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STRENGTH RATIO CAUSING LIQUEFACTION OF DILUVIAL SOIL

Ryo SAWADA [1], Takaki MATSUMARU[2] Motohiro OHKI[3]

ABSTRACT

The increasing costs of design and construction to combat the effects of liquefaction caused by major earthquakes are often considered, as conventional methods of evaluating the strength ratio suggest that the probability of liquefaction is high. The results given are not representative, and evaluation is made on the safe side in diluvial soil. We therefore carried out a systemized investigation into soil quality to understand the strength ratio that causes liquefaction in diluvial soil. The results confirmed that cementation was present in older sedimentation areas, and that the large amounts of fine-grained soil found there provided around twice the strength of alluvion soil. In addition, we suggest a design method based on these results. In diluvial soil, improvements in the rationality and economy of designing and building structures against liquefaction, as well as liquefaction countermeasures, have been made possible thanks to the increased precision of evaluating liquefaction.

Keywords: strength ratio causing liquefaction, diluvial soil, soil investigation, cementation

INTRODUCTION

Evaluating seismic-resistant structures in consideration of the adverse effects of ground liquefaction requires accurate prediction of the probability, degree and extent of such liquefaction. In assuming the behavior of a structure built on liquefied ground, the reduced bearing capacity caused by liquefaction is the biggest affecting factor to be addressed.

However, in previous earthquakes such as the Great Hanshin Earthquake, it is significant that liquefaction did not occur even under external forces due to the mega-seismicity of the ancient sedimentary diluvial sands in the area.

According to current seismic-resistant design codes for railway structures, evaluation is always performed on the safe side when determining liquefaction phenomena.

To improve the accuracy of evaluating liquefaction, we conducted an analysis of appropriate methods to evaluate the liquefaction strength ratio indicating a degree of ground resistance against diluvial sand ground based on the results of systematic soil surveys.

[1] Senior Researcher, Railway Technical Research Institute, Email: sawada@rtri.or.jp
[2] Researcher, Railway Technical Research Institute
[3] Researcher, Central Japan Railway Company

A WAY OF THINKING BY AN EXISTING SEISMIC DESGIN CODE FOR RAILWAY STRUCTURE

In current seismic-resistant design for railway structures, the reduced soil strength caused by liquefaction is related to the degree of liquefaction, and a resistance factor as an index applicable to judging the probability of liquefaction is in practical use (RTRI, 1999).

The resistance factor of liquefaction shown in Fig. 1 is derived from comparing the liquefaction strength ratio (obtained either from laboratory soil testing or in-situ testing using the *N*-value) and the external forces (an earthquake's shear stress ratio) that act on the ground during an earthquake (obtained either from the results of seismic response analysis or earth-surface maximum acceleration data).

