Applicability of the accumulative dissipation energy method for assessment of soil liquefaction

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ABSTRACT: The authors have proposed a new laboratory testing method for obtaining deformation properties of soils used for dynamic nonlinear seismic ground response analysis. The accuracy of the method was verified by comparing the results of the seismic ground response analysis based on the results of the proposed tests and results of the hybrid ground response simulator, which can give as accurate response as possible. In addition, the proposed method can give information for assessment of liquefaction with the use of cumulative dissipation energy theory. This paper describes accuracy of assessment for soil liquefaction by energy method with the results obtained from the proposed laboratory tests. It was confirmed that assessment for soil liquefaction based on the energy method using the results of the proposed laboratory tests gave almost the same results with those obtained from the hybrid ground response analysis. These results clearly shows high accuracy of assessment for soil liquefaction by energy method and effectivity of the proposed laboratory test method for seismic design of the structures.

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.

2 CUMULATIVE DISSIPATION ENERGY METHOD

The testing method for determining deformation properties of soils the authors have proposed is composed of two different test series: a strain controlled 1 cycle stage test (1CST) and a constant

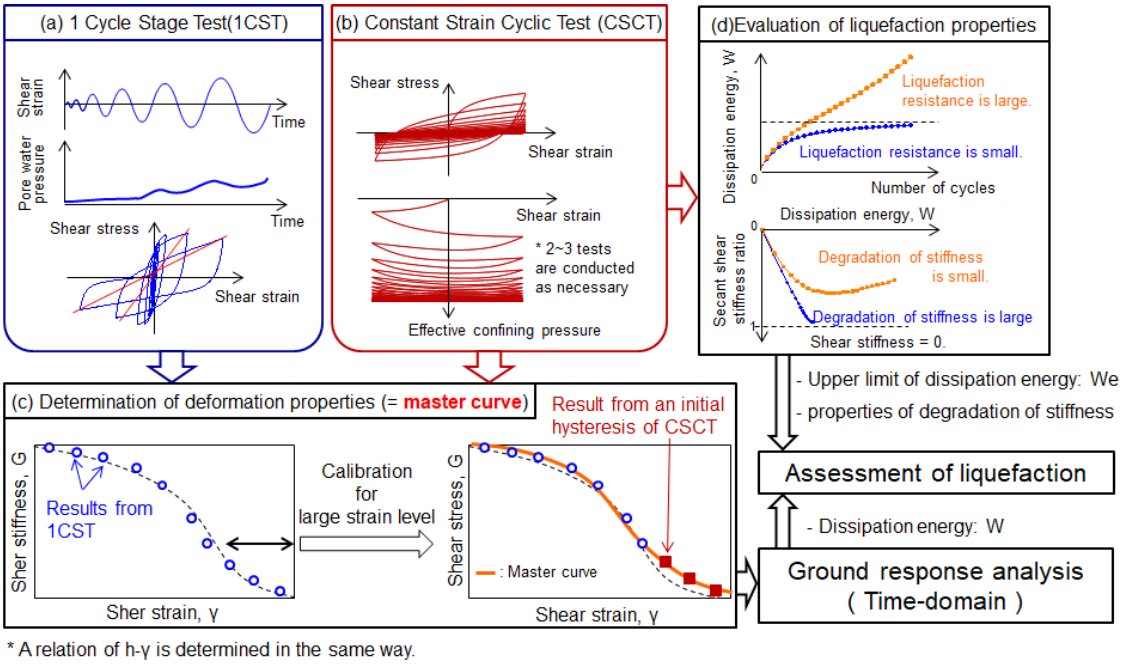


Figure 1. Concept of the proposed testing method.

