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EFFECT OF CYCLIC STRESS RATIO ON THE LIQUEFACTION RESISTANCE OF FINE SAND IN SOC TRANG, VIETNAM USING CYCLIC TRIAXIAL TEST

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ABSTRACT: In the literature, the effect of different factors on the liquefaction resistance of sand has been widely investigated using the cyclic simple shear test or cyclic triaxial test. In which, the effect of CSR on liquefaction resistance significantly depends on the type of sand. In Vietnam, the sandy soils are widely distributed in coastal areas where many wind power farms are built and planned to build. Thus, the liquefaction resistance of sandy soil in these areas should be evaluated. In this study, the effect of cyclic stress ratio (CSR) on the liquefaction resistance of sand distributed in the coastal area of Soc Trang province, Vietnam will be evaluated for the first time using cyclic triaxial apparatus (Wykeham Farrance). The sand samples were prepared using the dry pluviation method with a relative density of about 56%. The stress-controlled method with CSR from approximately 0.1 to 0.35, the effective confining stress of 50 kPa, and the frequency of 1 Hz were applied. The research results showed that the axial strain and build-up of pore water pressure significantly depended on the range of CSR. In particular, this research has indicated the threshold of CSR for the liquefaction of sandy soil in this study area. Accordingly, under the testing conditions, sand samples were not liquefied with a CSR of less than 0.25.

Keywords: Cyclic stress ratio, Liquefaction resistance, Cyclic triaxial test, Axial strain, Pore water pressure ratio.

1. INTRODUCTION

Soil liquefaction is a common geohazard that develops excess pore water pressure and a loss of shear strength in saturated sandy soil. It is well known that earthquake is one of the main causes of soil liquefaction. Besides, liquefaction can occur under some other dynamic loading sources such as wind turbine operation, sea waves, traffic, and machine foundations. So far, this phenomenon has caused serious damage to slopes, foundations, and structures in many places in the world [1]. The phenomenon of soil liquefaction has been widely investigated by different researchers, especially after the 1964 Niigata and Alaska earthquakes. In general, soil liquefaction resistance is affected by factors, such as soil type, fine content, grain characteristics, degree of saturation, relative density (void ratio), confining stress, cyclic loading frequency, and earthquake magnitude [2–14]. Recently, the soil liquefaction and the interaction between soil skeletion and pore fluid have been evaluated by using numerical modelling [15–20]. The liquefaction resistance is often accessed in terms of the cyclic stress ratio (CSR), which is the ratio of cyclic shear stress (τ_c) to the effective consolidation pressure (σ'_c). In laboratory testing, the cyclic stress ratio is calculated as the ratio of average cyclic deviator stress ($\Delta\sigma_a/2$) to the consolidation pressure (σ'_{3c}=cell pressure – back pressure). The effect of consolidation pressure and CSR on the liquefaction resistance (liquefied number of cycles) has been mentioned in different investigations. Typically, Rangaswamy et al. [6] indicated that the effect of consolidation pressure on the liquefaction resistance depended on the void ratio and type of soil. For example, for sandy soil, the consolidation pressure from 50 kPa to 100 kPa has no significant effect on the liquefaction resistance of dense sandy soils (void ratio, e= 0.908; 0.850). However, at a lower void ratio (e≤0.794), the liquefaction resistance decreases as the consolidation pressure increases from 50 kPa to 200 kPa. For loose sand, the consolidation pressure of less than 100 kPa does not significantly affect the liquefaction resistance. For silty sand with 30 and 50% fine content, the consolidation pressure of 100 kPa and 200 kPa does not significantly influence the liquefaction resistance of the sample with the same void ratio. These authors also showed that the consolidation pressure affected the build-up of pore pressure and the development of axial strain responses with the number of cycles. Accordingly, the number of cycles to liquefaction increases as the CSR decreases. This tendency is also observed in previous studies [3, 4, 7, 21]. Regarding the effect of effective consolidation pressure, Wijewickreme et al. [8] investigated the liquefaction resistance of tailing samples and revealed that the liquefaction resistance of laterite tailing samples tended to increase as the confining stress increased from 100 to 200 kPa. These authors also suggested that this phenomenon was attributed to the dilative behavior arising due to stress densification and larger than the contractive tendency due to the increase in confining stress. In general, previous studies showed that the effect of confining stress on liquefaction resistance depended on the range of stresses, relative density, and type of soil.

