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# SHEAR MODULUS REDUCTION AND DAMPING CONSTANT CURVES OF CEMENT-TREATED CLAYS IN HOLLOW CYLINDRICAL TORSIONAL SHEAR TESTS

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## Abstract

Cement stabilization, a technique for ground improvement, chemically solidifies the ground, and has been used for the foundation grounds of construction and civil engineering structures, as well as for protecting against liquefaction. The accurate seismic response of grounds that have received this type of cement stabilization is important for its continued active use.

The equivalent linear analysis method is generally used for the seismic response analysis of cement stabilization methods. Strain-dependent curves for both the shear modulus and damping constant of the analyzed ground are necessary for equivalent linear analysis. This is generally calculated with cyclic triaxial tests. However, the strain range of the strain-dependent curve of shear modulus (damping constant) for the cement-treated soil calculated from cyclic triaxial tests is limited due to its dynamic properties and the characteristic constraints of the triaxial testing device. However, it is assumed that shear strains that exceed the shear strains range calculated from these triaxial tests can occur in the cement-treated ground to be tested, depending on its ground and stabilization mixing conditions. There are many unknown factors regarding the strain-dependent curves of shear modulus and damping constants across the wide-ranging strain domain of cement-treated ground. A strain-dependent curve of shear modulus (damping constant) at a strain level that exceeds the strain range obtained in cyclic triaxial tests must be obtained, particularly in cases where seismic response analysis is conducted using a strain-dependent curve based on the Hardin–Drnevich (H–D) or Ramberg–Osgood (R–O) models, which are constitutive equations that express the shear strain–shear stress relationship.

The design and quality control of cement-treated ground in Japan are mostly evaluated with unconfined compressive strength. The unconfined compressive strength of cement-treated soil is considered a primary parameter when evaluating strength and deformation characteristics. It is assumed that the seismic response of cement-treated ground can be easily evaluated if the strain-dependent curve of shear modulus (damping constant) can be expressed using the unconfined compressive strength of this cement-treated soil.

The current study conducted hollow cylindrical torsional shear tests to determine the strain-dependent curve of shear modulus (damping constant) in stabilized soil within the wide-ranging shear strain domain, which cannot be determined with standard cyclic triaxial tests. We propose an evaluation method of the reference strain and maximum damping constant based on the results of the hollow cylindrical torsional shear tests and the unconfined compression tests. These are used to determine the strain-dependent curve of shear modulus (damping constant) in the cement-treated soil. Unconfined compressive strength is used as the primary parameter for this evaluation method. Compatibility with existing shear stress–shear strain relationships was confirmed using the proposed evaluation method. The reference strain $\gamma_r$ and the maximum damping constant $h_{max}$, which were determined from the proposed evaluation method, were used in the existing shear stress–shear strain relationship. We compare the strain-dependent curve of shear modulus (damping constant) obtained here with the present test results.

*Keywords: Cement-treated soil, Torsional shear test, Cyclic deformation properties, Shear modulus, Damping constant*

## 1. Introduction

Cement stabilization, a technique for ground improvement, chemically solidifies the ground, and has been used for the foundation grounds of construction and civil engineering structures, as well as for protecting against liquefaction. The accurate seismic response of grounds that have received this type of cement stabilization is important for its continued active use.

The equivalent linear analysis method is generally used for the seismic response analysis of cement stabilization methods. One reason for this is that many of the shear strains in cement-treated ground generated during an earthquake are within the scope of equivalent linear analysis. Another reason for this is that virtually none of the constitutive equations that express the shear stress–shear strain relationship of cement-treated ground has been formulated [1,2,3], and it is difficult to conduct the step-by-step integration-method-based analyses necessary for determining a detailed seismic response. Strain-dependent curves for both the shear modulus and damping constant of the analyzed ground are necessary for equivalent linear analysis. This is generally calculated with cyclic triaxial tests. However, the strain range of the strain-dependent curve of shear modulus (damping constant) for the cement-treated soil calculated from cyclic triaxial tests is limited due to its dynamic properties and the characteristic constraints of the triaxial testing device [4,5]. However, it is assumed that shear strains that exceed the shear strains range calculated from these triaxial tests can occur in the cement-treated ground to be tested, depending on its ground and stabilization mixing conditions.

There are many unknown factors regarding the strain-dependent curves of shear modulus and damping constants across the wide-ranging strain domain of cement-treated ground. A strain-dependent curve of shear modulus (damping constant) at a strain level that exceeds the strain range obtained in cyclic triaxial tests must be obtained, particularly in cases where seismic response analysis is conducted using a strain-dependent curve based on the Hardin–Drnevich (H–D) [6] or Ramberg–Osgood (R–O) [7] models, which are constitutive equations that express the shear strain–shear stress relationship.

The design and quality control of cement-treated ground in Japan are mostly evaluated with unconfined compressive strength. The unconfined compressive strength of cement-treated soil is considered a primary parameter when evaluating strength and deformation characteristics [8]. One reason for this is that unconfined compression tests are simple shear tests. An additional reason is that the unconfined compressive strength is a physical value that includes factors influencing the bonding strength of cementation (e.g., soil characteristics, stabilizer properties / mixing conditions) and that shows the extent of cementation effects [9]. It is assumed that the seismic response of cement-treated ground can be easily evaluated if the strain-dependent curve of shear modulus (damping constant) can be expressed using the unconfined compressive strength of this cement-treated soil.

