International Journal of GEOMATE, June., 2021, Vol.20, Issue 82, pp.34-39
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.82.Gx263
Geotechnique, Construction Materials and Environment

# DYNAMIC PROPERTIES OF RIGID POLYURETHANE FOAM IN CYCLIC TRIAXIAL TESTS

*Atsushi Koyama[1], Daisuke Suetsugu[1] and Yoshinori Fukubayashi[1]

[1]Faculty of Engineering, University of Miyazaki, Japan

*Corresponding Author, Received: 29 May 2020, Revised: 01 Jan. 2021, Accepted: 07 Mar. 2021

**ABSTRACT:** The aim of this study is to clarify the dynamic properties of rigid polyurethane foam. A method for renovating a deteriorated bridge as a lightweight embankment was proposed. The space underneath a bridge is filled with polyurethane to support the upper structure. In this case, the upper structure of the bridge is considerably heavier than the polyurethane. Therefore, it is important to examine the seismic behavior of this new lightweight embankment. However, the dynamic deformation characteristics of polyurethane have not been clarified previously. In this study, stress-controlled cyclic triaxial tests based on JGS0542-2009 are used to evaluate the effect of the confining stress and the presence of a rigid layer on the dynamic properties of rigid polyurethane foam. As a result, the shear modulus of rigid polyurethane foam increases with increasing confining stress regardless of the absence of the rigid layer. The shear modulus of polyurethane with the rigid layer is lower than that of polyurethane without the rigid layer. The value of shear modulus of rigid polyurethane foam was measured in the range of approximately 1.6~3.2MPa. Moreover, the stiffness degradation and of rigid polyurethane foam are in good agreement with the Hardin-Drnevich model.

*Keywords: Cyclic triaxial tests, Dynamic properties, Lightweight embankment, Rigid polyurethane*

## 1. INTRODUCTION

There are approximately 720,000 bridges in Japan will be more than 50 years old within 10 years. Along with a decline in the number of civil engineers engaged in bridge maintenance work, local governments may not be able to adequately cover inspection costs. Therefore, measures against bridge deterioration must be undertaken to improve maintenance efficiency [1]. Solution achieve this, the aim of this study is to establish a method for renovating a deteriorated bridge as a lightweight embankment by filling the bridge's substructure space with polyurethane foam, which is a lightweight embankment material. This lightweight embankment method takes advantage of the low weight (36 kg/m$^3$), adhesiveness, and foamability of polyurethane.

In this method, two types of rigid polyurethane foam stock solution are mixed and foamed at site. The volume increases by approximately 30 times because of the foaming, and a lightweight embankment of any shape can be formed to suit the topography and shape of the structure. Because the polyurethane is formed of closed cells, it is impermeable to water and air. In this study, this technology was applied to renovate deteriorated bridges as lightweight embankments by directly spraying/filling the substructure space and allowing the polyurethane to take the vertical load.

Figure 1 shows a schematic diagram of the method of renovation of a simple girder bridge to a lightweight embankment. Both dead and live loads are supported by spraying/filling the substructure space of the bridge with polyurethane. Owing to the adhesiveness of polyurethane, water/air is prevented from penetrating the bridge member in positions where the polyurethane adheres to the member, and this is expected to inhibit member deterioration. The design should be such that even if, after a long period of time, the bearing capacity of the support covered in polyurethane is reduced or lost because of deterioration and the condition cannot be confirmed visually, the dead and live loads are within a range that can be supported by the polyurethane.

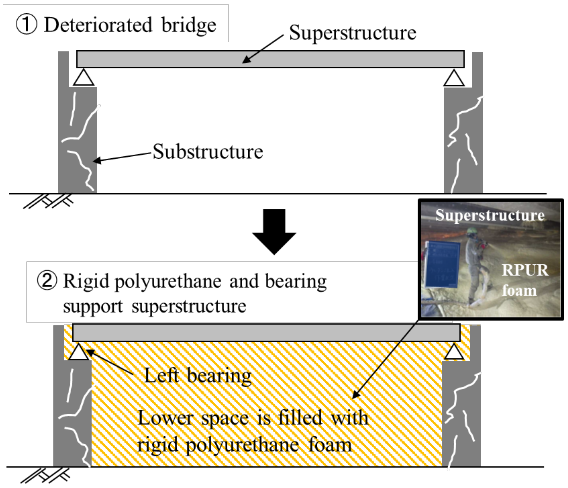


Fig.1 Renovation of the deteriorated bridge to lightweight embankment.

