

# A study on liquefaction strength of sandy soils containing different sizes of coarse and fine fraction

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**ABSTRACT:** Liquefaction damage for civil engineering structures on sand containing fine particles has been reported after significant earthquakes, and research has been conducted on this issue. However, when expecting the liquefaction of sandy soils, only the plasticity index has been considered, and there has been little research on the particle size and other properties of coarse and fine particles. The author's research aims to clarify the relationship between fine fraction content, which represents the skeletal structure of soil, and liquefaction strength. In the previous papers, we reported on the behavior of using Toyoura sand ( $D_{50}=0.16\text{mm}$ ) as the coarse grain fraction and some kinds of fine grain (silt and clay) using the fine fraction void ratio as a parameter. We could find good relations between the fine fraction void ratio and liquefaction strength. In this paper, we added Tohoku silica sand ( $D_{50}=0.67\text{mm}$ ), which has larger coarse grains than Toyoura sand. As a result of some experiments, we found it impossible to compare soils with different maximum and minimum void ratios for unity estimation. This study showed that it is important to change the index that expresses the state of sand depending on the grain size and fine fraction content of the sand. It also became clear that for the sand used in this study, the skeleton void ratio and skeleton relative density have a good relationship with the liquefaction strength. A good correlation was obtained with data published by other researchers.

**KEYWORDS:** Liquefaction Strength, Laboratory test, Sandy soil, Fine fraction, Skeleton.

## 1 INTRODUCTION

Notable examples of civil engineering structures that suffered significant damage due to liquefaction include the 1964 Niigata earthquake and the 1983 Sea of Japan earthquake. However, the liquefaction caused by these earthquakes occurred in clean sandy soil with uniform grain size (Mori et al., 1991). However, in the 1987 Chiba Prefecture Offshore Earthquake, the 1989 Loma Prieta Earthquake, the 1995 Southern Hyogo Prefecture Earthquake, the 2000 Western Tottori Prefecture Earthquake, the 2011 Tohoku Area Pacific Offshore Earthquake, it became clear that landfill sites containing a large amount of fine fractions, which were previously thought to be resistant to liquefaction, were liquefied, and cases of significant damage were reported. (Yasuda et al., 2011)

Against this background, numerous studies have been conducted to elucidate the liquefaction mechanism of soils containing fine fractions such as silt and clay, as well as their effects on liquefaction strength. In previous studies, the research conducted by Koseki et al. (1986) showed that the higher the plasticity index, the greater the liquefaction strength, and in low-plasticity specimens, the liquefaction strength decreased as the amount of fine fractions increased. Since then, the plasticity index has come to be used to determine the liquefaction of sandy soils containing fine fractions. Hyodo et al. (2015) also showed that in areas where coarse-grained soil forms a structure, there is a good correlation between the equivalent skeleton void ratio and the cyclic shear strength when a contribution factor is applied.

However, it is difficult to say that a unified opinion has been reached on the liquefaction strength of sandy soils containing fine fractions, and the authors are conducting a series of studies with the aim of providing a unified explanation (Liu et al., 2021, Ishii et al., 2022, 2023).

## 2 EXPERIMENTAL OVERVIEW

### 2.1 Soil samples

The samples that were used are shown in Tables 1 and 2, with two types of soil: Toyoura sand ( $D_{50} = 0.16 \text{ mm}$ ) for coarse-

grained soil and the larger-grained Tohoku silica sand No. 4 ( $D_{50} = 0.67 \text{ mm}$ ). To examine the effects based on differences in plasticity index, three types of fine-grained soil were used: Kaolin clay ( $D_{50} = 0.0030 \text{ mm}$ ), Fujinomori silt ( $D_{50} = 0.0070 \text{ mm}$ ), and Kasaoka clay ( $D_{50} = 0.0027 \text{ mm}$ ). The mean grain size  $D_{50}$  of Kaolin clay and Kasaoka clay are almost the same. However, the plasticity indices are significantly different. The particle size distribution of each sample is shown in Figure 1. These samples were mixed to create four types of test specimens: Toyoura-Kaolin mixed soil, Toyoura-Fujinomori mixed soil, Toyoura-Kasaoka mixed soil, and Tohoku-Kasaoka mixed soil. Additionally, the mixing ratio was set as the percentage of the dry mass of fine fractions relative to the total dry mass, and the mixture was defined as having a fine fraction content of 0 to 60%.