The current study conducted hollow cylindrical torsional shear tests to determine the strain-dependent curve of shear modulus (damping constant) in stabilized soil within the wide-ranging shear strain domain, which cannot be determined with standard cyclic triaxial tests. Hollow cylindrical torsional shear tests are highly effective in reproducing the stress conditions in ground. Additionally, we conducted unconfined compression tests to investigate these evaluation methods. Multiple cement-treated soils with variable stabilizer mixing conditions were used in each test. Multiple hollow cylindrical torsional shear tests were conducted by varying the consolidation stress. First, we examine the strain-dependent curve of shear modulus (damping constant) obtained from the hollow cylindrical torsional shear tests. Next, we propose an evaluation method of the reference strain and maximum damping constant based on the results of the hollow cylindrical torsional shear tests and the unconfined compression tests. These are used to determine the strain-dependent curve of shear modulus (damping constant) in the cement-treated soil. Unconfined compressive strength is used as the primary parameter for this evaluation method. Compatibility with existing shear stress–shear strain relationships was confirmed using the proposed evaluation method. The reference strain $\gamma_r$ and the maximum damping constant $h_{max}$, which were determined from the proposed evaluation method, were used in the existing shear stress–shear strain relationship. We compare the strain-dependent curve of shear modulus (damping constant) obtained here with the present test results.

## 2. Tests on cyclic deformation properties using hollow cylindrical torsional shear tests

### 2.1 Specimens, stabilizer mixing conditions, and test conditions

Kaolin clay was used to produce the cement-treated soil. The physical properties of the kaolin clay are shown in Table 1. Cemented stabilizer was used as a stabilizer for the cement-treated soil. The mixing conditions of the cemented stabilizer and the hollow cylindrical torsional shear test conditions are shown in Table 2. One of the standard values used for the stabilization of clayey-soil was used as the water-to-stabilizer ratio (W/C) of the cement-treated soil employed in the test. Three values of the stabilizer amount (C) of the cement-treated soil were used in the experiments. The test specimens of the cement-treated soil were prepared in accordance with the Japanese Geotechnical Society Standards JGS 0821. A hollow cylinder specimen (outer diameter 10 cm, inner diameter 6 cm, height 10 cm) was used for the hollow cylindrical torsional shear tests, and a cylinder specimen (diameter 5 cm, height 10 cm) was used for the unconfined compression tests.

Table 1 – Physical properties of sample

| Sample | Soil particle density $\rho_s$(g/cm$^3$) | Liquid limit $w_L$(%) | Plastic limit $w_P$(%) | Plasticity index $I_p$ |
|---|---|---|---|---|
| Kaolin | 2.663 | 63.5 | 33.0 | 30.5 |

Table 2 – Production conditions of specimen and test condition

| Stabilizer amount C(kg/m$^3$) | Water-to-stabilizer ratio W/C(%) | Mean effective stress $\sigma'_m$(kN/m$^2$) | Anisotropic consolidation stress ration K | Age (days) |
|---|---|---|---|---|
| 50 | 60 | 41,59,82 | 0.4 | 28～30 |
| 100 | | | | |
| 150 | | | | |

### 2.2 Test methods

The hollow cylindrical torsional shear tests were conducted by varying the stabilizer amount C and the mean effective stress $\sigma'_m(=(\sigma'_a+2\sigma'_h)/3)$, as shown in Table 2. The mean effective stress $\sigma'_m$ $(=(\sigma'_a+2\sigma'_h)/3)$ of the cement-treated ground at depths of approximately 10, 15, and 20 m was recreated. Consolidation was implemented with an arbitrary axial stress $\sigma'_a$ and lateral stress $\sigma'_h$ under anisotropic stress conditions [8] with a consolidation stress ratio K $(=\sigma'_h/\sigma'_a)$=0.4 to reproduce the stress deformation state in the cement-treated ground. Undrained cyclic loading (the number of cycles was 11) with a constant shear strain amplitude in accordance with JGS 0543 was conducted after the completion of consolidation. Loading was performed using the strain control method in a stepwise manner within the shear strain range of 0.001%–2%. Unconfined compression tests were conducted in accordance with JIS A 1216 using cylindrical specimens constructed simultaneously and sharing the same material age as the hollow cylindrical torsional shear test specimens.

## 3. Test results

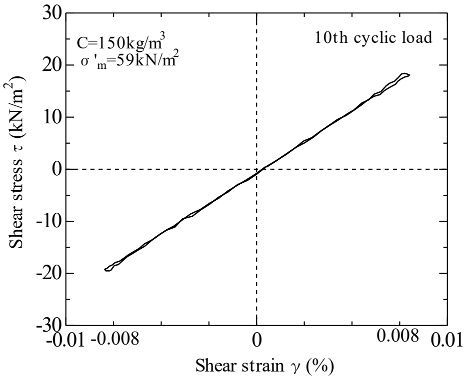
Test results of the shear stress–strain relationship at the 10th cycle are shown in Fig. 1a)–d). These test results are obtained with the stabilizer amount C=150 kg/m$^3$ and mean effective stress $\sigma'_m$=59 kN/m$^2$. The shear modulus G and damping constant h were calculated from these test results of the shear stress–strain relationship, which was calculated using Eq. (1) and (2) (Fig. 1b).