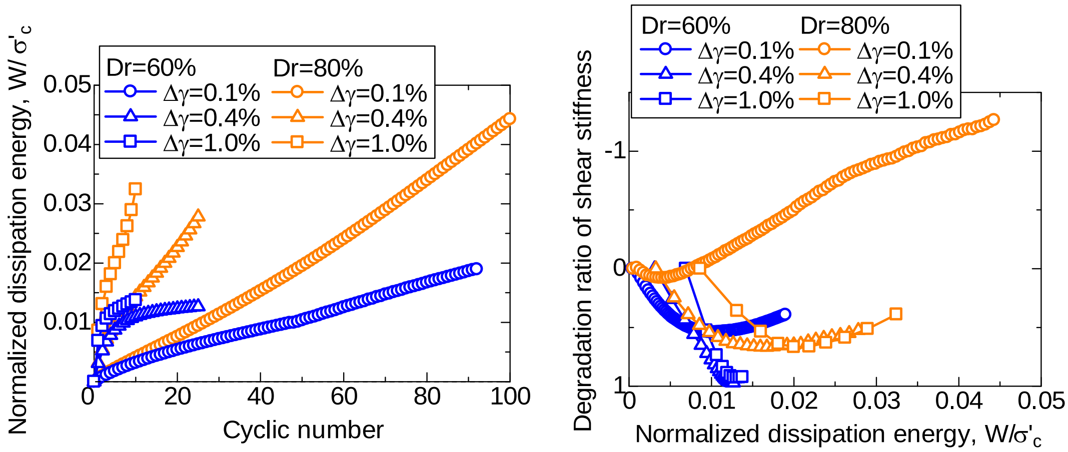
strain cyclic test (CSCT) as indicated in Figure 1. These tests are basically conducted with a torsion shear test apparatus or a simple shear test apparatus in order to simulate pure shear deformation. Details of the respective tests are as follows.

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 conducted 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 equation (1).

$$W = \int \tau(\gamma) d\gamma \quad (1)$$

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 dissipation energy as schematically shown in Figure 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 Figure 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



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

Figure 2. Results obtained from constant strain cyclic loading tests

can be estimated from a relationships between stiffness and cumulative dissipation energy as illustrated in Figure 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.

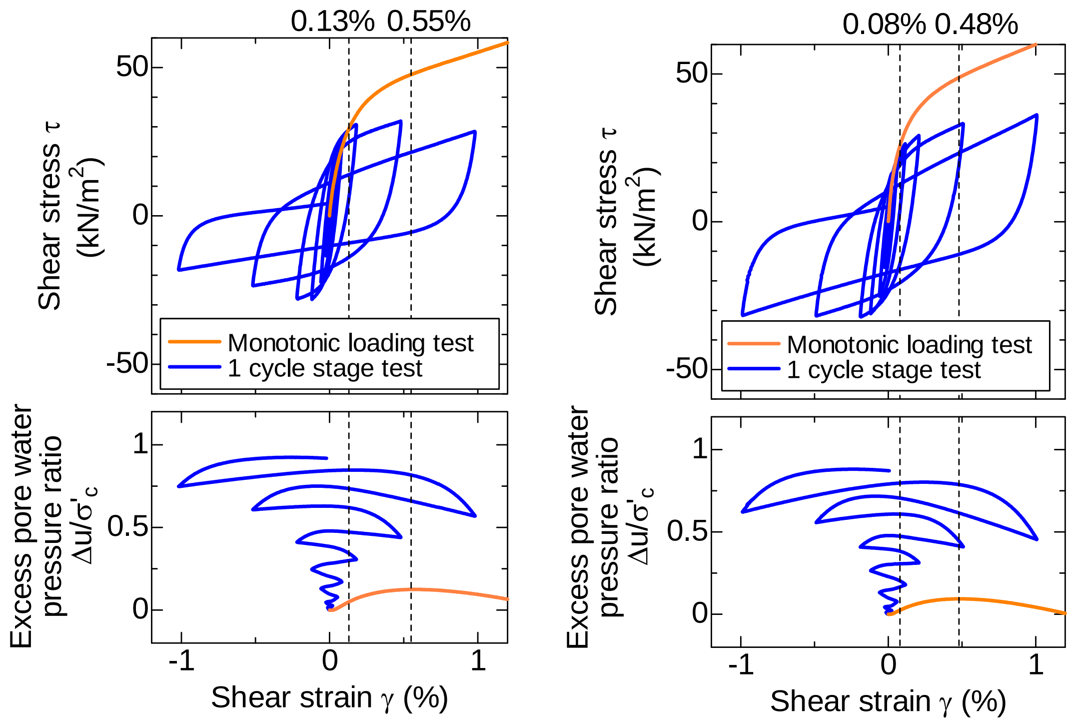
3 TRIAL TESTS

3.1 *Outline of the test*

In order to verify the above mentioned theory, firstly, trial tests were conducted using Toyoura sand (G_s=2.645, D_{50}=0.190mm, e_{max}=0.973, e_{min}=0.609, U_c=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 2.0% were applied to the specimens at the strain velocity of 0.1%/min. All of the tests were conducted under undrained condition.

