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EFFECT OF FINES CONTENT ON LIQUEFACTION CHARACTERISTICS

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ABSTRACT: The 1995 Hanshin Earthquake confirmed that soil containing fine fraction would be liquefied. In many cases, the effect of the fine fraction on liquefaction strength has not been clarified yet. In particular, it is not so many researchers have used samples containing a large amount of fine fraction, although the fine fraction presents the predomination in its field. Therefore, the purpose is to clarify the fine fraction's effect on the liquefaction strength of sand-clay within the parameters of the skeleton void ratio. The fine fraction content of the specimens has a distinct span from small to large. The coarse-grained soil used Toyoura sand mixed with 0 ~ 40% Kaolin clay in a dry state. The specimens (D=50mm, H=100mm) are made by using the dry tamping method. These specimens were used to do the undrained cyclic triaxial test. The test results show that when the skeleton void ratio does not exceed the maximum void ratio of sand, the fine fraction does not affect liquefaction strength regardless of its type. And the liquefaction strength of the specimen has a certain relationship with the skeleton void ratio. When the skeleton void ratio exceeds the maximum void ratio of sand, the fine fraction is in a remarkable position. And the liquefaction strength has a good correlation with the fine fraction void ratio.

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, liquefaction of fine fraction has been confirmed by the 1995 Hanshin Earthquake [1]and the 2011 Great East Japan Earthquake， which caused severe liquefaction of reclaimed land in the Tokyo Bay area from Shinkiba to Urayasu. Researches have 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) The liquefaction strength decreases with the increase of fine fraction content, and there is a fine fraction content with the lowest liquefaction strength [2-6]. (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 a void [2-5,7-8]. However, there is no unified view on the fine fraction of liquefaction strength due to different density control methods 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 fraction are dominant. The fine fraction on liquefaction strength in the region where the fine fraction is dominant has not been clarified. The purpose of this study is to clarify the effect of fines content on liquefaction characteristics by performing undrained cyclic triaxial tests.

All the tests were performed on specimens with the same method from small to large fines content. In this study, the skeleton void ratio e_s [9] is defined as the void ratio of all the fine grains in the sand as pore space. The skeleton void ratio e_f is defined as the porosity of clay only, assuming that the silt content is part of the skeletal structure. The void ratio e_{ff} is the void ratio that ignores the coarse grains' volume and focuses only on the fine grains. It is an indicator of the degree of grain blockage.

2. EXPERIMENT OVERVIEW

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

2.1 Materials

For all samples, Toyoura sand was used as the coarse-grained material, and Kaolin clay, Fujinomori clay were used as the fine fraction material. The mixing ratio (percentage of the dry mass of fine fraction material to total dry mass) was varied by 5% in the range of 0 ~ 40%. To examine the effect of the difference in the properties of the fine fraction. A sample of Fujinomori clay with a mixing ratio of 5 ~ 15% was used. Each soil mixture shall be referred to as K5 or F10, depending on the initials of the names of the fine fractions and the proportion of the mixture. Each mixed soil was prepared by mixing each sample in an air-dried state until it became homogeneous in a container. The main physical properties and particle size distributions of each sample are shown in Table 1 and Fig. 1.

As shown in Table 1, Kaolin clay and Fujinomori clay were used to compare clay types' influence on liquefaction strength. As shown in the clay content, Fujinomori clay contains more silt than Kaolin clay.

Table 1 Physical properties of the sample

Sample	Soil particle density	Plasticity index	Fine particle fraction content	Clay fraction content	Mean diameter
	ρ_s (g/cm^3)	I_P	FC (%)	CC (%)	D_{50} (mm)
Toyoura	2.640	NP	0	0	0.161
Kaolin	2.714	13.7	100	64	0.003
Fujinomori	2.535	20.4	92	37	0.009

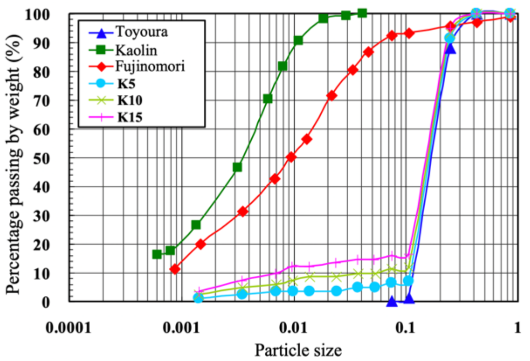

Fig. 1 Particle size distribution curves the sample

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 was compacted 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 then saturated by applying 200 kPa of back pressure with de-aired water, which is about three times the volume of the specimens. Subsequently, Consolidation was performed with effective constraint pressure σ_c'=100kPa. As shown in Table 2 for each sample, the consolidation time was set, taking into account 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 2.