Table 1. Typical properties of coarse-grained soil.

Coarse-grained soil	Soil particle density $\rho_s$ ( $\text{Mg/m}^3$ )	Mean grain size $D_{50}$ (mm)	Maximum void ratio $e_{\max}$ (-)	Minimum void ratio $e_{\min}$ (-)
Toyouura sand	2.64	0.16	0.97	0.62
Tohoku sand (#4)	2.66	0.67	0.76	0.52

Table 2. Typical properties of fine-grained soil.

Fine-grained soil	Soil particle density $\rho_s$ ( $\text{Mg/m}^3$ )	Mean grain size $D_{50}$ (mm)	Clay fraction content $C_c$ (%)	Fine fraction content $F_c$ (%)	Plasticity index IP (-)
Kaolin clay	2.71	0.0030	64.0	100.0	13.7
Fujinomori silt	2.54	0.0070	37.0	92.0	20.4
Kasaoka clay	2.71	0.0027	46.0	100.0	30.8

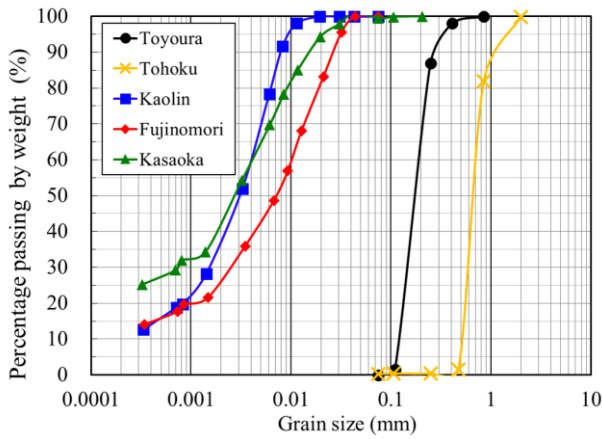


Figure 1. The particle size distribution of used soils.

### 2.2 Test methods and conditions

Relative density is used as a general indicator for managing the density of sand test specimens. Relative density is commonly used as a parameter for managing the density of sand test specimens. However, according to Japanese Industrial Standards (JIS, 2020), for soil materials containing 5% or more fine fractions, this test method is considered "not applicable", so it was decided to use the same value as the void ratio of soil specimens containing only coarse fractions. The density control of each soil sample and mixed soil used in the test is shown in Table 3.

Table 3. Density of the soil samples used in this study.

Sample	Relative density	Void ratio	Condition
	Dr (%)		
Toyoura sand	80	0.684	Dence
	60	0.757	Medium
	40	0.858	Loose
Tohoku sand	60	0.617	Medium
	40	0.666	Loose
Toyoura + Kaolin	80	0.684	Dence
	60	0.757	Medium
	40	0.828	Loose
Toyoura + Fujinomori	60	0.757	Medium
Toyoura + Kasaoka	60	0.757	Medium
Tohoku + Kasaoka	60	0.617	Medium

※: The Japanese standard for the density of sand (JIS A 1224, 2020) does not apply to sand containing 5% or more fine fractions. For such soils, the relative density of only the coarse-grained soil was applied in this study.

### 2.3 Cyclic triaxial test apparatus

Figure 2 shows the details of the cyclic triaxial testing apparatus used in this study. The cyclic triaxial testing apparatus has a triaxial cell, a cell pressure and back pressure supply device, an axial cyclic loading device or an axial displacement device, and load, displacement, pore water pressure measuring and recording devices.

The effective confining pressure was set to 100 kN/m<sup>2</sup>, and the cyclic load was a sine wave with a frequency of 0.1 Hz. The specimens measured 50 mm in diameter and 100 mm in height, and were prepared to a specified density by tapping using a mold filled with dry sand and dry fine particles.