In a situation where the vertical load is supported by the polyurethane, the embankment would be heavier at the top, and its seismic stability could decrease. However, the dynamic properties of

Table 1 Properties of polyurethane

| Name | Density $\rho$ (kg/m$^3$) | Yield strength $\sigma_y$ (kPa) | Allowable stress $\sigma_a$ (kPa) | Poisson's ratio $\nu$ | Cell type |
|---|---|---|---|---|---|
| Rigid polyurethane | 36 | 120 | 60 | 0.05 | Closed |
| Golpazir et al. | 31.3 | 68 | — | 0.02 | Open |

polyurethane required to evaluate the seismic stability of an embankment have not been investigated [2]. The mechanical properties of expanded polystyrene (EPS), which is a lightweight polymeric material with properties similar to those of polyurethane, have been evaluated in static and dynamic shear tests. For example, the higher is the density of EPS, the greater is its compressive strength. Moreover, the shear modulus *G* also increases. The density is reported to have little influence on the damping ratio *h* [3-6]. Gatto et al. [7] investigated the dynamic properties of polyurethane using resonance tests. They reported that, in the micro-strain range, *G* and *h* were not affected by the changes in the confining pressure when the confining pressure was in the range 50–300 kPa. Golpazir et al. [8] used stress-controlled cyclic triaxial tests to show the influence of initial shear stress on the dynamic properties of one-liquid type polyurethane. Their results showed that, as the initial shear stress increases, *G* decreases. They also reported that, unlike typical soil materials, *h* of polyurethane decreases with increasing shear strain, and the viscoelasticity of polyurethane is considered to be the cause. A decrease in *h* with increasing shear strain was also reported for EPS [6].

Currently, there is limited research on the dynamic properties of polyurethane foam using cyclic triaxial tests, and data needs to be accumulated. The rigid polyurethane foam used in this study is foamed approximately every 10 cm, and polyurethane layers form inside the embankment. A rigid surface, called a "skin," exists at the boundaries between layers (see Fig. 3). The influence of this skin on the dynamic properties has not been examined previously.

Therefore, the objective of this study was to examine the influence of the presence or absence of a skin and the differences in confining pressure on the dynamic properties of polyurethane using stress-controlled cyclic triaxial tests.

## 2. MATERIALS AND METHOD

### 2.1 Sample Preparation

The rigid polyurethane foam used in this study is a two-liquid (polyol and isocyanate) mixed-type that is used in lightweight embankment construction methods. Table 1 shows the values of the physical

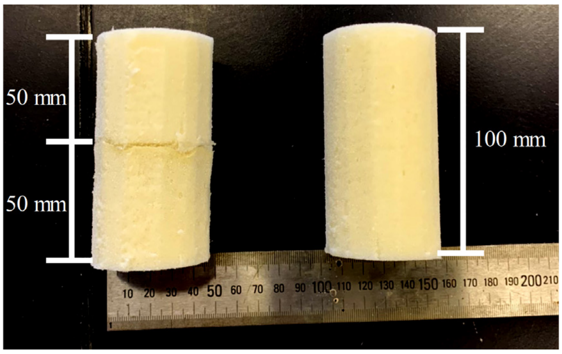


Fig.2 Test specimens of polyurethane (left: two-layer sample; right: one- layer sample, $\phi$=50mm).

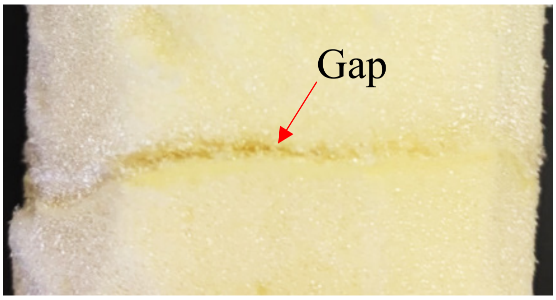


Fig.3 Gap due to the rigid layer (skin) of two-layer specimen.