2. RESEARCH SIGNIFICANCE

The coastal area of Soc Trang province, Vietnam, is planned to build many wind power projects. In this area, sandy soils are widely distributed, with a thickness from a few meters to more than 10 meters. These sand layers can be used as a bearing layer for the foundation of wind turbines. However, the sand in this area is fine with loose to medium density which is prone to liquefy. Therefore, the investigation of the liquefaction resistance of sandy soil distributed in this area is very important. In Vietnam, the soil liquefaction potential has received attention in recent years. However, most of the investigations in Vietnam evaluated the liquefaction potential for soil based on the results of the Standard Penetration Test (SPT) [22] or for soil distributed in big cities [23], [24]. Recently, Phong et al. [25] investigated the liquefaction of sand in the coastal area of Soc Trang province distributed from about 6m to more than 43m with a loose and dense density. The research was conducted using the cyclic triaxial test with the confining stress from 50 to 300 kPa and a frequency of 1 Hz. The research results of Phong et al. [25] showed that the loose sand at the depth of less than or equal to 15m was liquefied while the dense sand at the depth of more than 30m was not liquefied under testing conditions. However, Phong et al. [25] mainly focused on the relationship between the depth and the liquefaction resistance of loose and dense state sand. Besides, the liquefaction resistance of medium-density sand located near the surface ground has not been mentioned in Phong et al. [25]. In this study, the liquefaction resistance of sand near the surface ground distributed in Soc Trang coastal's area will be further investigated using the cyclic triaxial test. Accordingly, the sand from dunes with medium density distributed in the study area was taken for testing in the laboratory. The effect of CSR on the liquefaction resistance of sand will be investigated for the first time in Vietnam. Different average cyclic deviator stresses were applied in the cyclic triaxial test using the stress-controlled method. As mentioned above, the relationship between CSR and the number of cycles to liquefaction for different types of soil has been presented in various studies. However, the threshold of CSR for the liquefaction potential of sand has not been reported. In this study, the wide range of CSR from 0.097 to 0.35 will be used to evaluate the liquefaction resistance and to determine the CSR threshold for liquefaction. Besides, to simulate the distribution of sand near the surface, the effective confining stress of 50 kPa was applied, which equals to the depth of about 3m.

3. MATERIALS AND TEST PROCEDURE

3.1 Materials

Sand samples were taken from dunes in the coastal area of Vinh Chau town, Soc Trang province, Vietnam (Fig. 1). This is a key planning area for wind power development. According to the geological and mineral map of Vietnam, the dunes in this area are all marine sediments distributed to a depth of 5-10m. The grain size distribution graph of the sand sample is plotted in Fig. 2. Some physical properties are listed in Table 1. According to standard ASTM D 2487-00 [26], the sand sample is classified as poorly graded sand.

