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Deformation properties of soils for a nonlinear dynamic response analysis

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ABSTRACT: Accuracy of deformation properties of soils at large strain level is of great importance for a ground response analysis to determine seismic action used in seismic design of structures against Level 2 earthquake. The authors have proposed a new laboratory testing method for deformation properties of soils used for a nonlinear dynamic ground response analysis, and studied the accuracy of the method using the RTRI hybrid ground response simulator. As a result, it was found that the proposed testing method could give very accurate deformation properties for a dynamic ground response analysis as compared with the conventional method based on the Standard of the Japanese Geotechnical Society, and the conventional method might evaluate extremely small shear stiffness at large strain level.

1 INTRODUCTION

Deformation properties of soil used in seismic ground response analysis are very important factors for seismic design of infrastructures, because inertia force and ground displacement acting on structures are greatly dependent on the results of ground response analysis. In general, two relationships, i.e. G/G_0-γ and h-γ relationships, are typically used as parameters indicating deformation properties of soils, where G is shear stiffness; G_0, initial shear stiffness; h, hysteresis damping; and γ, shear strain. For determining these parameters, a cyclic shear test is conducted using a tri-axial loading test apparatus, a torsion shear test apparatus and so on. As a testing method, as it is called, “a stage loading testing method” is generally adopted. For example, the Japanese Geotechnical Society (2018) define that a soil specimen is repeatedly sheared 11 times at a particular shear stress level at one loading stage, and G and h are determined as a secant shear stiffness and an area of a 10^{th} hysteresis loop of shear stress and shear strain relationship, i.e. τ-γ relationship, respectively. After each loading stage, excess pore water pressure in a soil specimen generated during 11 times cyclic shear is dissipated, i.e, a soil specimen is consolidated, and a next loading stage is conducted at a next shear stress level. The ASTM international (2013) also define similar testing method. These testing method was probably developed in the late 1960s – 1970s, in order to determine deformation properties for simulating relatively small scale and long duration earthquake, for example, the Loma Prieta earthquake. Nowadays, deformation properties for large shear strain level is necessary for the current seismic design of structures against a large-scale earthquake, in which the use of the time-domain nonlinear seismic ground response analysis is recommended. Some researchers, therefore, pointed out some problems of the conventional stage loading testing method (e,g. Silver and Park, 1975).

The authors, therefore, propose a new testing method to determine appropriate G/G_0-γ and h-γ relationships necessary for a nonlinear seismic ground response analysis against a large-scale earthquake. This paper describes outline of the proposed method, results of trial tests and analysis and verification with the hybrid ground response simulator developed by Railway Technical Research Institute.

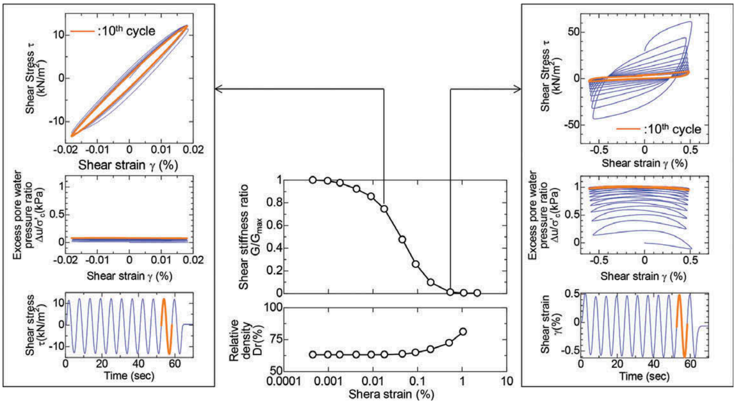


Figure 1. Results of an elemental test for deformation properties based on the JGS standard

2 OUTLINE OF THE PROPOSED TESTING METHOD

2.1 *Conventional testing methods*

As mentioned above, G/G_0-γ and h-γ relationships are determined from a 10th loop of τ-γ relationship in 11 times cycle loading at a constant shear stress under undrained condition in the JGS standard testing method. This loading stage is repeated at various shear stress levels after a soil specimen is consolidated at each loading stage. The major problems of the conventional method are schematically indicated in Figure 1 and summarized as follows:

- G and h may change during 11 times cycles due to excess pore water pressure, especially at large shear strain levels.
- Density of a soil specimen may change after each loading stage due to consolidation.
- It is difficult to control a target strain level because a test is conducted at stress controlled method and shear strain may rapidly increase during 11 times cyclic loading especially at large shear strain level.
- Tri-axial test apparatus cannot give an accurate loop of τ-γ relationship because an apparatus cannot simulate pure shear deformation.

The above problems had not been important for a seismic design against a relatively small-scale earthquake because shear strain level of the surface ground and increase of excess pore water pressure were relatively small. They have become obviously important in the current seismic design in which a level 2 earthquake is considered.

2.2 *The proposed method*

Deformation properties of soils depend on shear strain, γ and pore water pressure, u as mathematically indicated in the equation (1).

$$dG = \frac{\partial G}{\partial \gamma} d\gamma + \frac{\partial G}{\partial u} du \tag{1}$$

Since both of them have strong non-linearity respectively and it is impossible to consider their effects on deformation properties separately, an effective stress analysis must be conducted in order to adequately calculate ground response during an earthquake. It is, however, very cumbersome to make an effective stress analysis in practice. On the other hand, accuracy of a total stress analysis is acceptable for seismic design if deformation properties can be appropriately determined. The aim of the proposed testing method is to determine deformation properties used for a time-domain nonlinear ground response analysis based on the total stress analysis.

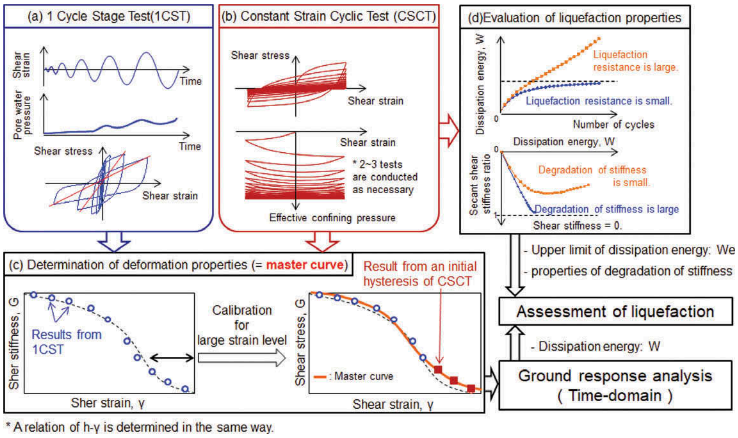


Figure 2. Concept of the proposed testing method.

Furthermore, soil liquefaction of the surface layer is also very important phenomena for seismic stability of structures. The proposed method can also give information for an assessment of soil liquefaction potential. The first opining of the proposed method is to determine the deformation properties dependent only on strain level, in which effect of excess pore water pressure is eliminated as much as possible. The G/G_0-γ and h-γ curve relationships dependent only on strain level is defined as "Master curves". Effect of excess pore water pressure is considered later as necessary after master curves are obtained. A conceptual scheme of the proposed method is shown in Figure 2. 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). 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.

1 *Strain controlled 1 cycle stage shear test (1CST)*

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 in order to eliminate change in unit weight of a soil specimen. A purpose of doing this test is to determine G/G_0-γ and h-γ relationships in a wide strain range eliminating the effect of pore water pressure as much as possible.

2 *Constant strain cyclic shear test (CSCT)*

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, an accumulated dissipation energy, W, can be calculated by the equation (2).

$$W = \int \tau(\gamma)d\gamma \tag{2}$$

An assessment of soil liquefaction potential based on a theory of dissipation energy (Kazama et al. 2000) can be used with W and degradation of shear stiffness of liquefiable layer. Suzuki et al. (2019) describes details of an assessment of soil liquefaction.