Table 2 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
F5	Medium	0.757	4	0.10, 0.11, 0.12
F10	Medium	0.757	12	0.10, 0.11, 0.12
F15	Medium	0.757	20	0.10, 0.11, 0.12

*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

2.3 Density Management Method

In liquefaction studies, the relative density D_r is often used as a parameter to express the density of specimens, and the density is also controlled by the relative density D_r in studies with samples containing fine fraction. However, the applicable scope of the "Minimum and Maximum Density Test of Sand (JIS A 1224)" for calculating the relative density is defined as the sand that remains more than 95% in a 75 μm sieve. It is difficult and inappropriate to control the density by using the relative density for a sample containing many fine fractions such as the one used in this study.

Therefore, the minimum and maximum densities of Toyoura sand (ρ_{dmin}=1.341 g/cm^3 and ρ_{dmax}=1.633 g/cm^3) were used for liquefaction tests using only Toyoura sand in this study. To consider the effect of density change, the relative density D_r was adjusted to be 40% (Loose), 60% (Medium), and 80% (Density). The void ratio e_0 was adjusted to 0.828 (Loose), 0.757 (Medium), and 0.684 (Density) to be the same value as the void ratio e_0 when the density was adjusted by using Toyoura sand only. The effect of density change was considered.

3. EXPERIMENT RESULTS

3.1 Liquefaction Strength Curve

Figure 2(a)-(c) shows the liquefaction test results for each sample. It shows the relationship between the cyclic stress ratio $R=\sigma_d/2\sigma_c'$ and the number of cycles N required to reach both amplitude axial strains DA=5%. Fig. 2(a) shows the cyclic strength curves for the liquefaction test using Toyoura sand only and for the cyclic triaxial test using Fujinomori mixed soil with a constant density varying only the fines content. As the density of Toyoura sand increases, the cyclic stress ratio at a certain number of loading cycles increases. The curve moves upward, indicating that the resistance to liquefaction becomes stronger. Also, Dense shows a tendency for the curves that are commonly found in dense sand to rise.

Besides, the cyclic strength curve of Fujinomori mixed soil moved to the bottom as the fines content increased, indicating that the soil's resistance to liquefaction became weaker. 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 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 curve's bottom 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.

3.2 Relationship Between Fine Particle 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 cyclic loading (shown as the dashed line in Fig.2). Fig. 3 shows the relationship between the liquefaction strength R_{20} and the fines content F_C calculated from the cyclic strength curve for each sample. The fines content F_C in the figure is equal to the ratio of fines content in the Kaolin mixed soil but is slightly smaller than the ratio of fines content in the Fujinomori mixed soil. The reason is that a small amount of sand is contained in the Fujinomori clay. The figure shows that the liquefaction strength of the Kaolin mixed soil, Medium, decreases with the increase in the fines content. Then, increases after the lowest liquefaction strength R_{20}, is found at F_C=20%. In the range of F_C=0~15%, the liquefaction strength R_{20} increased with rising density in all the samples.

