Effect of Loading Frequency on the Liquefaction Resistance of Poorly Graded Sand

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Abstract Cyclic simple shear tests were carried out to study the effect of frequency (f) on the poorly graded sand's liquefaction resistance. The samples are prepared in the medium state ($D_r = 60\%$) by the deposition method, and a wide range of f ($f = 0.03, 0.05, 0.1, 0.2,$ and 0.5 Hz) is considered. The results show that the liquefaction resistance is uninfluenced by low f (0.03 and 0.05 Hz). When the f is higher than the optimum frequency ($f_{opt} = 0.1$ Hz), the liquefaction resistance increases with increasing f.

Keywords Cyclic simple shear test · Liquefaction resistance · Loading frequency · Poorly graded sand

1 Introduction

It has been extensively studied how loading frequency (f) affects liquefaction resistance of sand; however, the issue is highly controversial. In several studies, liquefaction resistance of sandy soil was found to be small or unaffected by loading frequency. Peacock et al. [1] applied several cyclic simple shear tests (CSS) with the range from 1/6 to 4 Hz of f and noted that the frequency effects were small. The

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same conclusions have been reached by other studies [2, 3]. More recently, Zhu et al. [4] performed cyclic triaxial tests to highlight the effect of f on the sand liquefaction response. Medium dense and dense samples were subjected to a various f (in both stress-controlled mode and strain-controlled mode). It was found that the effect of the f was insignificant for dense sand in stress-controlled mode.

Moreover, numerous researchers [5, 6] reported that the sand exhibited a higher cyclic strength at the higher loading frequencies. A series of CSSs was conducted on Nakdong sand with a wide range of f (0.05–1 Hz) by Nong et al. [6] to examine the f effects on the cyclic strength. It showed that an increase in the f resulted in increasing liquefaction resistance, regardless of the vertical effective stress or relative density.

In contrast, other researchers [7, 8] found that varying the frequency resulted in a decrease in cyclic strength. Dash et al. [8] observed that cyclic liquefaction resistance decreased as f increased in range of 0.1–0.5 Hz, due to an increase in the excess pore water pressure.

Therefore, the relationship between the loading frequency and liquefaction resistance of sand remains unclear and requires more investigation. In this study, CSS tests on poorly graded medium density sand samples are conducted with various f (0.03, 0.05, 0.1, 0.2, and 0.5 Hz) to evaluate the influence of f on the liquefaction resistance of sand.

2 CDSS Tests

2.1 Material

The characteristic and particle size analysis of the silica sand are shown in Table 1 and Fig. 1, respectively. The specific gravity (G_S) is 2.60, the maximum void ratio (e_{max}) and minimum void ratio (e_{min}) are 1.02 and 0.63, respectively. Based on the Unified Soil Classification System, the sand is classified as poorly graded sand (SP).

2.2 Testing Condition and Sample Preparation

The CSS device used in this study is described in Fig. 2. The system includes a shear box, a lateral load cell, a vertical load cell, and a horizontal and vertical LVDT. In the CSS tests, typical cylindrical samples have initial diameter of 63.5 mm and height of 25 mm, respectively. The dry funnel deposition technique is used to prepare the sample in this study. All dry sand samples are conducted with a relative density of 60%, consolidated under the initial vertical effective stress (σ') of 100 kPa. The cyclic stress ratio (CSR) is defined as the ratio between the cyclic shear stress (τ_{cyc}) and the initial vertical effective stress (σ'). Upon the consolidation stage, the cyclic stage

Table 1 Physical properties of testing samples

Index property	Value
Specific gravity (G_S)	2.60
D_{10} (mm)	0.128
D_{30} (mm)	0.28
D_{50} (mm)	0.64
D_{60} (mm)	0.68
C_u	5.31
C_c	0.87
e_{max}	1.02
e_{min}	0.63
Unified soil classification system classification	SP

Fig. 1 Grain size distribution curve
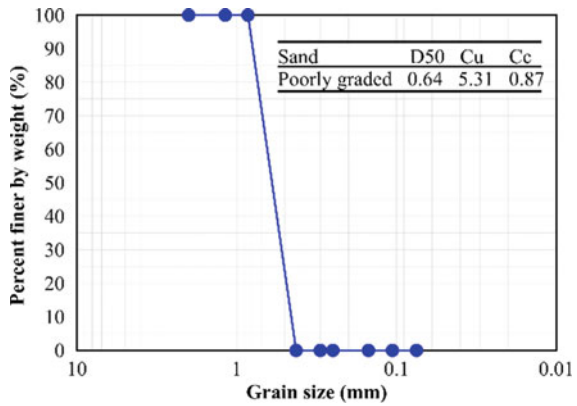
is conducted with CSR values (0.1, 0.12, 0.15, and 0.18), as well as f (0.03, 0.05, 0.1, 0.2, and 0.5 Hz).