3 TRIAL TEST

3.1 *Outline of the test*

In order to check discrepancy between results obtained from the proposed method and the JGS standard method, a set of 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) with relative density of 60%. A torsion shear test apparatus was used for all of the trial 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. In the 1CSTs, shear strain time histories with triangle waves were applied to the specimens at the strain velocity of 0.1%/min. In the CSCTs, constant strain of 0.1%, 0.4% and 2.0% were applied to specimens at a strain velocity of 0.1%/min. The JGS standard tests used shear stress time history of sin wave shape with 0.1Hz. All of the tests were conducted under undrained condition. Densities of soil specimens before and after loadings at each test are indicated in Table 1.

3.2 *Test results*

Figure 3 shows G/G_{max}-γ and h-γ relationships obtained from the proposed test and the conventional stage test for Toyoura sands with relative density of 60% with relative densities of the JGS standard method, where G_{max} means the maximum shear stiffness measured in a test and is usually obtained from an 1st stage. The relative density before final loading stage reached to 80.9 % as compared with initial value of 62.9%. This result clearly shows that the soil specimens with adequate density may not be used and accurate deformation properties may not be obtained in the conventional stage tests especially at large strain level.

The G/G_{max} and h obtained from the initial loop of τ-γ relationship obtained from CSCTs were almost the same with those obtained from 1CTs at large strain level. This means that the CSCT can give the G/G_{max}-γ and h-γ curve relationships, which contains minimum effect of excess pore water pressure, i.e. "Master curves". On the contrary, the results of the conventional stage test was different from the master curve. The conventional method gave relatively larger G values at small-medium strain level and smaller values at large strain level. In addition, smaller h values were obtained from the conventional method for all of the strain level. Figure 4(a) and (b) indicate relationships between the shear stress and the shear strain at the strain level of

Table 1. Test conditions of Toyoura sand (Dr=60%) in each shear test.

Test type		Proposed method				
			Constant strain test			
		1 cycle stage test	Strain amplitude 0.1%	0.4%	1.0%	JGS standard
Before loading	Dry density (g/cm^3)	1.517	1.517	1.506	1.504	1.509
	Void ratio, e	0.749	0.749	0.762	0.764	0.759
	Relative density (%)	65.4	65.4	62.2	61.6	62.9
After loading	Dry density (g/cm^3)	1.512	1.512	1.510	1.509	1.573
	Void ratio, e	0.755	0.755	0.757	0.758	0.686
	Relative density (%)	64.0	64.0	63.4	63.2	80.9

※ Values of the conventional test is values after the final loading stage.

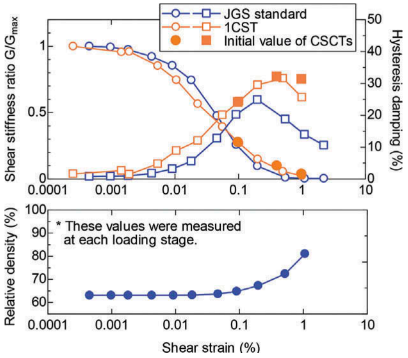
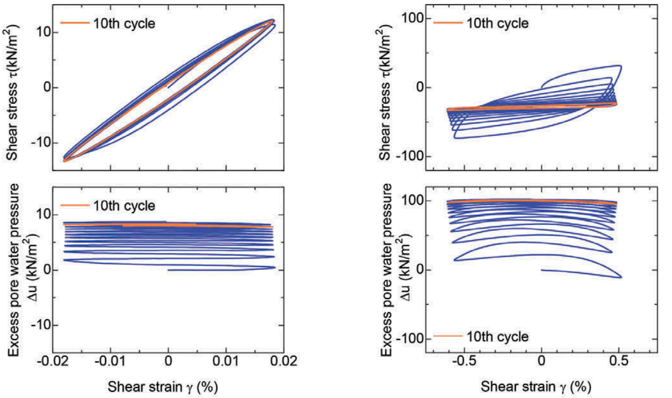


Figure 3. Comparison of deformation properties obtained from the conventional test and those from the proposed tests. Dr=60%.



