SIMPLIFIED METHOD IN EVALUATING LIQUEFACTION OCCURRENCE AGAINST HUGE OCEAN TRENCH EARTHQUAKE

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ABSTRACT :

Effectiveness of the existing simplified method for evaluating liquefaction potential under ocean trench long duration earthquakes is investigated. Effective stress analyses are made at more than 200 sites. Accuracy of the existing simplified method is evaluated by comparing the onset of liquefaction by both methods. It is found that existing method is applicable to a near field or inland earthquake but not to an ocean trench earthquake and that it overestimate liquefaction potential resulting in dangerous design although PGA is smaller in ocean trench earthquake. It comes from the difference of effective number of loading cycles; that for ocean trench earthquake is about 10 times larger than that considered in the existing method. Then a correction factor is proposed for liquefaction strength; liquefaction strength is set about a half of that used in the existing method. This method works so that both dangerous ratio (ratio of the cases where onset of liquefaction is identified by effective stress analysis but is not by existing simplified procedure) and accuracy ratio (ratio where both effective stress and simplified method show same result) keep nearly the same as for the case of the inland earthquake.

KEYWORDS: liquefaction, ocean trench earthquake, simplified method, duration

1. INTRODUCTION

As soil liquefaction has caused significant damage to various structures, Prediction liquefaction is important. In Japan, huge ocean trench earthquakes, which occur at the intersection of the Philippines and Eurasian Plates, become a big threat (Central Disaster Prevention Council, 2005). They are named Tonankai and Nankai earthquakes, and expected JMA seismic intensity exceeds 6 in widespread area. Therefore liquefaction is also expected to occur in the wide area. These earthquakes have characteristics that magnitudes are very large to be 8 or more, and duration is very long because fault length is very long. According to the MECSST (2007), the duration yields nearly 600 seconds. It indicates that number of cycles of loading will become huge compared with that in the past earthquakes. Actually, the authors showed through a case study by means of effective stress earthquake response analysis that liquefaction can occur during these earthquake even if it does not occur under the 1995 Hyogoken-nambu (Kobe earthquake), an inland earthquake, although maximum acceleration is smaller in the ocean trench earthquake than that in the inland earthquake (Sawada et al, 2005).

Onset of soil liquefaction is usually identified by, so called, F_L method, a method based on liquefaction resistant factor. In this method, expected shear stress is compared with liquefaction strength. Here, liquefaction strength is evaluated as the shear stress when liquefaction occurs at certain number of loading (usually 15 or 20) under constant amplitude loading, whereas maximum value is used for shear stress. Since shear stress and liquefaction strength are evaluated under different backgrounds, they cannot be compared directly. Iwasaki et al. (1978) took five factors to be multiplied to liquefaction strength into consideration so as to compare cyclic liquefaction strength with maximum shear stress. Among them, effect of irregular nature of earthquake motion is considered as an effective number of cycles, and is classified either less than or equal to 2 or greater than or equal to 3 depending on shock type and cyclic type earthquake motions. Considering the difference of duration mentioned above, however, these effective numbers seems much smaller than that expected at the coming huge ocean trench earthquake. In this paper, we evaluate accuracy of the simplified method by making effective stress earthquake response analysis at many sites.

2. INVESTIGASTED SITE, EARTHQUAKE MOTION, AND METHOD OF ANALYSIS

2.1. Investigated site

Totally 275 sites that have been used in the past researches are collected (PWRI, 1996). Among them, 236 sites are investigated because 39 sites do not have liquefiable layer. Natural period of these grounds is summarized in Figure 1; natural periods scatter widely between 0.084 and 0.609 seconds. In order to make the analysis simple, the ground is modeled based on the following procedure.

