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RELATIONSHIP BETWEEN LIQUEFACTION STRENGTH OF SAND WITH FINE FRACTION AND VARIOUS VOID RATIOS

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ABSTRACT: Liquefaction damage has been reported in the ground containing fine fractions. It is necessary to investigate the effect of soil containing fine fractions on liquefaction strength. This study aims to clarify the relationship between the liquefaction strength and the skeleton void ratio, representing the skeletal structure of the soil and the fine fraction void ratio. For the utilized samples, Toyoura sand was used as the coarse fraction, Kaolin clay worked as the fine fraction, and mixed soil in which the mixing ratio was altered in the range of 0 to 40% was applied. Besides, considering the difference in the fine fraction properties, the experimenter made use of Fujinomori clay, Kasaoka clay, and the three combined soils. The specimens were prepared using the dry tamping method and repeatedly subjected to cyclic undrained triaxial tests. As a result, when the skeleton void ratio does not exceed the maximum void ratio of sand, it is located on the same line as the liquefaction strength regardless of the types of fine fractions. We can declare that it is a unique relationship. When the skeleton void ratio exceeds the maximum void ratio of sand, there is an excellent correlation between the fine fraction void ratio and the liquefaction strength. However, In the region with skeleton void ratio e_s exceeding the maximum void ratio e_{max} of sand alone ($e_s > e_{max}$), liquefaction strength tends to be different depending on the plasticity index I_p of fine fraction.

Keywords: Liquefaction strength, Fines content, Undrained cyclic test, Sand clay

1. INTRODUCTION

The main grounds where seismic liquefaction events occur are generally recognized as loosely deposited, saturated sand grounds. However, the liquefaction of fine fractions has been confirmed by the 1995 Hanshin Earthquake and the 2011 Great East Japan Earthquake[1], which caused severe liquefaction of reclaimed land in Tokyo Bay area from Shinkiba to Urayasu. And the research has been carried out to clarify the liquefaction mechanism of fine fraction and its effects on liquefaction strength. As a result of these studies, it was found that (1) liquefaction strength decreases with the increase of fine fraction content, and there is a fine fraction content with the lowest liquefaction strength [2] [3]. (2) There is a good correlation between the skeleton void ratio and the liquefaction strength, where a part of the fine fraction content is considered as a void [4] [5]. However, there is no unified view on the effect of the fine fraction of liquefaction strength, due to different methods of density control and specimen preparation among researchers. In particular, few studies have been conducted on samples that contain a large amount of fine fraction up to the region where fine fractions are dominant. And the effect of the fine fraction on liquefaction strength in the region where the fine fraction is dominant has not been clarified. So far, the authors have repeatedly conducted the undrained cyclic triaxial tests using a mixed sample in which the void ratio e is constant and the fine fraction content is changed in the range of 0 to 40% [6] [7]. In the region with a skeleton void ratio e_s that does not exceed the maximum void ratio of sand only ($e_s<e_{max}$), the liquefaction strength R_{20} is categorically related to the Skeleton void ratio e_s, notwithstanding the type of fine fraction. With a skeleton void ratio e_s above the maximum void ratio for sand only ($e_s>e_{max}$), the liquefaction strength R_{20} has a good correlation with the "Fine fraction void e_{ff}" in the region where the fine fraction is predominant. An intermediate region exists between these two regions. The R_{20} is approximately equal to the R_{20} when the skeleton void ratio es is total up to the maximum void ratio of sand only.

The purpose of this study is to clarify the effect of the fine fraction on liquefaction characteristics by performing undrained cyclic triaxial tests on specimens with the same method from small to large fine fractions. In this study, the skeleton void ratio e_s [6] [7] [8] [9] is defined as the void ratio of all the fine fractions in the sand as void space. The fine fraction void ratio e_{ff} [6] [7] [8] [9] is the void ratio that ignores the volume of the coarse grains and focuses only on the fine fraction. It is an indicator of the degree of fine fraction blockage.