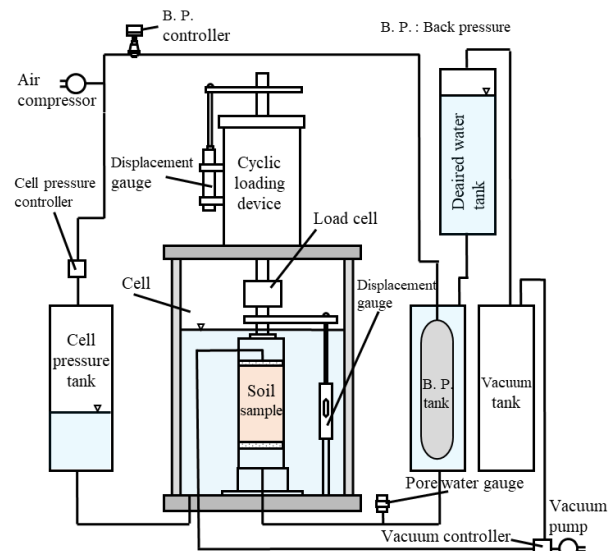


Figure 2. The cyclic triaxial testing apparatus.

## 3 EXPERIMENTAL RESULTS AND DISCUSSION

### 3.1 Liquefaction strength curves for each soil sample

The liquefaction strength curve obtained through cyclic non-drained triaxial tests using Toyoura-Fujinomori mixed soil is shown in Figure 3. For the Toyoura-Fujinomori mixed soil, tests were conducted with all sample mixtures with the density adjusted to "Medium". As indicated in Figure 3, the curve moves downward up to a fine fraction content  $F_c$  of 20%, showing low resistance to liquefaction, but the curve shifts upward thereafter, resulting in an increase in liquefaction strength. The liquefaction strength curves obtained from cyclic undrained triaxial tests using the Toyoura-Kasaoka mixed soil and Toyoura-Kaolin mixed soil show a similar trend to that exhibited by the Toyoura-Fujinomori mixed soil. (Figures 4 and 5.) The liquefaction strength curve obtained from cyclic undrained triaxial tests using the Tohoku-Kasaoka mixed soil is shown in Figure 6. In the Tohoku-Kasaoka mixed soil, the curve moves downward until the fine fraction content reaches 20%, and the resistance to liquefaction decreases. However, the curve moves upward thereafter, and the liquefaction strength increases. In other words, increasing the grain size of coarse fractions did not change the trend in liquefaction strength.

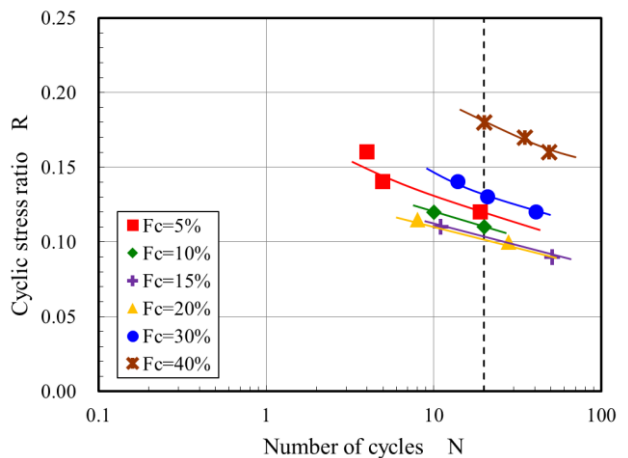


Figure 3. The liquefaction curves. (Toyoura-Fujinomori soil)

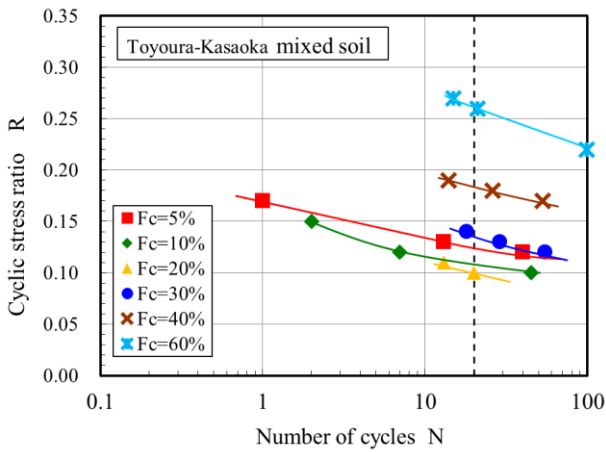


Figure 4. The liquefaction curves. (Toyouira-Kasaoka soil)

