Effects of soil types in estimating fines content for evaluating liquefaction strength

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***Abstract* –Relationships between soil type names written in the borehole logging data and fines content are investigated based on a statistical analysis of the estimation of the liquefaction strength determined without conducting a grain size analysis. Approximately 7700 borehole logging data sets were collected in the Miyagi Prefecture including Sendai City, Japan and approximately 1500 of these were selected for grain size analysis. These include 4409 results of grain size analyses and there are a total of 392 soil names. Soils were classified into 17 major soil types (gravel to clay, fill, surface soil, etc.); fines content was found to scatter significantly and there were significant difference between the investigated data and the representative value used in practical applications. Then, further classification was made in terms of adjectives such as "sandy", "silty", "with sand", "with silt", etc., and the average fines contents and standard deviations were investigated. Significant variations were found in the fines content distribution between the soils, even within the same major classification. Finally, several case studies were carried out to show the effect of the soil type on the liquefaction resistance strength (F_L value). This showed the importance of the grain size analysis because liquefaction strength is highly sensitive to the F_c value.**

I. INTRODUCTION

Liquefaction strength is, in almost all design specifications, evaluated from an SPT N-value if a specific test is not carried out. The SPT-*N* value is corrected in order to consider the effect of overburden stress and fines content when calculating the liquefaction strength. The fines content is obtained by a grain size analysis. However, in engineering practice, a grain size analysis is not always conducted, in which case a representative fines content is to be used from relevant references. The Japan Road Association [1] and the Japanese Geotechnical Society [2], for example, prepare these tables.

Soils are, however, not classified in detail in these references. For example, JRA [1] classifies soils into only nine types. As a result, three difficulties arise in the engineering practice. The first is that the engineer needs to choose the soil type name in the table although a variety of names are used in the borehole report. The second is a large scattering in fines content results. In fact, JRA [1] wrote "It must be recognized that error may become large when predicting average grain size or fines contents from soil name because data scatters significantly". Moreover, since there is no reference for the background data in these tables, the engineer cannot evaluate possible errors associated with using representative value. The third is that the soil name may be evaluated differently as it is determined from visual judgement by the borehole operator.

In this paper, a more detailed classification is made based on numerous test data, and the differences between the visual judgment of the soil type, and the soil type determined from the grain size analysis are discussed. The classification is made not only for sandy soil, which is necessary for evaluating the liquefaction strength, but also for unliquefiable soils. Finally, the error in evaluating a liquefaction resistance factor is discussed when a representative value is used based on the numerical study.