2. EXPERIMENT OVERVIEW

In this study, undrained cyclic triaxial tests were carried out to determine the liquefaction strength of each sample. An overview of the experiment is given below

2.1 Sample

The sample used was Toyoura sand whose grain size was adjusted to 75 µm to 2 mm as the coarse fraction content, and kaolin clay as the low plastic fine fraction content, and the mixing ratio. The author used kaolin-mixed clay which was changed by 5% in the range of 0% to 40%. In addition, Fujinomori clay and Kasaoka clay were used to examine the effect of different properties of fine fractions. The author used Fujinomori clay whose grain size was adjusted to 75 µm or less. The mixing ratio of Fujinomori mixed soil and Kasaoka mixed soil was in the range of 0 to 30%.

Table 1 Main soil property values of Toyoura sand

Corse fraction	Soil particle density	Mean diameter	Fine fraction content	Clay fraction content
	ρ_s (g/cm^3)	D_{50}	FC (%)	CC (%)
Toyoura sand	2.64	0.161	0	0

Table 2 Main soil property values of fine fraction

Fine fraction	Soil particle density	Plastisity index	Fine fraction content	Clay fraction content
	ρ_s (g/cm^3)	I_P	FC (%)	CC (%)
Kaolin clay	2.714	13.7	100	64
Fujinomori clay	2.535	20.4	92	37
Kasaoka clay	2.710	30.8	99.8	46

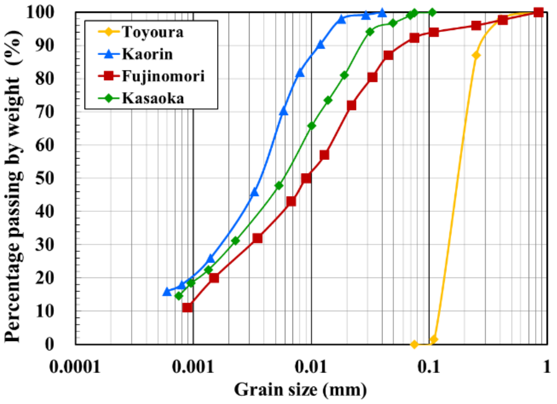

Fig. 1 grain size accumulation curves the sample

Table 3 Test conditions for cyclic triaxial tests

Sample	Density	Initial void ratio	Consolidation time	Cyclic stress ratio
	( ) indicates D_r (%)	e_0	t (hour)	R(=$\sigma_d/2\sigma_c'$)
Toyoura	Loose (40)	0.828	0.5	0.12, 0.13, 0.15
	Medium (60)	0.757	0.5	0.16, 0.17, 0.18
	Dense (80)	0.687	0.5	0.21, 0.22, 0.24
K5	Loose	0.828	1	0.09, 0.10, 0.14
	Medium	0.757	1	0.12, 0.14, 0.16
	Dense	0.687	1	0.15, 0.17, 0.18
K10	Loose	0.828	5	0.08, 0.10, 0.12
	Medium	0.757	5	0.08, 0.10, 0.12
	Dense	0.687	5	0.10, 0.11, 0.12
K15	Loose	0.828	12	0.08, 0.10, 0.12
	Medium	0.757	12	0.08, 0.10
K20	Medium	0.757	24	0.07, 0.08, 0.09
K25	Medium	0.757	24	0.08, 0.09
K30	Medium	0.757	24	0.10, 0.12, 0.15
K35	Loose	0.828	24	0.08, .0.09
	Medium	0.757	24	0.09, 0.11, 0.13
K40	Loose	0.828	24	0.09, 0.13
	Medium	0.757	24	0.11, 0.13, 0.15
F3	Medium	0.757	0.5	0.2, 0.17, 0.125
F5	Medium	0.757	1	0.16, 0.14, 0.12
F10	Medium	0.757	5	0.12, 0.11
F15	Medium	0.757	15	0.11, 0.09
F20	Medium	0.757	18	0.105, 0.115
F25	Medium	0.757	24	0.11, 0.12
KS5	Medium	0.757	1	0.17, 0.13
KS10	Medium	0.757	5	0.15, 0.12, 0.10
KS20	Medium	0.757	15	0.11, 0.10
KS30	Medium	0.757	48	0.12, 0.13, 0.14