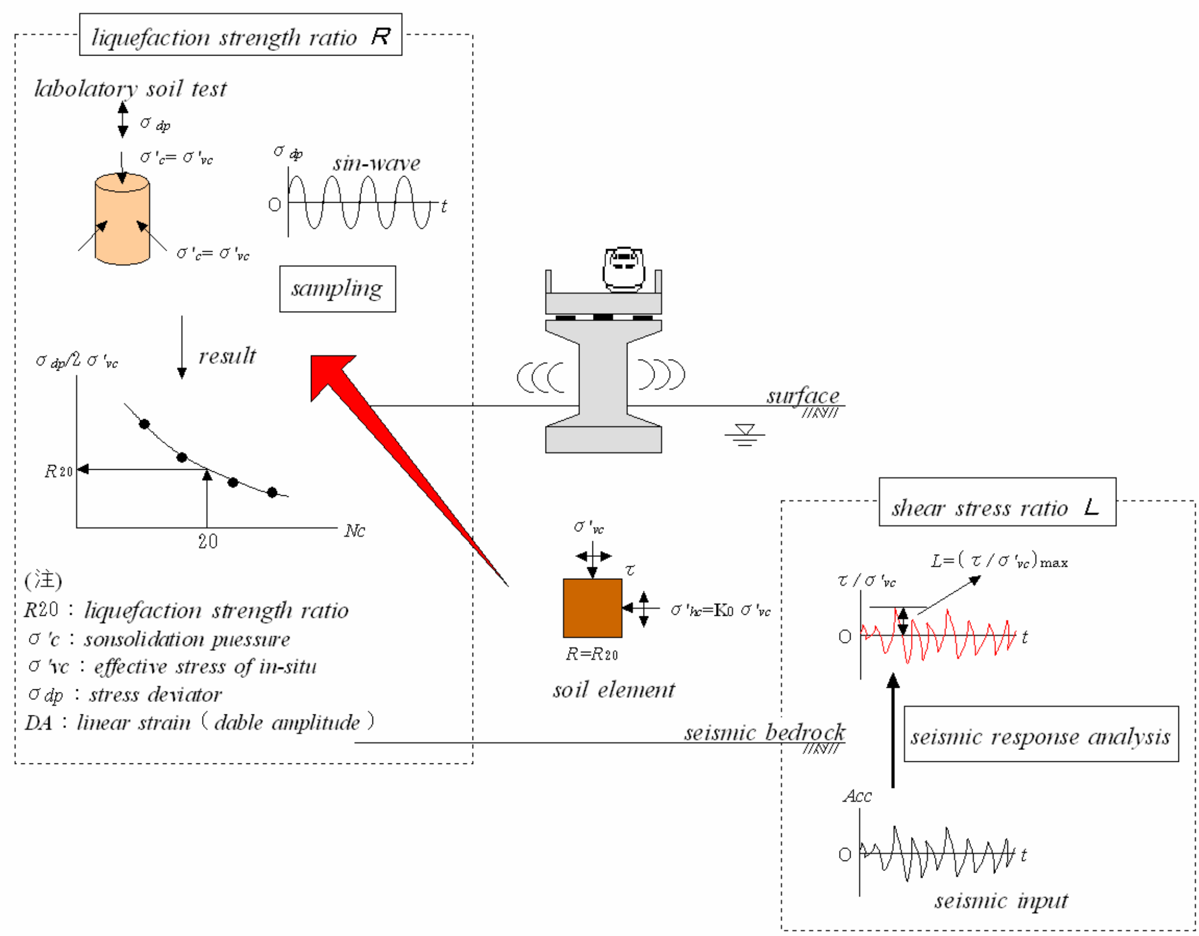


Fig. 1. Presumed method of liquefaction strength ratio and shear stress ratio

In other words, the liquefaction resistance factor of 1.0 calculated for expression (1) at each examination depth represents liquefaction in the following earth layers, and the degree of liquefaction is judged using the liquefaction resistance factor value calculated.

$$F_L = \frac{R}{L} \qquad (1)$$

where F_L is the liquefaction resistance factor, R is the liquefaction strength ratio and L is the shear stress ratio of the earthquake.

In cases where the liquefaction strength ratio is estimated from a laboratory soil test and the shear stress ratio is derived from seismic response analysis at the time of an earthquake, the results of liquefaction judgment have a high level of precision. However, laboratory soil testing (involving a cyclic undrained triaxial soil test) to find the liquefaction strength ratio is expensive. The relative density has a strong influence on this ratio, and the *N* value and related factors have an effect on the relative density. This means that the *N* value and the liquefaction strength ratio are directly connected, and it is common for the liquefaction strength ratio to be estimated using the *N* value.

However, in recent years it has been pointed out that liquefaction can occur in ground conditions that were previously thought safe for the depth of the presumed precision of seismic force with a liquefaction strength ratio estimated from experience using the *N* value. Evaluation of the safe side is considered to be excessive in diluvial sand, as outlined above. In particular, it cannot be said that a proper judgment is obtained when examples of the previous and original strength characteristics of soil were considered.

EXAMINATION ABOUT AN INFLUENCE FACTOR TO GIVE TO LIQUEFACTION STRENGTH

The factors influencing the liquefaction strength characteristics of diluvial sand were examined using test results from an undisturbed sample (PWRI, 1988). This examination looks at sandy ground with infinitesimal grains, and the fine soil content is around several percent in alluvial ground in particular. An undisturbed sample can be obtained by freezing the soil before taking an overall sample.

Figure 2 compares the ratio (i.e. the R_{test}/R_{code} value) of a design value demanded for examination (R_{test}) and the existing seismic design code presumed expression (R_{code}). The presumed expression of the liquefaction strength ratio has a standard *N* value (N1), a relative density (Dr) and a fine soil content (Fc) each. These three properties of matter are the parameters used for the presumed expression when the liquefaction strength ratio is estimated with the existing seismic design code for railway structures using the *N* value.