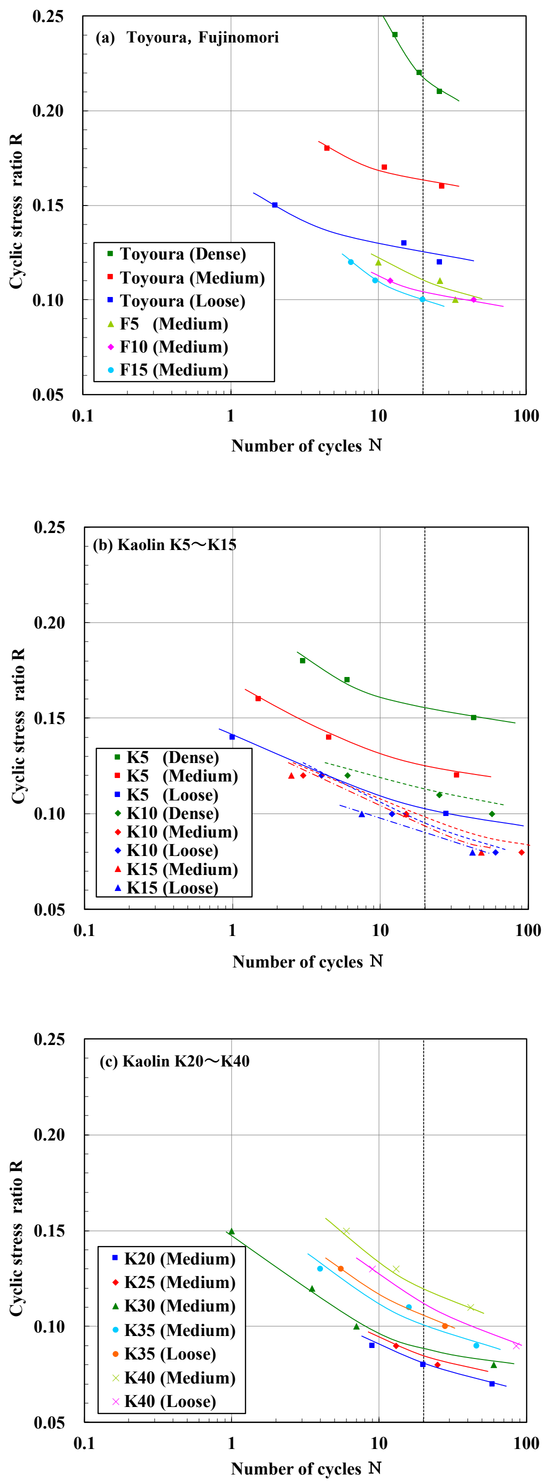

Fig. 2 Cyclic strength for each sample

The growth in liquefaction strength R_{20} became smaller with increasing fines content. The liquefaction strength R_{20} in K15 was almost the same for Loose and Medium.

The liquefaction strength of R_{20} decreased due to an increase in the fraction of fine fraction in the soil, although it was slightly different from that of Kaolin mixed soil.

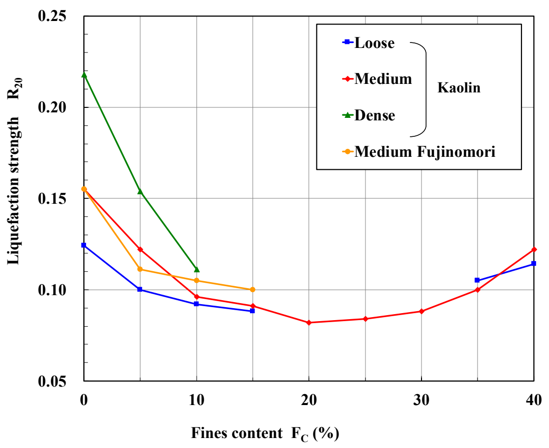

Fig. 3 Effect of fines content on liquefaction strength R_{20}

3.3 Relationship Between Various Void Ratios and Fine Particle 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 essential to pay attention to the soil's skeletal structure.

Therefore, in this study, with the void ratio e, the effect of the fine fraction on liquefaction properties was considered using Skeleton void ratio e_s, e_f [8] and Fine fraction void ratio e_{ff} [10]. The skeletal void ratio e_s is the void ratio when all fine fractions are considered as pores, while the skeletal void ratio e_f is the void ratio. When only clay is considered as a void, it was assumed that the silt content contributes to the skeletal structure. 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, which indicates how well the fine fraction is plugged. The void ratios can be obtained by the following Eq. (1)-(3) using the symbols shown in Fig. 4.