3 Result and Discussion

3.1 Test Results

The details of CSS test results, including CSR, f and average number of cycles to liquefaction (N_{cyc}), are shown in Table 2. Figure 3 presents the typical result for the case CSR = 0.1 and f = 0.1 Hz. To determine the cyclic resistance of silica sand, at least three CSS distinct test cases with various CSRs are conducted for a given f.
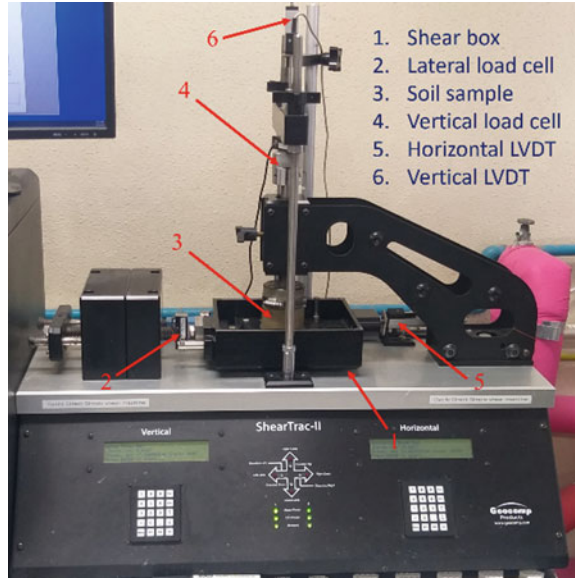
Fig. 2 CDSS device

1. Shear box
2. Lateral load cell
3. Soil sample
4. Vertical load cell
5. Horizontal LVDT
6. Vertical LVDT

Table 2 CDSS test results

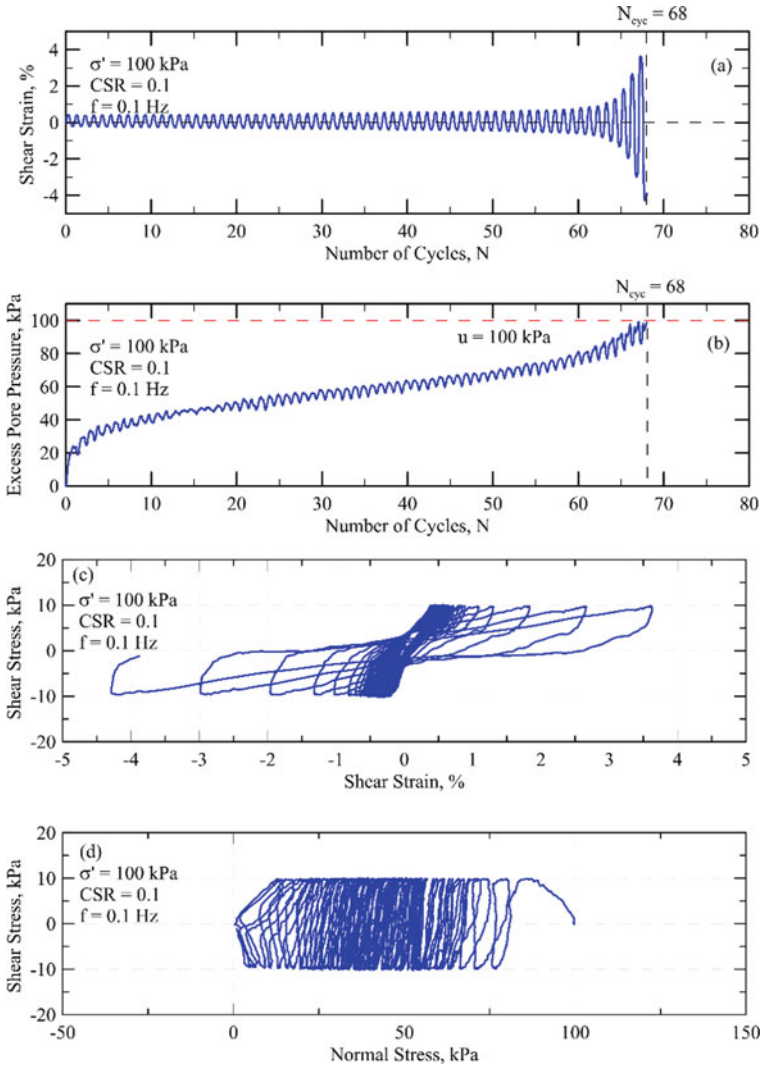| Dr (%)	σ' (kPa)	CSR	f (Hz)	N_{cyc}
60	100	0.1	0.03	69
			0.05	69
			0.1	69
			0.2	77
			0.5	111
		0.12	0.03	35
			0.05	35
			0.1	35
			0.2	53
			0.5	67
		0.15	0.03	11
			0.05	11
			0.1	11
			0.2	16
			0.5	18
		0.18	0.2	5
			0.5	6