The relationship between the values of N1 and R_{test}/R_{code} shows that R_{test}/R_{code} is around 1.0 in the area where N1 is almost 10, but the overall tendency is not clear. In addition, when evaluated individually, the N1 value shows an emission tendency at around 25 for alluvial ground. Thus, a few examples liquefied at an N1 value of around 25, but it is thought that this evaluation is on the safe side.

However, the R_{test}/R_{code} value is large at an N1 value of around 5-10 in diluvial ground, but does not show a good tendency. However, the liquefaction strength in diluvial ground generally tends to be larger than in alluvial ground, which suggests that resistance against liquefaction increases under the influence of the sedimentation era.

In addition, when *Dr* is more than around 80%, according to the relationship between *Dr* and R_{test}/R_{code}, a tendency showing a slight emission is shown. In the *N* value and the expression of the relationship with *Dr* shown in the seismic design code for railway structures, *N1* is evaluated as being safe if *Dr* exceeds 80% when it is around 25. It is therefore thought that *Dr* emits at around 80%, and there is no clear difference between alluvial and diluvial ground.

In terms of the relationship between *Fc* and R_{test}/R_{code}, the distribution shape reveals a difference between diluvial and alluvial ground. The tendency for the R_{test}/R_{code} values of diluvial ground to increase when the fine soil content increases was confirmed. This suggests that there is a correlation between the fine soil content and the sedimentation era.

The liquefaction strength of diluvial sand is influenced by the sedimentation era, and it is estimated that a high correlation increases the strength and content of fine soil. It may therefore be necessary to consider the fine soil content and the influence of the sedimentation era to clarify the liquefaction strength of diluvial sand (Sawada et al., 2002).