Fig.4 Cyclic triaxial apparatus.

properties of the rigid polyurethane foam. For comparison, Table 1 also shows the physical property values of the one-liquid type polyurethane used by Golpazir et al. [8] The density of the rigid polyurethane foam used in this study is higher than that used by Golpazir et al. [8] and the yield strength is approximately double. Furthermore, the rigid polyurethane foam used in this study is a closed-cell type, whereas Golpazir et al. [8] used an open-cell type.

The time required since the spraying until the completion of foaming is approximately 1 min. When the foam hardens, more than 95% of the prescribed strength develops within 24 h. In this study, a sample in which polyurethane foam is foamed continuously to a height of 100 mm is called a "one-layer sample," and a sample in which polyurethane foam is foamed to a height of 50 mm and a second layer is sprayed/foamed on top such that it has two layers and a skin is called a "two-layer sample" (Fig. 2). As shown in Fig. 3, an area where the density of the polyurethane is low occurs at the boundary in the samples with a skin.

### 2.2 Test Procedure For Cyclic Triaxial Shear Tests

In this study, a stress-controlled cyclic triaxial test was performed to evaluate the effect of the confining stress and the presence or absence of a rigid layer on the dynamic properties, namely, the shear modulus and damping ratio of polyurethane.

Figure 4 shows the cyclic triaxial test apparatus. The cyclic triaxial test was performed in accordance with the Japanese Geotechnical Society standard 0542-2009 [9]. The sample was covered with a membrane and placed in the tester and an isotropic stress was applied until the prescribed confining pressure $\sigma_c$ was reached. The sample was left to stand for 1 h, and then cyclic loading was started immediately. At each cyclic loading stage, a sinusoidal cyclic load at a frequency $f = 0.1$ Hz was applied for 11 cycles, under a prescribed deviator stress $q$. The deviator stress was increased in 15–17 stages. The load and axial displacement were measured during the cyclic loading. The axial displacement was measured using a gap sensor.

In the polyurethane lightweight embankment method, the allowable compressive stress of the polyurethane is established as 60 kPa. To minimize the creep deformation of the polyurethane when a bridge is renovated as a lightweight embankment, the dead load acting on the polyurethane should be designed to be approximately 20 kPa. Therefore, $\sigma_c$ was set at 20 kPa and 40 kPa in the cyclic triaxial test. These values of $\sigma_c$ are within the elastic region of the rigid polyurethane foam. The one-layer and two-layer samples were tested with the two aforementioned values of $\sigma_c$.

The equivalent Young's modulus $E_{\mathrm{eq}}$ was obtained from the hysteresis loop using Eq. (1) and this was converted to the equivalent shear modulus $G_{\mathrm{eq}}$ using Eq. (2). Here, $v = 0.05$.

$$E_{\mathrm{eq}}=\frac{\sigma_{\mathrm{d}}}{(\varepsilon_{\mathrm{a}})_{\mathrm{SA}}}\times\frac{1}{10}\quad (\mathrm{MPa}) \tag{1}$$

where

$\sigma_{\mathrm{d}}$: single amplitude cyclic deviator stress (kPa)
$(\varepsilon_{\mathrm{a}})_{\mathrm{SA}}$: single amplitude axial strain (%)

$$G_{\mathrm{eq}}=\frac{E_{\mathrm{eq}}}{2(1+v)}\quad (\mathrm{MPa}) \tag{2}$$

The hysteresis damping ratio h was determined using Eq. (3).

$$h=\frac{1}{2\pi}\cdot\frac{\Delta W}{W}\times 100\quad (\%) \tag{3}$$

where

$\Delta W$: area of the hysteresis curve (N・cm)
$W$: equivalent elastic energy in that loading cycle

In this study, $G_{\mathrm{eq}}$ and $h$ were calculated using data from the 10th cycle in each loading stage. Figure 5 is an example of hysteresis loops that show the relationship between $q$ and $(\varepsilon_{\mathrm{a}})_{\mathrm{SA}}$ for one-layer samples at $\sigma_c = 20$ kPa. It is evident from the figure that polyurethane deforms to the same extent in compression and extension. However, when $(\varepsilon_{\mathrm{a}})_{\mathrm{SA}}$ exceeded approximately 0.4%, the extension deformation of the polyurethane did not follow the load on the extension side and pulled the membrane. Therefore, in this study, the test was stopped at approximately $(\varepsilon_{\mathrm{a}})_{\mathrm{SA}} = 0.4\%$.