[*] The confining pressure of consolidation is 100 kPa

[*] The load repeats with a sinusoidal wave of 0.1 Hz frequency at the specified cyclic stress ratio

Each mixed soil is called K5, F3, or KS5, according to the acronym of the fine fraction’s name and the mixing ratio. This study mixing ratio is the percentage of the dry mass of the mixed fine-grained sample to the total dry mass. Each mixed soil was prepared by mixing each sample in an air-dried state until it became homogeneous in a container. main physical properties and particle size distributions of each sample are shown in Table 1 and Table2, Fig. 1.

2.2 Experimental Method

The specimen is a cylindrical sample of 5 cm in diameter and 10 cm in height. The specimens were divided into ten equal parts and then divided into ten layers, each layer of which was solidified with a rammer. After the specimens were prepared at a predetermined density, the specimens were first allowed to stand on their own at a constraint pressure of 20 kPa and were saturated by aerating carbon dioxide, passing sufficient degassed water, and then saturated by applying 200 kPa of backpressure, which is about three times the volume of the specimens. Subsequently, consolidation was performed with effective constraint pressure σ_c'=100 kPa. The consolidation time was set as shown in Table 3 for each sample, considering that the consolidation could be completed sufficiently. After the consolidation was completed, the B-value was measured to confirm the saturation, and the backpressure was further applied to make the B-value more than 0.95. After confirming that the B-value was more than 0.95, the material was repeatedly loaded with a sinusoidal wave of 0.1 Hz frequency at the prescribed cyclic stress ratio $R(=\sigma_d/2\sigma_c')$. The test conditions for each sample are shown in Table 3.

2.3 Density Management Method

In the field of liquefaction, the relative density D_r is often used as a parameter expressing the density of specimens, and even in the study using samples mixed with fine fraction, the relative density controls the density, and the same relative density is used. There are many examples of comparing densities with each other. For example, the reason why the relative density is often used is that in the case of sand, the relationship between the relative density and the liquefaction strength is proportional. but the "minimum/maximum density test of sand (JIS)" for determining the relative density the range of soil to which A 1224) is applied is said to be sand in which 95% or more remains in a 75 μm sieve, and when using a sample containing a large amount of fine fraction as used in this study, the relative density It is difficult to control the density using, and it is considered inappropriate. Therefore, in this study, the most densely packed sand is called "Dense", the most loosely packed sand is called "Loose", and the sand with a density in between is called "Medium". When only Toyoura sand was used, to consider the effect of density change, the relative densities were adjusted in three ways: D_r=40% (Loose), D_r=60% (Medium), and, D_r=80% (Dense). When the same test was conducted using mixed soil, the density was controlled so that the initial pore ratio e_0 was e_0=0.828(Loose), e_0=0.757(Medium), and e_0=0.684 (Dense), respectively, which was the same value as the initial pore ratio e_0 when the density was adjusted using only Toyoura standard sand. Therefore, the density control method in this study can be considered as a constant void ratio.