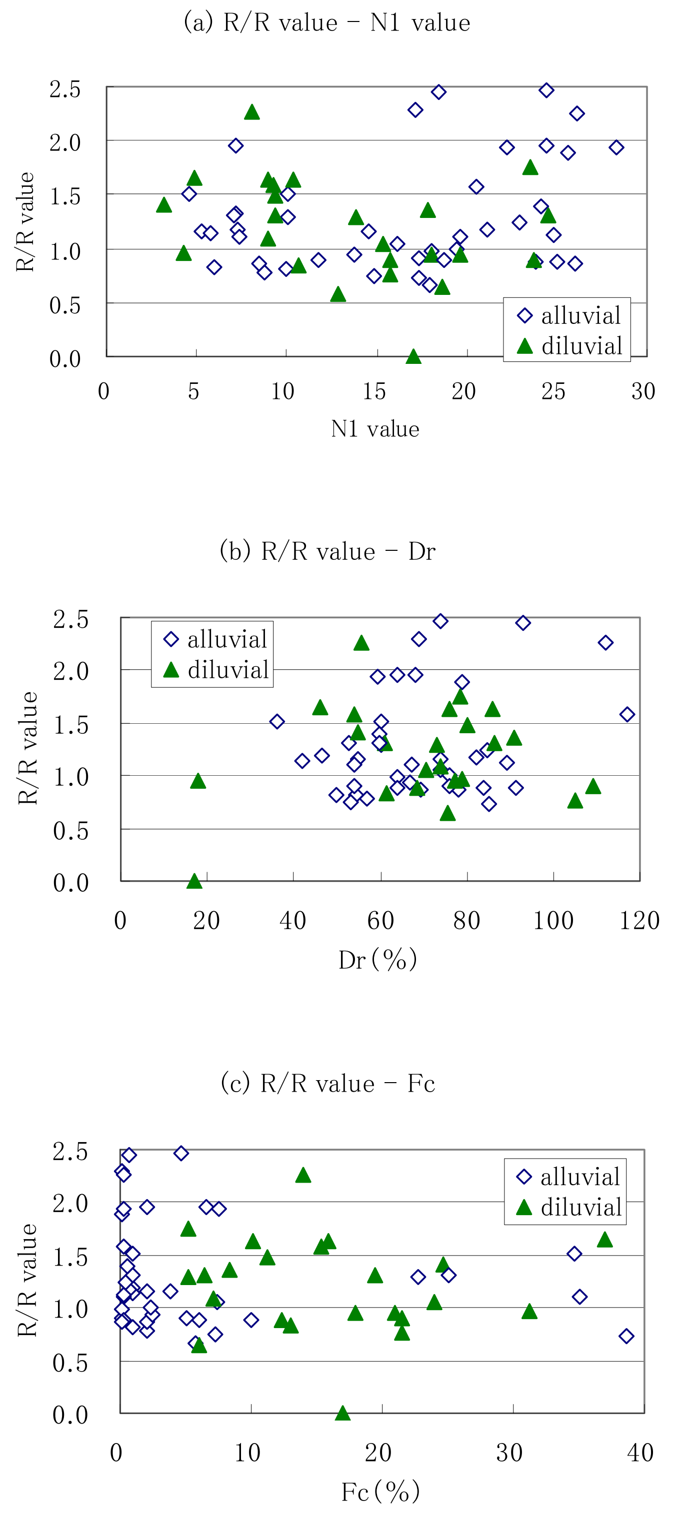


Fig. 2. Comparison of the ratio (R_{test}/R_{code} value) - N value (N1 value), relative density (Dr) and fine soil content (Fc)

EXAMINATION OF A LIQUEFACTION STRENGTH CHARACTERISTIC OF DILUVIAL SAND

Examination of a generation effect to give to liquefaction strength

Examination by a non-disturbance sample

In the examination outlined above, a tendency for the liquefaction strength characteristics of diluvial sand to increase with the progress of the sedimentation era was suggested. Systematized soil investigation was therefore carried out, and the factors that cause an increase in liquefaction strength were examined. The examination used an undisturbed sample gathered locally and a disturbed sample, and looked at the degree of change in the liquefaction strength, internal friction angle and cohesion. In addition, the disturbed sample was evaluated as being unaffected by the era. The influence of infinitesimal grains was also considered in collecting an undisturbed sample, and a tube was used to gather it.

The physical characteristics of the soil for examination are shown in Table 1. An example of the liquefaction test results for samples collected in the three spots shown in Table 1 is shown in Figure 3. According to these results, the liquefaction strength ratio of an undisturbed sample is large in comparison with a disturbed sample, and the tendency is remarkable at point C where the sedimentation era is old. From the above, the sedimentation era can be thought to have some influence on the liquefaction strength.

Table 1. Sample used for examination and CD test results

		A spot		B spot		C spot	
Geological time		300,000 years		150,000 years		1,700,000 years	
Depth (m)		6.5	10.5	13.0	21.0	17.0	21.0
N value		14.0	20.0	21.0	14.0	5.0	7.0
Fc (%)		5.0	5.0	21.0	13.0	37.0	22.0
effective stres (kPa)		78.5	118.0	78.5	117.7	98.1	117.7
undisturbed sample	c_d (kPa)	2.0	2.4	5.2	6.4	61.0	59.0
	φ_d (°)	44.0	44.9	41.1	40.3	28.6	30.1
disturbed sample	c_d (kPa)	0.9	2.1	1.6	6.8	2.4	9.5
	φ_d (°)	38.1	33.2	36.3	34.9	31.9	32.2

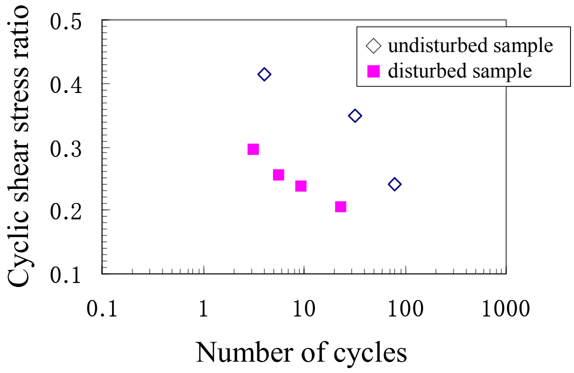
Fc ; content of fine soils, c_d ; cohesion, φ_d ; internal friction angle

However, from the internal friction angle and the cohesion value obtained through CD examination (a compaction drained triaxial soil test) of the undisturbed sample shown in Table 1, the cohesion at point A is the lowest, and the value is large at C where the sedimentation era is the oldest. This shows a correlation between cohesion and liquefaction strength. In addition, comparing point B at 13m and point C at 21m with an approximately equal fine soil content demonstrates that the cohesion is different. This suggests that the cohesion value is strongly influenced by the sedimentation era.