$$G = \frac{\tau_d}{\gamma_{(SA)}} (kN/m^2) \tag{1}$$

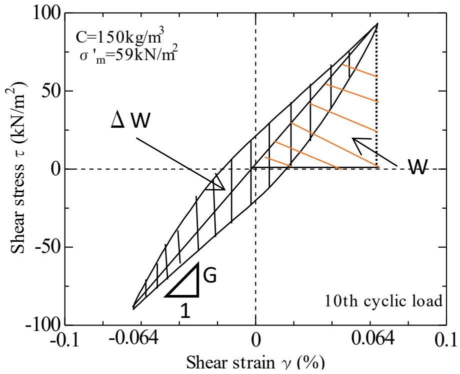
$$h = \frac{1}{2\pi} \cdot \frac{\Delta W}{W} \times 100(\%) \tag{2}$$



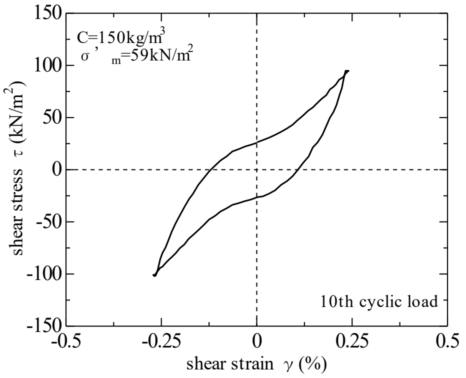
 



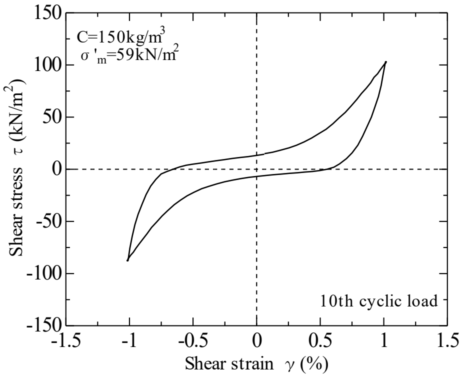

a) γ(SA)=0.008%




b)γ(SA)=0.064%

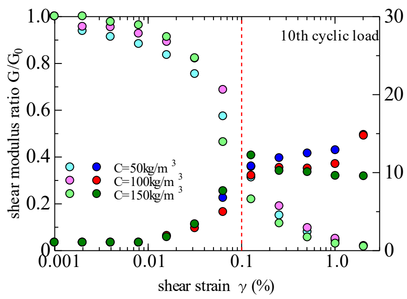



c) γ(SA)=0.25%

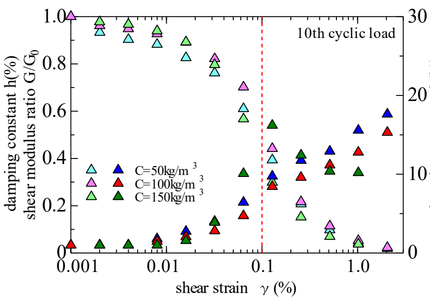



d) γ(SA)=1%

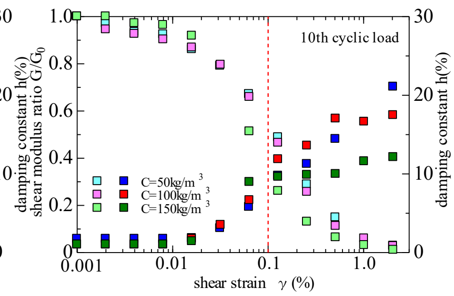
Fig. 1 – Shear stress-shear strain relation




a) σ'm=41kN/m2

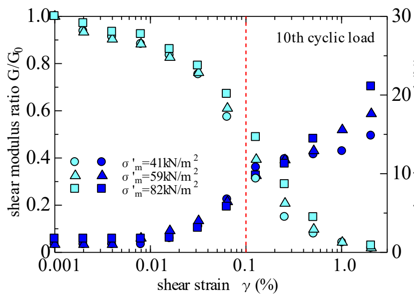



b) σ'm=59kN/m2

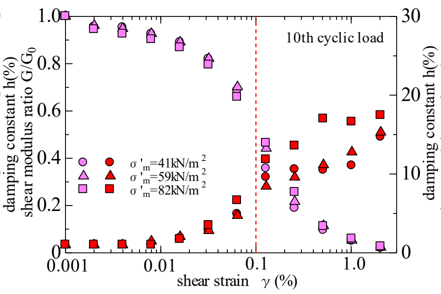



c) σ'm=82kN/m2

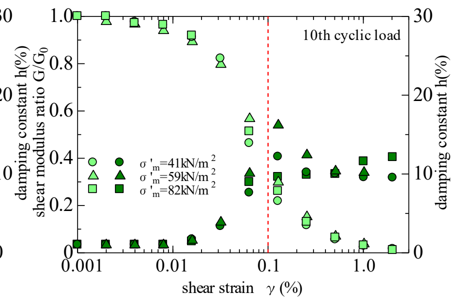
Fig. 2 – Effect of stabilizer amount




a) C=50kg/m3




b) C=100kg/m3




c) C=150kg/m3

Fig. 3 – Effect of mean effective stress



Here, $\tau_d$ is the one-sided shear stress amplitude, $\gamma_{(SA)}$ is the one-sided shear strain amplitude, $\Delta W$ is the damping energy (kN/m$^2$), and W is the equivalent elastic energy (kN/m$^2$).