3. EXPERIMENT RESULTS

3.1 Liquefaction Strength Curve

Figure. 2(a)~(d) shows the liquefaction test results for each sample. It shows the relationship between the cyclic stress ratio R and the number of cycles N required to reach both amplitude axial strains DA=5%. Fig. 2(a) shows the liquefaction strength curve when the undrained cyclic triaxial test was repeatedly performed using Toyoura standard sand. As the density of Toyoura sand increases, the cyclic stress ratio at a certain number of loading cycles increases, the curve moves upward, and the resistance to liquefaction increases. In Dense, the liquefaction intensity curve, commonly seen in dense sand, tends to rise. Fig. 2(b) shows the cyclic strength curves for K5 to K15 with varying densities; as for K5, the curve moves upward with increasing density, as in the case of Toyoura sand, but it becomes weaker as the content of K10, K15, and Kaolin clay increases. For the same densities, the cyclic strength curve is located at the bottom of the curve as the fines content increases. Fig. 2(c) shows the cyclic strength curves for the cyclic triaxial tests using from K20 to K40. It was found that the curve was located upward for samples with higher fines content, and the liquefaction resistance was higher. Fig. 2 (d) shows the cyclic strength curves for the cyclic triaxial tests using from F3 to F25 and KS5 to KS30. In Fujinomori mixed soil, the liquefaction strength curve moves to the bottom as the fine fraction content increases, and the liquefaction strength gradually increases beyond FC = 15%, increasing the liquefaction resistance. In addition, the Kasaoka mixed soil shows the same tendency as the Fujinomori mixed soil.