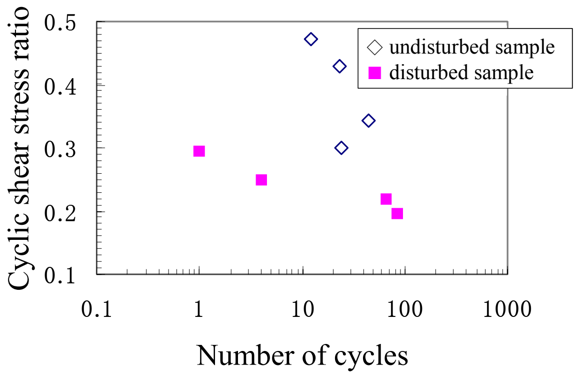
The CD test results of the disturbed sample showing that the cohesion and internal friction angle were small were confirmed in comparison with the undisturbed sample at points A and B. It was also confirmed that the cohesion of the disturbed sample was extremely small at point C and small at other points. In terms of the factors influencing the liquefaction strength, the increase in cohesion according to the sedimentation era is suggested by previous examination results.

In addition, the increase in the internal friction angle is identified as 6.5m deep and 10.5m deep at spot A where the fine soil content is around 10%. Spot B shows a similar result at 21m in depth. Close inspection of the factors increasing liquefaction strength in the case of infinitesimal grains is needed so that liquid strength increases if the internal friction angle is large.

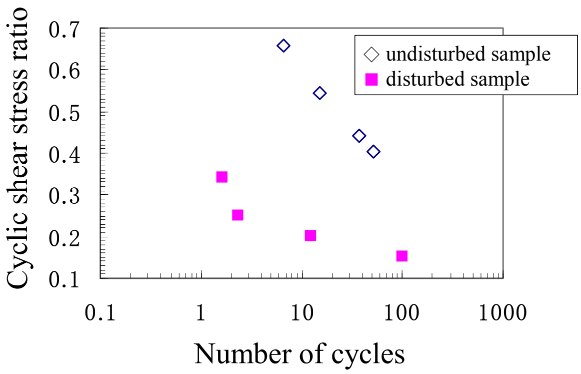
However, it is possible that the disturbed frame structure of the soil at the time the disturbed sample was made is one of the factors causing an increase in the internal friction angle. The frame structure is stable to some extent, so the soil can be tense from the era effect if the frame structure is disturbed, and the internal friction angle is thought to change significantly. It should be pointed out that this tendency was confirmed in the test results of spot C that included a large quantity of infinitesimal grains. However, the influence of the change in the degree of cohesion is large, but is not obvious. In spots A and B, the sedimentation era is younger than in spot C. It is also thought that this influence was clear because there is little an infinitesimal grain.



(1) A spot (6.5m)



(2) B spot (13.0m)



(3) C spot (17.0m)

Fig. 3. Results of cyclic undrained triaxial soil test

Inspection by a disturbed sample

In the above examination of the factors that influence increased liquefaction strength, it was supposed that the increased degree of cohesion from the era effect was a factor, and it was suggested that this degree was dependent on the numerousness of infinitesimal grains.

The increased degree of liquefaction strength in the short run was examined, and there was thought to be a difference of 150,000 years in the undisturbed and disturbed samples within the era. The period required for the effect of the era to have an influence was also examined.

The examination was carried out using a disturbed sample of Inagi sand with a fine soil content *Fc* of 16%, the same content as that found at a depth of 21m at spot B. The laboratory soil test was similar to the one outlined above, and cases with a pre-loading period of zero months and one month were carried out.

The liquefaction test results for the two different pre-loading periods are shown in Figure 4. At one month, it can be seen that the liquefaction strength increases just a little, and the increase of the adhesion ingredients from the results of the CD examination displayed in Figure 5 is also small. This shows that the liquefaction strength increases little by the sedimentation era, and demonstrates a qualitative tendency of agreement with past findings.

These results also suggest that the expression of cohesion from the effect of the sedimentation era is one of the factors that increases liquefaction strength (Sawada et al., 2002). However, the degree of the increase is not large, and it is thought that a period of hundreds of thousands of years is necessary to increase strength to the degree considered by the design. No effect is therefore expected from the sedimentation era of the alluvial period (Kimura et al., 1986; Yasuda et al., 2003).

