A FUNDAMENTAL STUDY ON A RELATIONSHIPS BETWEEN INCREASE OF PORE WATER PRESSURE AND ACCUMULATED DISSIPATION ENERGY OF LIQUEFIABLE SOILS

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Abstract

Soil liquefaction of surface layer would greatly influence seismic stability and restorability of structures. It is, therefore, necessary to detect soil layers susceptible to liquefaction, evaluate liquefaction potential and determine appropriate seismic actions used in a seismic design of a structure. Stress-based methods are widely used for evaluating liquefaction potential, in which a factor of safety is generally determined by comparing an undrained cyclic strength of liquefiable soil with an induced seismic shear stress. On the other hand, some energy-based method have been proposed and reported that they give more accurate evaluations on liquefaction potential comparing to the other stress-based method[e.g. [1]].

In the meantime, the authors proposed a new testing method for determining appropriate deformation properties of soils used for time-domain nonlinear seismic ground response analysis, which is conducted to determine seismic actions applied to a structures in seismic design[2]. Validity of the proposed method was verified by comparing the results of time-domain nonlinear seismic ground response analysis with deformation parameters obtained from the conventional testing method and the proposed method with the results of the RTRI hybrid ground response simulations, which can produce appropriate seismic response of soil layers. The proposed method is composed of two different test series: a strain controlled 1 cycle stage test (1CST) and a constant strain cyclic test (CSCT). The CSCT also gives information used for an assessment of soil liquefaction potential based on a theory of dissipation energy[3], which are accumulated dissipation energy, increase of pore water pressure, degradation of shear stiffness and so on. The hybrid ground response simulation also proved higher accuracy of the dissipation energy method as compared with the conventional stress-based method.

It was also confirmed that the relationships between the accumulated dissipation energy and increase of pore water pressure or degradation of shear stiffness could be influenced by applied shear strain level, loading history and so on. Such relationships are very important for determining various factors used in structural design considering influence of soil liquefaction conducted after an assessment of soil liquefaction potential. This study, therefore, investigated influence of shear strain level and loading history on the relationships between accumulated dissipation energy and increase of pore water pressure based on the results of 1CSTs, CSCTs and hybrid ground response simulations. As a result, it is revealed that the relationship can be uniquely determined by normalizing the accumulated dissipation energy by an appropriate value.

Keywords: soil liquefaction, assessment of soil liquefaction potential, accumulated dissipation energy

1. Introduction

Soil liquefaction of surface layer would greatly influence seismic stability and restorability due to residual deformation of structures. It is, therefore, necessary to detect soil layers susceptible to liquefaction, evaluate liquefaction potential and apply seismic actions to a design model of a structure adequately in a seismic design. Stress-based methods are widely used for evaluating liquefaction potential (e.g. Railway Technical Research Institute. 2012.), in which a factor of safety is generally determined by comparing an undrained cyclic strength with an induced seismic shear stress. On the other hand, some energy-based method (e.g. Berrill and Davis 1985, Figueroa et al. 1994, Kokusho, 2013) have been proposed and reported that they give more accurate evaluations on liquefaction potential comparing to the other stress-based method.

In the meantime, the authors (Izawa et al. 2019) have proposed a new testing method for determining appropriate deformation properties of soils used for time-domain nonlinear seismic ground response analysis, which is conducted to determine seismic actions applied to a structures in seismic design. The proposed method can also provide information of soil liquefaction, which can be used for evaluations of liquefaction potential based on the cumulative dissipation energy method proposed by Kazama et al. (2000). This study examines applicability of the cumulative dissipation energy method for evaluations of soil liquefaction potential.

The relationship between the cumulative dissipation energy and increase of pore water pressure is important for determining various factors used in structural design considering influence of soil liquefaction conducted after an assessment of soil liquefaction potential. This study investigates influence of shear strain level and loading history on the relationships between the cumulative dissipation energy and increase of pore water pressure.

2. Dissipation Energy

The testing method for determining deformation properties of soils the authors have pro-posed is composed of two different test series: a strain controlled 1 cycle stage test (1CST) and a constant strain cyclic test (CSCT) as indicated in Fig. 1. These tests are basically conducted with a torsion shear test apparatus or a simple shear test apparatus in order to simulate pure shear deformation. Details of the respective tests are as follows.