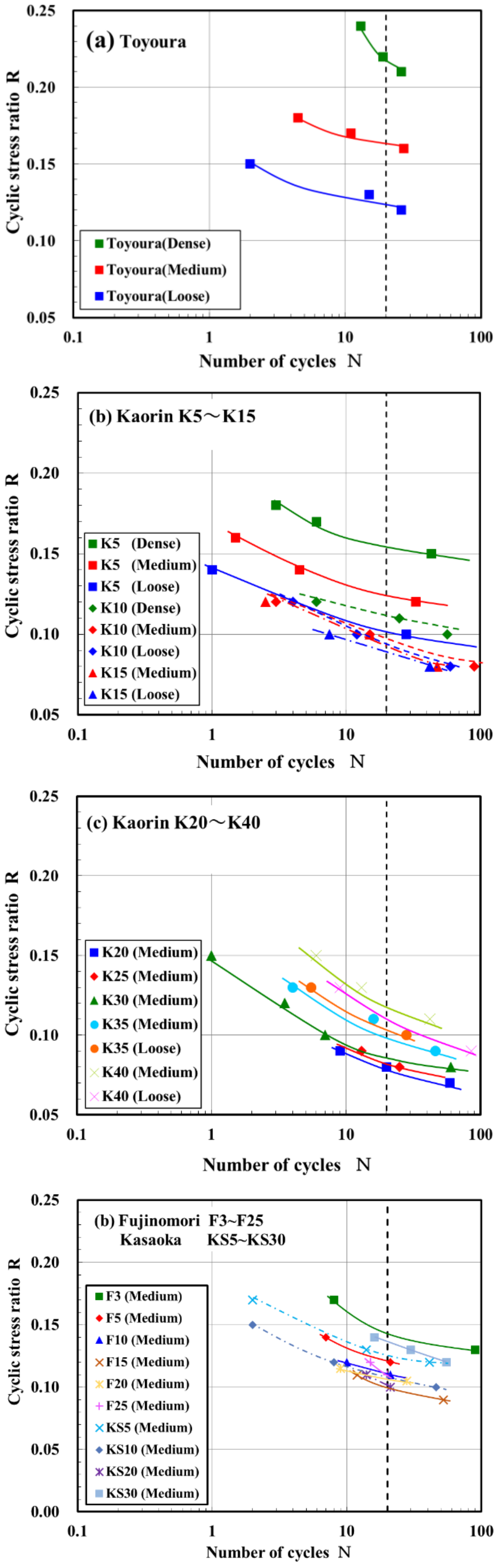

Fig. 2 Liquefaction strength curves for each sample

3.2 Relationship Between Fine Fraction Content and Liquefaction Strength

In this study, the cyclic shear stress R was used as "liquefaction strength R_{20}" to indicate the liquefaction resistance when both amplitudes of strain DA=5% were reached at 20 times of cyclic loading (shown as the dashed line in Fig.2). The relationship between the liquefaction strength, R_{20}, and the Fine fraction content FC, is shown in Fig.3. From the figure, the R_{20} of kaolin mixed soil Medium decreased with the increase of Fine fraction content, showed the lowest R_{20} at FC=20%, and then increased. In the range of FC=0~15%, the R_{20} of Kaolin mixed soil increases with the increase of density of specimen, but the effect of density of specimen on liquefaction strength gradually decreases with the increase of fine grain content. at FC=15%, the strength of Loose and Medium are almost the same. The R_{20} of Fujinomori mixed soil Medium decreased with the increase of Fine fraction content. The lowest R_{20} was observed at FC=15% and then increased. The R_{20} of Kasaoka mixed soil Medium decreased with the increase of FC. After FC=10%, under the same density of specimen, Fujinomori mixed soil and Kasaoka mixed soil show higher liquefaction strength than Kaolin mixed soil.

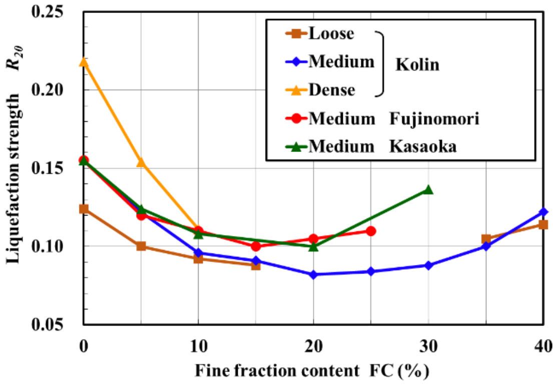

Fig. 3 Effect of fine fraction content FC on liquefaction strength R_{20}

3.3 Relationship Between Various Void Ratios and Fine Fraction Content

When investigating the strength of soil with a grain size intermediate between sand and clay, such as the sample used in this study, it is very important to pay attention to the skeletal structure of the soil.

Therefore, in this study, the effect of the fine fraction on liquefaction properties was considered using " Skeleton void ratio e_s" and "Fine fraction void ratio e_{ff}". The skeleton void ratio e_s is the void ratio when all fine fractions are considered as pores while the skeleton void ratio e_s is the void ratio. The fine fraction void ratio e_{ff} is a void ratio that ignores the volume of coarse-grains and focuses only on the fine fraction content, which is an indicator of how well the fine fraction content is plugged. The void ratio can be calculated by the following equations (1) and (2). Equations (1) and (2) use the symbols shown in Fig. 4.

Fig. 5 and Fig. 6 show the changes in the skeleton void ratio e_s and the fine fraction void ratio e_{ff} due to the increase in the fine fraction content in the medium of each mixed soil. The various void ratios in the figure are the values at the time of preparing the specimen. From Fig. 5, the value of the skeleton void ratio does not change regardless of the type of fine fraction, and the skeleton void ratio increases as the fine fraction content increases. The skeleton void ratio e_s exceeds the maximum void ratio e_{max} of sand only (broken line in Fig. 5) near FC = 10%. Therefore, before FC = 10%, a skeleton of sand particles is formed and fine fractions are formed. After FC = 10%, it is considered that the fine fractions enter between the sand particles to form a skeleton, or the sand particles are floating in the fine fraction. Fig. 6 shows the relationship between the fine fraction void ratio e_{ff} and the fine fraction content FC. As FC increases, the fine fraction void ratio e_{ff} decreases.