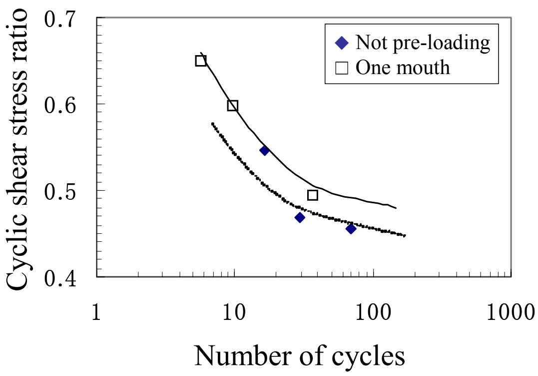


Fig. 4. Results of cyclic undrained triaxial test of soil (Inagi sand)

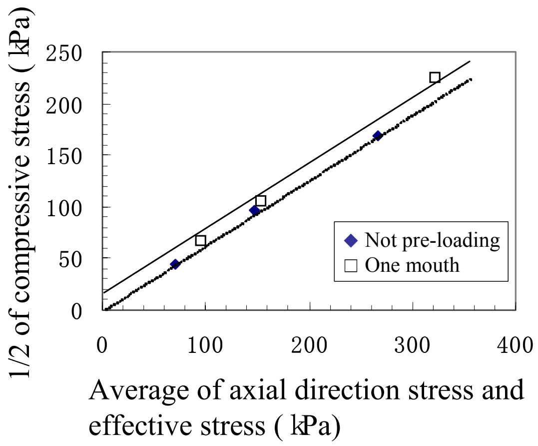


Fig. 5. Results of CD test (Inagi sand)

Evaluation of the liquefaction strength characteristic that considered an effect in the generation
The examination outlined above looked at the cohesion developed by fine soil content and the sedimentation era, and an increase in the liquefaction strength was confirmed. With the fine soil content as a parameter, the effect of the sedimentation era and its relationship with the increase in liquefaction strength is shown in Figure 6. This demonstrates that the ratio of increase in liquefaction strength changes greatly according to the degree of fine soil content, and is from 15% to around 30% at the highest fine soil content *Fc* value.

In addition, the degree of increase tends to taper off when the fine soil content *Fc* is more than around 30%. At *Fc* levels above this, properties similar to those of clay are shown, and any changes in resistance against liquefaction and sensitivity related to the sedimentation era are thought to be small.

On the basis of these tendencies, we decided to consider a method of evaluating the liquefaction strength characteristics of diluvial sand using a surcharge coefficient that includes the sedimentation era and the degree of fine soil content, as shown in Figure 6. Liquefaction strength is commonly estimated using the *N* value, as this strength is easily evaluated through normal soil investigation at the time of design. In this method, the evaluation technique for conventional alluvion ground is followed, and in consideration of the unevenness of the examination results, the sedimentation era is divided into chronological first and second halves as a border. The method also uses an evaluation technique dividing the surcharge degree of liquefaction strength calculated using the *N* value with a fine soil content *Fc* of 15 % as a border.

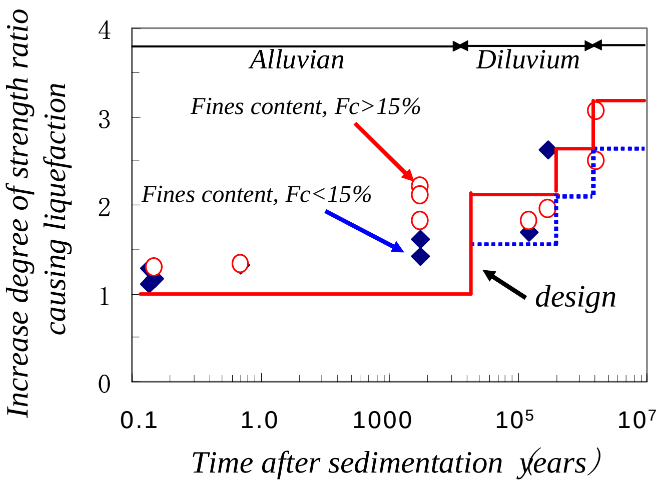


Fig. 6. Relationship between the increase in the strength ratio causing liquefaction and the time after sedimentation

EVALUATION EXAMPLE BY SUGGESTION METHOD

The ground used for the test calculations consisted of diluvial sand with a small *N* value distributed over a comparatively shallow range, and had an intended earthquake vibration spectrum Ⅱ of the L2 level.