1) Soil is classified into sand, silt, gravel, or clay. Sand is treated as liquefiable material, but layers with liquefaction strength ratio greater than 0.6 or layers with SPT−*N* value greater than or equal to 25 are treated as non-liquefiable material. The term "liquefiable layer" will be used to indicate sand layers that does not composed of non-liquefiable material defined here. Total number of liquefiable layers is 1345.
2) SPT-*N* value is averaged in the same layer. Then, shear wave velocity V_s is evaluated as V_s=100$N^{1/3}$ for clay and V_s=80$N^{1/3}$ for other soil (JRA, 2002). Internal friction angle ϕ of sand is evaluated based on Hatanaka and Uchida (1996) as $\phi = \sqrt{20N_1} + 20$, $N_1 = N/(\sigma'_v/98)^{0.5}$, where N denotes SPT–N value and σ'_v effective overburden stress in kPa. This equation is also applied to silt and gravel. Shear strength c of clay is calculated by c=25N (kPa).
3) Liquefaction strength is evaluated as a function with respect to mainly SPT−*N* value (JRA, 2002), which will be explained later. Since it gives shear stress ratio when liquefaction occurs under 20 cycles of loading, R_{20}, liquefaction strength curve is extrapolated based on Seed et al. (1981), by which shear stress when liquefaction occurs under 5 cycles of loading, R_5, is obtained by R_5 = 1.429 R_{20}.

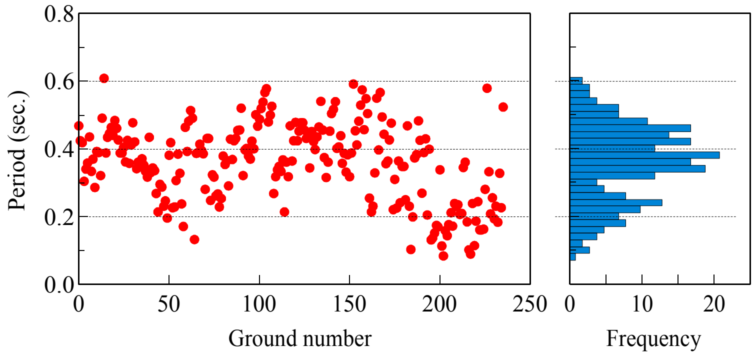
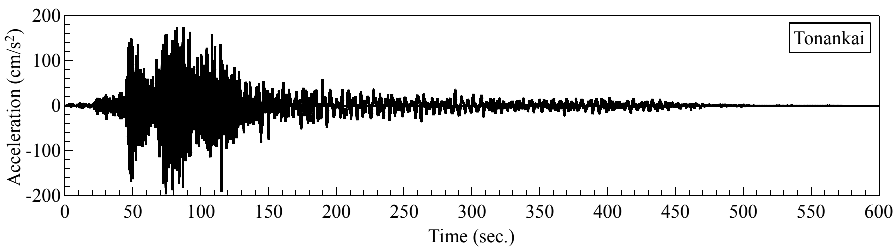
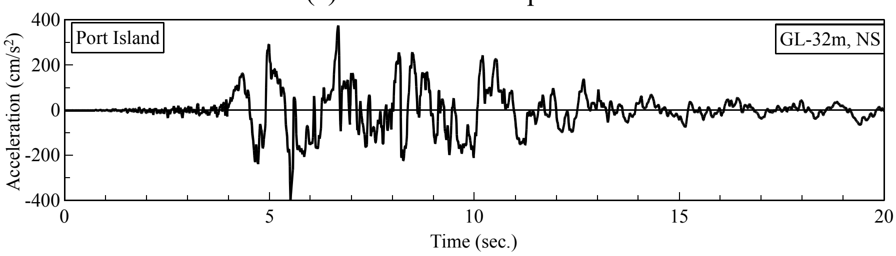


Figure 1 Distribution of natural period of investigated sites



(a) Tonankai earthquake



(b) Port Island, Kobe earthquake

Figure 2 Waveforms of the earthquake motions

2.2. Earthquake motions

Two earthquake motions, shown in Figure 2, are used. The one is a synthesized earthquake motion for the coming Tonankai earthquake (Sawada et al., 2005), which is a huge ocean trench earthquake motion that is expected to hit Japan in future. The other is a recorded earthquake motion at Port Island, GL-33 m, during the 1995 Kobe earthquake, which is an inland or near field earthquake and is used to compare effectiveness of the simplified method. These earthquake motions are used as base motion of each site. It is noted that duration of the ocean trench earthquake is about 600 seconds, whereas that of the Kobe earthquake is several tens seconds at maximum, and that PGA in the inland earthquake is about two times as large as that of the ocean trench earthquake.