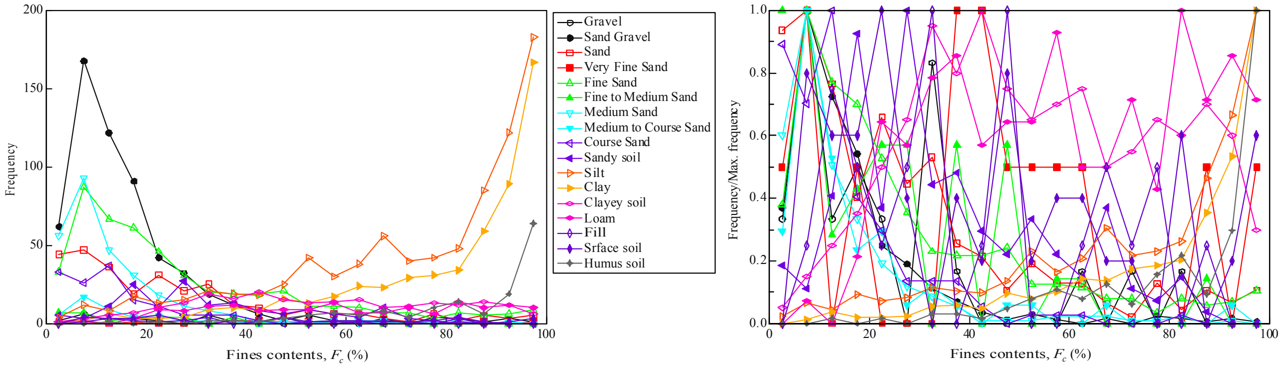
II. DATA SET

Approximately 7,700 borehole data sets are used in this research, which were collected to compile the earthquake geotechnical map of the Miyagi Prefecture, Japan [3]. Among them, there are approximately 1,500 that include the results of grain size analysis; there are 4,409 grain size analysis data sets. This result clearly indicates that a grain size analysis is not consistently conducted in the engineering practice.

There are 392 soil type names used in these 4,409 data sets. These were assigned by the borehole operators; they are determined from the visual judgement, and not from the grain size analysis.

Among the 392 soil type names, the following soils are eliminated from this research. Names that include "rock", such as “clayey rock” are eliminated because they are not

ISBN: 978-92-990075-0-1



(a) Frequency vs. Fines contents (b) Frequency ratio vs. Fines contents

Figure 1. Distribution of fines contents

soil. Names that include "alternate layer" such as "alternate layer with clay and sand" are eliminated because they are not a single soil. In addition, "peat" is eliminated. In total 76 names from 301 test results are eliminated.

Furthermore, soil name that have less than 10 data sets are eliminated, because statistical investigation is difficult. In total 336 names and 800 test results are eliminated in this category.

By eliminating these names, totally 46 names and 3760 test results are used in this research. These soil type names are classified into 17 categories in the major classification and 39 categories in the detailed classification. Since the purpose of this study is fines content for liquefaction strength, unliquefiable soils, such as clay, are not of interest. However, since they may be of interest in other fields, they are included in this paper.

III. DISTRIBUTION OF FINES CONTENTS

A. Major classification

Figure 1(a) shows the distribution of fines content F_c for each major classification shown in the legend of the figure. Here, the number of data sets is recorded at 5 % interval. Since there are significant differences in the total number of data sets between the soil names, the distribution cannot be clearly seen in this figure for soils with small numbers of data sets. Then, the ratio of frequency to the maximum frequency is shown in Figure 1(b).

It is shown that the distribution is not a normal distribution. Sand gravel, sand, medium sand, course sand, fine sand, and course sand have a distribution similar to a logarithmic normal distribution with peaks at small fines content. Silt, clay, and humus soil have a distribution similar to the logarithmic normal distribution with peaks at large fines content. On the other hand, the distributions of fines content do not appear to be well known theoretical distributions for other soils.

Figure 2 shows the average, μ, and standard deviation,

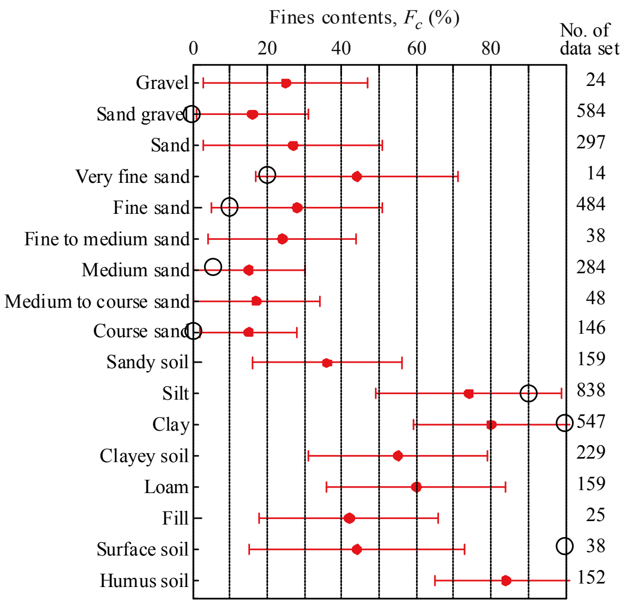


Figure 2. Average and standard deviation of F_c

σ, of each soil type in the major classifications and the total number of data set shown at the right end in the figure. Here

$$\mu = \sum F_{c,i} / n, \quad \sigma = \sqrt{\sum (F_{c,i} - \mu)^2 / n} \qquad (1)$$

where n denotes the total number of data sets in each category; the solid red circles in the figure denote the average, and the region $\mu \pm \sigma$ is shown by horizontal bars.