In a 1CST, 1 cyclic shear is repeatedly applied to a specimen under a strain controlled while gradually increasing strain level at each loading stage without consolidation after each loading stage. A purpose of doing this test is to determine G/G_0-γ and h-γ relation-ships in a wide strain range eliminating the effect of pore water pressure as much as possible.

The 1CST may give G/G_0-γ and h-γ relationships in a wide strain range without effect of pore water pressure, i.e. master curves, to some extent. Effect of excess pore water pressure, however, would be large for large strain level. To obtain the more accurate master curves for large strain level, a few cyclic shear tests under constant strain (CSCT) are con-ducted at a few strain level, and G and h are determined from an initial loop of τ-γ relationship of each test. By replacing G and h values of a 1CST with such initial values of CSCTs at large strain level, an accurate master curve can be determined. Additionally, change in G and h only due to excess pore water pressure at a particular shear strain level can be obtained from the CSCT. This information can be effectively used to evaluate effect of pore water pressure on deformation properties for a long duration earthquake. Furthermore, the cumulative dissipation energy, W, can be calculated by the Eq. (1).

$$W = \int \tau(\gamma) d\gamma \tag{1}$$

Evaluation of soil liquefaction potential based on the theory of cumulative dissipation energy (Kazama et al. 2000) can be adopted. In general, a liquefiable soil tends to show an upper limit of cumulative

