Chapter 7 Ground Liquefaction

[Public Notice] (Ground Liquefaction)

Article 17

Ground liquefaction shall be assessed with appropriate methods based on ground conditions in consideration of the actions due to the earthquake ground motion.

[Interpretation]

7. Setting of Natural Conditions

(6) Subjects related to the earthquake (Article 6 of the Ministerial Ordinance and the interpretation related to Article 16 and 17 of the Public Notice)

⑧ Ground Liquefaction

a) Effects of Liquefaction in the Case of Level 1 Earthquake Ground Motions

For ground liquefaction in the case of Level 1 earthquake ground motions, measures against ground liquefaction are basically taken when liquefaction is predicted and assessed to occur by taking into account the effects of liquefaction on structures, surrounding situations of the target facilities, etc.

b) Effects of Liquefaction in the Case of Level 2 Earthquake Ground Motions

For the consideration of ground liquefaction in the case of Level 2 earthquake ground motions, the methods of taking measures against liquefaction and the necessity of their implementation are determined on the basis of a comprehensive consideration of the situations of the facilities surrounding the target facilities.

1 General

The subjects described in this chapter may refer to the *Handbook of Liquefaction Measures Works for Reclaimed Land* (Revised Edition).[1)]

The following methods are basically for the consideration of ground liquefaction in the case of Level 1 earthquake ground motions. When liquefaction is predicted and assessed to occur by applying the following methods to the Level 1 earthquake ground motions, consider the effects on structures, and take the liquefaction countermeasure works in principle. The option to not perform liquefaction countermeasure works may be taken as long as there are strict restrictions in construction, such as the improvement of existing facilities. In that case, pay attention to the fact that the commonly used earth pressure formula, calculation equation for the modulus of subgrade reaction, bearing capacity formula, and others cannot be applied. Furthermore, the method of performance verification should be examined by considering the effect of liquefaction.

For the consideration of ground liquefaction in the case of Level 2 earthquake ground motions, careful consideration is needed because the equivalent linear analysis shown in **2(3)②** below may become an unsafe side evaluation for a certain ground composition when the strain level is high. Moreover, the methods of liquefaction countermeasure works and the necessity of their implementation shall be determined on the basis of a comprehensive consideration of the situations of the facilities surrounding the target facilities. Refer to the description on the performance verification of facilities in **[Action] Chapter 6 Earthquakes and Facilities**.

2 Prediction and Assessment of Liquefaction

(1) The prediction and assessment of whether the ground is liquefied are generally performed by proper methods using grain sizes and *SPT-N* values or using the results of cyclic triaxial compression tests. **Figs. 2.1.1** and **2.1.2** show the basic prediction and assessment procedure of liquefaction and the prediction and assessment procedure with the grain size and *SPT-N* value.

