water Pressure (a) 1.4 Hz, (b) 1.6 Hz, and (c) 1.8 Hz
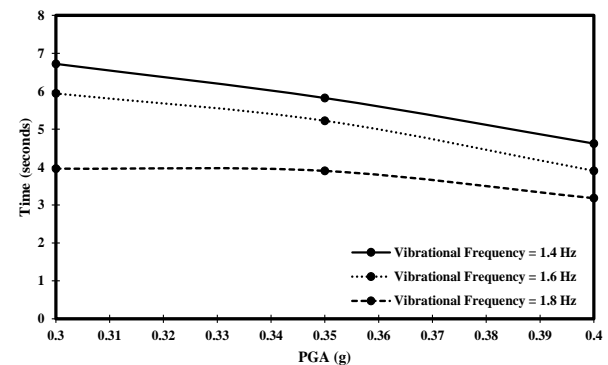

Figure 5. Starting Time to Liquefy (a) 1.4 Hz, (b) 1.6 Hz, and (c) 1.8 Hz

The Initial Time of Pore Water Pressure Dissipation

The initial time of pore water pressure dissipation is presented in Figure 6. Generally, the increase of dynamic load may result in the longer initial time of pore water pressure dissipation. On the contrary, the decrease of dynamic load tends to result in the shorter initial time of pore water pressure dissipation. Those results seem to be influenced by the harmonic motion due to free vibration, which still contributes to maintain excess pore water pressure. After the loading stopped, the remained energy of vibration (free vibration effect) is still able to generate a small amount of excess pore water pressure and maintain it at the threshold of liquefaction ($r_u \geq 1$). This effect maintains liquefaction up to 5 seconds. However, when the remained energy decreases or there is no more contribution of free vibration, pore water pressure starts to dissipate and liquefaction stops.

The Duration of Liquefaction

The duration of liquefaction is stated as the differrence between the initial time of liquefaction and the initial time of pore pressure dissipation. The liquefaction duration corresponding to vibration frequency is shown in Figure 7. Generally, the liquefaction duration tends to increase when the applied dynamic load increases. As elaborated in two previous sections, both initial time of liquefaction and initial time of pore pressure dissipation strongly depend on the applied dynamic load. In Figure 7, due to the larger dynamic load (the higher PGA and vibration frequency), the required time to generate liquefaction is shorter and the required time to dissipate pore water pressure is longer. A shorter initial time of liquefaction and a longer initial time of dissipation mean a longer duration of liquefaction.
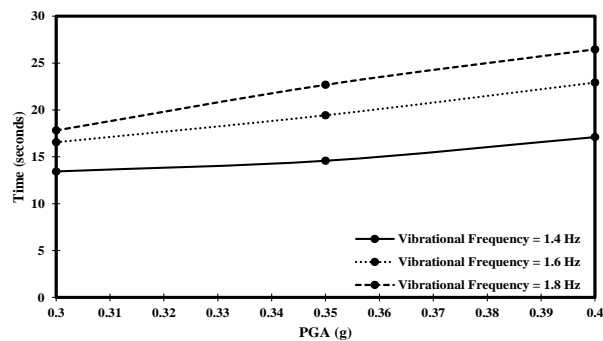

Figure 6. Dissipation Time (a) 1.4 Hz, (b) 1.6 Hz, and (c) 1.8 Hz

The Maximum Excess Pore Water Pressure Ratio ($r_u$max)