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

Skeleton void ratio $$e_f = \frac{V_v + V_{s(silt)}}{V_{s(sand)} + V_{s(silt)}} \quad (2)$$

Fine fraction void ratio $$e_{ff} = \frac{V_v}{V_{s(clay)} + V_{s(silt)}} \quad (3)$$

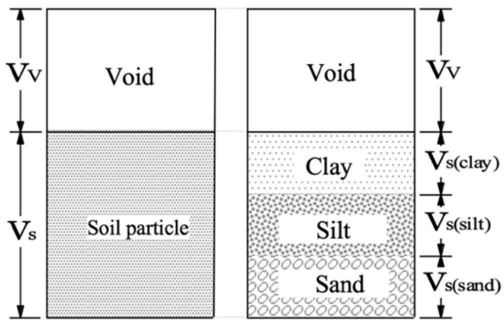

Fig. 4 Schematic of mixed samples

The changes in void ratio e, skeleton void ratio e_s and e_f, and fine fraction void ratio e_{ff} with increasing fine fraction content in Medium of Kaolin mixed soils are shown in Fig. 5. The void ratios in the figure are values immediately before the cyclic loading process. They are calculated from the initial void ratio e_0 of the specimen, the axial displacement until the consolidation process, and the consolidated drainage amount. The void ratio e is smaller than the initial void ratio e_0 (dashed line in the figure) in the range of F_C=0 ~ 25%. It decreased with an increase in fine fraction content. This may be since the fine fraction content in the specimens made in the dry state shrinks due to the pore water, and the volume compression increases with the increase of the fine fraction content.

Like the void ratio e, the void ratio of fine fraction e_{ff}, also tends to decrease with the increase in fine fraction content, same as the void ratio e. The void ratio drops sharply in the region with lower fine fraction content. It then gradually decreases, ascending to Kaolin clay's void ratio when it is compacted at 100kPa (single dotted line in the figure).

On the other hand, the skeletons' void ratio is increasing due to the growth of fine fraction content. The skeletons' void ratio tends to increase rapidly from around F_C=25%, suggesting a structural change. The skeletal void ratio e_s exceeds the maximum void ratio of Toyoura sand only (the two-dotted line in the figure) at around F_C=5%. From this, it is considered that before F_C=15%, sand particles form a skeleton, and fine fractions have a skeleton structure that enters the gap formed by sand particles. While after F_C= 15%, it is thought that fine fraction form a skeleton between sand particles or that sand particles are floating in the fine fraction.

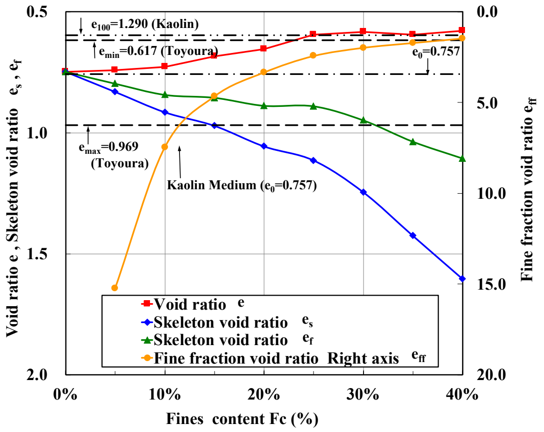

Fig. 5 Relationship between fines content and various void ratios

3.4 Relationship Between Various Void Ratios And Liquefaction Strength

The relationship between the void ratio e and the liquefaction strength R_{20} is shown in Fig. 6. In the figure, it can be seen that the volume compression tends to increase with a looser initial void ratio. And that liquefaction strength, R_{20}, decreases and then increases with an augmentation in the fine fraction content. However, there is no direct relationship between the void ratio *e* and the liquefaction strength R_{20} since the liquefaction strength varies greatly depending on the sample, even at the same void ratio.

Figures 3 and 5 show that the relationship between the void ratio and the liquefaction strength R_{20} decreases in the range of F_C=0~20%, even though the density rises with increasing void ratio *e*. This suggests that the decrease in liquefaction strength R_{20} in the range of F_C=0~20% is due to the increase in the skeleton void ratio, and the skeleton void ratio may have a strong influence on the liquefaction strength. The relationship between the skeleton void ratio e_s and e_f and the liquefaction strength R_{20} of each sample with F_C=0~20% is shown in Fig. 7. The liquefaction strength of both skeleton void ratio decreased with the increase in the skeleton void ratio. However, the liquefaction strength R_{20} varies in the small void ratio e_f. In contrast, the liquefaction strength e_s lies on the same curve in all the void ratios, regardless of whether the soil is mixed with Kaolin or Fujinomiri, and it can be said that the void ratio e_s and the liquefaction strength R_{20} are categorically related. In the range of F_C=0~15%, the skeletal structure of the soil is formed by sand, and the fine fraction content has no effect on the liquefaction strength; the skeleton void ratio es determines the liquefaction strength R20.