A large scattering of fines content is shown in this figure. Fines contents shown in JRA as representative values are shown as hollow black circles. There are significant differences between the representative and average values. Sometimes, a hollow circle is located outside of $\mu \pm \sigma$, or is located near the extreme edge. In other words, actual soil includes fewer fines than the representative value of the soil with a large fines content, and more fines for soil with a small fines content. In addition, there is no soil that has a medium fines content,

Table 1. Summary of fine sand

Classification	$F_{c,max}$	$F_{c,min}$	μ	σ	No.
All file sand	100	0	28	23	484
Fine sand	97	0	21	19	318
Silty fine sand	100	6	47	27	71
Clayey fine sand	53	11	31	14	12
Fine sand with silt	100	0	40	24	44

such as clayey soil, loam, and fill in the JRA table.

It is noted that this fact does not indicate that representative value is not relevant, because soils are classified based on the soil type name obtained by the visual judgement. In other words, classification may not be made correctly.

It is also noted that the scattering of the fines contents vary greatly. For example, fines contents of sand ranges from 1 to 99%, and the minimum fines content of clay is 9%. These observations again indicate the difficulty of soil classification by visual judgement only.

B. Distribution of F_c in major classification

A category in the major classification includes several soil type names. Then the distribution of the fines content may not be the same even within the same category. In order to observe this in more detail, fine sand is examined in more detail as an example. It is composed of fine sand, silty fine sand, clayey fine sand, and fine sand with silt.

A summary of these soils is shown in Table 1, where $F_{c,min}$ and $F_{c,max}$ denote the minimum and maximum fines contents, respectively, and "No." denotes the number of data sets.

Figure 3 shows the distribution of fines content in which the ordinate is expressed by the frequency ratio. Here, "All soils" is sum of all soils that are included in the fine sand category. It is further noted that the term "fine sand" has in two meaning, as a category name and a soil type name. In order to distinguish between them, the soil type name is written in quotations "fine sand" only in this section. There is no soil that exhibits a normal distribution. Fine sand exhibits a logarithmic normal distribution. It is clear that this can be attributed to the logarithmic normal distribution of "fine sand". The distibutions of remaining soils scatter and are not similar to well known theoretical distributions.

Scattering may occur when the number of samples is small, however, there are several tens of data sets for silty fine sand and fine sand with silt. This implies that soil classification is difficult in these soils only by visual