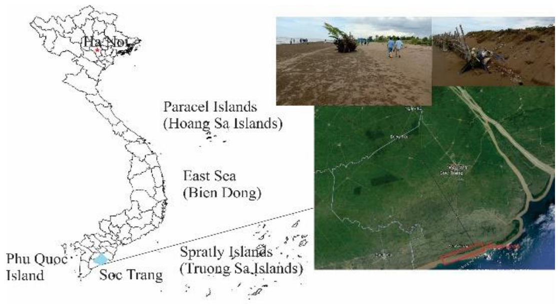

Fig. 1 The study area

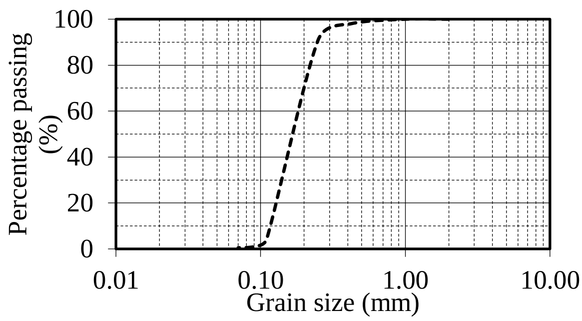

Fig. 2 Grain size of sand sample

Table 1. Some physical properties of sand sample

Grain size			Specific density (g/cm^3)	Max void ratio	Min void ratio
D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	γ_s	e_{max}	e_{min}
0.189	0.148	0.115	2.65	1.002	0.683

3.2. Test Procedure

a. Sample preparation

In cyclic triaxial tests, the sand samples can be prepared using four methods: dry and wet pluviations, dry and moist tamping [27, 28]. The methods of dry and wet pluviations, and dry tamping can produce specimens with a low density (high void ratio) [28]. Besides, the dry pluviation method will create the remolded sample with high homogeneity. In this study, the desired relative density of the sand sample is about 0.5-0.6 (50-60%). Thus, this study employed the dry funnel pluviation method using a split mold (Fig. 3a) for sample preparation which has been presented by Phong et al. [25] and Della et al. [29]. In this method, the desired density of remolded sample is controlled by the weight of dry sand pouring into the mold. The weight of dry sand is estimated based on the following formula:

$$\boldsymbol{W_s = \frac{\gamma_s}{(1+e)}.V} \qquad (1)$$

where, W_s is the weight of dry sand (g); γ_s is specific density (g/cm^3);

V is the volume of sample (equal to the volume of the mold) (cm^3); e is the void ratio of sample,

$$\boldsymbol{e = e_{max} - D_{r0}(e_{max} - e_{min})}; \ (2)$$

e_{max} is the maximum void ratio; e_{min} is the minimum void ratio; D_{r0} is the desired density.

The sample after preparation has a diameter of about 70mm and a height of 140mm (Fig. 3b). The details of remolded sand samples after preparation are shown in Table 2. As shown in Table 2, all the remolded samples are medium dense with the density D_{r0} from 0.53 to 0.59 (0.56±0.017).

Table 2. Sand sample after preparation

No.	Dry density (g/cm^3)	Intial void ratio	Intial relative density
	γ_c	e_0	D_{r0}
STs_1	1.453	0.824	0.56
STs_2	1.462	0.815	0.59
STs_3	1.454	0.823	0.56
STs_4	1.454	0.822	0.56
STs_5	1.449	0.829	0.54
STs_6	1.453	0.824	0.56
STs_7	1.443	0.834	0.53
STs_8	1.453	0.824	0.56
STs_9	1.449	0.829	0.54

b. Test procedure

In this study, the cyclic triaxial apparatus Tritech 50KN is employed (Fig. 3c). The test procedure (saturation, consolidation, and cyclic loading stages) is conducted following the standard ASTM-D5311 [30].

Fig. 3 a) Split mold for sample preparation; b) Sample after preparation; c) Triaxial apparatus

**Saturation and consolidation stage*

In the saturation stage, the back and cell pressures are increased together with a difference of about 10 to 20 kPa ($\sigma_r = \sigma_{cell} - \sigma_{back}$=10 to 20 kPa). The de-aired water was used for the saturation stage. The saturation process is completed until the saturation degree (B) is higher or equal to 0.95 [30]. The B-value is the ratio of a change in pore water pressure (Δu) to a change in cell pressure ($\Delta\sigma_c$) in an undrained condition ($B=\Delta u/\Delta\sigma_c$). In this study, the full saturation of sample was obtained under a back pressure of about 70 to 80 kPa and a cell pressure from 90 to 100 kPa (Table 3). In Table 3, the density of the sample after consolidation was calculated based on the change of water volume.