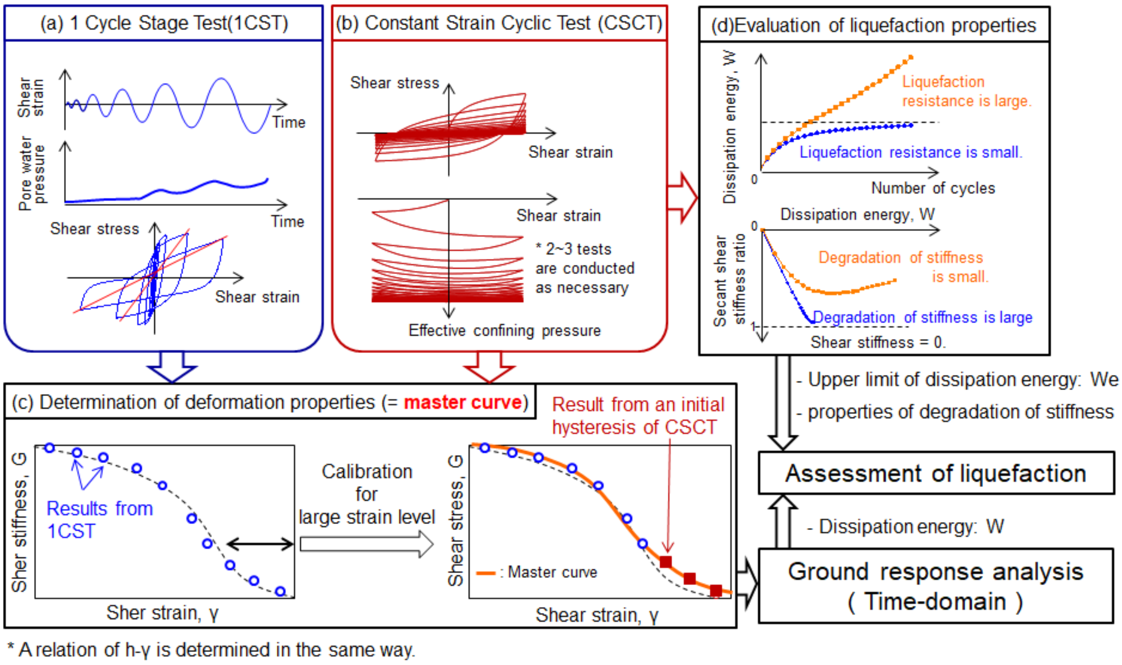


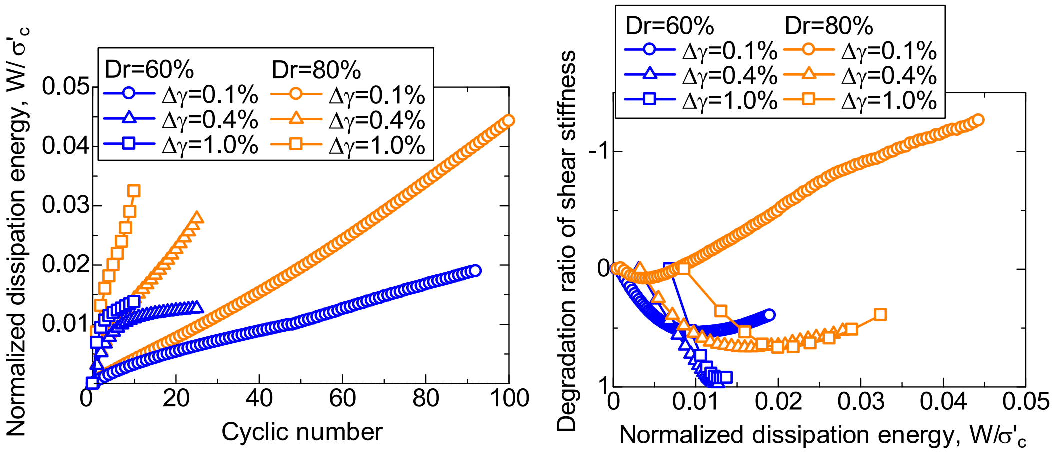
Fig. 1. Concept of the proposed testing method.

dissipation energy as schematically shown in Fig. 1, because stiffness of the soil may reach to approximately zero due to increase of pore water pressure. On the contrary, non-liquefiable soil wound not show clear upper limit since it can keep stiffness and area of τ-γ loops wound not reach to zero even if a large number of cyclic loading is applied as illustrated in Fig. 1(d). We can decide whether a soil layer is liquefiable or non-liquefiable from a result of a CSCT easily, and can suppose an upper limit of cumulative dispersion energy obtained from a CSCT as a kind of liquefaction strength. That is, we can evaluate that a target layer may show soil liquefaction if cumulative energy applied to the target layer may exceed an upper limit of cumulative dispersion energy. Cumulative energy applied to the target layer have to be calculated from a τ-γ relationships obtained from a ground response analysis. Furthermore, degradation of soil stiffness can be estimated from a relationships between stiffness and cumulative dissipation energy as illustrated in Fig. 1(d). This relation is expected to be greatly helpful for a seismic design of structures in consideration of decrease in bearing capacity of foundation ground although it has not been specifically constructed how to use a such relation.

3. TRIAL TESTS

In order to verify the above mentioned theory, firstly, trial tests were conducted using Toyoura sand (Gs=2.645, D_{50}=0.190mm, e_{max}=0.973, e_{min}=0.609, Uc=0.682) for two cases of relative density of 60% and 80%. The torsion shear test apparatus was used for all of the tests. Confining pressure was 100kPa in isotropic condition (back pressure=200kPa), and the size of the soil specimen was 70mm in the outer diameter, 30mm in the inner diameter and 70mm in the height. Constant strain amplitude of 0.1%, 0.4% and 1.0% were applied to the specimens at the strain velocity of 0.1%/min. All of the tests were conducted under undrained condition.

Fig. 2(a) shows the relationships between the normalized cumulative dissipation energy, W/σ'_c, and the cyclic number, obtained from the cyclic shear tests under constant strain, where σ'_c is confining pressure in the tests. The results of Toyoura sand with Dr=60% at γ=0.4% and 1.0% showed the clear upper limit at around W/σ'_c=0.01, which means that soil liquefaction may occur if the cumulative dissipation energy in the soil layer reaches to W/σ'_c =0.01 approximately. On the other hand, the upper limit was not observed for the case of γ=0.1%. It might be inferred from the results that soil liquefaction may not occur even if the



(a) W/σ'c ~ Cyclic number relationship (b) Degradation ratio ~ W/σ'c relationship

Fig. 2. Results obtained from constant strain cyclic loading tests

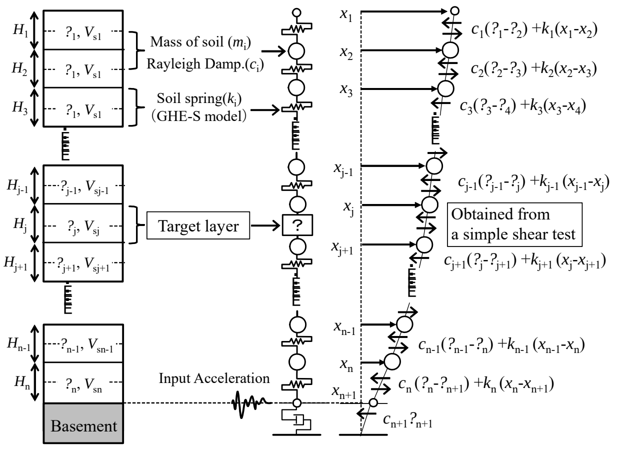


Fig. 4. A conceptual Fig. of a hybrid ground response analysis (HGRA).