Fig. 3 CDSS test results for the case $CSR = 0.1, f = 0.1$ Hz, **a** shear strain and N, **b** excess pore pressure and N, **c** shear stress versus shear strain, and **d** shear stress versus normal stress

3.2 Liquefaction Resistance of Poorly Graded Sand

Effect of f on cyclic behavior of poorly graded sand with various CSRs is shown in Fig. 4. The figure describes the undrained cyclic simple shear response of poorly graded silica sand with various f_s ($f = 0.03, 0.05, 0.1, 0.2$, and 0.5 Hz) at different CSRs ((a) CSR $= 0.1$, (b) CSR $= 0.12$, and (c) CSR $= 0.15$). The shear strain is accumulated continuously and nearly the same with low f ($f = 0.03, 0.05$, and

0.1 Hz). The double amplitude of the shear strain exceeds 7.5% at the same number of cycles ($N_{cyc} = 71$ with CSR $= 0.1$, $N_{cyc} = 31$ with CSR $= 0.12$, and $N_{cyc} = 15$ with CSR $= 0.15$). With higher f, the shear strain accumulation is different. When f increases from 0.1 to 0.5 Hz, the number of cycles to liquefaction increases from 71 to 111 with CSR $= 0.1$, from 31 to 69 with CSR $= 0.12$, and from 15 to 18 with CSR $= 0.15$.

Figure 5 shows the change of the excess pore pressure with N with different f when CSR changes between 0.1, 0.12, and 0.15.

The relationship between f and number of cycles to liquefaction is shown in Fig. 6. Accordingly, when the f increases, the number of cycles to liquefaction remains unchanged. However, after a certain optimum loading frequency (f_{opt}), the increasing in f increases the number of cycles to liquefaction. The f_{opt} is the one at
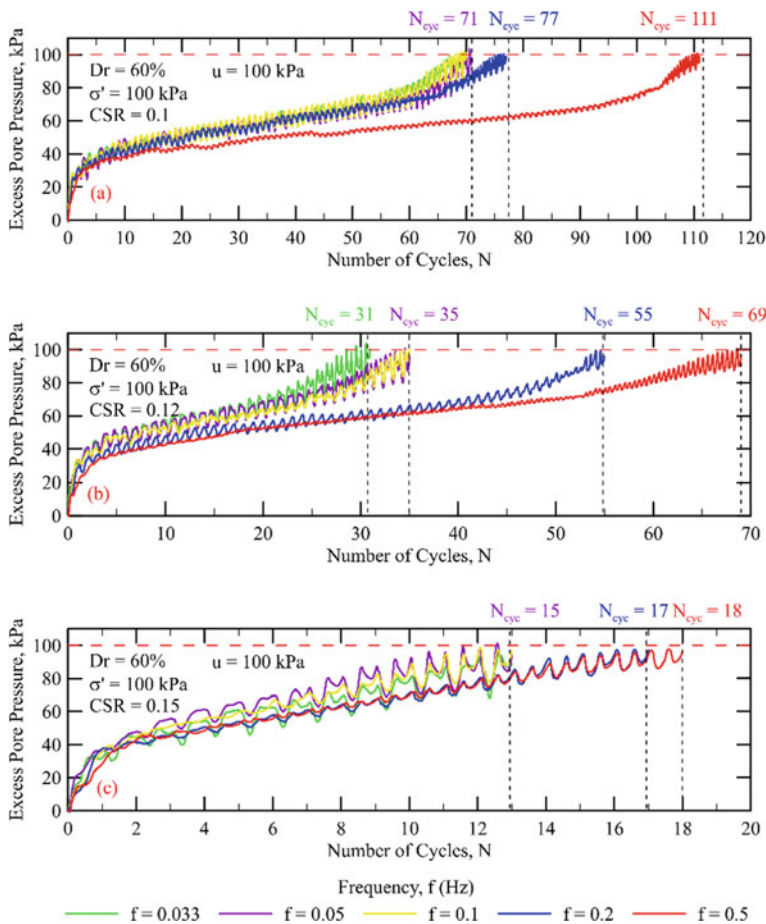