We investigate the influence of the stabilizer amount C and the mean effective stress $\sigma'_m$ on the strain-dependent curve of shear modulus (damping constant). The shear modulus ratio $G/G_{max}$ and the damping constant h–shear strain $\gamma$ relationships obtained from the present test results for the mean effective stress $\sigma'_m$=41, 59, and 82 kN/m$^2$ are shown in Fig. 2a)–c). Test results for the stabilizer amounts C = 50, 100, and 150 kg/m$^3$ are compared in the same figure. Here, the initial shear modulus $G_{max}$ is the shear modulus G when the test result obtained $\gamma_{(SA)} \fallingdotseq 10^{-5}$. The $G/G_{max}$ and h–$\gamma$ relationships obtained from the present test results for the stabilizer amounts C = 50, 100, and 150 kg/m$^3$ are shown in Fig. 3a)–c). Test results for the mean effective stress $\sigma'_m$=41, 59, and 82 kN/m$^2$ are compared in the same figure. Additionally, the red dotted lines ($\gamma$=0.1%) in both figure indicate the approximate shear strain range that can be obtained from cyclic triaxial tests.

We focus on the $G/G_{max}$–$\gamma$ relationship of the cement-treated soil. The influence of the stabilizer amount C changed at a shear strain $\gamma$ boundary of approximately 0.03%, as shown in Fig. 2. Increases in C in the range of shear strain $\gamma$ below approximately 0.03% resulted in an increasing $G/G_{max}$ trend, whereas increases in C in the range of shear strain $\gamma$ above approximately 0.03% resulted in a decreasing $G/G_{max}$ trend. Furthermore, from Fig. 3, we can observe that the $G/G_{max}$–$\gamma$ relationship is largely unaffected by the changes in the mean effective stress $\sigma'_m$. Therefore, it is assumed that the influence of the mean effective stress $\sigma'_m$ on the $G/G_{max}$–$\gamma$ relationship is unclear.

We focus on the h–$\gamma$ relationship of the cement-treated soil. The stabilizer amount C and the mean effective stress $\sigma'_m$ have virtually no influence up to a shear strain $\gamma$ of approximately 0.1%, as shown in Fig. 2 and 3. However, a certain degree of variation in the h–$\gamma$ relationship test results was observed once the shear strain $\gamma$ exceeded approximately 0.1%. We can observe from Fig. 2 that increases in the stabilizer amount resulted in a smaller h value. We can observe from Fig. 3 that increases in the mean effective stress resulted in an increasing h value.

## 4. Strain-dependent curves of shear modulus and damping constant

The reference strain $\gamma_r$ and the maximum damping constant $h_{max}$ are generally required to express the strain-dependent curve of the shear modulus (damping constant) of the ground material as a nonlinear model.

In the present study, we investigate the evaluation methods of the reference strain $\gamma_r$ and the maximum damping constant $h_{max}$ using the hollow cylindrical torsional shear tests. The strain-dependent curve of the shear modulus (damping constant) of the cement-treated soil can be easily determined using these methods. Additionally, the $G/G_{max}$–$\gamma$ and h–$\gamma$ relationships were calculated using the reference strain $\gamma_r$ and maximum damping constant $h_{max}$, which was determined from this evaluation method, as nonlinear model parameters of existing shear stress–strain relationships. Additionally, the $G/G_{max}$–$\gamma$ and h–$\gamma$ relationships were calculated using the reference strain $\gamma_r$ and the maximum damping constant $h_{max}$ determined from this evaluation method as nonlinear model parameters of existing shear stress–strain relationships. These $G/G_{max}$–$\gamma$ and h–$\gamma$ relationships were compared with the corresponding relationships in the wide strain domain obtained from the present test results. We also confirmed the applicability of each evaluation method proposed for the nonlinear model and the compatibility of the $G/G_{max}$–$\gamma$ and h–$\gamma$ relationships and the present test results in cases where the nonlinear model was used.

### 4.1 Evaluated equation of reference strain $\gamma_r$

The reference strain $\gamma_r$ is defined as the shear strain $\gamma$ in the strain-dependent curve of shear modulus when the shear modulus ratio $G/G_{max}$ is 0.5. The reference strain $\gamma_r$ was calculated from the present test results for each condition. The obtained reference strain $\gamma_r$ and the mean unconfined compressive strength $q_u$ obtained from the unconfined compression tests are shown in Table 3. The mean unconfined compressive strength $q_u$ is determined from the average of the unconfined compressive strengths $q_u$ of the three specimens with the same material age. We can observe from Fig. 2 and Table 3 that increases in the stabilizer amount C are accompanied by decreased reference strain $\gamma_r$ in the cement-treated clays. Based on these results, the present investigation focuses on the cementation effects, which contribute to the expression of cement-treated clay strength. The relationship between the reference strain $\gamma_r$ obtained from the test results and the index $q_u/q_{uo}$, which shows the