## 3. RESULTS AND DISCUSSION

### 3.1 Dynamic Properties of Rigid Polyurethane Foam

Figure 6 shows the relationship between the vertical displacement and time for one-layer and two-layer samples under each $\sigma_{\mathrm{c}}$. As shown in the figure, the vertical displacement of each sample increased with an increase in $\sigma_{\mathrm{c}}$. The amount of compression was greater in the two-layer samples at both the confining pressures. This is because the gap caused by the skin (Fig. 2) was filled when the sample was isotropically compressed. Two-layer samples have a gap between the bottom and top layer. It is probable that the density of polyurethane is low in this gap. In all the samples, the vertical displacement became constant after approximately 120 s from the initiation of loading. Therefore, isotropic compression was stopped at 1 h.

Figure 7 shows the relationship $G_{eq}$–$\gamma_{SA}$ and $h$–$\gamma_{SA}$ for the one-layer and two-layer samples, respectively. $\gamma_{SA}$ is the single amplitude shear strain.

As shown in Fig. 7, the value of $G_{eq}$ increases and the value of $h$ decreases with increasing $\sigma_c$, regardless of the presence or absence of a skin. This is assumed to be because the higher the confining pressure, the harder the polyurethane becomes.

At either value of $\sigma_c$, $h$ increased with increasing $\gamma$. This trend is opposite to that shown in the test results by Golpazir et al. [8]. Additionally, the value of $h$ in this study was approximately one tenth of the value in their test results. The loading frequency of the cyclic load in tests performed by Golpazir et al. [8] was 0.02 Hz, whereas in this study it was 0.1 Hz. However, Athanasopoulos et al. [4] reported that, in the case of EPS, the loading frequency has little effect on the dynamic properties. Therefore, it is assumed that the differences in the structure of the polyurethane, such as open and closed cells, and strength influence the test results, not the different test methods. Therefore, data must be collected from tests performed using several types of polyurethane with different physical properties.

Figure 8 shows the relationship $G_{eq}$–$\gamma_{SA}$ and $h$–$\gamma_{SA}$ comparing the presence and absence of a skin. Regardless of the size of $\sigma_c$, $G_{eq}$ was larger and $h$ was smaller in the one-layer samples compared with the two-layer samples. $G_{eq}$ was small in the two-layer samples because there was cyclic loading at the gap caused by the skin. The effect of the presence or absence of a skin on $G_{eq}$ and $h$ was smaller when $\sigma_c$ = 40 kPa than when $\sigma_c$ = 20 kPa. This is considered to be because, as shown in Fig. 6, the greater the value of $\sigma_c$, the more the gap caused by the skin was filled, and therefore the differences in $G_{eq}$ and $h$ between the one-layer and two-layer samples were smaller.

### 3.2 Degradation Curves of Rigid Polyurethane Foam

Figure 9 shows the relationship between $G/G_0$, which is $G_{eq}$ normalized by the initial shear modulus $G_0$, and $\gamma_{SA}$. Figure 9 also shows the $G/G_0$–$\gamma_{SA}$ relationship approximated by the Hardin-Drnevich model (H-D model) [10], which is a nonlinear soil model represented by Eq. (4). The H-D model is a nonlinear formula that easily determines the related model parameters. Table 2 shows the parameters used in the H-D model.

$$\frac{G}{G_0}=\frac{1}{1+\gamma/\gamma_r} \tag{4}$$

where

$G_0$: shear modulus at minimum shear strain

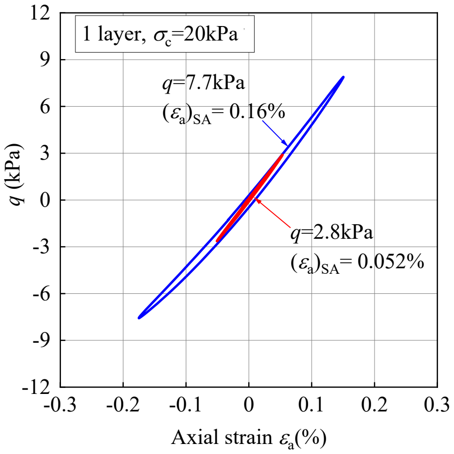


Fig.5 Stress-strain hysteresis loops for rigid polyurethane samples with different deviator stress.