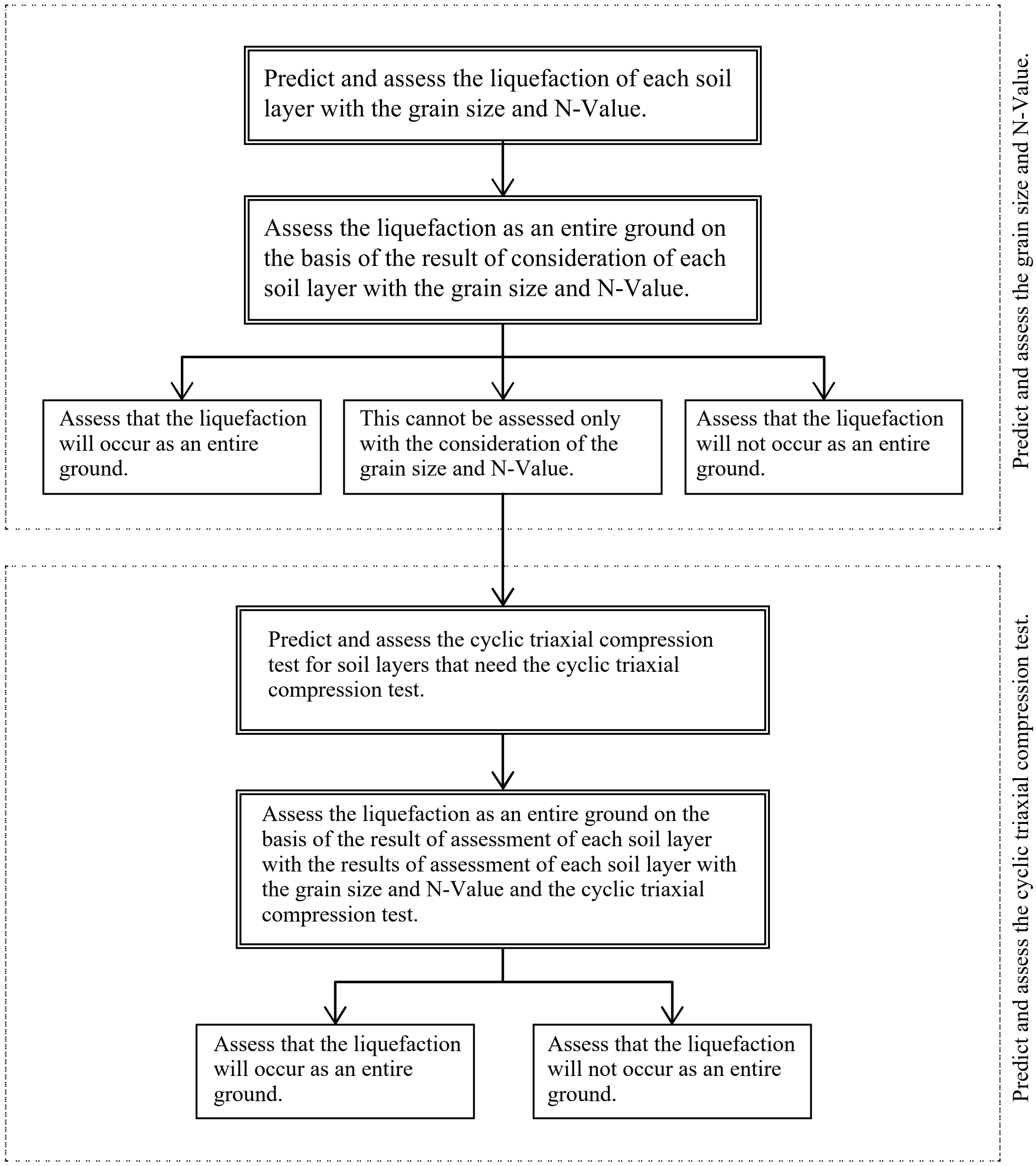

Fig. 2.1.1 Basic Prediction and Assessment of Liquefaction

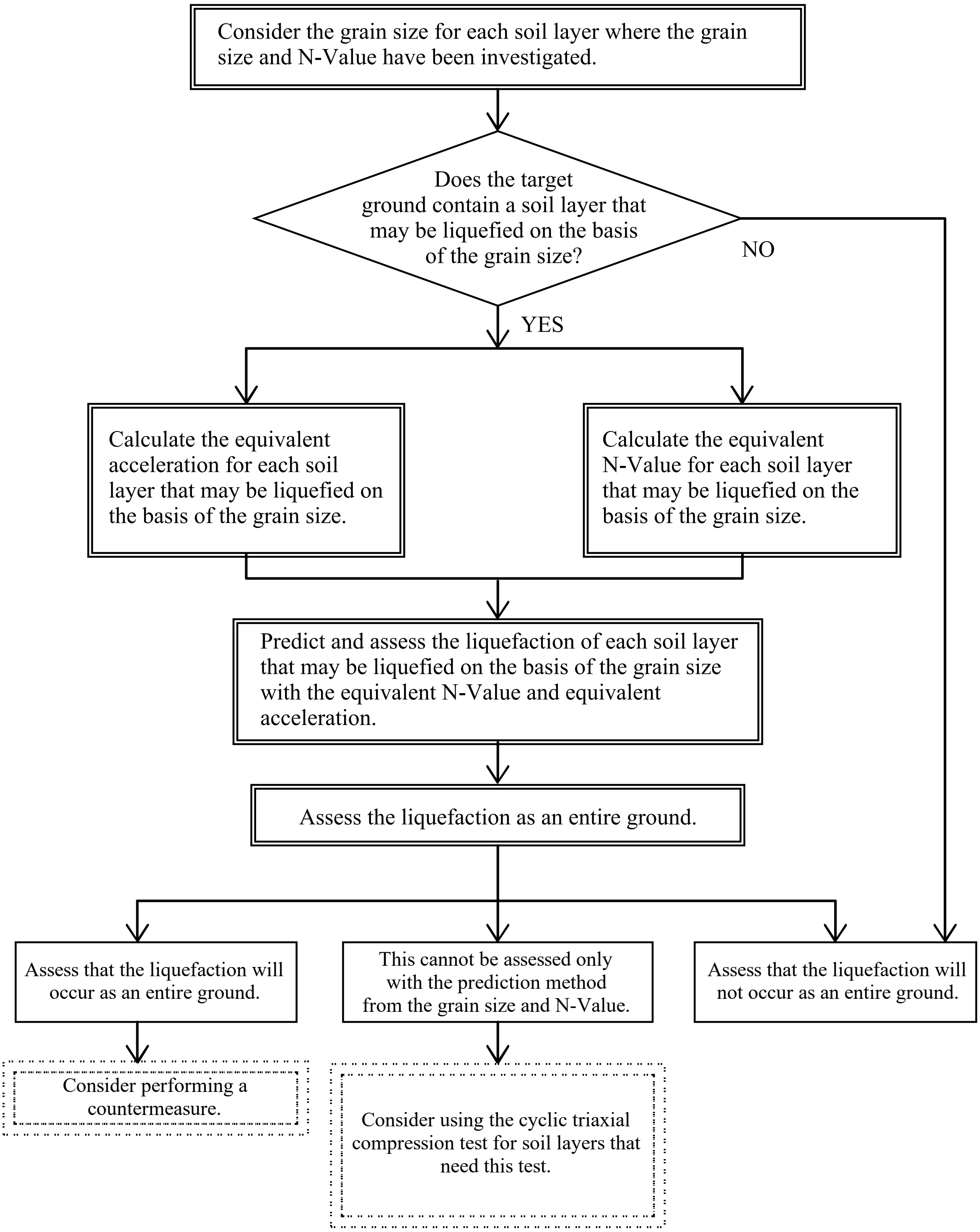

Fig. 2.1.2 Prediction and Assessment Procedure with the Grain Size and *SPT-N* value

(2) Types of Prediction and Assessment of Liquefaction

Liquefaction prediction and assessment methods include the method using grain sizes and *SPT-N* values or the method using the results of cyclic triaxial compression tests. The method using grain sizes and *SPT-N* values is simple and easy and