(a) Shear stress ratio = 11kPa (b) Shear strain amplitude = 0.2%

Figure 4. Shear stress – shear strain relationship of Toyoura sand with Dr=60% obtained from the conventional cyclic loading test

0.017% and 0.20%. As shown in Figure 4(a), variation of shear stiffness during cyclic loading due to excess pore water pressure was small at the medium strain level (0.017%). However, relatively larger stiffness was shown after 2^{nd} cycle. This is probably because the specimen was sheared within its yield surface after the 2^{nd} cycle. In addition, area of the τ-γ curve tended to shrink which resulted in decrease of hysteresis damping. On the other hand, at the large strain level (0.20%), shear stiffness greatly decreased with increase of the cyclic number due to excess pore water pressure.

4 VERIFICATION OF THE PROPOSED METHOD

The seismic standard for railway structures in Japan (Railway Technical Research Institute, 2012) recommends that seismic actions applied to structures should be calculated by a ground response analysis using a discrete mass-spring model. In addition, deformation properties of soil layers are modelled with the GHE-S model (Murono and Nogami, 2006), of which parameters are determined in order to fit both G/G_{max}-γ and h-γ relationships obtained from elemental tests. As indicated in Chapter 3, both G/G_{max} γ and h-γ relationships are greatly dependent on testing method. 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.

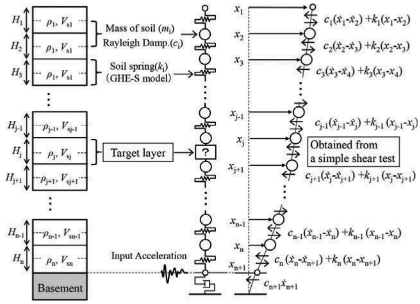


Figure 5. A conceptual figure of a hybrid ground response analysis (HGRA).

4.1 *Hybrid ground response analysis (HGRA)*

A conceptual figure of Hybrid Ground response analysis (HGRA) is shown in Figure 5. 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 Figure 6. Nonlinear deformation properties of the soils except for the target layer were modeled by the GHE-S model with its standard parameters (Nogami et al. 2012). The level 2 spectrum II earthquake used for the seismic design of Japanese railway structures was applied to all of the models.

4.2 *USUAL dynamic ground response analysis (UGRA)*

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 proposed and the conventional tests 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 7. The GHE-S model can adequately fit the deformation properties obtained from the proposed and the conventional cyclic tests except for the τ-γ curve at large strain level of the conventional test which is extremely underestimated by the test.

4.3 *Results and discussions*

Figure 8 shows vertical distributions of maximum response acceleration and horizontal displacement of the HGRA and UGRAs using results of the proposed test and the conventional test. Horizontal displacement of the UGRA using results of the proposed test was corresponding to that of the HGRA, although that of the conventional test was extremely large. This means that the proposed method can give accurate deformation properties method and the conventional method may evaluate smaller stiffness. On the other hand, maximum acceleration of the UGRA using results of the proposed test was smaller than that of the HGRA. Figure 9 shows time histories of response acceleration, shear stress and excess pore water pressure ratio of the HGRS and the UGRS with input acceleration. The maximum acceleration of the HGRS is detected at approximately 6.0 seconds due to quick increase of shear stress accompanying with recovery of pore water pressure, as it is called, cyclic mobility. Such behavior cannot be sufficiently simulated by the GHE-S model because it is made based on the total stress theory. Figure 10 indicate a comparison of response acceleration spectra of the HGRS and the UGRSs. As natural period of usual railway structures in Japan is around 0.5~1.0 second, short period response due to cyclic mobility may not affect dynamic behavior of railway structures.

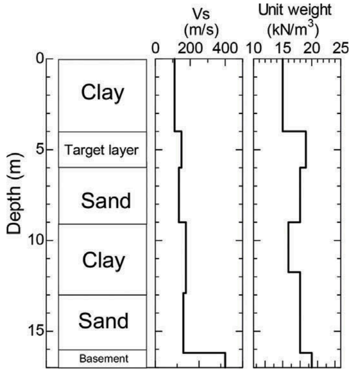


Figure 6. Model ground for hybrid and usual ground response analyses.