2.3. Simplified method

Design specification for the road bridge (JRA, 2002) is used as simplified method to predict onset of liquefaction. This is one of the most frequently used methods in Japan, and is based on F_L value.

2.3.1 Fundamental

The F_L defined in the JRA method under level 2 ground motion (huge earthquake) is as follows:

$$F_L = R / L \tag{1}$$

where $L = r_d k_{hg} \sigma_v / \sigma'_v$: Shear stress ratio during earthquake

$r_d = 1 - 0.015z$: Reduction factor of the shear stress ratio in the vertical direction

$R = c_w R_L$: dynamic shear strength ratio

$$R_L = \begin{cases} 0.0882\sqrt{N_a/1.7} \\ 0.0882\sqrt{N_a/1.7} + 1.6\times10^{-6}(N_a - 14)^{4.5} \end{cases}$$: cyclic triaxial strength at 20 cycles of loading

$N_a = cN_1 + c_2$: Corrected SPT−N value accounting for the effects of grain size

$N_1 = 170N/(\sigma'_v + 70)$: SPT−N value converted to $\sigma'_v = 100$ kPa

c_1 and c_2 : Modification factor of the N value based on the fine-grain fraction

$$c_w = \begin{cases} 1.0 & (R_L \le 0.1) \\ 3.3R_L + 0.67 & (0.1 < R_L \le 0.4) \\ 2.0 & (0.4 < R_L) \end{cases}$$: Modification factor based on earthquake motion properties for huge inland earthquake (c_w=1 for ocean trench earthquake).

The design seismic coefficient in horizontal direction, k_{hg}, is specified in this specification, but ratio of the maximum acceleration obtained by the earthquake response analysis to the acceleration of gravity is used to examine accuracy of the simplified method.

2.3.2 Consideration of irregular nature of earthquake

Since shear stress ratio during earthquake and liquefaction strength defined at 20 cycles of loading are defined under different backgrounds, one and/or both must be modified to compare under the same conditions. According to Iwasaki et al. (1978), origin of the JRA method, only liquefaction strength is modified in order to compare liquefaction strength with maximum shear stress ratio as

$$R_{max} = c_1 c_2 c_3 c_4 c_5 R_L \tag{2}$$

Here, R_{max} is liquefaction strength to be compared with L. Coefficient c_1 considers effect of coefficient of earth pressure at rest, K_0, and is $(1+2K_0)/3$, c_2 considers effect of irregular nature of earthquake motion and is discussed later, c_3 and c_4 consider loosening at sampling and/or handling, and densification during traveling, and c_5 corrects effect of multi-directional loading and is 0.9. They found that multiplication of all 5 factors is nearly unity, yielding $R_{max} = R_L$.

The irregular nature of the earthquake motion is considered as effective cycles of loading. The earthquake motions are classified into shock and cyclic types. Shock type earthquake motions is defined when number of effective cycles is less than or equal to 2, whereas cyclic type when it is greater than or equal to 3. The correction factors are 1/0.55 and 1/0.7, respectively, and the average value 1/0.65 is applied in Eq. (2).

2.4. Earthquake response analysis

YUSAYUSA (Yoshida and Towhata, 1991), an earthquake response analysis computer program for horizontally deposited ground based on effective stress, is used. This program is the most frequently used program in the engineering practice in Japan. It employs hyperbolic model with Masing's rule for shear stress-shear strain relationships. The shear strength defined in the preceding is sufficient to define the stress-strain model. The stress paths are defined in an effective overburden stress−shear stress plane in order to consider excess porewater pressure generation, which is schematically shown in Figure 3, where τ denotes shear stress and p denotes effective stress. Parameters B_p and B_u that define the stress paths are determined so that R_{20} and R_5 agree with that evaluated in the preceding section. The value of κ, a parameter to define shear stress ratio under which excess porewater pressure does not generate, is set 0.06, a suggested value in the program. Maximum excess porewater pressure ratio is set 0.97 for the stability purpose of the program, which is equivalent with the minimum effective stress of 0.03.