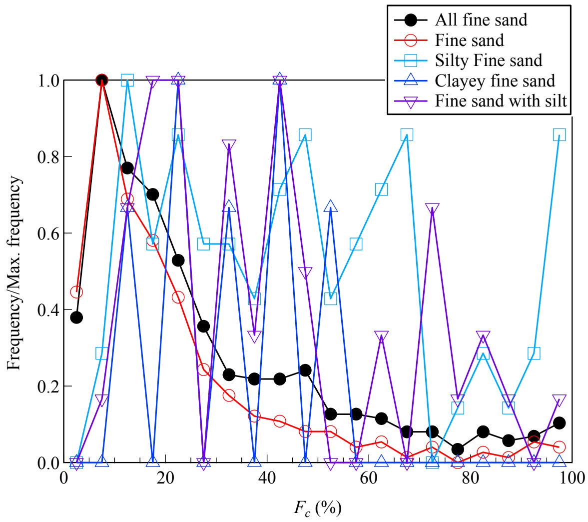
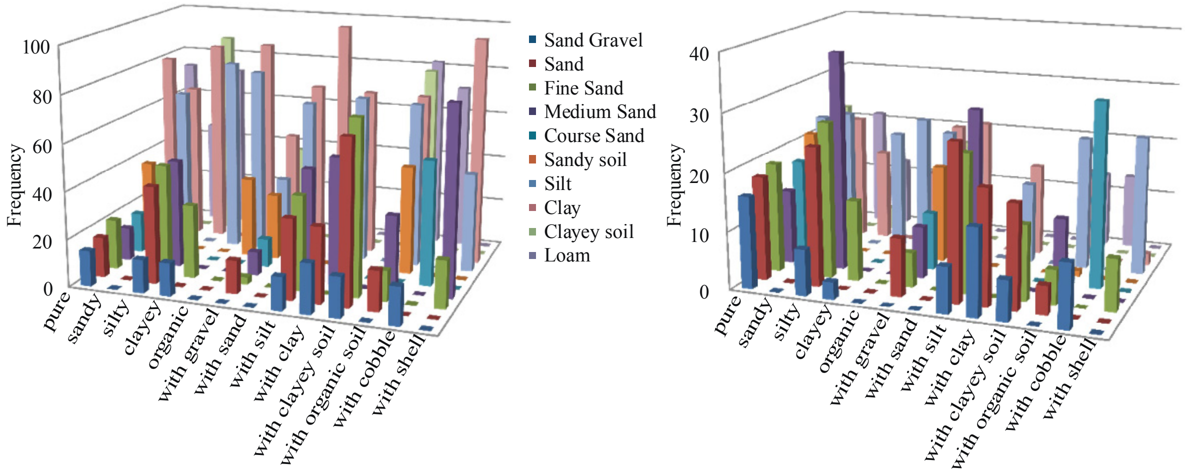


Figure 3 Distribution of fines contents of fine sand

Table 2 Average and standard deviaiton in fine classification

	Sand gravel	Sand	Fine sand	Medium sand	Course sand	Sandy soil	Silt	Clay	Clayey soil	Loam
Pure	15±16	17±18	21±19	14±13	17±17	37±21	31±23	80±22	58±23	73±19
Sandy	–	–	–	–	–	–	67±24	67±22	–	45±21
silty	14±8	41±24	47±27	46±38	–	–	–	87±16	89±4	72±12
clayey	14±3	–	31±14	–	–	–	82±21	–	–	66±0
organic	–	–	–	–	–	34±0	79±24	89±13	–	–
with gravel	–	14±10	35±6	10±9	12±10	28±17	32±22	49±22	40±18	29±10
with sand	–	–	–	–	15±1	–	67±23	72±23	–	–
with silt	14±8	34±27	40±24	48±30	17±8	–	–	99±0	–	–
with clay	21±15	32±20	–	54±0	–	–	71±14	71±16	–	–
with clayey soil	17±7	69±18	74±13	–	–	–	–	–	–	–
with organic soil	–	17±5	13±6	32±13	–	46±1	70±23	71±16	80±15	82±13
with cobble	16±11	–	–	–	53±32	–	–	–	–	71±13
with shell	–	–	20±19	80±0	–	–	42±24	97±2	–	–

Total number of data set is distinguished by color: 1-5 by red, 6-9 by blue, and >10 by black



(a) Average value

(b) Standard deviation

Figure 4. Average and standard deviation in detailed classification

judgement.

C. Detailed classification

Soil type is sometimes named according to appropriate adjectives, such as sandy and silty. Another naming method is to use "with" plus including soil, such as "with sand" and "with clay". Considering these, a more detailed classification is made and is summarized in Table 2 and Figure 4. Ten typical soil names are shown among 17 major classifications. Here, the average and standard deviation are shown in the form of $\mu\pm\sigma$. The number of data sets in each category is distinguished by color. Those greater than or equal to 10 are shown in black, those in the 6 to 9 range in blue, and those in the 1 to 5 range in red. It is noted that data in red and blue may not be statistically significant because of limited data points. For example, zero standard deviation may be the case where there is only one soil in the case of a red soil name. Then they are not discussed in this research.