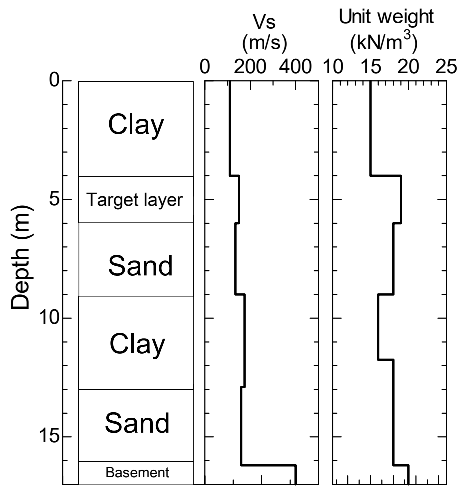
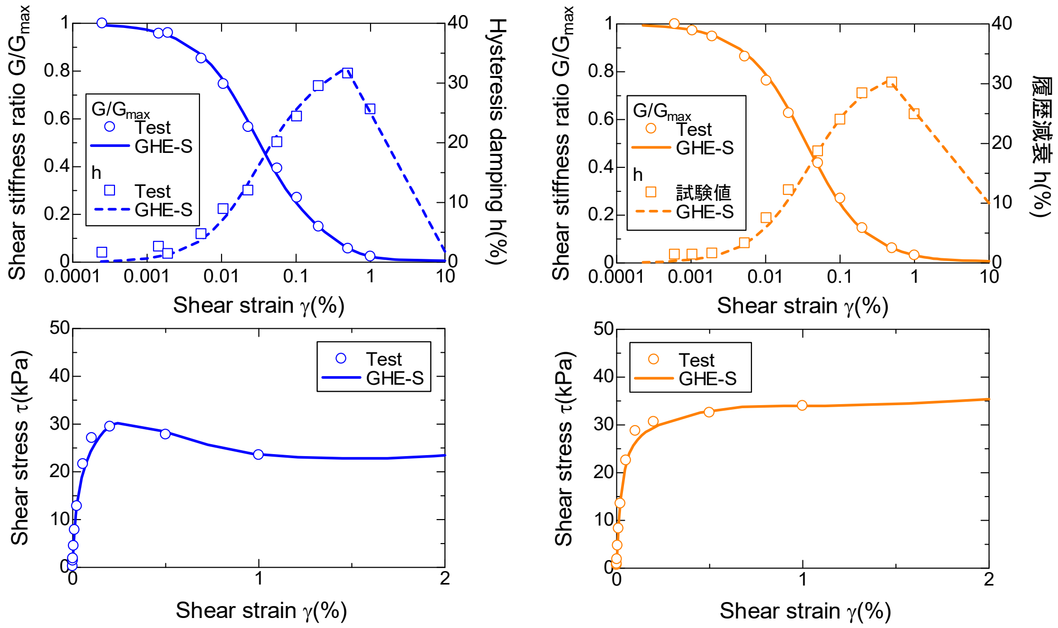


Fig. 5. Model ground for hybrid and usual ground response analyses.

cumulative dissipation energy reaches to 0.01 against a small-scale earthquake, for which strain level of the surface ground may be small. Similarly, Toyoura sand with Dr=80% did not show any upper limits at all the strain levels, which means that possibility of soil liquefaction is very low. This trend is corresponding to the past experiences. Fig. 2(b) shows the relationships between the degradation ratio of shear stiffness and the nor-malized cumulative dissipation energy. This shows that Toyoura sand with Dr=60% may lose its stiffness due to liquefaction. On the other hand, Toyoura sand with Dr=80% can maintain approximately 30% of its shear stiffness even if a large number of shear cycles may be applied during an earthquake. In this way, the 1CST can provide us with very valuable information on soil liquefaction, and may make more accurate evaluation of soil liquefaction possible.