YUSAYUSA uses two definitions on onset of liquefaction. The first one is initial liquefaction which is defined when stress path cross the phase transform line. The second one is complete liquefaction which is defined to be the state that effective stress becomes minimum value. These usages, however, are not commonly used terms. In the engineering practice, initial liquefaction is defined when excess porewater pressure becomes equal to initial effective confining stress (Japanese Geotechnical Society, 2000), which state is nearly identical with the complete liquefaction in YUSAYUSA. Therefore, complete liquefaction by YUSAYUSA is used to identify the onset of liquefaction.

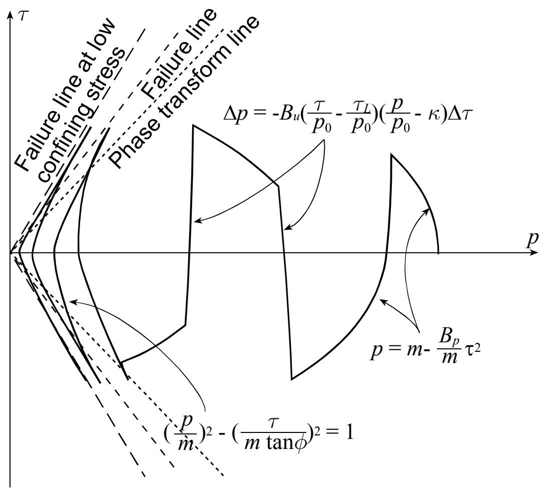


Figure 3 Stress paths used in YUSAYUSA

3. RESULT OF EARTHQUAKE RESPONSE ANLAYSIS

Peak accelerations at the ground surface (PGA) obtained by the effective stress earthquake response analysis is shown in **Figure 4**. All PGA's are less than 600 cm/s^2 under inland earthquake, and they are less than 400 cm/s^2 under ocean trench earthquake; PGA under ocean trench earthquake are smaller than that under inland earthquake. Time when shear stress becomes maximum (Time at PT) in the liquefiable layer (1345 layers) and time when PGA becomes maximum is compared in **Figure 5**. Times concentrates around 5 seconds for inland earthquake, which corresponds to the first large wave in the earthquake motion. On the other hand, they scatter in the ocean trench earthquake, but each time corresponds to the appearance of peak value in the input motion. It is noted that both times cannot be the same, which indicates that time at maximum shear stress cannot be predicted from the time at PGA. Time when shear stress becomes maximum and time at liquefaction are compared in **Figure 6**. Almost all points lie above the line with 45 degrees gradient, which indicates that maximum shear stress appears before the onset of liquefaction. Maximum shear stress occurs after liquefaction at several layers; cyclic mobility is responsible of this behavior.

Numbers of effective cycles in the liquefied layers and nonliquefied layers are shown in **Figure 7** in the liquefiable layers. Almost all of them are less than or equals to 2 for inland earthquake, which indicates that correction factor for shock type earthquake may be reasonable. On the other hand, those for the ocean trench earthquake spreads up to 65 and many of them are much larger than 3, which indicates that correction by means of cyclic type earthquake may not be sufficient for the huge ocean trench earthquake considered here.