Table 3 – Measured values of $q_u$,$\gamma_r$, and $h_{max}$

| Stabilizer amount C(kg/m³) | Mean effective stress σ'm(kN/m²) | Unconfined compressive strength qu(kN/m²) | Reference strain γr(%) | Maximum damping constant hmax(%) |
|---|---|---|---|---|
| 50 | 41 | 147 | 0.09 | 14 |
| | 59 | 147 | 0.10 | 16 |
| | 82 | 134 | 0.11 | 18 |
| 100 | 41 | 221 | 0.09 | 13 |
| | 59 | 172 | 0.10 | 14 |
| | 82 | 237 | 0.10 | 18 |
| 150 | 41 | 400 | 0.06 | 11 |
| | 59 | 513 | 0.07 | 14 |
| | 82 | 441 | 0.06 | 12 |

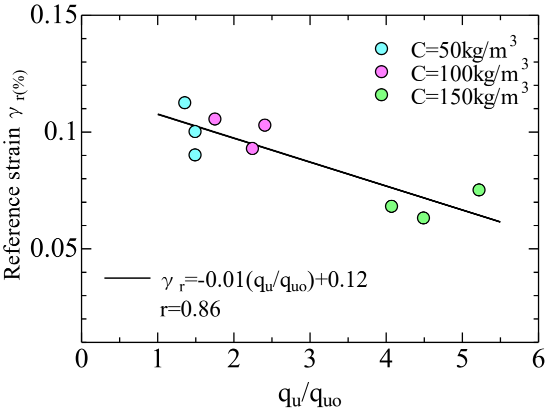



Fig. 4 – Relation between $\gamma_r$ and $q_u/q_{uo}$

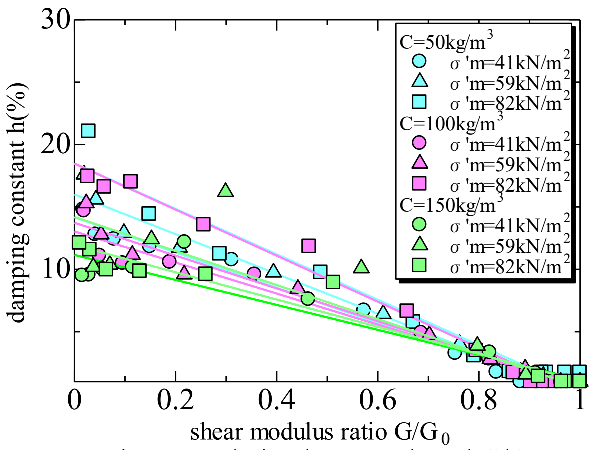



Fig. 5 – Relation between h and $G/G_{max}$

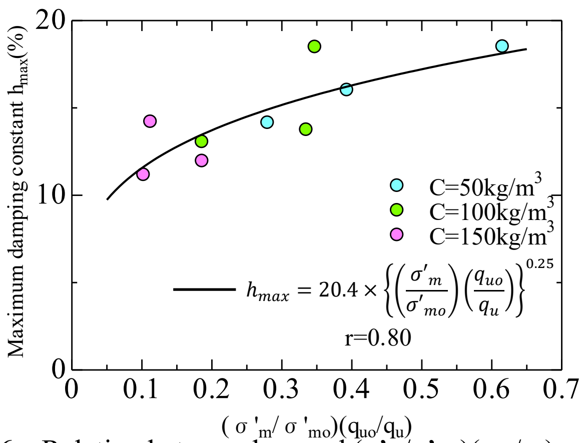



Fig. 6 – Relation between $h_{max}$ and $(\sigma'_m/\sigma'_{mo})(q_{uo}/q_u)$

extent of cementation effects [9], is shown in Fig. 4. Here, $q_{uo}$ is the reference unconfined compressive strength ($q_{uo}$=98 kN/m²). A good correlation between the reference strain $\gamma_r$ and $q_u/q_{uo}$ can be observed from the same figure. This relational expression between the reference strain $\gamma_r$ and $q_u/q_{uo}$ (Eq. (3)) was also expressed as a solid line. This suggests that the reference strain $\gamma_r$ of the cement-treated clays can be evaluated from the unconfined compressive strength $q_u$ within the scope of the present test results, independent of the stabilizer amount C and consolidation stress conditions.

$$\gamma_r = 0.01 \cdot \left(\frac{q_u}{q_{uo}}\right) + 0.12 \quad (\%) \tag{3}$$

4.2 Evaluated equation of the maximum damping constant $h_{max}$

The relationship between the damping constant h and the shear modulus ratio $G/G_{max}$ of the ground material is determined using Eq. (4) [6].

$$h = h_{max} \cdot \left(1 - \frac{G}{G_{max}}\right) \tag{4}$$

The h–$G/G_{max}$ relationship obtained from the present test results is shown in Fig. 5. Additionally, the figure also depicts the relationship between h and $G/G_{max}$ obtained from the present test results for each test condition as a straight line. The maximum damping constant $h_{max}$ of the present test results was set as the h value in each straight line when $G/G_{max}$ was 0.5. The maximum damping constant $h_{max}$ values determined from Fig. 5 are shown in Table 3. Increases in the stabilizer amount C are accompanied by decreased maximum damping constant $h_{max}$, and increases in the mean effective stress $\sigma'_m$ are accompanied by increased maximum damping constant $h_{max}$, based on the test results of the h–γ relationship shown in Fig. 2 and 3. The present investigation