can be generally used for predicting and judging liquefaction. The method using the results of cyclic triaxial compression tests is more detailed and can be used when the prediction and assessment using grain sizes and *SPT-N* values are difficult or when more detailed considerations are needed.

(3) Prediction and Assessment of Liquefaction Using Grain Size and *SPT-N* values [2)]

① **Assessment based on grain size**

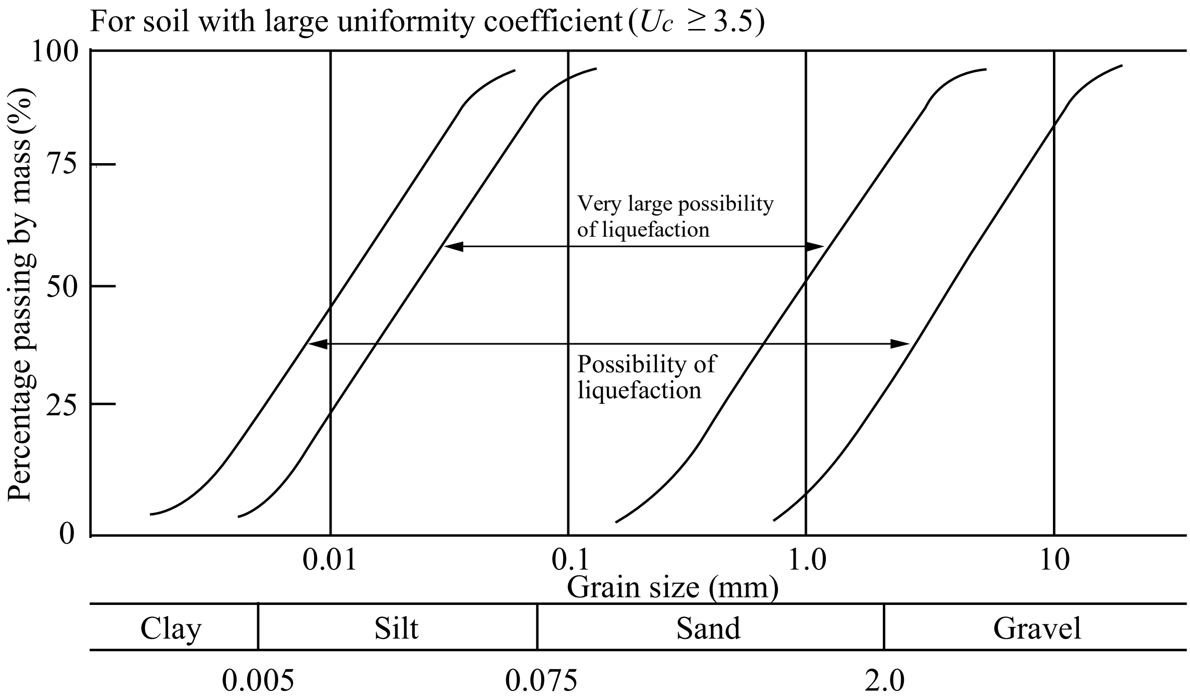

Fig. 2.1.3(a) Range of Possible Liquefaction ($U_c \geq 3.5$)