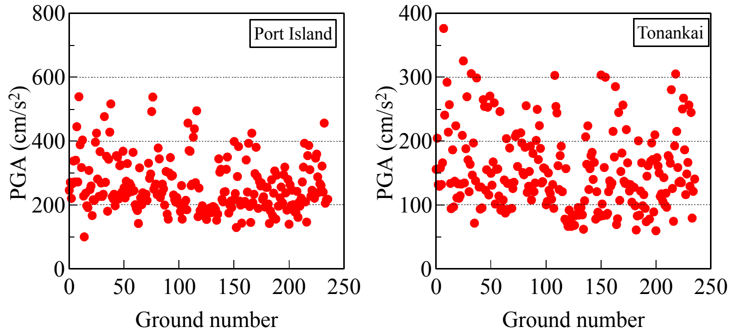


Figure 4 Peak ground accelerations

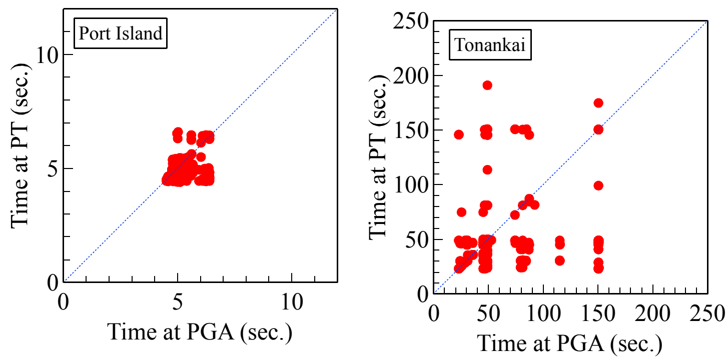


Figure 5 Comparison of times when shear stress and PGA becomes maximum

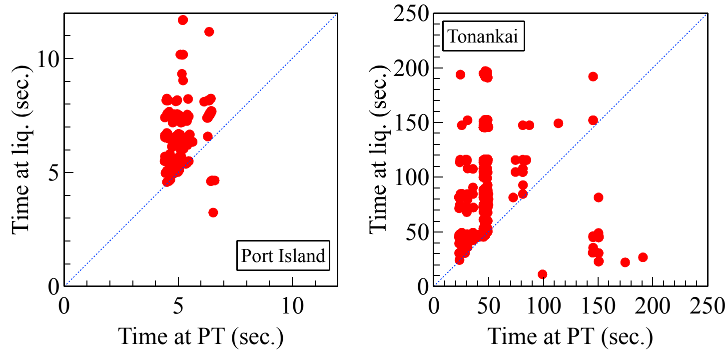


Figure 6 Comparison of times at liquefaction and maximum shear stress

4. ACCURACY OF SIMPLIFIED METHOD AND IMPROVEMENT

4.1. prediction of maximum shear stress

Maximum shear stress evaluated by the simplified method is compared with that by the earthquake response analysis. At first, shear stress by the simplified method is divided by that by the earthquake response analysis. Average of the ratios in each site is shown in Figure 8 with standard deviation. In general, predictions by the simplified method are very good. Actually, average and standard deviation values in Figure 8 are 0.986 and 0.071 for the inland earthquake, and 0.997 and 0.105 for the ocean trench earthquake, respectively. It is noted that accuracies are nearly same for both inland and ocean trench earthquakes.

Figure 9 shows typical comparison of maximum stresses and excess porewater pressure evaluated by the earthquake response analysis. Agreement is good at site 1, and the worst at site 162. Comparisons at site 77 and 142 suggest that agreement is good above the liquefied layer, but not below the liquefied layer. It suggests that error of maximum shear stress by the simplified method is better than that in Figure 8 for the purpose to predict onset of liquefaction.

4.2. Onset of liquefaction

Prediction on onset of liquefaction is summarized in Figure 10 (a) and (b). Here, ordinate is F_L value by the simplified method and liquefaction is expected to occur when $F_L \leq 1.0$. On the other hand, abscissa is excess porewater pressure ratio (PWPR hereafter) by effective stress analysis and liquefaction occurs when it is close to unity. Note that maximum PWPR is set 0.97 as described in the preceding, PWPR=1.0 is used to indicate this state. There is no excess porewater pressure between about 0.85 an 1.0, which indicates that liquefaction occurs very quickly after phase transform; stress path model used in YUSAYUUA enable it. In order to evaluate accuracy of the simplified method, we define three criteria