Table 4 – Nonlinear model of geomaterial

| Nonlinear model | Constitutive expression | Parameter |
|---|---|---|
| H-D model | $\frac{G}{G_{max}} = \frac{1}{1+\left(\frac{\gamma}{\gamma_r}\right)}$ <br> $h = h_{max}\left(1-\frac{G}{G_{max}}\right)$ | $G_{max}$:Initial shear modulus <br> $\gamma_r$:Reference strain <br> $h_{max}$:Maximum damping constant |
| R-O model | $\frac{G}{G_{max}} = \frac{1}{\left[1+\alpha\left(\frac{G}{G_{max}}\cdot\frac{\gamma}{\gamma_r}\right)^{\beta-1}\right]}$ <br> $h = \frac{2}{\pi}\frac{\beta-1}{\beta+1}\left(1-\frac{G}{G_{max}}\right)$ | $G_{max}$:Initial shear modulus <br> $\gamma_r$:Reference strain <br> $h_{max}$:Maximum damping constant <br> $\alpha=2^{\beta-1}$ <br> $\beta=\frac{2+\pi h_{max}}{2-\pi h_{max}}$ |
| Y-A model | $\frac{G}{aG_{max}} = 1-\frac{\left(\frac{\gamma}{\gamma_r}\right)^c}{\left[1+\left(\frac{\gamma}{\gamma_r}\right)^c\right]^D}$ <br> $h = h_{max}\cdot\frac{\left(\frac{\gamma}{\gamma_r}\right)^c}{\left[1+\left(\frac{\gamma}{\gamma_r}\right)^c\right]^D}$ | $G_{max}$:Initial shear modulus <br> $\gamma_r$:Reference strain <br> $h_{max}$:Maximum damping constant <br> a,C,D:Material constant |

Table 5 – Parameters of $G/G_{max}$,h～γ curves for three nonlinear models

| Stabilizer amount C(kg/m$^3$) | Mean effective stress $\sigma'_m$(kN/m$^2$) | Unconfined compressive strength $q_u$(kN/m$^2$) | Reference strain $\gamma_r$(%) | Maximum damping constant $h_{max}$(%) | Initial shear modulus $G_{max}$(kN/m$^2$) | R-O | | Y-A | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | α | β | a | C | D |
| 50 | 41 | 147 | 0.103 | 13.81 | 65498 | 0.12 | 0.55 | 0.98 | 1.27 | 1 |
| | 59 | 147 | 0.103 | 15.32 | 65498 | 0.09 | 0.63 | 0.98 | 1.27 | 1 |
| | 82 | 134 | 0.104 | 18.28 | 60765 | 0.06 | 0.81 | 0.98 | 1.27 | 1 |
| 100 | 41 | 221 | 0.095 | 12.56 | 91129 | 0.14 | 0.49 | 0.99 | 1.32 | 1 |
| | 59 | 172 | 0.100 | 14.54 | 74383 | 0.09 | 0.59 | 0.99 | 1.32 | 1 |
| | 82 | 237 | 0.093 | 14.71 | 96437 | 0.10 | 0.60 | 0.99 | 1.32 | 1 |
| 150 | 41 | 400 | 0.076 | 11.45 | 147356 | 0.13 | 0.44 | 0.99 | 1.6 | 1 |
| | 59 | 513 | 0.064 | 11.58 | 180257 | 0.14 | 0.44 | 0.99 | 1.6 | 1 |
| | 82 | 441 | 0.072 | 12.56 | 159475 | 0.09 | 0.49 | 0.99 | 1.6 | 1 |

also focused on cementation effects, similar to Section 4.1. Additionally, we considered the mean effective stress $\sigma'_m$, as we confirmed its influence on these processes. The relationship between the maximum damping constant $h_{max}$ obtained from the present test results and the normalized mean effective stress $\sigma'_m$ divided by the index $q_u/q_{uo}$, which shows the extent of cementation effects, is shown in Fig. 6. Here, $\sigma'_{mo}$ is the reference mean effective stress (=98 kN/m$^2$). As shown in the figure, although there is some variation, a relatively strong correlation can be observed between the maximum damping constant $h_{max}$ and the normalized mean effective stress $\sigma'_m$ as well as the unconfined compressive strength $q_u$. Additionally, the relational expression (Eq. (5)) obtained from the present test results is shown as a solid line in the same figure. Fig. 6 suggests that the maximum damping constant $h_{max}$ of cement-treated clays can be evaluated from the unconfined compressive strength $q_u$ and the mean effective stress $\sigma'_m$, independent of the stabilizer amount C.