Fig. 4 Effect of f on the shear strain accumulation (medium sand and $\sigma' = 100$ kPa): **a** CSR $= 0.1$, **b** CSR $= 0.12$, and **c** CSR $= 0.15$
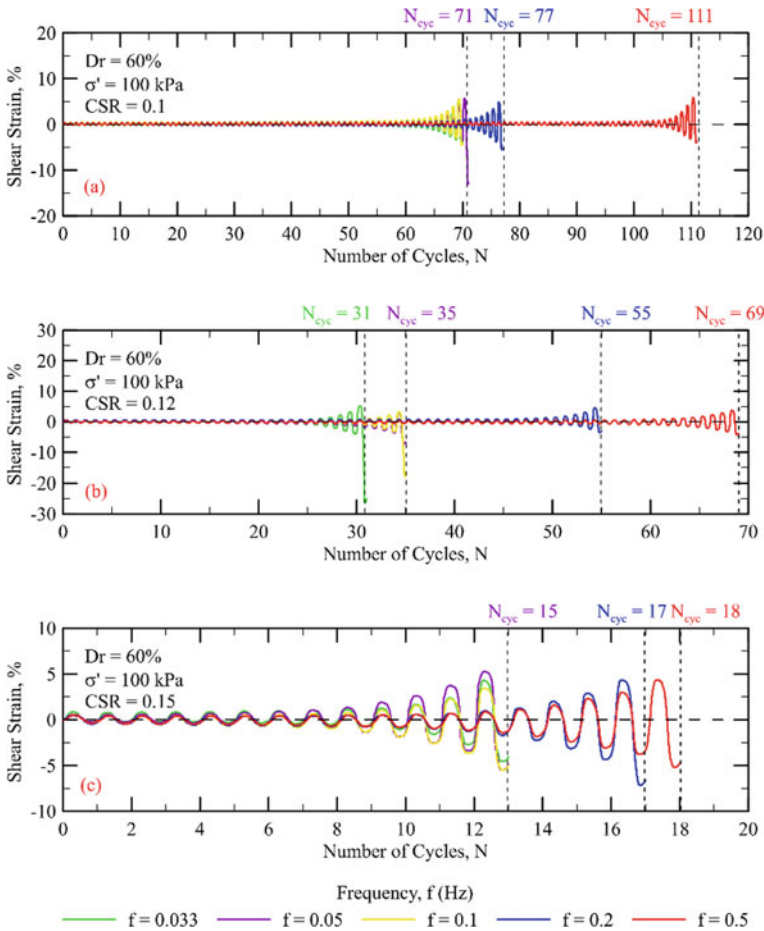
Fig. 5 Effect of f on the excess pore pressure accumulation (medium sand and $\sigma' = 100$ kPa): **a** CSR = 0.1, **b** CSR = 0.12, and **c** CSR = 0.15

which the liquefaction resistance remains unchanged with decreasing f and increases with increasing f. When f is less than 0.1 Hz, the number of cycles to liquefaction is not influenced by the f at a constant CSR ($N_{cyc} = 15$ at CSR = 0.15, $N_{cyc} = 35$ at CSR = 0.12, and $N_{cyc} = 71$ at CSR = 0.1). The increasing in f corresponds to the increasing trend of the liquefaction resistance. N_{cyc} increases from 71 to 111 at CSR = 0.1, from 31 to 69 at CSR = 0.12, and from 15 to 18 at CSR = 0.15 when f increases from 0.1 to 0.5 Hz. Moreover, the f_{opt} ($f_{opt} = 0.1$ Hz) is the same for three cases of CSRs. Therefore, it can be stated that the f_{opt} does not depend on the CSR.