The first row shown as "Pure" is the soil name that does not include an adjective.

As with discussed in the previous section, the scatter is large in the same major classification. For example, the average of fines content ranges from 17 to 69, and those of medium soil from 10 to 80. This indicates that a representative classificaiton of approximately 10 is too small.

D. Ranking of soil classification

As discussed in the following chapter, fines content affects the liquefaction strength significantly. Therefore, in this study, the ranking of soil classification is made as shown below, where soil type names are ranked A to D according to standard deviation; A for $\sigma\leq10$, B for $11\leq\sigma\leq15$, C for $15\leq\sigma\leq20$ and D for $\sigma>20$. Table 3 shows the ranking of the soil type in each classification.

Table 3. Ranking of soil classification
(a) Major classification

A	Very fine sand
B	Fint~medium sand, Medium sand, Course sand
C	Sand gravel, Sand, Fine sand, Medium~course sand, Loam, Humus soil
D	Gravel, Sandy soil, Silt, Clay, Clayey soil, Fill, Surface soil

(b)Detailed classification

A	Sand gravel with silt, Sand gravel with clayey soil, Sand with gravel, Medium sand with gravel, Course sand with gravel, Clay with shell
B	Sand gravel with clay, Sand gravel with cobble, Clayey fine sand, Organic clay, Silty clay, Silty loam
C	Sandy soil with grave, Silt with sand gravel, Clayey soil with humus, Clayey soil with gravel
D	Silty sand, Sand with gravel, Silty fine sand, Clayey silt, Silt with humus, Silt with shell, Sand loam, Loam with gravel, Sandy clay, Clay with sand

IV. EFFECT OF F_c ON LIQUEFACTION STRENGTH

In order to determine the accuracy of the evaluated liquefaction strength, two case studies are conducted: the effect on the liquefaction strength, and the case study on actual soils

A. Liquefaction strength

Liquefaction strengths based on two design specifications, JRA [1] (Japan Road Association) and AIJ [4] (Architectural Institute of Japan), are examined to evaluate the effect of fines. Liquefaction strength R_L is calculated as

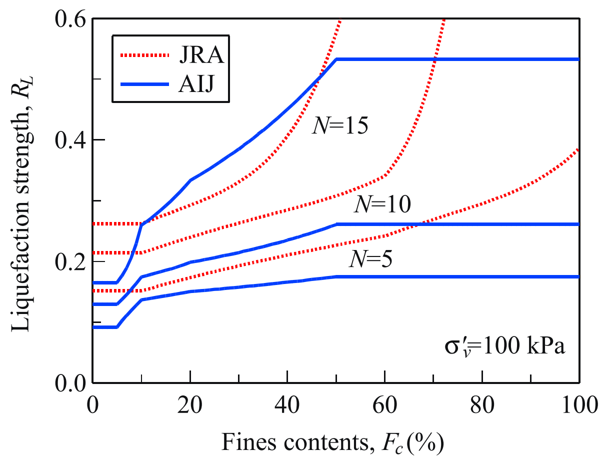


Figure 5 Liquefaction strength vs. fines contents

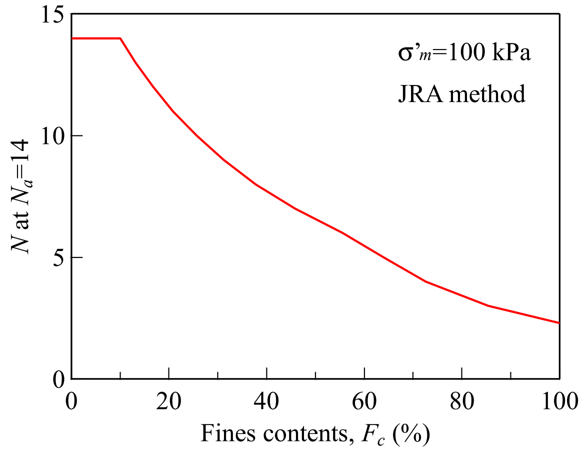


Figure 6. Fines contents at N_a=14

JRA:

$$R_L = \begin{cases} 0.0882\sqrt{N_a/1.7} & (N_a < 14) \\ 0.0882\sqrt{N_a/1.7} + 1.6\times10^{-6}\cdot(N_a - 14)^{4.5} & (N_a \geq 14) \end{cases}$$

$$N_a = C_1 N_1 + C_2, \quad N_1 = 170N/(\sigma'_v + 70)$$

$$C_1 = \begin{cases} 1 & (0\% \leq F_c < 10\%) \\ (F_c + 40)/50 & (10\% \leq F_c < 60\%) \\ F_c/20 - 1 & (60\% \leq F_c) \end{cases}$$

$$C_2 = \begin{cases} 0 & (0\% \leq F_c < 10\%) \\ (F_c - 10)/18 & (10\% \leq F_c) \end{cases} \quad (2)$$

AIJ:

$$R = aC_r\left[\frac{16\sqrt{N_a}}{100} + \left(\frac{16\sqrt{N_a}}{C_s}\right)^n\right]$$

$$N_a = N_1 + \Delta N_1, \quad N_1 = \sqrt{98/\sigma'_{v0}}\cdot N \quad (3)$$

$$\Delta N_1 = \begin{cases} 0 & F_c < 0 \\ 1.2F_c - 6 & 5 \leq F_c < 10 \\ 0.2F_c + 4 & 10 \leq F_c < 20 \\ 0.1F_c + 6 & 20 \leq F_c \leq 50 \end{cases}$$

where σ'_v denotes initial effective overburden stress, a=0.45, C_r=0.57, n=14, and C_s=80 [5]. The SPT-N value is corrected twice; N_1 is the SPT-N value that has been corrected by considering the effect of the overburden stress and N_a is the SPT-N value after the correction of the effective overburden stress and fines content. The definition of the shear strain at liquefaction differs between the two specificaiton; double the amplitude of axial strain DA is 5% (single shear strain amplitude γ=3.75 %) in the JRA method, whereas γ=5 % in the AIJ method. The definition of the liquefaction strengths are also different; τ_a/σ'_m is used in the JRA method, whereas τ_a/σ'_v is used in the AIJ method, where τ_a denotes the shear stress amplitude and σ'_m the initial effective confining stress. Although correction of fines content ΔN_1 is not specified for F_c>50 in the AIJ method, it is assumed to be constant (ΔN_1=11) following engineering practice. In the JRA method, soils with fines content greater than 35% and a plasticity index greater than 15 are considered to be unliquefiable, but are treated as liquefiable in this study because there is no data on the plasticity index.

Figure 5shows an example of the liquefaction strength R_L as a function of fines contents where the effective overburden stress is set as 100 kPa which corresponds to soil at several meters deep. Liquefaction strengths differ siginificantly between soil with very low and very high fines content.

The latter case occurs as the correction term of fines content, ΔN_1, is assumed to be constant at high fines content in the AIJ method. On the other hand, as seen in Eq. (2), the liquefaction strength increases rapidly when N_a>14 in the JRA method. In order to examine this effect clearly, relatonships between the SPT-N value and the fines content at which N_a=14 is shown in Figure 6. Fines contents are 44 and 64 % for N = 10 and 5, respectively. This figure shows that the liquefaction strength can become very large even in weak soil if the fines content is high. This case has high possibility of occurrence for very fine sand and silt by referring to Figure 2, and for soil with silt by reffeering to Table 2.