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

Fine fraction void ratio $$e_{ff} = \frac{V_v}{V_{s(clay)}+V_{s(silt)}} \quad \cdots(2)$$

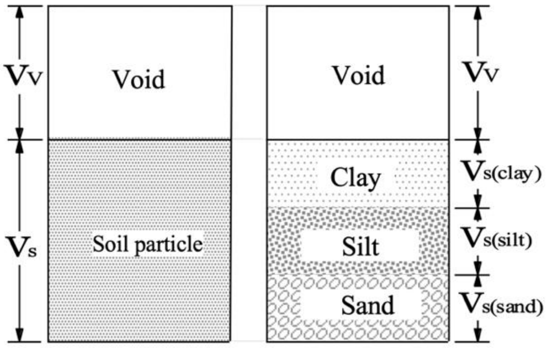

Fig. 4 Schematic of mixed samples

3.4 Relationship Between Various Void Ratios and Liquefaction Strength

The relationship between the Skeleton void ratio e_s and liquefaction strength R_{20} is shown in Fig. 7. When the Skeleton void ratio e_s does not exceed the maximum void ratio of Toyoura sand only e_{max} (vertical black dashed line in the figure), the Skeleton void ratio e_s, and liquefaction strength are on the same curve regardless of the type of fine fraction of the density of the specimen. This indicates that the skeletal structure of the sample is formed by sand and fine fraction does not affect the liquefaction strength and R_{20} is determined by the Skeleton void ratio e_s, within the range of the maximum void ratio of sand only. However, even after exceeding e_{max}, there is a good relationship between R_{20} and es up to about e_s=1.1. This skeleton void ratio is the skeleton void ratio at the time of specimen preparation and is due to the change in the volume of fine fractions due to consolidation. Therefore, it is considered to be in the region of not exceeding e_{max} up to about e_s=1.1. Furthermore, the Skeleton void ratio e_s gradually increases after e_{max}. The results also show a tendency for the skeleton void ratio e_s to split into three curves depending on the plasticity index I_p of each fine fraction after exceeding e_{max}. The liquefaction strength starts to increase after reaching the lowest point, suggesting

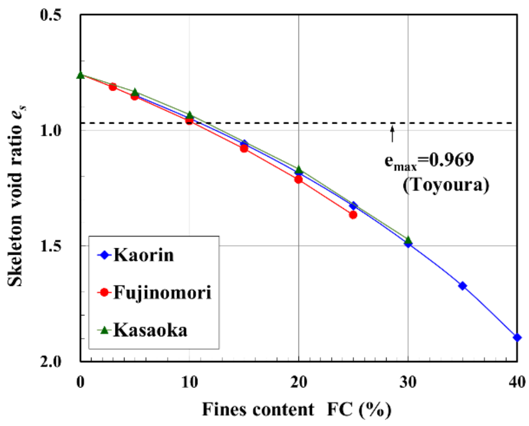

Fig. 5 Relationship between fine fraction content and skeleton void ratio e_s

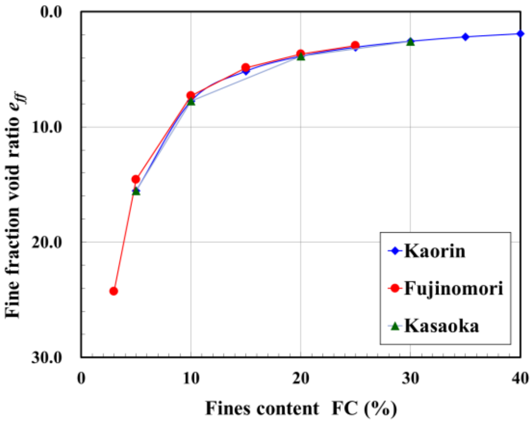

Fig. 6 Relationship between fine fraction content and fine fraction void ratio e_{ff}