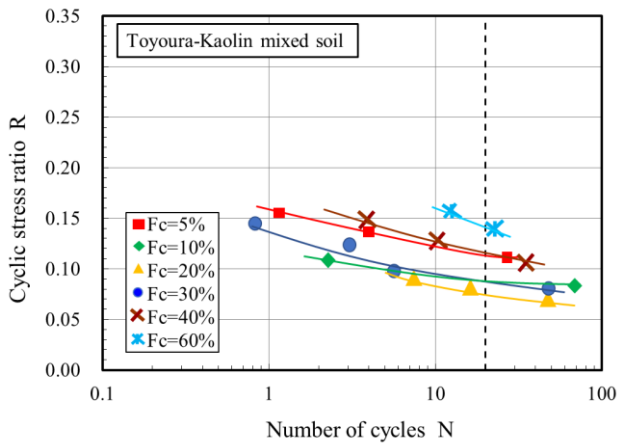


Figure 5. The liquefaction curves. (Toyouira-Kaolin soil)

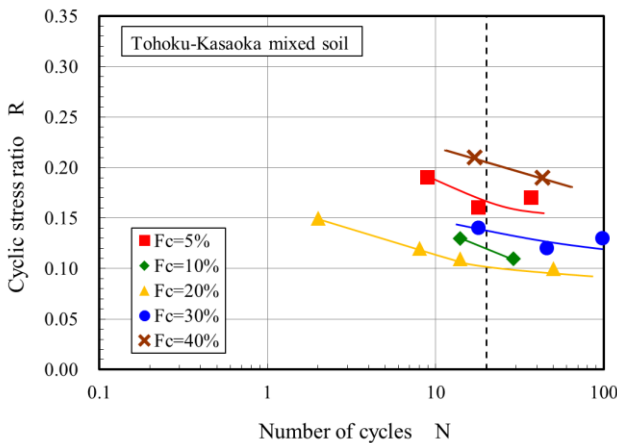


Figure 6. The liquefaction curves. (Thoku-Kasaoka soil)

### 3.2 Liquefaction strength and fine fraction content

The relationships between liquefaction strength and fine fraction content are shown in Figure 7 (a)-(c). Figure 7 (a) focuses on the difference in density, Figure 7 (b) focuses on the differences in the sizes of fine-grained soil, and Figure 7 (c) focuses on the differences in the sizes of sand. In all of the mixed soils, the liquefaction strength initially decreased as the fine fraction content increased, but then began to increase again when the fine fraction content reached around 20%. This trend is similar to previous studies (Yajima et al., 1991).

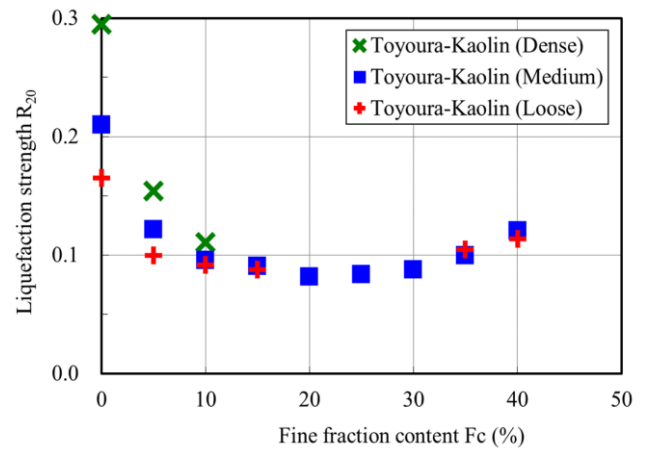


Figure 7(a). The particle size distribution of each sample.