Liquefaction occurs according to the results of evaluation using the technique outlined in the existing seismic design code for railway structures in the whole area of the class of sand as shown in Figure 7. The liquefaction resistance factor is less than 0.6, which is severe. In this case, a large-diameter pile foundation or adoption of large-scale soil improvement is necessary to make structures safe against liquefaction. This is expected to cause serious problems from the viewpoint of execution and cost.

However, according to the evaluation technique suggested here, the liquefaction resistance factor of the sand layer exceeds 1.0, and is therefore not considered to be at risk of liquefaction. This result takes into account the history of earthquake-related liquefaction in diluvial sand to give a realistic value, and in this case the specifications of the pile foundation are commonly used. Execution in the spread foundation is also possible depending on the conditions, and a large reduction in cost is anticipated in comparison with conventional evaluation techniques. This suggests the feasibility of rational design in accordance with actual conditions.

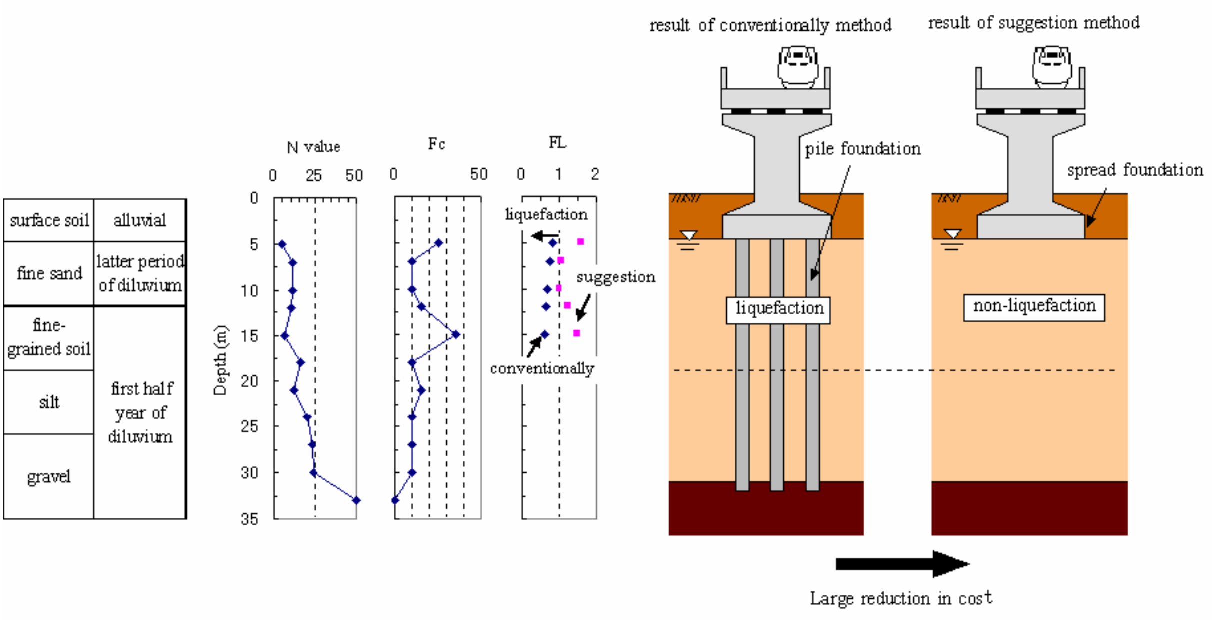


Fig. 7 An example of evaluation results using the suggested method

CONCLUSIONS

(1) The results of examining the liquefaction strength characteristics of diluvial sand based on detailed soil investigation clarified that the cohesion expression was a major factor affecting increases in liquefaction strength with the effect of the sedimentation era, and that the degree of this effect is influenced by the fine soil content.

(2) When the liquefaction strength characteristics of diluvial sand were estimated to consider design by the conventional technique using the *N* value, an extra degree of liquefaction strength was identified according to the sedimentation era and its relationship with the fine soil content.

(3) Potential plans for rationalizing basic design were confirmed through test calculations applied to real ground conditions using the simple technique suggested for the liquefaction strength characteristics of diluvial sand.

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