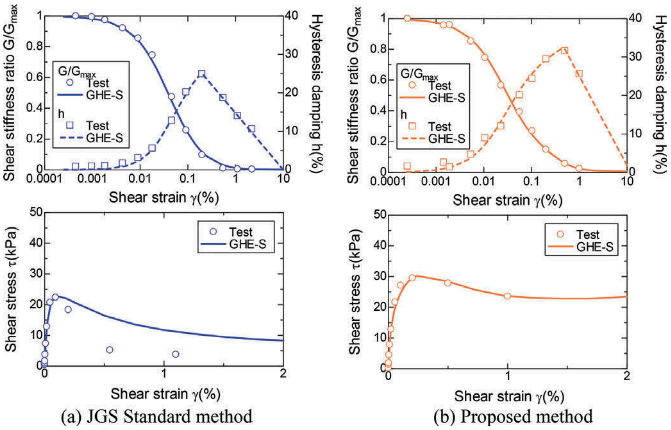


Figure 7. Deformation properties used in the hybrid and usual ground response analyses modeled by the GHE-S model.

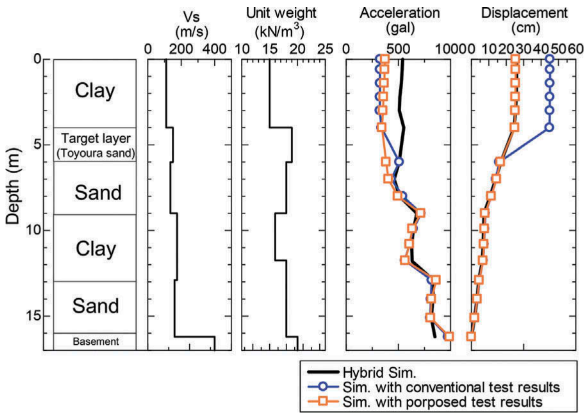


Figure 8. Vertical distributions of maximum response acceleration and horizontal displacement of the hybrid and the usual ground response analyses

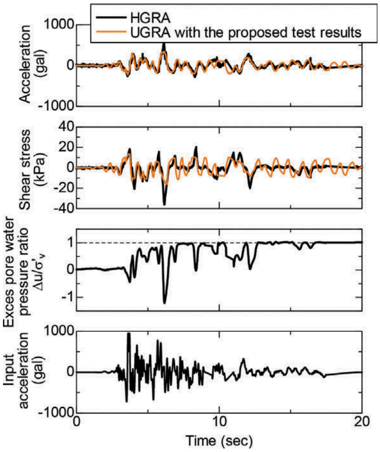


Figure 9. Time histories of response acceleration, shear stress and excess pore water pressure ratio of the HGRS and the UGRS with input acceleration.

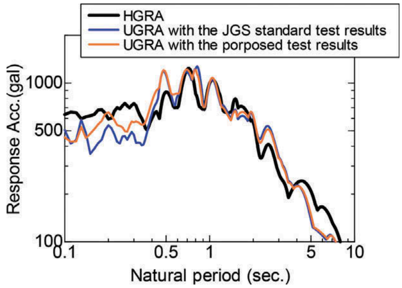


Figure 10. Response acceleration spectra at surface of the HGRS and the UGRSs

5 CONCLUSION

The authors have proposed a new cyclic loading testing method for the determination of defor mation properties, that is, the modulus and damping properties, which are used for dynamic ground response analysis. Comparison between test results of the proposed and the conventional tests clearly shows that the conventional testing method is likely to evaluate smaller shear stiffness of soils at large strain level, which may lead to evaluate larger horizontal displacement in a ground response analysis. On the other hand, results of the hybrid ground response analysis revealed that the proposed test can give adequate deformation properties for a ground response analysis against a large scale earthquake.

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