(a) Dr=60% (b) Dr=80%

Fig. 6. Deformation properties used in the hybrid and usual ground response analyses modeled by the GHE-S model.

4. Verification of the energy method

4.1 Outline of the verification

In order to verify the validity of the proposed testing method, a hybrid ground response analysis (HGRA) was conducted, and results of usual ground response analyses (UGRA) using deformation properties obtained from the proposed and the conventional tests were compared to the results of the hybrid simulation.

A conceptual Fig. of Hybrid Ground response analysis (HGRA) is shown in Fig. 4. In this analysis, a target layer in a ground response analysis is replaced with a soil specimen of a simple shear test with a confining pressure, and reaction force of the target layer can be obtained from the soil specimen by applying a seismic displacement obtained from a previous step of a response analysis without a mathematical modelling. Therefore, the HGRA can give very accurate response of a target layer without errors in numerical modelling, setting of parameters, a testing and so on. In this paper, the result of the HGRA is considered to be correct values.

The model ground used in the analysis is shown in Fig. 5. Nonlinear deformation properties of the soils except for the target layer were modeled by the GHE-S model (Murono and Nogami, 2006) with its standard parameters (Nogami et al., 2012). The level 2 spectrum II earthquake used for the seismic design of Japanese railway structures (Railway Technical Research Institute, 2012) was applied to all of the models.

To assess a soil liquefaction potential by the proposed method based on the dissipation energy, we have to calculate an applied dissipation energy in the target layer by conducting a ground response analysis. Then, two cases of usual ground response analyses (UGRA) were conducted for the same model ground shown in Fig. 5, in which deformation properties obtained from the elemental test that the authors (Izawa et al., 2019) have proposed method were applied to the target layer. Parameters for GHE-S model were determined so that G/G_{max}-γ and h-γ relationships modeled as the GHE-S model correspond to those of the test results as shown in Fig. 6. The GHE-S model can adequately fit the deformation properties.