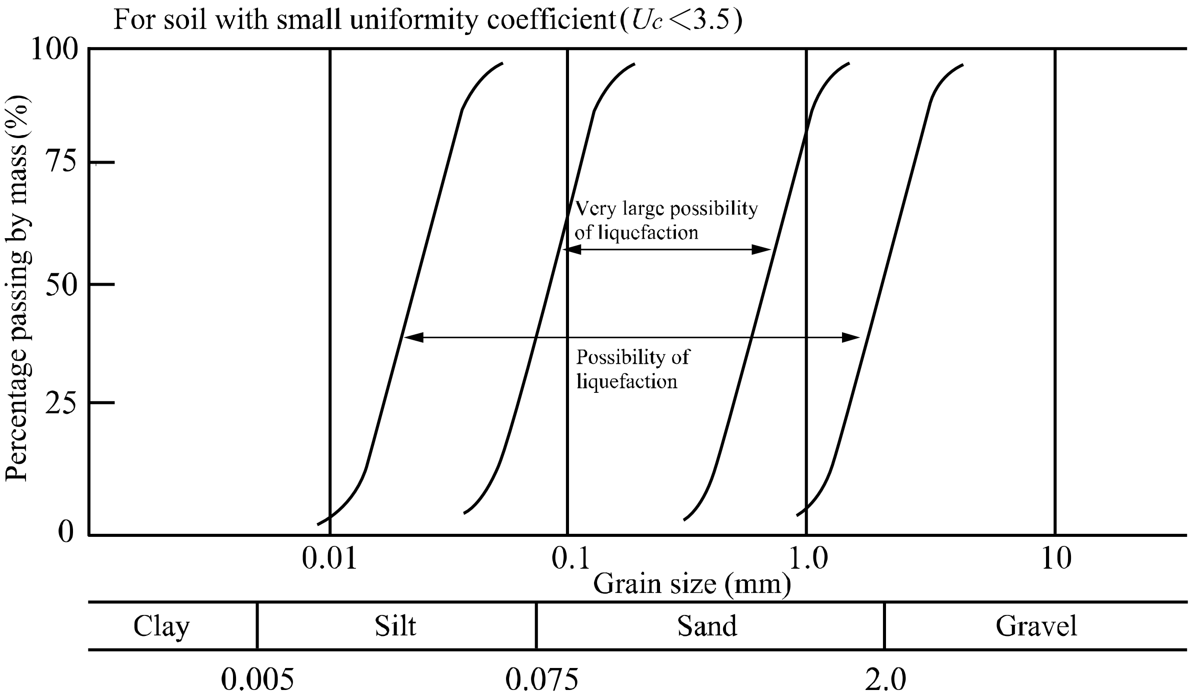

Fig. 2.1.3(b) Range of Possible Liquefaction ($U_c < 3.5$)

The soil shall be classified by grain size by using **Fig. 2.1.3**, which shall be used according to the multitude of the uniformity coefficient. The standard of the multitude of uniformity coefficient is $U_c = D_{60}/D_{10} = 3.5$, where U_c is the uniformity coefficient, D_{60} is the 60% diameter, and D_{10} is the effective diameter (10% diameter). Soil is assessed to not liquefy when its grain size accumulation curve is not included in the "possibility of liquefaction" range.

If the classification is difficult (for example, when the grain size accumulation curve spans the "possibility of liquefaction" range), proper countermeasures, such as the use of a prediction and assessment method via a cyclic triaxial compression test, is needed for soil with a large clay portion. For soil with a large gravel portion, the soil may be determined to not liquefy when the permeability factor is confirmed to be 3 cm/s or greater. When there are soil layers with poor permeability, such as clay or silt layers, on top of the target soil layer in this case, it should be treated as a type of soil that falls within the "possibility of liquefaction" range. A permeability test for the soil with a large coefficient of permeability of 3 cm/s shall be a special method.[3] A method of indirect estimation of a coefficient of permeability is available when the measurement of a coefficient of permeability is difficult.[4] However, when applying the indirect estimation method, careful consideration should be paid on the soil characteristics, such as content of fine particles.

② Prediction and assessment of liquefaction using equivalent *SPT-N* values and equivalent acceleration

For the soil layer with a grain size that falls within the range "possibility of liquefaction" shown in **Fig. 2.1.3**, further investigations should be based on the descriptions below.

(a) Equivalent *SPT-N* value

The equivalent *SPT-N* value should be calculated from **equation (2.1.1)**.

$$(N)_{65} = \frac{N - 0.019(\sigma_v' - 65)}{0.0041(\sigma_v' - 65) + 1.0} \qquad \textbf{(2.1.1)}$$

where

$(N)_{65}$: equivalent *SPT-N* value

N : *SPT-N* value of the soil layer

σ_v' : effective overburden pressure of the soil layer (kN/m^2)
(It should be noted that the effective overburden pressure used to calculate the equivalent *SPT-N* value should be calculated with respect to the ground elevation at the time of the standard penetration test.)