Table 3. Saturation and consolidation stages

Test No.	Saturation		Cosoli-dation	After consolidation	
	σ_{cell} (kPa)	σ_{back} (kPa)	σ'_c (kPa)	Volume change, ml	Den-sity, D_r
STs_1	100	80	50.0	0.60	0.56
STs_2	90	70	50.2	0.86	0.58
STs_3	90	70	50.1	0.34	0.56
STs_4	90	70	49.8	0.45	0.56
STs_5	90	70	50.0	3.77	0.53
STs_6	90	70	50.1	1.16	0.55
STs_7	90	70	49.9	4.19	0.51
STs_8	90	70	49.9	0.33	0.56
STs_9	90	70	50.1	3.66	0.53

In the consolidation stage, the back pressure is kept constant while the cell pressure is increased to reach the desired effective consolidation pressure (σ'_c) of 50 kPa. During saturation and consolidation processes, the changes in pressure, strain, and volume of the sample are automatically recorded.

The parameters in the saturation and consolidation stages are listed in Table 3. All the samples are consolidated under the effective confining stress (σ'_c) of about 50 kPa. After the consolidation stage, the density of sample is re-calculated based on the change of the volume sample. As presented in Table 3, the density of sample after consolidation is almost similar to the initial density and ranges from 0.51 to 0.58 (0.55±0.021).

*Cyclic loading

For research and design of wind turbines, the frequency is often ranged from 0.4 to 1.0 Hz [31]. In this study, the frequency f=1.0 Hz is applied. To investigate the effect of CSR on liquefaction resistance, the stress-controlled procedure is used in the cyclic triaxial test. The cyclic deviator stress is determined based on the desired CSR value as the formula: $\boldsymbol{\Delta\sigma_a = CSR.2}\sigma_c'$. The CSR values are chosen based on the CRR values (Cyclic Resistance Ratio) from the chart of Seed and De Alba [32]. The studied sand sample has a fine content, FC<1% and the initial density, D_{r0} = 0.56 ($N_{1(60)} \approx 20$), so the estimated CRR is approximately 0.20. This study chose CSR_{min} = 0.5CRR and CSR_{max} = 1.5CRR. Therefore, the range of CSR is from 0.10 to 0.35.

4. TEST RESULTS AND DISCUSSION

In this study, nine sand samples with an initial density of 0.56±0.017 were tested in cyclic triaxial apparatus under different CSR values from 0.097 to 0.350. The test results are presented in Table 4. Data in Table 4 show that the sand samples STs_1, STs_2, STs_3, STs_4, and STs_9 are not liquefied whereas the sand samples STs_5, STs_6, STs_7, and STs_8 are liquefied at the different number of cycles under the testing conditions. As shown in Figs. 4, 5, 6, and 7, the build-up of pore water pressure ratio (R_u) and the stress-strain behavior siginificantly depends on the CSR values. At CSR <0.140 (for STs_1, STs_2 samples), the value of Ru insignificantly increases (a few percent) (Fig. 4); the stress-strain loop is small and balanced (Fig. 6); the amplitude strain $\Delta\varepsilon_a$ is also small and less than 0.1% (Fig. 7). At CSR=0.183 to 0.245 (for STs_3, STs_4, STs_9 samples), the value of Ru considerably increases with the maximum of R_u ranging from 17.3 to 53.0%; the stress-strain loop is rather large and unbalanced; the amplitude strain $\Delta\varepsilon_a$ is from 0.114 to 0.513 %. When CSR is higher than 0.25 (for STs_5, STs_6, STs_7, STs_8 sand samples), these samples are liquefied with R_u reaching 100% at different numbers of cycles (Fig. 4); the stress-strain loop is large and unbalanced; the axial strain $\Delta\varepsilon_a$ is from 1.039 to 3.107 % (Figs. 6, 7).