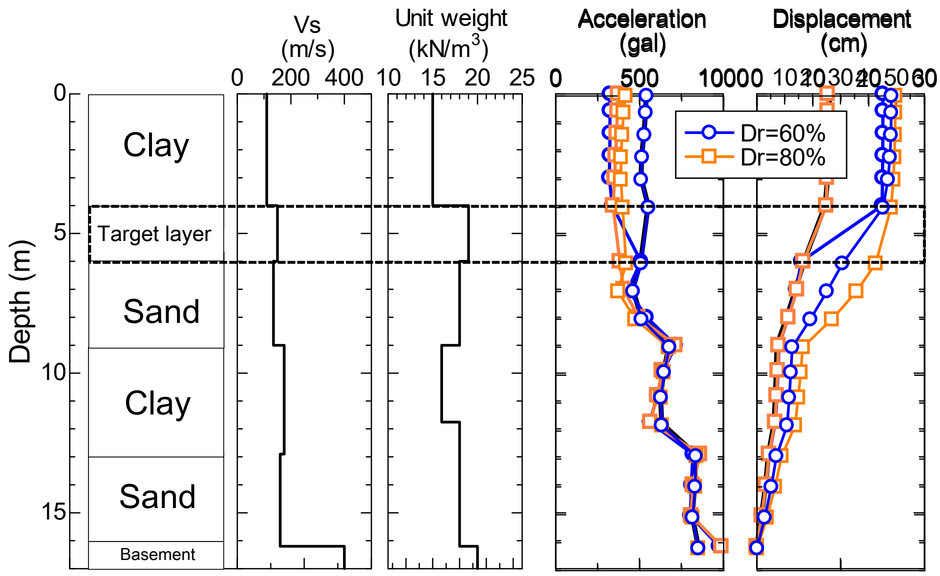


Fig. 7. Vertical distributions of maximum response obtained from the HGRAs

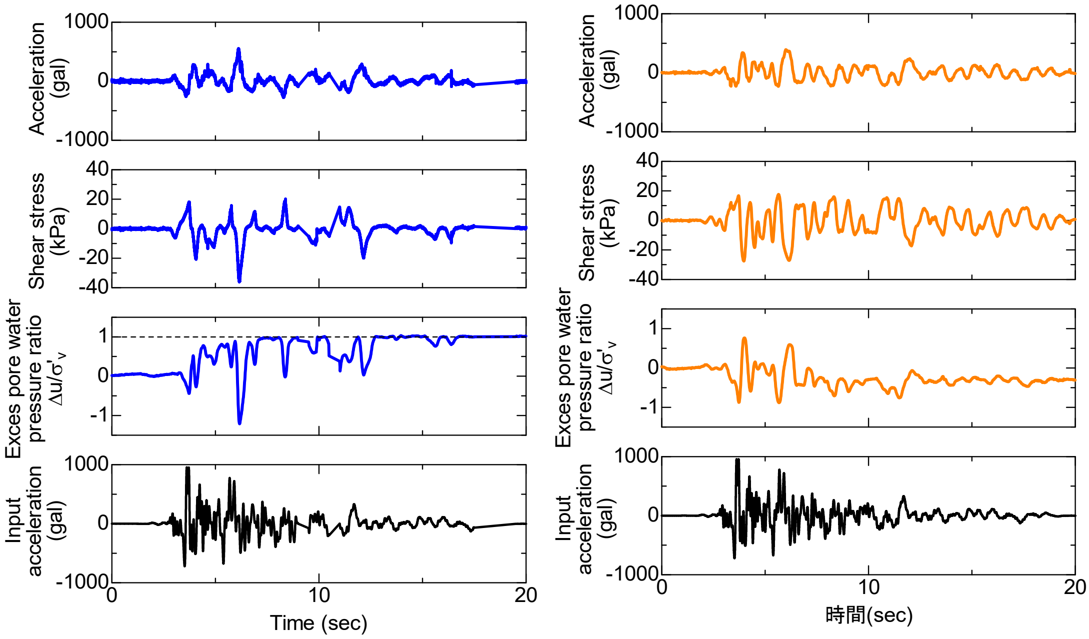


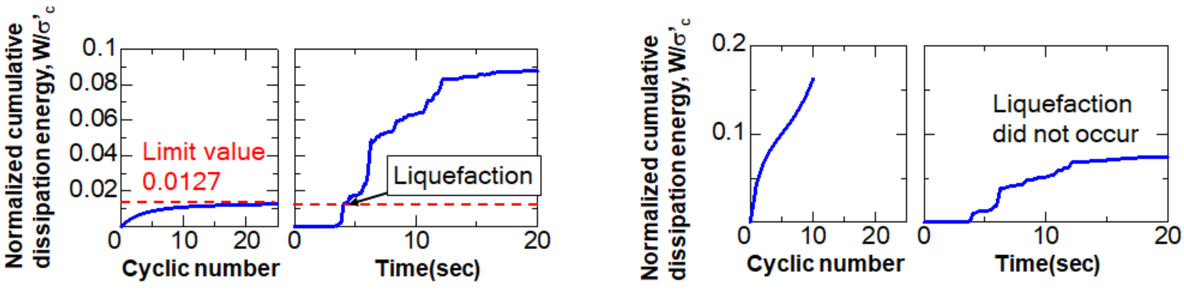
Fig. 8. Time histories of seismic response obtained from the HGRAs

4.2 Test results and verification

Fig.s 7 and 8 show vertical distributions of maximum response and time histories of some typical indexes observed in the HGRAs. As indicated in the time histories of the excess pore water pressure ratio in the case of Dr=60%, the excess pore water pressure ratio reached to 1.0 at approximately 7 seconds, which means soil liquefaction occurred. On the other hand, the excess pore water pressure ratio did not reach to 1.0 in the case of Dr=80% although it gradually increased with shaking.

4.3 Liquefaction potential evaluation based on the dissipation energy

Fig. 9 show relationships between the normalized cumulative dissipation energy and the cyclic number obtained from the CSCT, and time histories of the normalized cumulative dissipation energy calculated from