Fig. 2.1.4 shows the relationship given by **equation (2.1.1)**. When using **equation (2.1.7)**, the *SPT-N* values themselves of the soil layer are assumed to be equivalent *SPT-N* values.

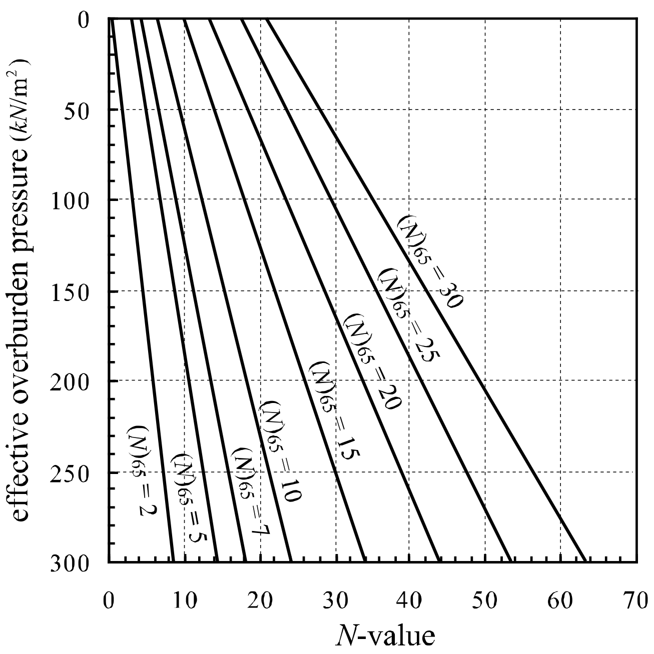

Fig. 2.1.4 Calculation Chart for an Equivalent *SPT-N* value

(The straight lines show the relationship between *SPT-N* values and effective overburden pressures when relative density and others are constant.)

(b) Equivalent acceleration

Equivalent accelerations are calculated from **equations (2.1.2)** to **(2.1.6)**. They are calculated for each soil layer by using the time history of the maximum shear stresses obtained from the seismic response calculation based on the equivalent linear analyses [5)] of the ground.

$$\alpha_{eq} = 0.7 \cdot \frac{\tau_{\max}}{\sigma_v'} \cdot g \cdot \frac{1}{c_\alpha} \quad \textbf{(2.1.2)}$$

$$c_\alpha = 5^{-d_1} \cdot n_{ef}^{\ d_1} \quad \textbf{(2.1.3)}$$

$$d_1 = 0.2 - 0.7 \cdot D_r \quad :\left(D_r \geq \frac{0.2}{0.7} \right) \quad \textbf{(2.1.4)}$$

$$d_1 = 0 \quad :\left(D_r < \frac{0.2}{0.7} \right) \quad \textbf{(2.1.5)}$$

$$D_r = 0.16 \cdot \sqrt{\frac{170 \cdot N}{70 + \sigma_v'}} \quad \textbf{(2.1.6)}$$

where

α_{eq} : equivalent acceleration (Gal)

τ_{max} : maximum shear stress (kN/m^2)

g : gravitational acceleration (980 Gal)

c_α : wave correction coefficient [6)–8)]
(If the liquefaction is predicted and assessed by correcting the *SPT-N* value with the plasticity index described below, c_α shall be obtained by plugging in –0.3 for d_1 in **equation (2.1.3)**.)

d_1 : exponent of **equation (2.1.3)**

N_{ef} : effective number of waves [6)–8)]
(**Fig. 2.1.5** shows half of the number of wave crests, which is 60% or more of the maximum shear stresses in the time history of the shear stresses.)

N : *SPT-N* value

D_r : relative density
(If $D_r \leq 1.0$, this may be obtained from the *SPT-N* value and the effective overburden pressure at the time of *SPT-N* value measurement by using **equation (2.1.6)**.)

σ_v' : effective overburden pressure (kN/m^2)
(Note that the effective overburden pressures used for calculating equivalent accelerations are obtained on the basis of the ground heights at the time of earthquakes, and the effective overburden pressures used for calculating relative densities are obtained on the basis of the ground heights at the time of the *SPT-N* value measurement.)