Figure 7 shows the cyclic resistance curves of poorly graded sand for various f. The trend curves shown in Fig. 7 define the relationship between CSR and N_{cyc}. The liquefaction resistance of sand, expressed in terms of the cyclic resistance ratio (CRR), is defined as the cyclic stress ratio at 15 cycles based on the cyclic resistance

Fig. 6 Relationship between
f and number of cycles to
liquefaction
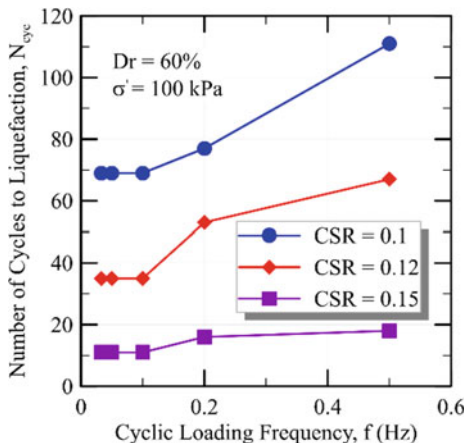
curves. In this study, the coefficients of determinations (R^2) are quite high, with
values of 0.972, 0.993, and 0.985, respectively, indicating that CSR and number of
cycles have a good relationship.

The change of CRR with *f* is shown in Fig. 8 for medium sand ($D_r = 60\%$) and
$\sigma' = 100$ kPa. CRR remains initially unchanged at low *f* (CRR = 0.1413 at $f \leq$
0.1 Hz). This finding is consistent with some previous research [1–3]. Besides that,
when *f* increases from 0.1 to 0.5 Hz, CRR increases from 0.1413 to 0.1532. This
phenomenon could result from a slippage or rearrangement of grain structure.

Fig. 7 Comparison of cyclic
resistance curve at medium
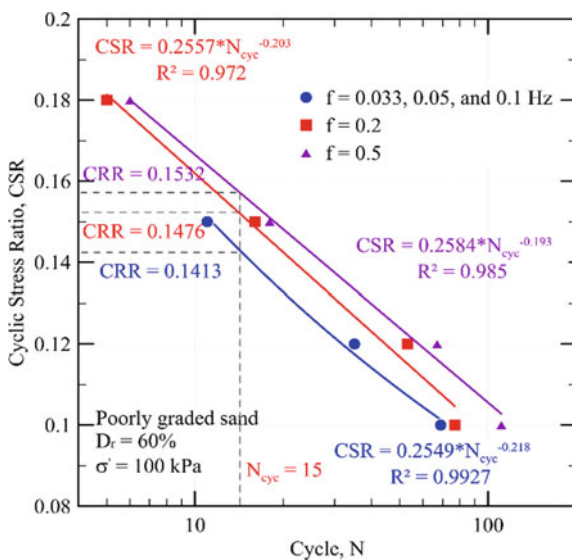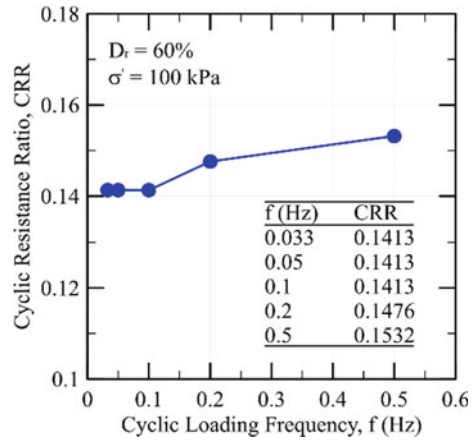density states for $\sigma' =$
100 kPa

Fig. 8 Effect of loading frequency on cyclic resistance

4 Conclusion

In this study, the influence of f on cyclic liquefaction resistance of poorly graded sand has been investigated. Numerous CSSs were conducted on silica sand with various f ($f = 0.03, 0.05, 0.1, 0.2,$ and 0.5 Hz). Based on the test results, the cyclic liquefaction resistance of sand was unchanged at low f ($f = 0.03$ and 0.05 Hz). In this study, the optimum loading frequency was about 0.1 Hz. When the loading frequency was greater than the optimum loading frequency, the increasing of loading frequency increased the liquefaction resistance of sand.

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