(a) Dr=60%   (b) Dr=80%

Fig. 9. Result of evaluation on liquefaction potential

Table 1 - Summary of evaluations on liquefaction potential

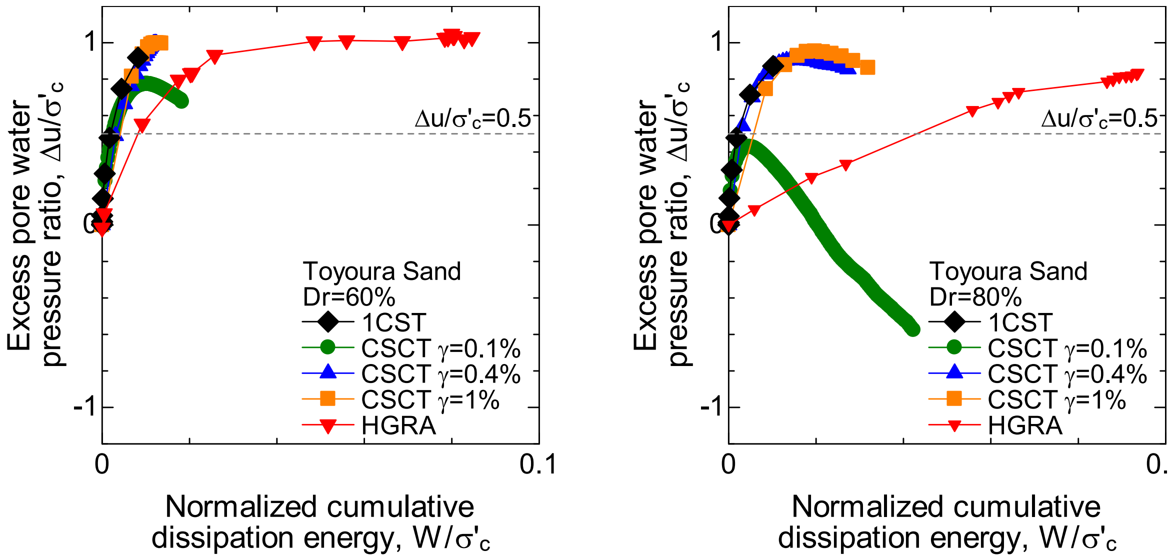
		Dr=60%	Dr=80%
Stress-based method	R_{20}	0.120	0.200
	R_L	0.151	0.382
	L	0.954	1.048
	F_L	0.158	0.365
	P_L	12.6	9.53
	Judge	×	×
Dissipation Energy method	W_e/σ'_c	0.0127	∞
	W_a/σ'_c	0.0930	0.0910
	F_s	0.136	∞
	Judge	×	○
Hybrid ground Response sim.	$(\Delta u/\sigma'_c)_{max}$	1.04	0.779
	Judge	×	○

R_{20} : Liquefaction strength at 20 cycles
R_L : Liquefaction strength based on accumulated damage method
F_s : Factor of safety on liquefaction ($F_s=W_a/W_e$)
×=Liquefiable layer ○=non-liquefiable layer

the result of the ground response analysis for the case of Dr=60% and 80%. In the case of Dr=60%, the normalized cumulative dissipation energy applied to the target layer calculated from a ground response analysis exceeds at approximately 4 second. This means that the target layer would show soil liquefaction. This evaluation result is corresponding to the result of the HGRS as shown in Fig. 9 although the times of occurrence are different. On the other hand, the target layer with Dr=80 is judged to be non-liquefiable layer as the Wa/σ'c did not exceed its upper limit, which was not clearly observed in the CSCT at all. Table 1 summaries the results of evaluation of liquefaction potential based on the dissipation energy together with the results of the ordinary FL method. The FL method judged the target layer with Dr=80% would show liquefaction, which is different from the result of the HGRA. This clearly shows that the evaluation of liquefaction potential based on the dissipation energy can give valid result as compared with the ordinary stress based method.