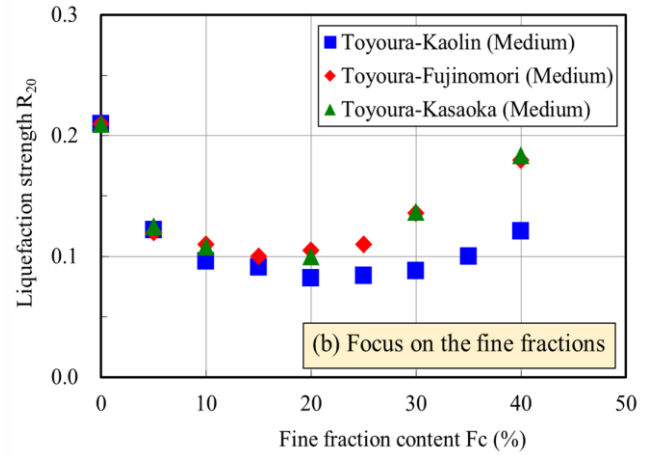


Figure 7(b). The particle size distribution of each sample.

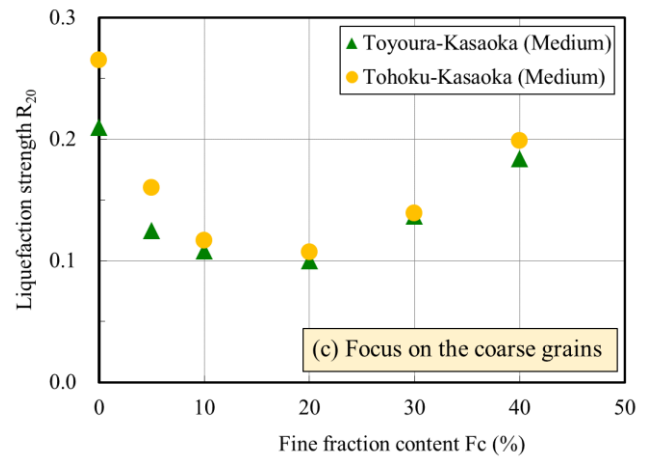


Figure 7(c). The particle size distribution of each sample.

### 3.3 Skeleton void ratio and plasticity index of mixed soil

Based on the relationships between the fine fraction content and liquefaction strength shown in Figure 7(a)-(c), the experimental results showed that relative density is related to areas with low fine fraction content, while parameters representing clay properties are related to areas with high fine fraction content. Therefore, in areas with lower amounts of fine fractions where sand skeleton dominates and the influence of fine fractions is less apparent, the relationship between skeleton void ratio  $e_s$  (Sato et al., 1997) and liquefaction strength  $R_{20}$  was examined,

and in areas with large amounts of fine fractions, the relationship between plasticity index  $I_p$  and liquefaction strength, which has been studied extensively in mixed soils, was examined. In this study, the skeleton void ratio  $e_s$  is defined by Equation (1) and indicates the void ratio when all fine fractions (silt and clay) are considered as voids, and only sand particles are considered as soil particles.

$$e_s = \frac{V_v + V_{s(silt)} + V_{s(clay)}}{V_{s(sand)}} \quad (1)$$

where,

- $V_v$  : Volume of void
- $V_s$  : Volume of soil particles
- $V_{s(sand)}$  : Volume of sand particles
- $V_{s(silt)}$  : Volume of silt particles
- $V_{s(clay)}$  : Volume of clay particles

Figure 8 shows a schematic diagram of the skeleton structure of coarse and fine mixed soil. When the skeleton void ratio value is between the minimum void ratio  $e_{min}$  of sand in Figure 8 (a) and the maximum void ratio  $e_{max}$  of sand in Figure 8 (c), the fine particles enter the voids of the sand particles in Figure 8 (b). The sand particles interlock with each other, forming a sand skeleton. Figure 8(d) shows that sand particles are scattered among the clay particles, and in this state, the soil can be considered to indicate the properties of clay. In other words, the properties of the soil can be evaluated using the plasticity index, which is an index of clayey soil.