3.2 *Test results*

Figure 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 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. Figure 2(b) shows the relationships between the degradation ratio of shear stiffness and the normalized 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 CST 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%

Figure 3. Relationships between Shear stress and shear strain, and excess pore water pressure ratio and shear strain obtained from monotonic loading tests and 1 cycle stage tests.

3.3 *Amplitude of applied strain levels*

Different upper limits were obtained in a test series of Dr=60%. Toyoura sand with Dr=60% did not show an upper limit at a constant strain level of 0.1%. On the other hand, upper limits of 0.0137 and 0.0127 could be obtained at a constant strain level of 0.4% and 1.0% although these two cases also showed approximately 10% discrepancy. Applied constant strain levels should be carefully set when an upper limit of a soil is determined by CSCT. Figures3 (a) and (b) show τ-γ relations of strain controlled 1 cycle stage shear tests (1CSTs) and monotonic torsion shear tests of Toyoura sand with Dr=60% and 80% respectively. Both τ-γ relations for Dr=60% seems to be identical before shear strain reach to approximately 0.13% as shown in the upper figure of Figure 3(a), which means soil specimens behave elastically and may show hardening with cyclic loadings in elastic area. An excess pore water pressure ratio in the monotonic torsion shear test for Dr=60% increased with increase of shear strain at first, and tended to show decrease after the shear strain of 0.55%. This means that Toyoura sand with Dr=60% tends to show recovery of effective stress after the shear strain of 0.55%. It is supposed that Toyoura sand with Dr=60% showed lowest upper limit in the CSCT for the constant strain level of 0.4%, at which excess pore water pressure is likely to accumulate due to shearing. Therefore, applied constant strain levels in CSCTs for determining upper limit of W should be set in consideration of properties of accumulation of excess pore pressure obtained from both a 1CST and a monotonic shear test. More detailed discussion is necessary on this point based on more test results and case histories.

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.

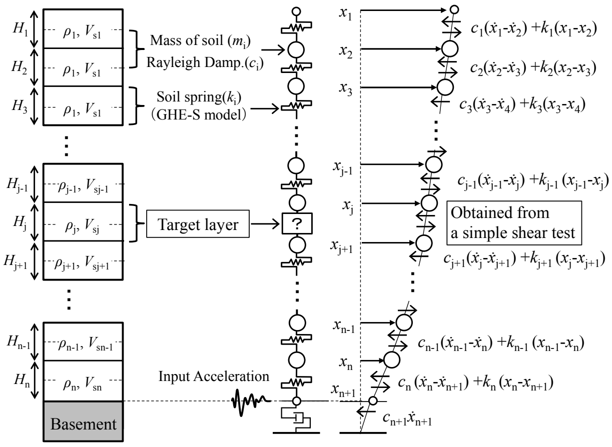


Figure 4. A conceptual figure of a hybrid ground response analysis (HGRA).