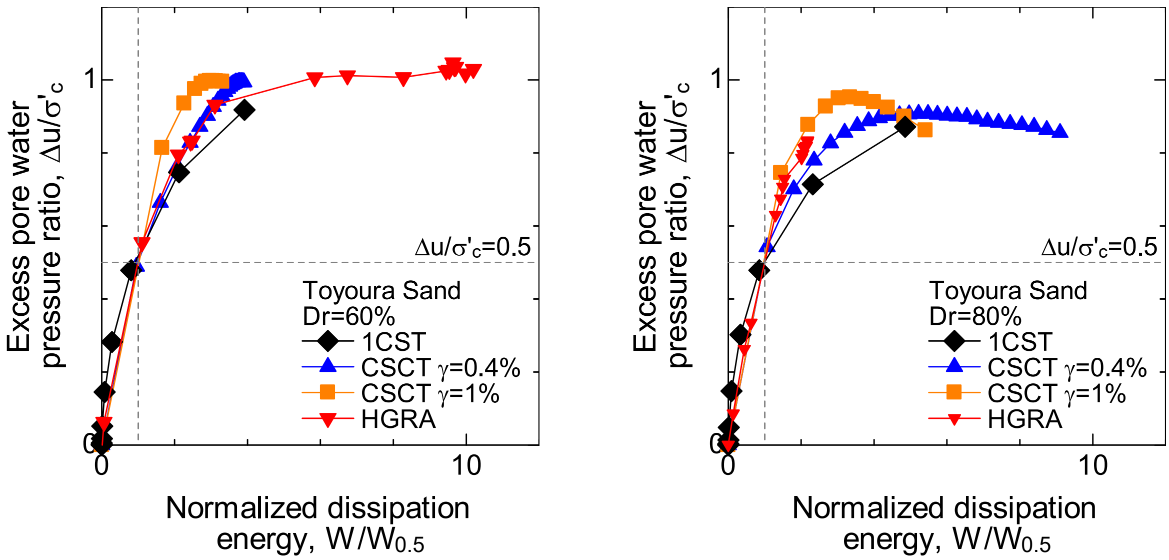
4.4 Evaluation of increase of pore water pressure

Fig. 10 shows relationships between the normalized cumulative dissipation energy and excess pore water pressure ratio obtained from the 1CSTs, CSCTs and HGRAs for the cases of Dr=60% and 80%. 1CSTs and CSCTs at γ=0.4% and 1.0% showed almost the same. On the other hand, CSCTs at γ=0.1% showed different behavior. The value of $\Delta u/\sigma'_c$ in CSCT at γ=0.1% with Dr=60% decreased after reaching approximately 0.8 while the normalized cumulative dissipation energy increased. The result with Dr=80% shows similar



(a) Dr=60% (b) Dr=80%

Fig. 10. $\Delta u/\sigma'_c \sim W/\sigma'_c$ relationship obtained from the results of 1CSTs, CSCTs and HGRAs



(a) Dr=60% (b) Dr=80%

Fig. 11. $\Delta u/\sigma'_c \sim W/W_{0.5}$ relationship obtained from the results of 1CSTs, CSCTs and HGRAs

process, and $\Delta u/\sigma'_c$ decreased after reaching approximately 0.4. This means that the relationship between the normalized cumulative dissipation energy and excess pore water pressure ratio could be influenced by applied shear strain level. The excess pore water pressure ratios of HGRA were less than that of 1CSTs and CSCTs at the same normalized cumulative dissipation energy. As a reason for that, we consider that the γ=0.4% of CSCTs and the Spectrum II earthquake contains relatively small shear strain level which did not influent the increase of excess pore water pressure.

In order to remove the influence of small shear strain level, we attempted to normalize the cumulative dissipation energy by a reference value. In this study, we define the cumulative dissipation energy at $\Delta u/\sigma'_c$=0.5, $W_{0.5}$, as the reference value. $\Delta u/\sigma'_c$=0.5 is approximately the 1st cycle of the γ=0.4% of CSCTs. Fig. 11 shows relationships between the cumulative dissipation energy normalized by $W_{0.5}$, $W/W_{0.5}$, and excess pore water pressure ratio obtained from the 1CSTs, CSCTs and HGRAs for the cases of Dr=60%

and 80%. All the case showed similar behavior. This result indicates that increase of excess pore water pressure can be estimated from the relationship between the cumulative dissipation energy normalized by a referent $W_{0.5}$ and excess pore pressure ratio can be uniquely determined.

5. Conclusions

The authors have proposed a new laboratory testing method for obtaining deformation properties of soils used for dynamic nonlinear seismic ground response analysis. This proposed method can give information for evaluation of liquefaction potential based on the cumulative dissipation energy theory. This paper examines the validity of the evaluation of liquefaction potential based on the dissipation energy. In order to compare the correct results and the evaluation results, the hybrid ground response analyses were conducted for the two model grounds with medium and dense layer susceptible to soil liquefaction. As a results, the evaluation based on the dissipation energy could evaluate correct liquefaction phenomenon, which were observed in the HGRA. In addition, this study investigated influence of shear strain level and loading history on the increase of pore water pressure based on the results of 1CSTs, CSCTs and hybrid ground response simulations. As a result, it is revealed that the relationship can be uniquely determined by normalizing the accumulated dissipation energy by an appropriate value.

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