### 3.4 Skeleton void ratio and liquefaction strength

The relationship between the skeleton void ratio  $e_s$  and the liquefaction strength  $R_{20}$  of each mixed soil is shown in Figure 9. The red trend line in Figure 9 represents the Toyoura mixed soil, and the yellow trend line represents the Tohoku mixed soil. In addition, the red vertical broken line indicates the range of sand skeletons consisting solely of Toyoura sand, while the yellow vertical broken line indicates the range of sand skeletons consisting solely of Tohoku sand and Tohoku mixed sand. The results showed that liquefaction strength decreased as the skeleton void ratio increased within the range smaller than the maximum void ratio  $e_{max}$  of sand alone. The skeleton void ratio represents the density of sand when fine fractions are considered as voids, and it is thought that the liquefaction strength also decreased due to the sand itself becoming less dense as a result of mixing fine-grained soil with the sand. Furthermore, since fine fractions have entered the spaces between the sand grains and the skeleton structure is formed solely by sand, it is presumed that the fine fractions do not contribute to liquefaction strength.

However, since the range of maximum void ratio  $e_{max}$  and minimum void ratio  $e_{min}$  of sand varies depending on the type of sand, they are represented by two curves. Therefore, it is difficult to evaluate the differences between sands with different grain sizes based on the skeleton void ratio alone. So, using the skeleton relative density  $Dr_{es}$  (Ito et al., 2001), which is an index that shows where the skeleton void ratio  $e_s$  is between the minimum void ratio  $e_{min}$  and the maximum void ratio  $e_{max}$  of sand, was examined in the following chapter.

### 3.5 Skeleton Relative Density and Liquefaction Strength

An examination was also conducted using skeleton relative density  $Dr_{es}$ , which indicates where the skeleton void ratio  $e_s$  falls between the minimum void ratio  $e_{min}$  and maximum void ratio  $e_{max}$  of sand. The definitional Equation is shown in (2).

When the skeleton void ratio becomes larger than the maximum void ratio of sand, sand particles float in the fine fractions and are not interlocked with each other, resulting in a

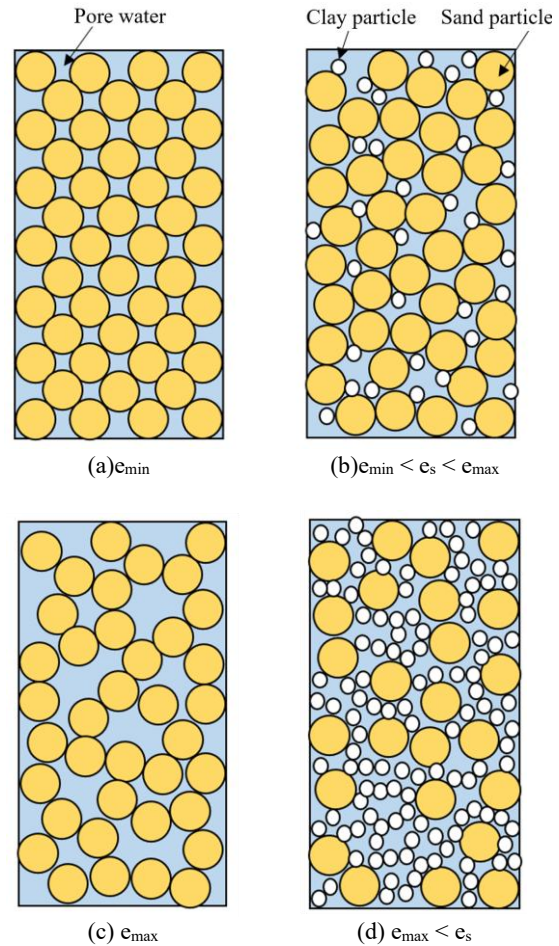


Figure 8 Schematic diagram of the skeleton structures of sand and mixed soils.