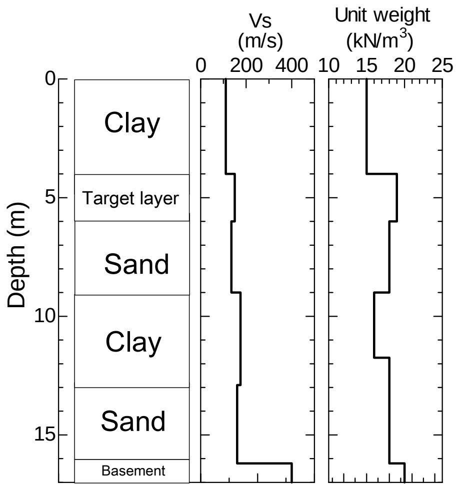
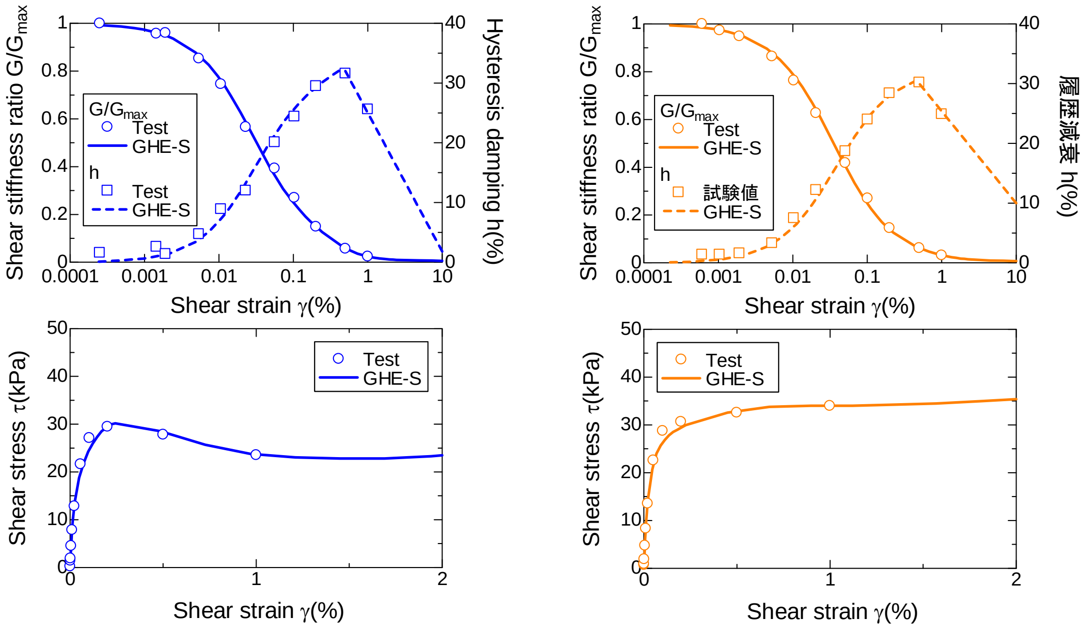


Figure 5. Model ground for hybrid and usual ground response analyses.



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

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

A conceptual figure of Hybrid Ground response analysis (HGRA) is shown in Figure 4. In this analysi, 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 Figure 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 an ground