The differences between the two methods are not significant in medium fines contents, but the differences when N=10 is approximately 0.05, and may be siginificant.

B. Case study

Two case studies are carried out in order to observe the effect of fines contents on the onset of liquefaction. The one is Yuriage site [6] and the other is Jingahara site [7] in Miyagi Prefecture, where liquefaction occurred during the 1978 Off-Miyagi and 2011 Tohoku earthquakes,

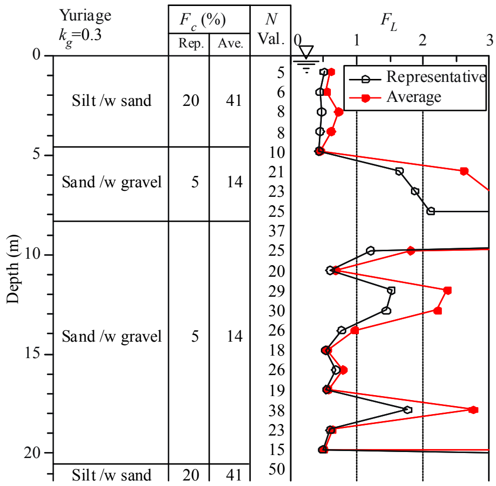


Figure 7. Yuriage site

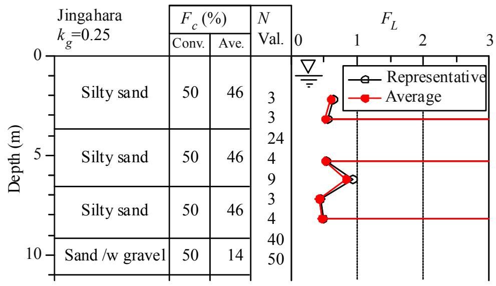


Figure 8. Jingahara site

respectively.

The JRA method is used to evaluate the liquefaction resistance factor F_L, where

$$F_L = R_L / L$$
$$L = r_d k_{hg} \frac{\sigma_v}{\sigma_v'} \quad (4)$$
$$r_d = 1 - 0.015z$$

Here, k_g denotes the design seismic coefficient, σ_v the initial total overburden stresses, and z the depth from the ground surface. In the actual situation, k_g is usually defined as a ratio of PGA to acceleration of gravity. It is set 0.3 and 0.25 at Yuriage and Jingahara sites, respectively, as suggested in [6] and [7]. The average fines contents and representative fines contents showin in Figure 2 are used in the analysis.

Figure 7shows result at the Yuriage site and Figure 8 shows result at the Jingahara site, respectively. Obviously, liquefaction is expected as it actually occurred. There is not significant differences in F_L values at the Jingahara because there is little difference between the average and representative fines contents. On the other hand, singificant differences is seen in F_L values at the Yuriage site although judgement of liquefaction occurrence is same. It is noted that the difference of fines contet is only 9%; it is not so large value refering in Figure 2. These detailed case studies suggest the importance of accurately evaluating the fines content.

V. CONCLUDING REMARKS

The distributions of fines contents were examined based on approximately 1500 borehole data, in which 4,409 grain size analysis data were included. There are 392 soil type names, which were determined by the borehole operator based on visual judgement. This indicates that a variety names are used to express a soil names. On the other hand, the number of soil names used for representative soil is limited compared with the variety of soil names that are given in engineering practice.

It is also noted that fines contents for representative soils are quite different to the actual distributions. They are generally at the extreme edge of the range of the average ± standard deviation values, or outside this region.

The examination of fines contents with regard to assessing the possibility of liquefaction based on liquefaction resistance factor F_L indicates that F_L is high sensitive. Differences of 10 % may result in differences of liquefaction strength for more than double especially at low fines contents.

It is further pointed out that the fines contents exhibit significant scatter, even within the same soil name.

Considering these observations, it is strongly recommended that a grain size analysis be conducted, and that the fines contents from typical classification in engineering practice not be used

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