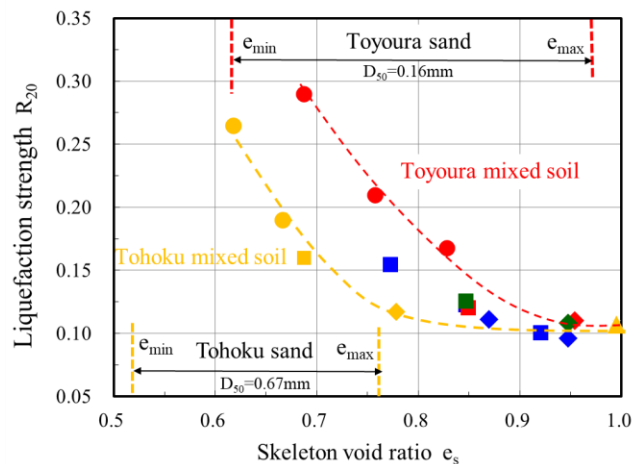


Figure 9. Skeleton void ratio and Liquefaction strength.

skeleton structure formed by fine-grained soil. Furthermore, since the properties of fine-grained soil are expected to become stronger in the same range, a study was conducted using the plasticity index  $I_p$  of mixed soil. The plasticity index is expressed by equation (3) and is calculated as the difference between the liquid limit and the plastic limit. This was examined using the plasticity index of mixed soil, but the plasticity index appeared when the fine fraction content  $F_c$  was around 30%, and the liquid limit test could not be performed for other values, so it was judged to be non-plastic (NP).

Figure 10 shows the relationship between the skeleton relative density  $Dr_{es}$  and liquefaction strength  $R_{20}$  of each mixed soil. The liquefaction strength increases as the skeleton relative density increases. Although the mixture of Tohoku silica sand, which has larger grain sizes than Toyoura sand, tends to exhibit higher liquefaction strength, the liquefaction strengths of the two mixtures can be considered to be almost the same. For comparison with previous studies, data from the literature by Hyodo et al. (2001), Yajima et al. (1999), and Sato et al. (1996) were used for analysis, and the results are shown in Figure 11. The black dotted line in Figure 10 is the experimental trend line of this study. Hyodo et al. used sand with a mean grain size of  $D_{50}=0.885$  mm, which is similar to the Tohoku silica sand used in this study, while Sato et al. and Yajima et al. used sand with a mean grain size of  $D_{50}=0.17-0.30$  mm, which is similar to the Toyoura sand used in this study, exhibiting almost the same trend.

$$Dr_{es} = \frac{e_{max} - e_s}{e_{max} - e_{min}} \times 100 (\%) \quad (2)$$

where,  $e_s$ : skeleton void ratio  
 $e_{max}$ : maximum void ratio  
 $e_{min}$ : minimum void ratio

$$I_p = w_L - w_P \quad (3)$$

where,  $w_L$ : liquid limit (%)  
 $w_P$ : plastic limit (%)

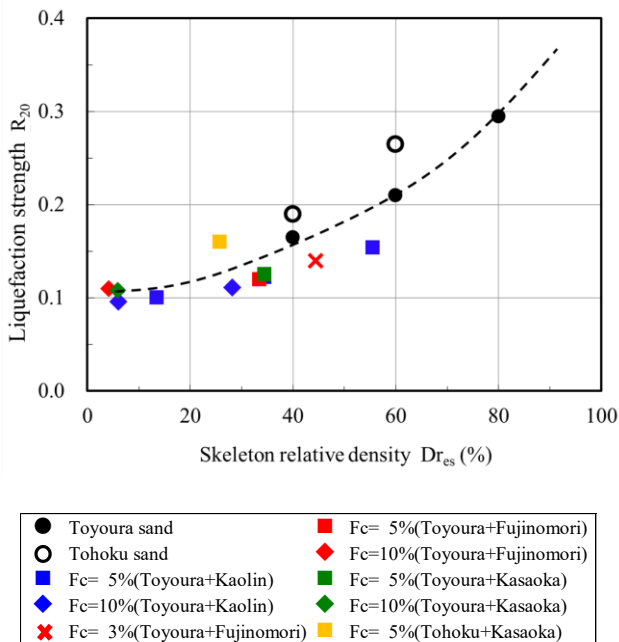


Figure 10. Skeleton relative density and Liquefaction strength.