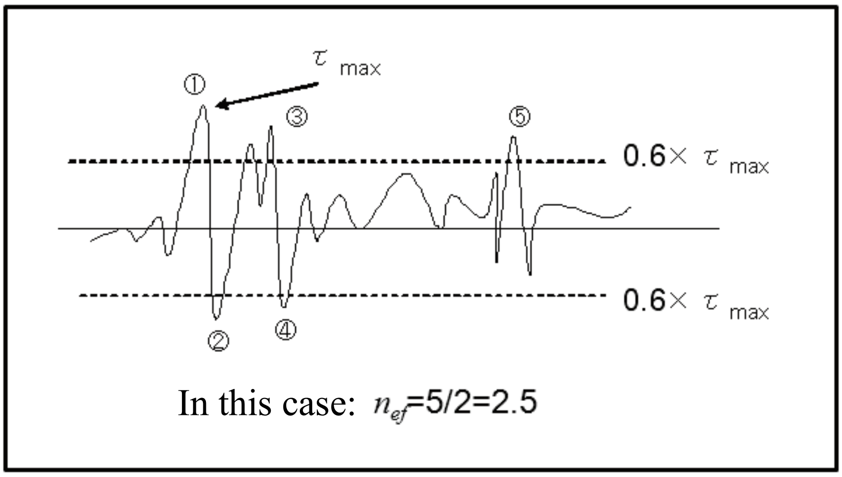

Fig. 2.1.5 Definition of the Effective Number of Waves N_{ef}

(c) Predictions and assessment using the equivalent *SPT-N* value and equivalent acceleration

It shall be assessed in which range (ranges I to IV in **Fig. 2.1.6**) the equivalent *SPT-N* value and equivalent acceleration of the target soil layer is contained.

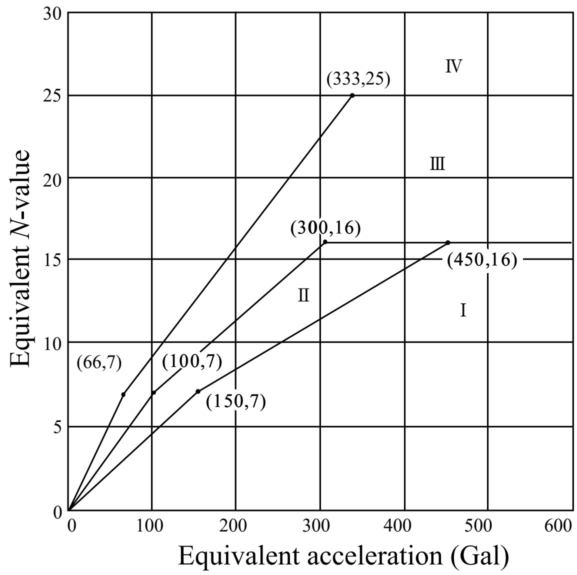

Fig. 2.1.6 Classification of Soil Layer with Equivalent *SPT-N* value and Equivalent Acceleration

③ **Correction of *SPT-N* values and prediction and assessment in cases with large fraction of fines content**

(a) When the fines content, namely, grain size of 75 µm or less, is 5% or greater, the equivalent *SPT-N* value should be corrected, and the subject soil layer should be assessed to which range of I to IV in **Fig. 2.1.6** it falls into using the corrected equivalent *SPT-N* value. The correction of the equivalent *SPT-N* value is divided into the following three cases:

1) Case 1: when the plasticity index is less than 10 or cannot be determined or when the fines content is less than 15%

2) Case 2: when the plasticity index is 10 or greater but less than 20, and the fines content is 15% or higher

3) Case 3: when the plasticity index is 20 or greater, and the fines content is 15% or higher

(b) Case 1: when the plasticity index is less than 10 or cannot be determined or when the fines content is less than 15%

The equivalent *SPT-N* value after correction should be set as $(N)_{65}/c_N$. The correction factor c_N is given in **Fig. 2.1.7**. The obtained equivalent *SPT-N* value after correction and the equivalent acceleration are used to determine the range in **Fig. 2.1.6**.

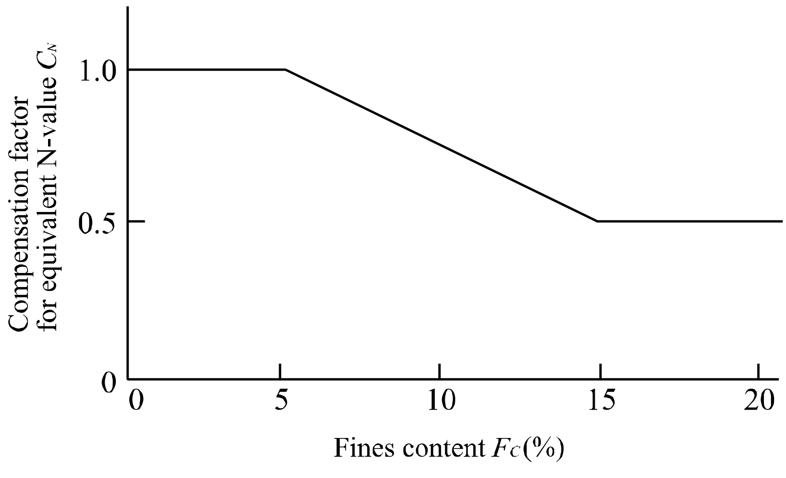

Fig. 2.1.7 Correction Factor of Equivalent *SPT-N* value Corresponding to Fines Content