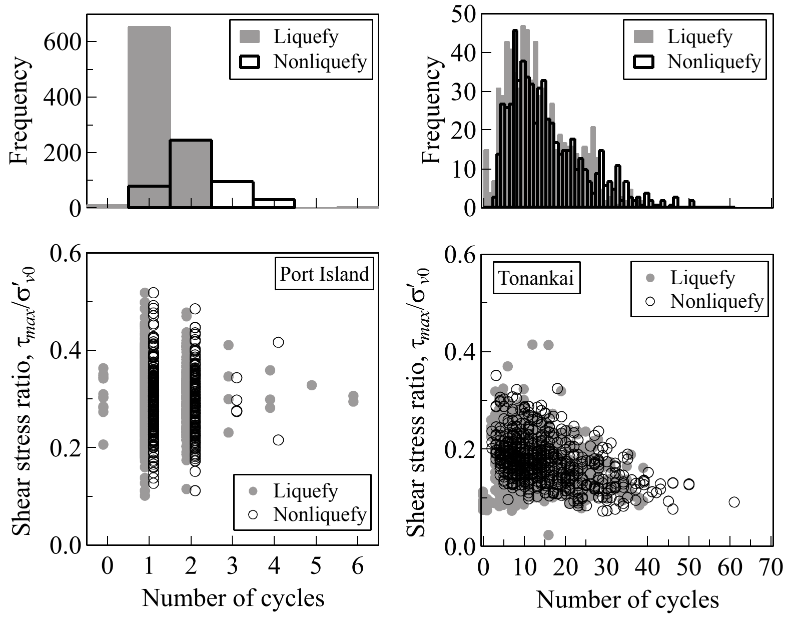


Figure 7 Effective number of cycles

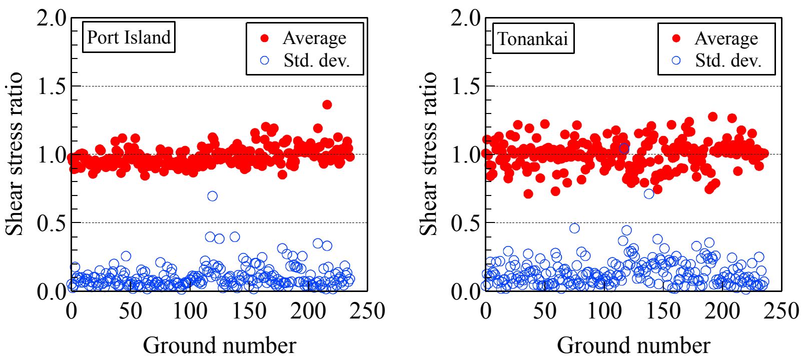


Figure 8 Accuracy of maximum shear stress

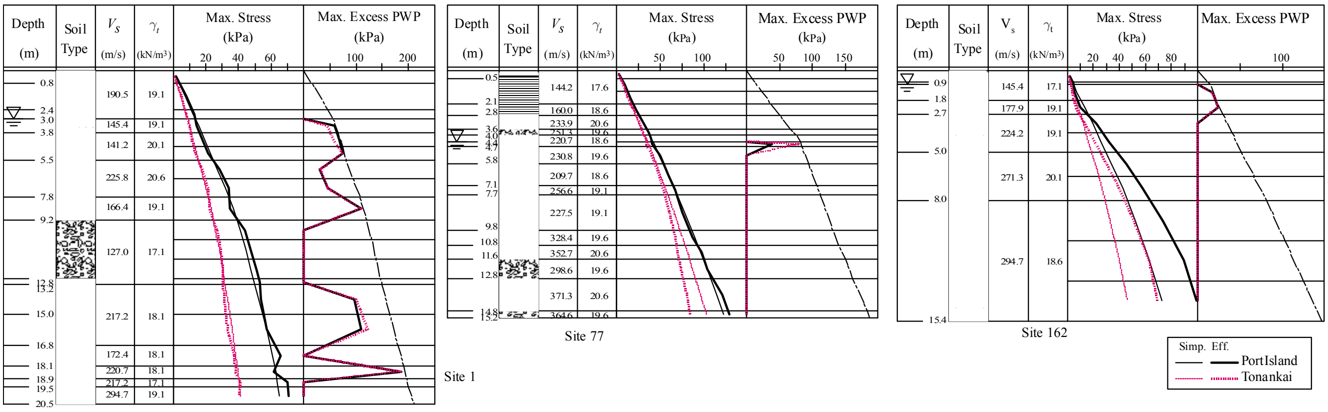
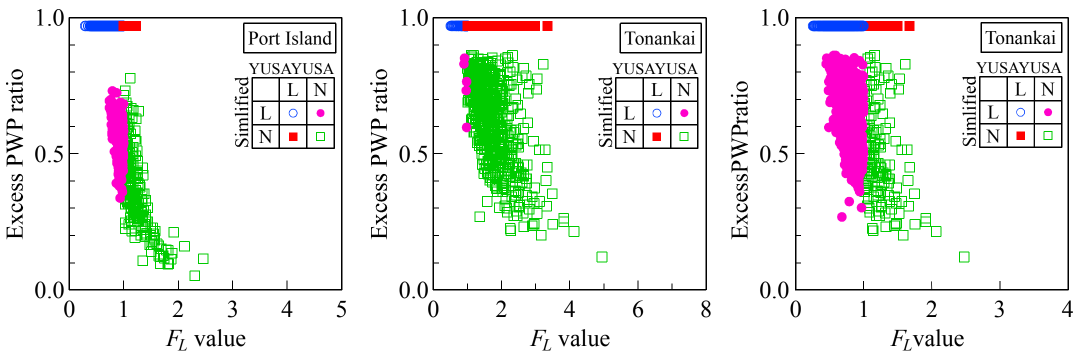