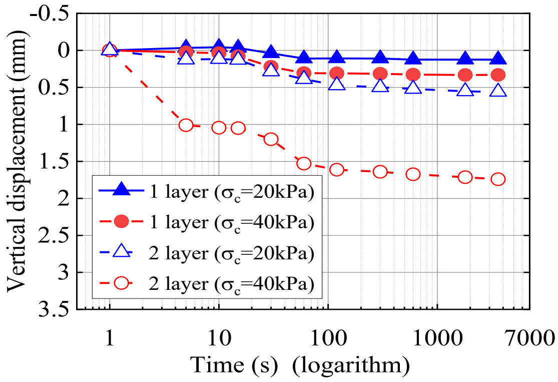


Fig.6 Vertical displacement of polyurethane during isotropic compression.

$\gamma_r$ : shear strain in $G/G_0$=0.5

In the cyclic triaxial test results, the relationship between $G/G_0$ and $\gamma_{SA}$ can be expressed using $\sigma_c$, regardless of the presence or absence of a skin. It is evident from Fig. 9 that there is good agreement between the experimental values and the H-D model.

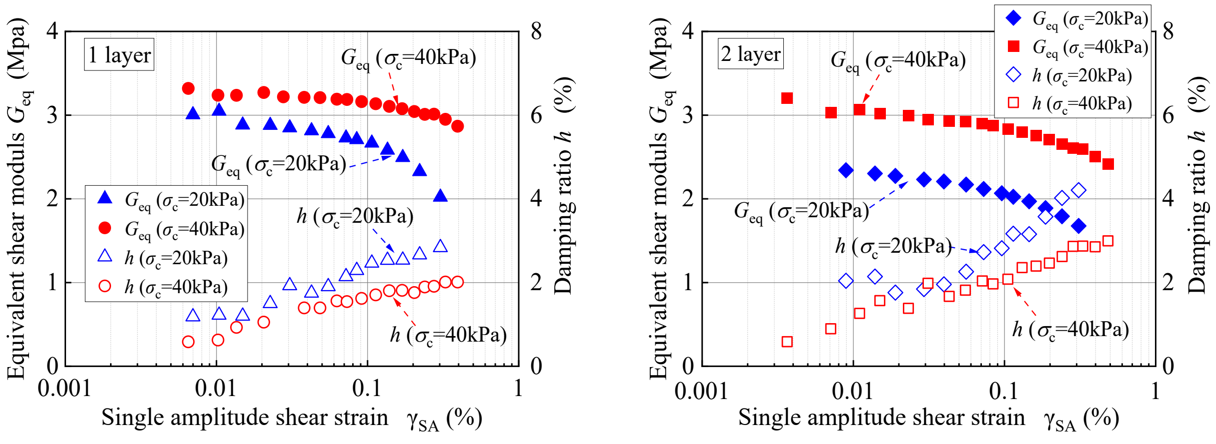
Figure 10 shows the relationship between $h$ and $\gamma_{SA}$ from the H-D model, calculated using Eq. (5), and the experimental values from the cyclic triaxial test.