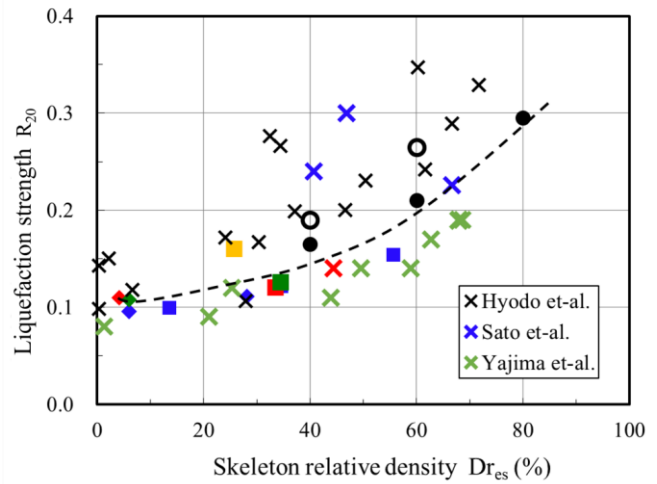


Figure 11. Relationship between skeleton relative density and Liquefaction strength. (Figure 10 with other researchers' data.)

### 3.6 Plasticity Index and Liquefaction Strength

Within the range where the skeleton void ratio exceeds the maximum void ratio of sand ( $e_{max} < e_s$ ), the interlocking of sand particles is lost, and the properties of clay become stronger, so a study was conducted to examine the relationship between the plasticity index and the liquefaction strength of mixed soil is shown in Figure 12. It was found that the liquefaction strength tends to increase with an increase in plasticity index, regardless of the type of sand or clay, and even when the fine fraction content is the same. When the maximum void ratio was less than the skeleton void ratio, and the mixture was non-plastic (NP), it was not possible to examine the results based on the skeleton relative density or the plasticity index, and the liquefaction strength of mixed soil is shown in Figure 12. Although this analysis could not be performed in this study, some sandy soils containing a large amount of non-plastic (NP) soil also exhibited low liquefaction strength. Since such soils are expected to be treated as non-liquefiable layers under current design rules, further research on their evaluation remains a key issue.

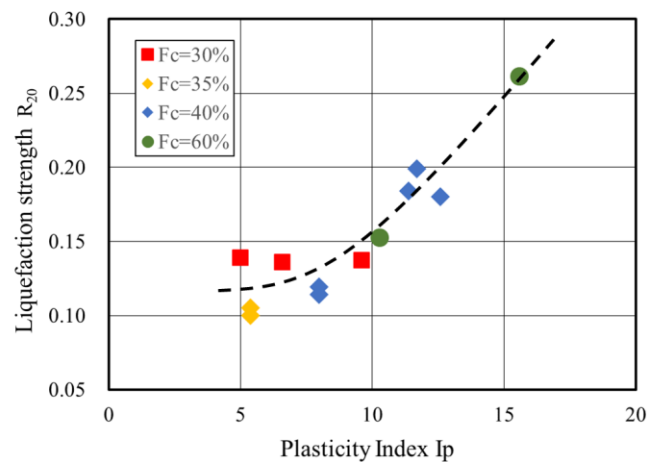


Figure 12. Plasticity index and liquefaction strength.

## 4 CONCLUSIONS

In this study, the authors conducted cyclic undrained triaxial tests using mixed soils with fine fraction content ranging from 0 to 60% to evaluate the liquefaction strength of sand containing fine fractions. As a result, the following findings were obtained.

- 1) Although liquefaction strength decreases as the skeleton void ratio increases, it was found that it is difficult to evaluate liquefaction strength using only the skeleton void ratio because of the different ranges of the maximum void ratio and minimum void ratio of sand. It was also found that the skeleton relative density is an effective evaluation method in such cases.
- 2) Within the range of minimum void ratio of sand  $\leq$  skeleton void ratio  $\leq$  maximum void ratio, it was found that there is generally a good correlation between the skeleton relative density and liquefaction strength.
- 3) Within the range of maximum void ratio of sand  $<$  skeleton void ratio, a good correlation was found between the plasticity index and liquefaction strength.

## 5 ACKNOWLEDGEMENTS

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