Figure 9 Examples of comparison of responses

Accurate ratio (AC): either $F_L \leq 1.0$ and PWPR ≈ 1.0, or $F_L > 1.0$ and PWPR < 1.0
Dangerous ratio (DN): $F_L > 1.0$ and PWPR ≈ 1.0
Overdesign ratio (OD): $F_L \leq 1.0$ and PWPR < 1.0

If AC is 100%, prediction by the simplified method is perfect. Dangerous ratio indicates that design based on the simplified method may yield dangerous result because layer in which liquefaction is not expected liquefies. Overdesign ratio indicates safe design but overdesigned because treatment may be made against liquefaction to the layers in which liquefaction does not occur. Prediction that shows smaller value for both DN and OD and larger value for AC is a good method. These three criteria are summarized in **Table 1** (top two lines).

The simplified method shows good performance against inland earthquake. It shows large AC of 83.6 % and very small DN of 1.4 %. The value of 15.0 % for OD may be acceptable in the engineering practice considering that it is a simplified method. On the other hand, performance against ocean trench earthquake is not good. It shows DN value of 46.8 %, which indicates that it misleads into dangerous design in about a half of the analyzed sites.



(a) Inland (b) Ocean trench (c) Improved

Figure 10 Comparison of onset of liquefaction

Table 1 Accuracy of the simplified method in percent

Earthquake	liquefy by both methods	non-liquefy by both methods	AC	DN	OD
Ocean trench	6.9	45.9	52.8	46.8	0.4
Inland	64.7	18.9	83.6	1.4	15.0
Improved	51.7	12.2	63.9	2.1	34.1

4.3. Alternate method, a proposal

As shown in the preceding that evaluation of maximum shear stress by the simplified method was very good for both inland and ocean type earthquakes. Therefore, it is concluded that difference of duration or number of effective cycles between two types of earthquake is not evaluated well for the ocean trench earthquake. It indicates that correction must be made to liquefaction strength, but not for maximum shear stress; coefficient such as c_w that is used to correct fewer numbers of effective cycles against huge inland earthquake is to be employed for the ocean trench earthquake.

The author suggests the value of 0.5 as the correction factor. It is noted that dangerous ratio DN can be made small if this correction factor is set small. The overdesign ration OD, however, becomes large at the same time, which cannot be said to be a rational method. The correction factor must be determined to take balance between these indices as well as accurate ratio AC, and the value of 0.5 is determined by considering it.

The result is compared in **Figure 10** (c) and summary is shown at the bottom lines of **Table 1**. Dangerous ratio DN decreases very much from 46.8 % to only 2.1 % which is the same order with the case for inland earthquake. In addition, AC is also improved from 52.8 % to 63.9 %, which is a little smaller than the case for inland earthquake, but is a good value. The only shortage is that overdesign ratio increases from 0.4% to 34.1 %, but it may be acceptable considering the serious damage associated with liquefaction. It also indicates difficulty to consider the effect of long duration or large number of effective cycles relevantly.

5. CONCLUDING REMARKS

It is found through many effective stress analyses that existing simplified method works well against inland type earthquake, but not against ocean trench huge earthquake such as coming Tonankai earthquake. The reason is that effect of irregular nature of earthquake motion is not considered well; number of effective cycles is significantly underestimated. A new correction factor of 0.5 that is to be multiplied to the liquefaction strength is introduced in this paper, by which the simplified method has the same accuracy with inland earthquake.

ACKNOWLEDGEMENTS

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