Table 4. Results of cyclic triaxial test

Test No.	Stress Amplitude $\Delta\sigma_a$ (kPa)	Max. of Strain Amplitude $\Delta\varepsilon_a$ (%)	CSR	Max. of Axial Strain $\varepsilon_{a(max)}$ (%)	Max. of R_u, $R_{u(max)}$ (%)	Liquefied number of cycles, N
STs_1	9.7	0.042	0.097	-0.074	4.4	NA
STs_2	14.0	0.056	0.139	0.069	5.6	NA
STs_3	18.3	0.114	0.183	-0.130	17.8	NA
STs_4	22.9	0.150	0.230	-0.254	21.3	NA
STs_5	25.0	1.039	0.250	-2.473	100.0	225
STs_6	25.5	1.084	0.254	-2.244	100.0	46
STs_7	28.1	1.859	0.282	-4.266	100.0	20
STs_8	34.9	3.107	0.350	-6.754	100.0	6
STs_9	24.5	0.513	0.245	-0.847	53.0	NA

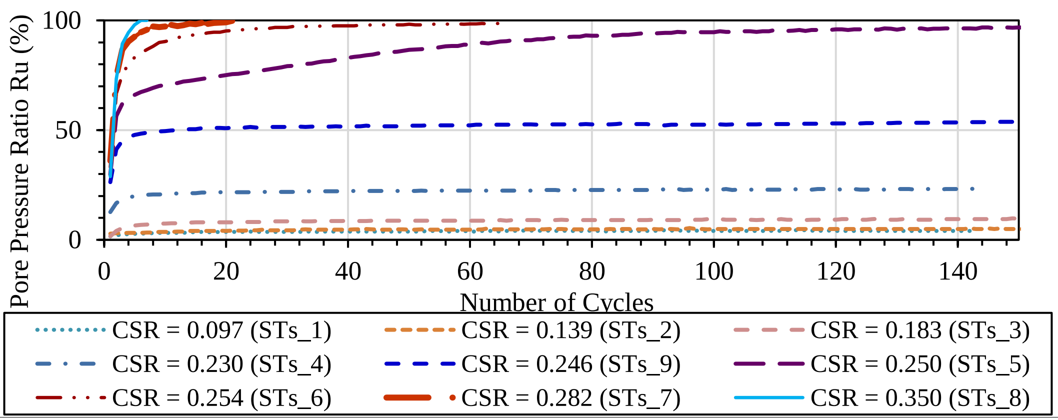

Fig. 4 Changes of R_u with different CSR values

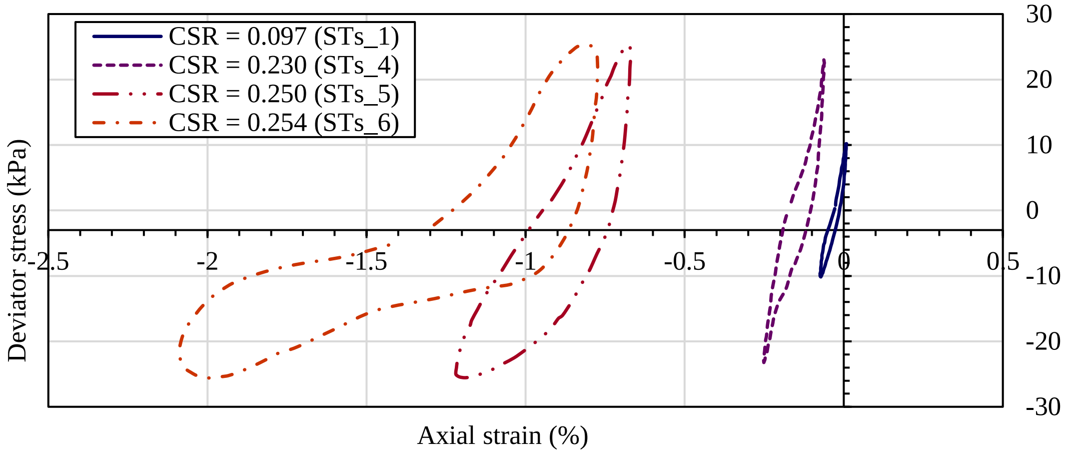

Fig. 5 Stress-strain response at cycle of 40 with different CSR values

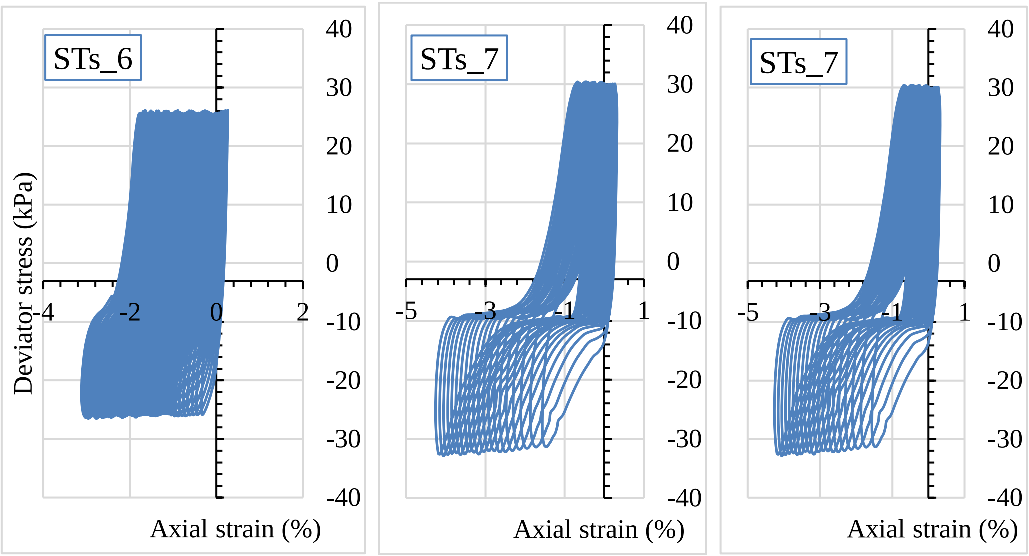

Fig. 6 Stress-strain for STs_6, STs_7, and STs_8

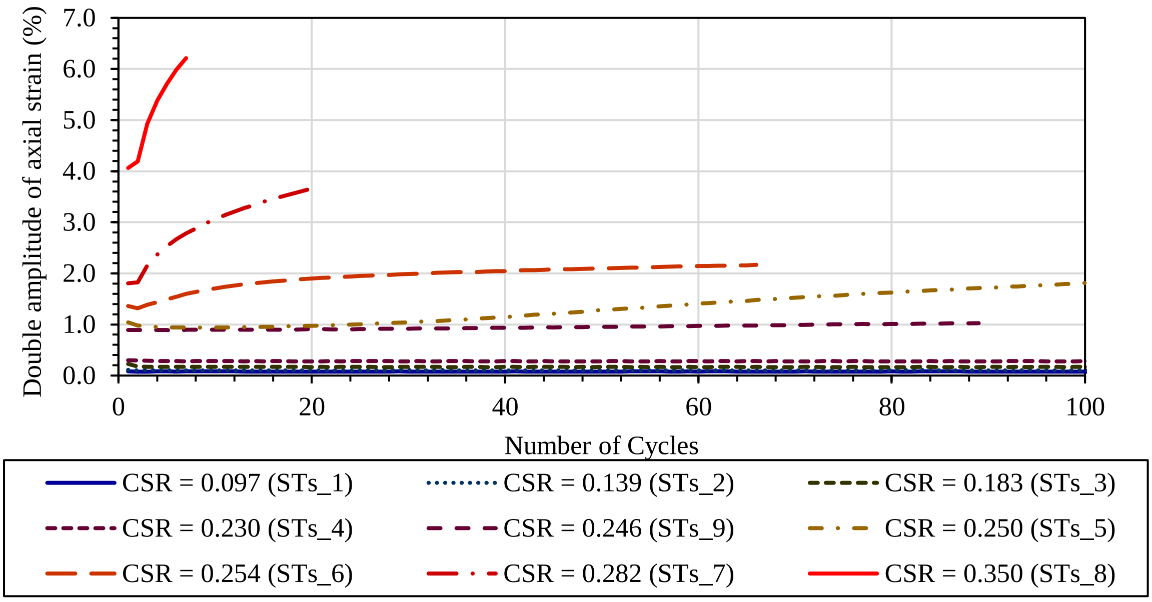

Fig. 7 Axial strain at different CSR values

The relationship between CSR and the number of cycles to liquefaction is plotted in Fig. 8. As shown in this figure, the number of cycles to liquefaction increases as the CSR decreases. Especially, when the CSR decreases from 0.254 to 0.250, the number of cycles increases from 46 to 250. The value of CSR of 0.250 is considered the threshold value of CSR causing liquefaction of studied sand. It is known that the operation of wind turbines will generate dynamic load acting on the soil ground for a long time while the earthquake motion generates dynamic load in a short time from a few seconds to about 30-40 seconds [33, 34]. In Table 4 and Fig. 8, it can be seen that when the CSR is higher or equal to 0.254, the number of cycles causing liquefaction is from 6 to 46 cycles. With the frequency, *f*=1 Hz, this value of cycles corresponds to the duration of earthquake seismic loading. Thus, the earthquake generating CSR of less than 0.254 may not cause the liquefaction of sandy soil in this area. However, if the dynamic load with CSR of 0.250 but acts on soil for a long time, the liquefaction of this sandy soil can occur. The tendency of increasing cycles to liquefaction with the decreasing of CSR is also observed in different previous studies [2–4, 6, 7, 21, 35] as shown in Fig. 9.