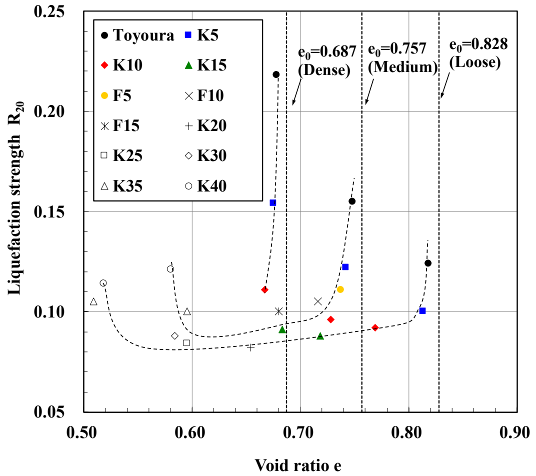

Fig. 6 Relationship between void ratio e and liquefaction strength R_{20}

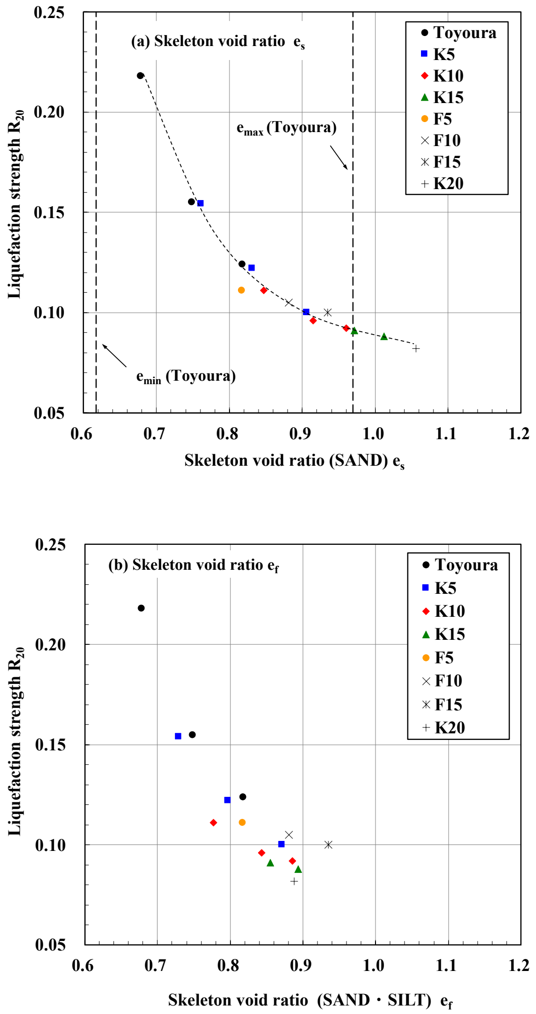

Fig. 7 Relationship between Skeleton void ratio e_s, e_f and Liquefaction Strength R_{20}

Furthermore, from Figs 3 and 5, the skeletal gap ratio e_s increases rapidly at F_C=25%, and since the R_{20} has also begun to increase, in the skeletal structure of the soil, the fine fraction cannot fit in the gaps of sand. It is considered that the sand is in a state of floating in the fine fraction and has a skeletal structure with properties similar to those of cohesive soil.