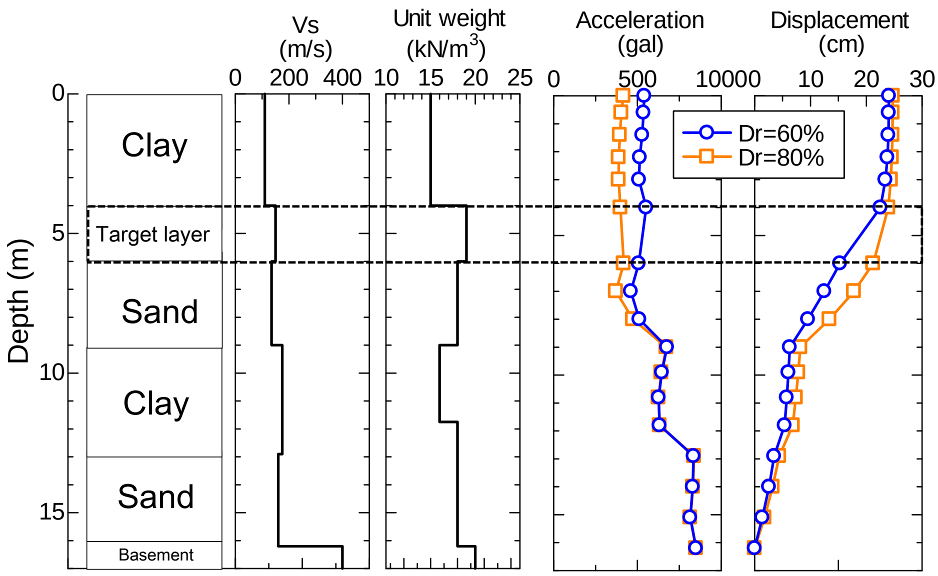


Figure 7. Vertical distributions of maximum response obtained from the HGRAs

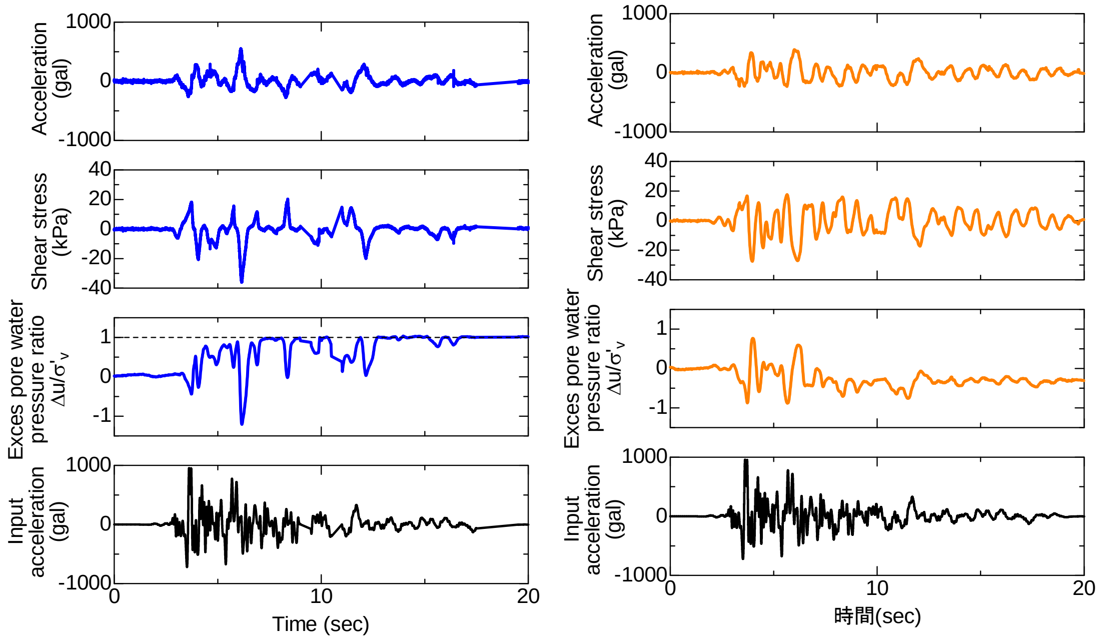
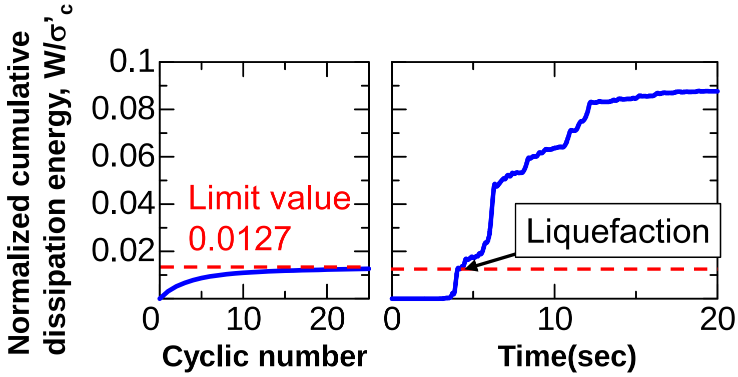


Figure 8. Time histories of seismic response obtained from the HGRAs

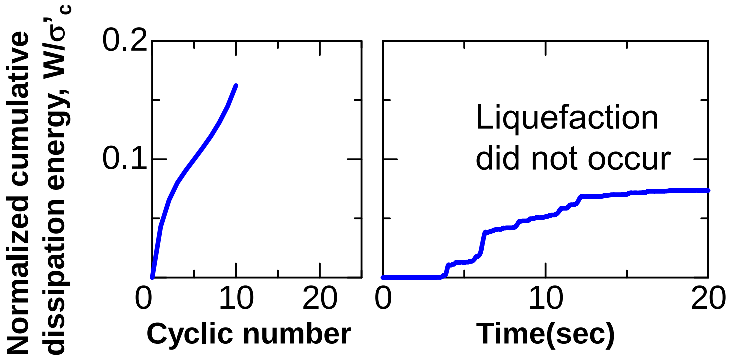
response analysis. Then, two cases of usual ground response analyses (UGRA) were conducted for the same model ground shown in Fig, in which deformation properties obtained from the elemental test that the authors(Izawa et al., 2019) have proposed method were applied to the target layer. Parameters for 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 Figure 6. The GHE-S model can adequately fit the deformation properties.

4.2 *Test results and verification*

Figures 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.



(a) Dr=60%



(b) Dr=80%

Figure 9. Result of evaluation on liquefaction potential (Dr=60%)

4.3 *Liquefaction potential evaluation based on the dissipation energy*

Figures 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 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 Figure 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 W_a/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.

5 CONCLUSION

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

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

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.

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