$$h=h_{max}\times\left(1-\frac{G}{G_0}\right) \tag{5}$$

where

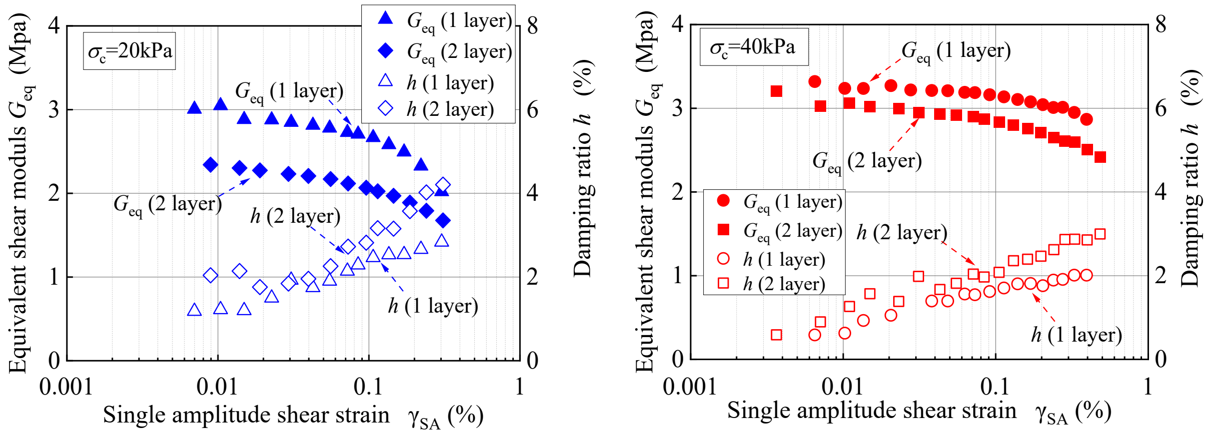
$h_{max}$: maximum value of damping ratio

Figure 10 shows that there is a difference in the $h$–$\gamma_{SA}$ relationship between the experimental values and the H-D model. Unlike the $G/G_0$–$\gamma_{SA}$ relationship, the $h$–$\gamma_{SA}$ relationship differs depending on the presence or absence of a skin under both values of $\sigma_c$,



(a) $\sigma_c$ = one-layer (b) $\sigma_c$ = two-layer

Fig.7 Relationship $G_{eq}$–$\gamma_{SA}$ and $h$–$\gamma_{SA}$ of rigid polyurethane foam with varying confining stress.



(a) $\sigma_c$ = 20 kPa (b) $\sigma_c$ = 40 kPa

Fig.8 Relationship $G_{eq}$–$\gamma_{SA}$ and $h$–$\gamma_{SA}$ of rigid polyurethane foam with different type of specimens.

particularly when $\gamma_{SA}$ = 0.02% or more. Although not illustrated here, even when a different nonlinear model (the modified Ramberg-Osgood model [11]) was used, it was not possible to accurately approximate the $h$–$\gamma_{SA}$ relationship. This means that the $h$–$\gamma_{SA}$ relationship obtained using Masing's rule, as in the H-D model and the modified R-O model, might not be appropriate for the rigid polyurethane foam.

Figures 9 and 10 show the test results for marine clay (void ratio e=1.391) at $\sigma_c$ = 50 kPa. In marine clay, $G/G_0$ decreases and $h$ increases with increasing $\gamma_{SA}$. In clay, $G/G_0$ decreases significantly after $\gamma_{SA}$ = 0.003%, whereas a striking decrease in $G/G_0$ is not observed in rigid polyurethane foam until $\gamma_{SA}$ = 0.1%. Furthermore, in clay, $G_0$ = 15.6 MPa, which is approximately three times greater than that in rigid polyurethane foam. Additionally, $h$ of rigid polyurethane foam is substantially small compared with that of clay. Consequently, rigid polyurethane foam can be considered as a material with lower stiffness than soil materials, but one whose stiffness does not readily decrease.

## 4. CONCLUSIONS

1. For the rigid polyurethane foam used in this study, the value of $G_{eq}$ increases and the value of $h$ decreases with increasing confining pressure. This trend was not affected by the presence or absence of a skin.
2. In samples with a skin, there was cyclic loading at the gap caused by the skin; therefore, $G_{eq}$ was smaller in two-layer samples than in one-layer samples. When $\sigma_c$ increased, the gap caused by the skin was filled, and thus, the difference in the

$G_{eq}$–$\gamma_{SA}$ relationship between the one-layer and two-layer samples became smaller.

3. When the H-D model representing the nonlinearity of soil was applied to the rigid polyurethane foam, there was good agreement with the experimental values for the $G/G_0$–$\gamma_{SA}$ relationship, but not for the $h$–$\gamma_{SA}$ relationship. Therefore, the applicability of other nonlinear models and prediction formulas must be examined.

## 5. ACKNOWLEDGMENTS

This study was financially supported by the geo-science center foundation and RBH Research technical committee. We wish to offer our sincere gratitude.