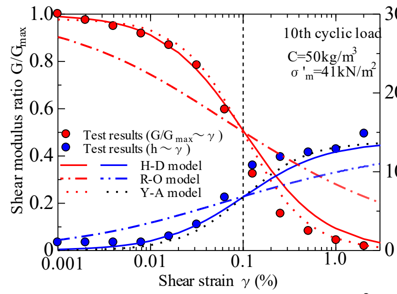
$$h_{max} = 20.4 \times \left\{\left(\frac{\sigma'_m}{\sigma'_{mo}}\right)\left(\frac{q_{uo}}{q_u}\right)\right\}^{0.25} \tag{5}$$

## 4.3 Investigation of applicability of the nonlinear model using the evaluated equation

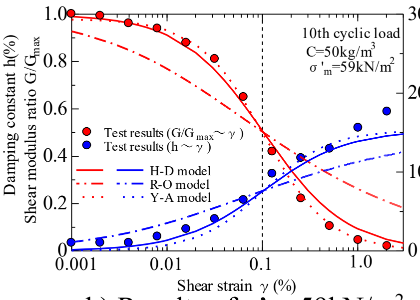
In the present section, the reference strain $\gamma_r$ and the maximum damping constant $h_{max}$ obtained from the proposed evaluation method are used as parameters for the nonlinear model of the existing shear stress–strain relationship to calculate the $G/G_{max}$–γ and h–γ relationships. These $G/G_{max}$–γ and h–γ relationships were compared with the corresponding relationships in the wide strain domain obtained from the present test results.



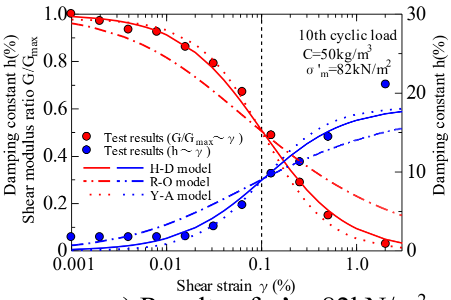
 



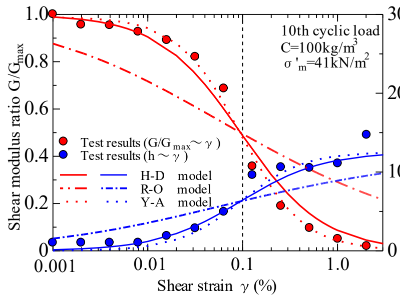

a) Results of $\sigma'_m$=41kN/m$^2$ for C=50kg/m$^3$



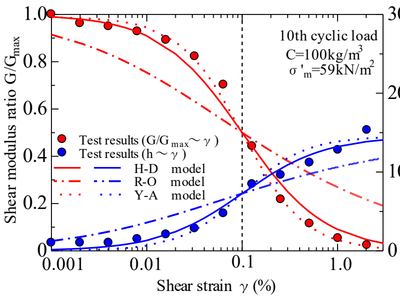

b) Results of $\sigma'_m$=59kN/m$^2$ for C=50kg/m$^3$



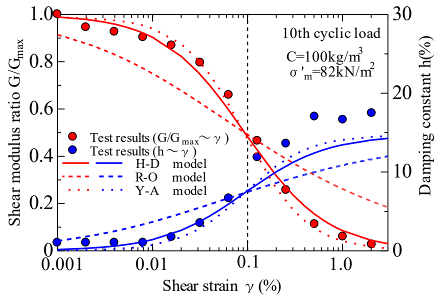

c) Results of $\sigma'_m$=82kN/m$^2$ for C=50kg/m$^3$



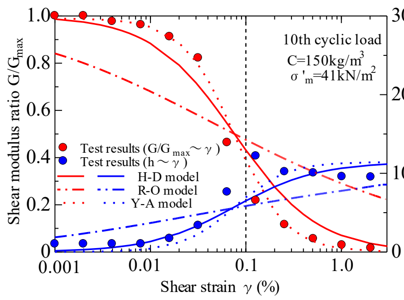

d) Results of $\sigma'_m$=41kN/m$^2$ for C=100kg/m$^3$



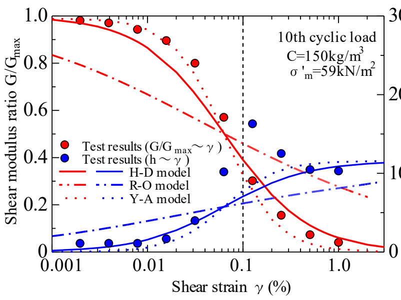

e) Results of $\sigma'_m$=59kN/m$^2$ for C=100kg/m$^3$



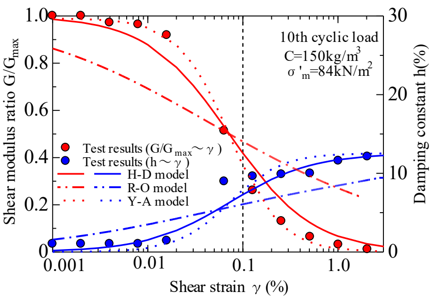

f) Results of $\sigma'_m$=82kN/m$^2$ for C=100kg/m$^3$




g) Results of $\sigma'_m$=41kN/m$^2$ for C=150kg/m$^3$




h) Results of $\sigma'_m$=59kN/m$^2$ for C=150kg/m$^3$




i) Results of $\sigma'_m$=82kN/m$^2$ for C=150kg/m$^3$

Fig. 7 – Comparison of $G/G_{max}$ ,h～γ curves for three nonlinear models

We also confirmed the applicability of each evaluation method proposed for the nonlinear model, and the compatibility of both the $G/G_{max}$–γ and h–γ relationships and the present test results in cases where the nonlinear model was used.