(c) Case 2: when the plasticity index is 10 or greater but less than 20, and the fines content is 15% or higher

The equivalent *SPT-N* value after correction should be set as both $\{(N)_{65}/0.5\}$ and $\{N + \Delta N\}$, and the range should be determined according to the following situations, where ΔN is given by the following equation:

$$\Delta N = 8 + 0.4\left(I_p - 10\right) \tag{2.1.7}$$

1) When $\{N + \Delta N\}$ falls within range I, determine it to be in range I.
2) When $\{N + \Delta N\}$ falls within range II, determine it to be in range II.
3) When $\{N + \Delta N\}$ falls within range III or IV and when $\{(N)_{65}/0.5\}$ is within range I, II, or III, determine it to be in range III.
4) When $\{N + \Delta N\}$ falls within range III or IV and when $\{(N)_{65}/0.5\}$ is within range IV, determine it to be in range IV.

(d) Case 3: when the plasticity index is 20 or greater, and the fines content is 15% or higher

The equivalent *SPT-N* value after correction should be set as $\{N + \Delta N\}$. The range should be determined according to the equivalent *SPT-N* value after correction and the equivalent acceleration.

(e) **Fig. 2.1.8** and **Table 2.1.1** show what was described in (b), (c), and (d) above in a figure and a table. **Table 2.1.1** shows a standard result of prediction by combining the prediction of the *SPT-N* valu*e* corrected by the fines content and the prediction of the *SPT-N* value corrected by the plasticity index.

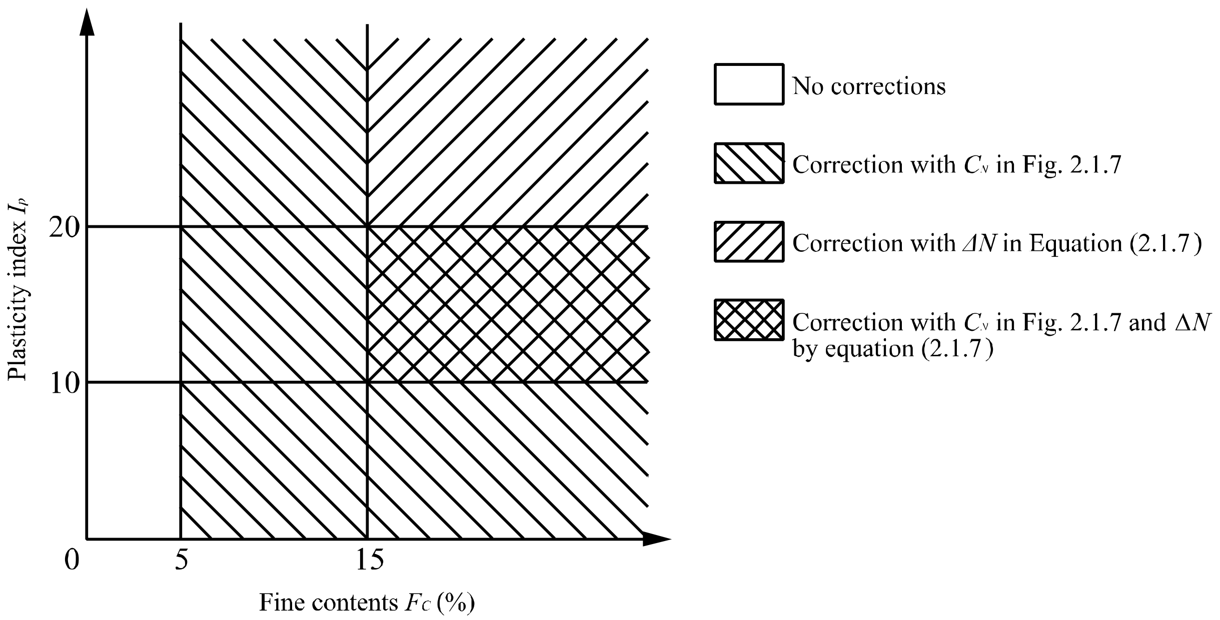

Fig. 2.1.8 *SPT-N* value Correction Method and Relationship between Fines Content and Plasticity Index

Table 2.1.1(a) When the Plasticity Index Is Less than 10 or Cannot Be Obtained or When the Fines Content Is Less than 15%