## 6. REFERENCES

[1] MLIT web page, https: //www.mlit. go.jp/en / index.html (accessed 2020-07-02)

[2] Nakamura H., Enomoto K., Aoki T. and Mitabe H., Full−scale shaking table tests on poured−in−place rigid polyurethane embankments, Tsuti to Kiso, Vol.51, No.4, 2003, pp.14-16 (in Japanese).

[3] Chun S. B., Lim S. H., Sagong. M. and Kim K., Development of a hyperbolic constitutive model for expanded polystyrene (EPS) geofoam under triaxial compression tests, Geotextiles and Geomembranes, Vol.22, 2004, pp.223-237.

[4] Athanasopoulos A., Pelekis P.C. and Xenaki V.C, Dynamic properties of EPS geofoam : an experimental investigation, Geosynthetics International, Vol.6, No.3, 1999, pp.171-194.

[5] Ossa A. and Romo M.P., Dynamic characterization of EPS geofoam, Geotextiles and Geomembranes, Vol.29, 2011, pp.40-50.

[6] Trandafir A. C., Bartlett S. F. and Lingwall B. N., Behavior of EPS geofoam in stress-controlled cyclic uniaxial tests, Geotextiles and Geomembranes, Vol.28, 2010, pp.514-524.

[7] Gatto M. P. A., Montrasio L., Tsinaris A., Pitilakis D. and Anastasiadis A., The dynamic behaviour of polyurethane foams in geotechnical conditions, in Proc. 7th International Conference on Earthquake Geotechnical Engineering, 2019, pp.2566-2573.

[8] Golpazir I., Ghalandarzadeh A., Jafari K. M. and Mahdavi M., Dynamic properties of polyurethane foam-sand mixtures using cyclic triaxial tests, Construction and Building Materials., Vol.118, 2016, pp.104-115.

[9] JGS0542-2009, Method for cyclic triaxial tests to determine deformation properties of geomaterials, 2009, pp.751-767.

Table 2 Parameters of H-D model

| $\sigma_c$ (kPa) | $G_0$ (MPa) | $\gamma_r$ (%) | $h_{max}$ (%) |
|---|---|---|---|
| 20 | 3.1 | 0.65 | 4.5 |
| 40 | 3.4 | 1.8 | 3.5 |

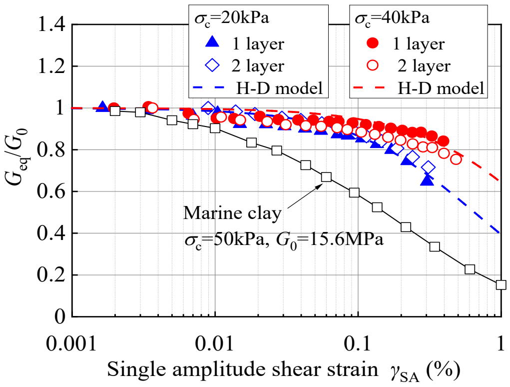


Fig.9 Relationship between normalized shear modulus and shear strain of rigid polyurethane foam with H-D model.

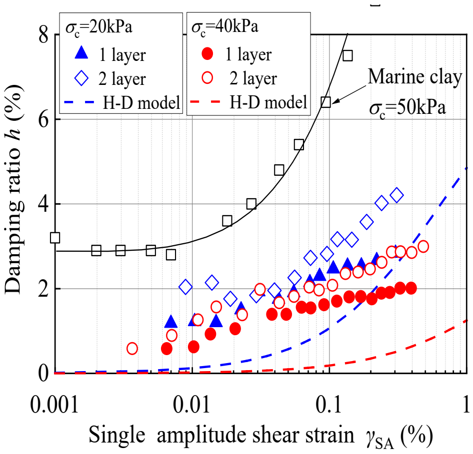


Fig.10 Relationship between damping ratio and shear strain of rigid polyurethane foam with H-D model.

[10] Hardin B. O. and Drnevich, V. P., Shear modulus and damping in soils: design equations and curves, in Proc. of the American Society of civil engineers, Vol.98, No.SM7, 1972, pp.667-692.

[11] Tatsuoka F. and Fukushima S, Stress-strain relation of sand for irregular cyclic excitation (1), Seisan Kenkyu, Vol.30, No.9, 1978, pp.26-29.