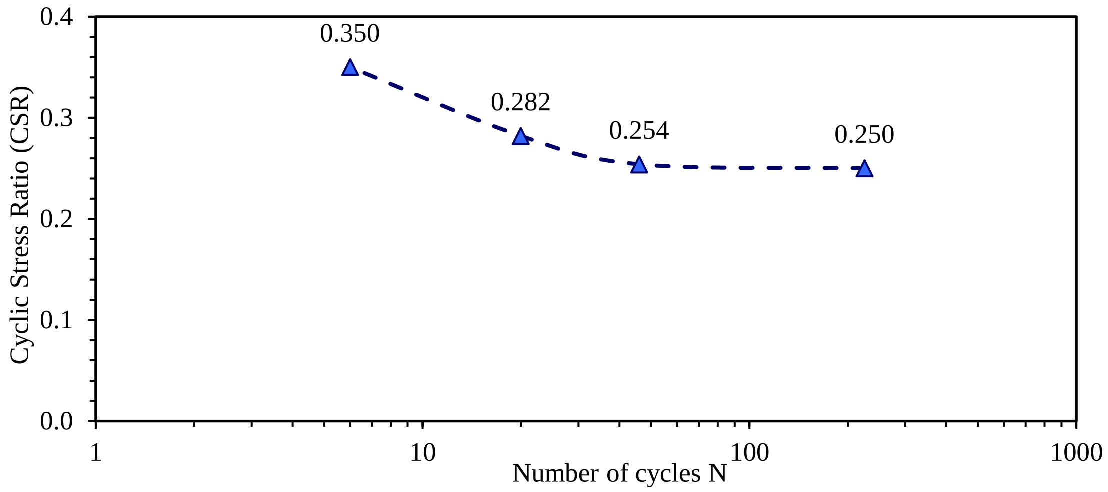

Fig. 8 Number of cycles vs. different CSR values

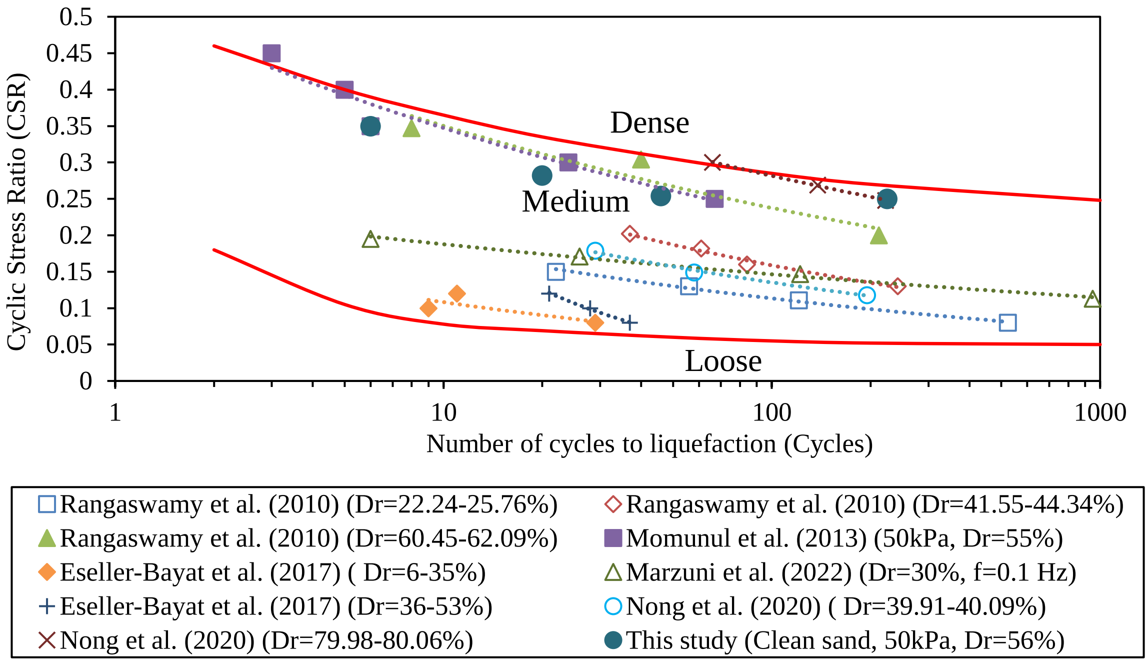

Fig. 9 Relationship between CSR and number of cycles to liquefaction

This figure shows the relationship between CSR and the number of cycles to liquefaction for sand samples with a density from 6% to 80.06% (from loose to dense density) which is collected from previous studies. It can be seen that the effect of CSR on the liquefaction resistance of sand significantly depends on the relative density. Based on collected data, the upper and lower boundaries for the effect of CSR on the liquefaction resistance of sand have been proposed as presented in Fig. 9. In particular, the value of CSR less than 0.05 may not cause sand liquefaction.

5. CONCLUSIONS

Based on the stress-controlled cyclic triaxial test conducted on reconstituted specimens of fine sand distributed in the coastal area of Soc Trang province, some conclusions are drawn as follows:

The liquefaction resistance, axial strain, and pore pressure build-up significantly depend on the CSR values. With CSR <0.140, the pore pressure ratio $R_{umax} \leq$ 5,6%, axial strain $\Delta\varepsilon_a$ < 0.1%. With CSR = 0.183 to 0.245, $R_{u(max)}$ = 17.3 to 53.0% and $\Delta\varepsilon_a$ = 0.114 to 0.513%. When the CSR ≥0.250, the $R_{u(max)}$ sharply increases and reaches 100%.

Based on the $R_{u(max)}$, liquefaction occurs when the CSR is higher or equal to 0.250. When the CSR is lower than 0.250, the sand is not liquefied. The value of CSR of 0.250 is considered the threshold of liquefaction occurrence. With a CSR above 0.250, the number of cycles to liquefaction tends to increase as the CSR value increases. In combination with data from previous studies, it is revealed that the relative density considerably affects the relationship between the CSR values and the number of cycles to the liquefaction of sand.

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