The three nonlinear models used in the present study are shown in Table 4. The H–D [6] and R–O [7] models are generally used as nonlinear models for the shear stress–strain relationship in ground materials. The Y–A [1,2] model is a nonlinear model proposed for cement-treated sands. A total of three, five, and six parameters are necessary for the H–D, R–O, and Y–A models, respectively, as shown in Table 4. An initial shear modulus $G_{max}$, reference strain $\gamma_r$, and maximum damping constant $h_{max}$ are necessary for each model. The α and β parameters necessary for the R–O model can be calculated from the maximum damping constant $h_{max}$. The parameters a, C, and D from the Y–A model were determined using a nonlinear least-squares method from the representative test result ($\sigma'_m$=59 kN/m$^2$) for each stabilizer amount. The initial shear modulus $G_{max}$ was calculated using the evaluated equation (Eq. (6)) [10], which can be estimated from the unconfined compressive strength. Here, $\sigma'_r$ is the reference stress (=98 kN/m$^2$).Table 5 shows the reference strain estimated using the evaluation methods proposed in Section 4.2, maximum damping constant, initial shear modulus calculated from Eq. (6), and parameters in each model calculated using the above-mentioned methods.

$$G_{max} = 455 \cdot \left(\frac{q_u}{q_{uo}}\right)^{0.87} \cdot \sigma'_r \quad (6)$$

The strain-dependent curves of shear modulus (damping constant) for the $G/G_{max}$ and h–γ relationships obtained from the present nonlinear test results, as well as those from each nonlinear model, are shown in Fig. 7a) –i). The R-O model exhibited poor compatibility with the $G/G_{max}$ and h–γ relationship test results in the wide strain domain and for each model, as shown in Fig. 7. This is because the nonlinearity of the R–O model is regulated by the parameter β, which is correlated with the maximum damping constant. Therefore, errors between the R–O model, which considers damping characteristics, and the test results become larger. Yoshida et al. [11] investigated the compatibility of the H–D and R–O models for multiple types of ground material such as sand and clay (excluding cement-treated clays), and reported that the R–O model shows weaker correlations than the H–D model. The H–D model shows relatively good correlations with the present test results for the $G/G_{max}$ and h–γ relationship when the range of shear strain γ is lower than 0.1%. However, the H–D model overestimated the test results for the $G/G_{max}$ and h–γ relationships when the shear strain γ exceeded 0.1%. The Y–A model is a nonlinear model proposed for cement-treated sands. Of the three nonlinear models used in the present investigation, the Y–A model showed the best correlations with the test results for the $G/G_{max}$ and h–γ relationship. Future work will need to investigate the validity of the evaluated equations of the initial shear modulus $G_{max}$, reference strain $\gamma_r$, and maximum damping constant $h_{max}$ obtained from the strain-dependent curve of shear modulus (damping constant). Accordingly, we intend to accumulate test data from the deformation characteristics tests of cement-treated soil.

## 5. Conclusions

The present study aimed to determine the strain-dependent curves of shear modulus and damping constant in cement-treated soil within a wide strain range, which could not be obtained with previous cyclic triaxial tests. To achieve this, we conducted hollow cylindrical torsional shear tests and unconfined compression tests for the cement-treated clays. An evaluation method of the reference strain $\gamma_r$ and the maximum damping constant $h_{max}$ was proposed using the present test results. The parameters determined from the proposed evaluation method were used in existing nonlinear models, and its applicability with the strain-dependent curves of shear modulus and damping constant in cement-treated clays obtained in the present test was investigated.

(1) The $G/G_{max}$–γ relationship in cement-treated clays showed that $G/G_{max}$ was high in the low-shear-strain range and low in the high-shear-strain range, with a shear strain γ boundary value of approximately 0.1%. However, the influence of the mean effective stress $\sigma'_m$ was not clarified.

(2) The h–γ relationship in cement-treated clays showed that the stabilizer amount C and the mean effective stress $\sigma'_m$ had virtually no effect up to a shear strain γ value of approximately 0.1%, but once this value was exceeded, increases in the stabilizer amount were accompanied by smaller h values, and increases in the mean effective stress were accompanied by increased h values.

(3) A good correlation was observed between the reference strain $\gamma_r$ and $q_u/q_{uo}$ obtained from the present test results, and a relational expression was obtained. This suggests that the reference strain $\gamma_r$ can be evaluated from the unconfined compressive strength $q_u$ within the scope of the present test results, independent of the stabilizer amount C and consolidation stress conditions.

(4) A good correlation was observed between the maximum damping constant $h_{max}$ and the mean effective stress $\sigma'_m$ normalized with the unconfined compressive strength $q_u$, and a relational expression was obtained. This suggests that the maximum damping constant $h_{max}$ can be evaluated from the unconfined compressive strength $q_u$ and the mean effective stress $\sigma'_m$ within the scope of the present test results, independent of the stabilizer amount C and consolidation stress conditions.



(5) When observing the applicability of each model with the present test results, the applicability of the R–O model was not favorable, and although the H–D model showed relatively good correlations in the shear strain γ domain smaller than 0.1%, it overestimated the test results for the $G/G_{max}$–γ relationship when the shear strain exceeded 0.1%. Among the existing nonlinear stress–strain models investigated here, the Y–A model showed favorable response test results for the $G/G_{max}$ and h–γ relationships. Therefore, this suggests that the response characteristics of stabilized ground can be suitably evaluated using the Y–A model.

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