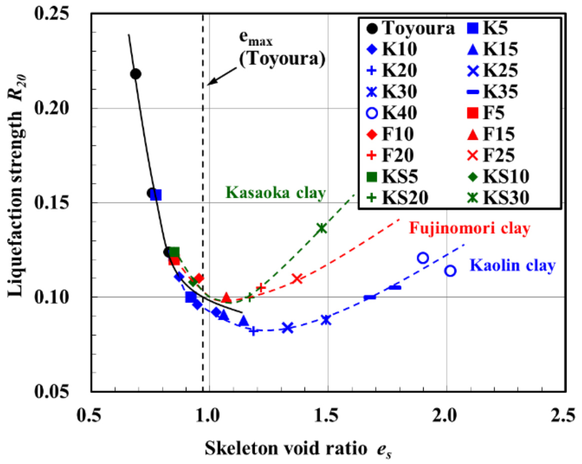

Fig. 7 Relationship between Skeleton void ratio e_s and Liquefaction Strength R_{20}

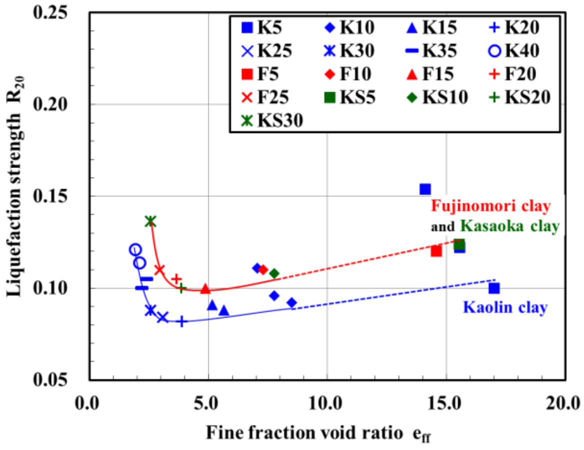

Fig. 8 Relationship between Fine fraction void ratio e_{ff} and liquefaction strength R_{20}

that the skeletal structure of the soil is similar to that the fine fraction does not fit into the spaces between the sand grain, and the sand grains float in the fine fraction.

Therefore, in such a state, the liquefaction strength R_{20} is presumed to be influenced by the state of fine fraction and is considered to be closely related to the Fine fraction void ratio e_{ff}. The relationship between the Fine fraction void ratio e_{ff} and the liquefaction strength R_{20} is shown in Fig. 8. The liquefaction strength R_{20} changes rapidly after the fine fraction void ratio e_{ff}=4.0 for each mixed soil. This indicates that there is a good relationship between the liquefaction strength R_{20} and the fine fraction void ratio e_{ff} in the region where the fine fraction is dominant. The same change tendency is shown in the Fujinomori mixed soil and the Kasaoka mixed soil. However, due to the difference in the plasticity index Ip, the results were represented by two curves, kaolin mixed soil (I_p＜15) and other mixed soil (I_p＞20). In addition, if we focus on the relationship between e_{ff} and R_{20} in the region where the skeleton void ratio e_s does not exceed the maximum void ratio e_{max} of sand alone (e_s<e_{max}), it can be said that there is no relationship between e_{ff} and R_{20} with a large variation depending on the density. In the future, we will increase the experimental data and investigate whether the skeleton void ratio e_s and fine fraction void ratio e_{ff} are suitable for evaluating the liquefaction strength of sand containing fine fractions.

4. CONCLUSION

The authors investigated an evaluation method using various void ratios as indicators for the liquefaction strength of sand and sandy soil through experiments. As a result, the following findings were obtained.

(1) In the region where the skeleton void ratio e_s does not exceed the maximum void ratio e_{max} of sand alone (e_s<e_{max}), the liquefaction strength R_{20} is uniquely related to the skeleton void ratio e_s regardless of the type of fine fraction.

(2) With a skeleton void ratio e_s above the maximum void ratio e_{max} for sand only (e_s>e_{max}), the liquefaction strength R_{20} has a good correlation with the "Fine fraction void e_{ff}" in the region where the fine fraction is predominant.

(3) In the region with skeleton void ratio e_s exceeding the maximum void ratio e_{max} of sand alone (e_s >e_{max}), liquefaction strength tends to be different depending on the plasticity index I_p of fine fraction.

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