		Correction with the fines content			
		I	II	III	IV
Correction with the plasticity index	–	I	II	III	IV
	–				
	–				
	–				

Table 2.1.1(b) When the Plasticity Index Is 10 or Greater but Less than 20 and When the Fines Content Is 15% or Higher

		Correction with the fines content			
		I	II	III	IV
Correction with the plasticity index	I	I	II	III	IV
	II	II	II	II	II
	III	III	III	III	IV
	IV	III	III	III	IV

Table 2.1.1(c) When the Plasticity Index Is 20 or Greater and When the Fines Content Is 15% or Higher

		Correction with the fines content			
		–	–	–	–
Correction with the plasticity index	I	I			
	II	II			
	III	III			
	IV	IV			

④ **Prediction and assessment of liquefaction**

The liquefaction shall be predicted and assessed for each soil layer by using **Table 2.1.2** according to the classification of I to IV soil layers in ② and ③. Given that liquefaction assessment also considers factors other than physical phenomena, such as the degree of safety anticipated for the target facilities, it is not possible to unambiguously set the assessments regarding each prediction result. **Table 2.1.2** shows the assessment that is considered standard for each result of the predictions.

In this table, the term "prediction of liquefaction" refers to the high or low possibility of liquefaction as a physical phenomenon. By contrast, the term "assessment of liquefaction" refers to the consideration of the high or low possibility of liquefaction and the determination of whether the target ground could liquefy. Therefore, it is necessary to consider factors other than physical phenomena, such as the degree of safety anticipated for the target facilities, when judging liquefaction.

Table 2.1.2 Prediction and Assessment of Liquefaction for Soil Layer According to Grain Size and *SPT-N* value

Range shown in **Fig. 2.1.6**	Prediction of liquefaction	Assessment of liquefaction
I	Possibility of liquefaction occurrence is very high	Liquefaction will occur
II	Possibility of liquefaction occurrence is high	Either to assess that liquefaction will occur or to conduct further evaluation based on cyclic triaxial compression tests.
III	Possibility of liquefaction is low	Either to assess that liquefaction will not occur or to conduct further evaluation based on cyclic triaxial compression tests. For a very important structure, either to assess that liquefaction will occur or to conduct further evaluation based upon cyclic triaxial tests.
IV	Possibility of liquefaction is very low	Liquefaction will not occur

(4) Application of Prediction and Assessment Methods of Liquefaction According to Grain Size and *SPT-N* values to Special Types of Soil

Special types of soil, such as shirasu, are known to have special characteristics that are different from common types of soil, on which the prediction and assessment methods with the grain size and *SPT-N* value are based. Therefore, it is preferable to conduct both of the predictions with the grain size and *SPT-N* value and with the cyclic triaxial compression test at typical locations on a trial basis. Furthermore, confirm their consistency when applying the prediction and assessment methods with the grain size and *SPT-N* value.

(5) Prediction and Assessment Based on the Results of Cyclic Triaxial Compression Tests

① When it is not possible to predict and assess the occurrence of liquefaction of the subject ground from the results of grain size and *SPT-N* values, the prediction and assessment for ground liquefaction need to be made by conducting a seismic response calculation of the ground and cyclic triaxial compression tests on undisturbed soil samples.

② The proper consideration of the stress state in the ground, the irregularity of the actions caused by earthquake ground motions, and others is important in obtaining the results of the seismic response calculations of the ground and those of cyclic triaxial compression tests and in showing actual phenomena in the ground.

(6) Assessment of Overall Liquefaction of the Ground

In the assessment of overall ground liquefaction, the comprehensive decision should be made on the basis of the results of the assessment for each soil layer.

(7) Consideration for Continuous Earthquake Ground Motion

During continuous earthquake ground motion, such as the principal earthquake and aftershock, it should be noted that the sandy layer just below the clayey layer of the ground, particularly where cohesive soil interposes, may possibly liquefy during or after subsequent aftershocks depending on the ground composition even if it was predicted under the principal earthquake that there would be no liquefaction or the possibility of liquefaction was low. In this case, the occurrence of liquefaction can be predicted and assessed by linking this type of earthquake ground motion as a long-duration earthquake ground motion [7) 8)] and by calculating the earthquake ground motion response.

(8) Worldwide use of the liquefaction prediction and assessment method

The liquefaction prediction and assessment method that is capable of considering the influence of the waveforms and durations of earthquakes has been generalized for overseas use [8)]. A unique feature of the new simplified method is its universality, allowing it to be applied to various types of liquefaction charts, facilitating more-rational liquefaction prediction and assessment worldwide. For details of the procedures, refer to Sassa and Yamazaki (2016) [8)].

[References]

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