Figure 8 shows the maximum excess pore water pressure ratio due to the short shaking duration. Like the other investigated time stages in the pre-

vious sections, the applied dynamic loads influence $r_u$max. The increase of $r_u$max results in the larger maximum excess pore water pressure ratio. In Figure 8, the generated $r_u$max of 1.067 is resulted by applying the maximum dynamic load (i.e. PGA of 0.4g and vibration frequency of 1.8 Hz), whereas the minimum load (i.e. PGA of 0.3g and vibration frequency of 1.4 Hz) can produce r_u max of 1.027. In general, there is no significance difference between maximum and minimum excess pore water pressure ratios resulted from tests. The maximum load may generate more excess pore water pressure rather than the minimum load. The more excess pore water pressure decreases the effective stress of soil and certainly results in the larger excess pore pressure ratio. Overall, the $r_u$max happens in the range of shaking duration, not in the free vibration duration. During shaking, the excess pore water pressure significantly builds up to reach the liquefaction threshold. Furthermore, once the main shaking (8 seconds duration) is stopped, the remained energy resulted from free vibration keeps pore water pressure ratio to concentrate on the threshold condition. However, the free vibration seems not significantly in producing more pore pressure compared to the main shaking. Once the excitation (including free vibration) is totally stopped, pore water pressure slowly dissipates and passes liquefaction threshold. At this stage, the excess pore water pressure ratio decreases.
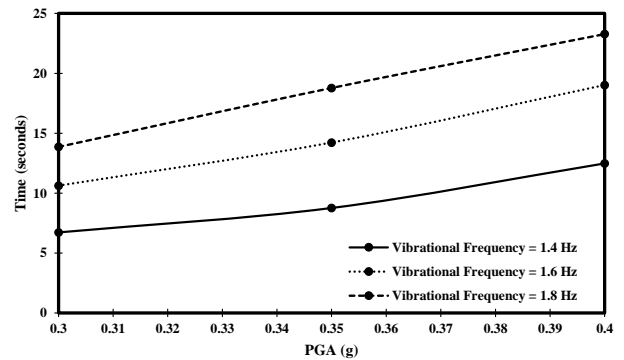

Figure 7. The Liquefaction Duration (a) 1.4 Hz, (b) 1.6 Hz, and (c) 1.8 Hz
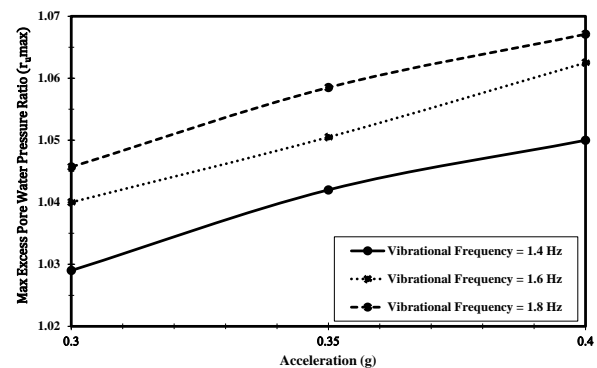

Figure 8. Maximum Excess Pore Water Pressure Ratio (r_u max) (a) 1.4 Hz, (b) 1.6 Hz, and (c) 1.8 Hz.

Concluding Remarks

The main points that can be concluded in this study are as follows:

1. The maximum excess pore water pressure is the main factor in studying liquefaction. In this study, the maximum excess pore water pressure ratio resulted on each test is larger than one, which means all dynamic loads applied trigger the soil liquefaction. The results also consistent with the previous studies conducted by Yogatama and Fathani [8], Fathani et al. [15] and Mase et al. [5] showing that the considered PGAs of 0.3g, 0.35g, and 0.4g, potentially triggered soil liquefaction in Southern Opak River riverbank.

2. Soil condition, soil type, and the dynamic loads may influence the liquefaction potential during a short shaking duration. The applied dynamic loads can influence the initial time of liquefaction, the initial time of pore water pressure dissipation, and the liquefaction duration.

3. After loading is stopped, the free vibration (a remained movement of shaking table after the shaking table operation was stopped) may maintain the excess pore water pressure at threshold condition for a few seconds. This phenomenon generally happens for about 5 seconds and obviously influences the liquefaction duration and pore water pressure dissipation.

4. There is no significant difference of the r_u max on each test, which is generated by either the larger dynamic load or the smaller dynamic load. It means both maximum and minimum loads generate a similar amount of excess pore water pressure.

Acknowledgement

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