Therefore, it is presumed that the liquefaction strength R_{20} depends on the state of the fine fraction. It is considered to be closely related to the fine fraction void ratio e_{ff}. The relationship between the e_{ff} and R_{20} is shown in Fig. 8. The R_{20} of K100 (Kaolin clay only) in the figure is taken from the study by Kuwano [6]. It is the same as the one in the previous article. In Fig. 8, the R_{20} is almost the same regardless of the F_C and density, at F_C=30% the R_{20} increases rapidly. From this, it can be said that F_C=30~40% of sand particles float in the fine fraction, and R_{20} has a good correlation with the e_{ff}. In the case of F_C=15~30%, the skeleton void ratio e_s exceeds the maximum void ratio e_{max} of Toyoura sand, but there was no increase in the liquefaction strength observed after F_C=30%. In the range, it is possible to judge it as an intermediate region between the region where sand particles form the skeleton and the region where the fine fraction is predominant.

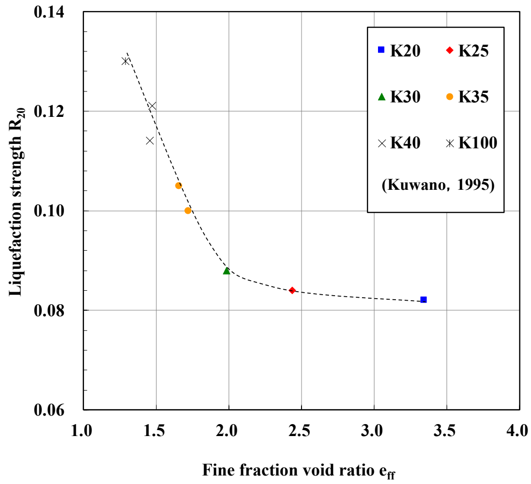

Fig. 8 Relationship between Fine fraction void ratio e_{ff} and liquefaction strength R_{20}

4. CONCLUSION

As a result, the following findings were obtained.

(1) In the region with a skeletal void ratio e_s that does not exceed the maximum void ratio of sand only (e_s<e_{max}), the fine fraction makes no difference to the liquefaction strength R_{20}. And the R_{20} is categorically related to the Skeleton void ratio e_s, notwithstanding the type of fine fraction.

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

(3) An intermediate region exists between these two regions. The R_{20} is approximately equal to the R_{20} when the skeleton void ratio e_s is total up to the maximum void ratio of sand only.

5. REFERENCES

[1] Kazama M., Kagatani T., Yanagisawa E., Peculiarities of liquefaction resistance of masado, Journal of JSCE No.645/III-50 pp153-160, 2000. (In Japanese only)

[2] Wen L., Kamao S., Yokoyama K., Effect of fines content on liquefaction characteristics, 10th Int. Conf. on Geotechnique, Construction Materials and Environment, pp211-216, 2020.

[3] Yokoyama K., Effect of fines content on liquefaction characteristics, Master thesis of Nihon University, 2011. (In Japanese only).

[4] Ishii K., Wen L., Yamasawa T., Kamao K., Effect of fines content on liquefaction characteristics, 17th JGS Kanto branch Annual meeting, 2020. (In Japanese only)

[5] Kaneko H., Tukamoto Y., Evaluation of liquefaction resistance focusing on the skeleton structure of sand containing a large amount of fine particles, 17th Annual meeting of JGS-Kanto branch, 2020. (In Japanese only)

[6] Kuwano J., Iimura H., Nakazawa H., Sugihara K., Liquefaction strength of sand containing kaolin clay , 50th JSCE Annual meeting, pp.506-507, 1995. (In Japanese only)

[7] Ishikawa S., Masayuki H., Ikuko S., Rolando O., Nakata Y., Norimasa Y., Cyclic shear properties of non-plastic low plastic fine fraction mixed soil, 42nd JGS Annual meeting, pp.158-159, 2007. (In Japanese only)

[8] Nabeshima Y., Nagasaw T., Tamotsu M., Evaluation of liquefaction strength of sands containing fines based on clay fraction, 38th JGS Annual meeting, pp.239-240, 2003. (In Japanese only)

[9] Thevanayagam S., Shenthan T., Mohan S., Liang J., Undrained fragility of clean sands, silty sands, and sandy silts, Journal of geotechnical and geoenvironmental engineering 128 (10), pp.849-859, 2002.

[10] Sato M., Oda M., Kazama H., Ozeki K., Fundamental study on the effect of fines on liquefaction strength of reclaimed ground, Journal of JSCE No.561/III-38, pp.271-282, 1997. (In Japanese only)