Shear modulus at small strain of normally consolidated peat

Hirochika Hayashi i) and Satoshi Nishimoto ii)

i) Senior Research Engineer, Civil Engineering Research Institute for Cold Region (CERI), 1-3, Hiragishi, Sapporo 062-8602, Japan.
ii) Director, CERI, 1-3, Hiragishi, Sapporo 062-8602, Japan.

ABSTRACT

This paper describes the characteristics of shear modulus at small strain in a normally consolidated region of peat and organic clay. When the seismic response of the ground is analyzed, the shear modulus at small strain ($G_0$) of soil is an important parameter. However, previous studies on peat in this area are fewer than on inorganic soils such as sand and clay. Therefore, it is impossible to obtain a highly accurate $G_0$ for peat. Due to the above, although some large earthquakes in Hokkaido, Japan, have caused great damage to earth structures on peat, the results of seismic response analysis cannot be expected to be highly credible under the current conditions.

Therefore, a series of cyclic torsional shear tests were conducted on normally consolidated samples with a wide range of physical properties, from organic clay to fibrous peat, and the influence of effective confining pressure and physical index on $G_0$ was studied.

Keywords: peat, organic clay, shear modulus at small strain, normal consolidation, cyclic torsional shear test

1. INTRODUCTION

In analyzing the seismic response of the ground, the shear modulus of soil at small strain ($G_0$) is an important parameter. However, the $G_0$ of peat and organic clay has been studied less than those of inorganic soils such as sand and clay.

Previous studies on peat that used a cyclic triaxial test include the following: Noto and Kumagai (1986) clarified that the $G_0$ of peat sampled from various areas in Hokkaido can be expressed as a function of water content ($W$) and effective confining pressure ($\sigma'_c$). Ishihara et al. (2003) reported on the relationship between the $G_0$ of highly organic soil from Tokyo and the void ratio ($e$) and $\sigma'_c$. Wehling et al. (2003) reported on the characteristics of the $G_0$ of peaty organic soil from California, USA. Ogino et al. (2010) conducted experiments on highly organic soil sampled in Hokkaido and Akita prefectures, Japan, and reported on the relationship between the $G_0$ and the density of soil particles, $e$ and $\sigma'_c$.

Questions have been raised as to whether triaxial tests are applicable when the shear modulus ($G$) is indirectly obtained by assuming the samples to be isotropic and the cyclic load to act on a 45-degree inclined plane of a sample that has strong structural anisotropy because of horizontally existing plant fibers such as those of peat. The cyclic torsional shear test, in which cyclic shear stress is directly applied horizontally to the sample and the $G$ value is able to be directly obtained is considered as more an appropriate test than the triaxial test. However, examinations of the dynamic properties of peat obtained from the results by the cyclic torsional shear test are limited to those done by Ohmi et al. (2007) and Hayashi et al. (2010).

Under the above research state, it is necessary to promote previous studies with a focus on the cyclic triaxial test and to clarify the influence of $\sigma'_c$ and physical indexes on the dynamic properties of peat. In this study, the relationships between $G_0$ and the $\sigma'_c$, the $W$ and the ignition loss ($L_i$) were investigated by conducting a series of cyclic torsional shear tests on organic clay and fibrous peat sampled in Hokkaido, Japan. In addition, an empirical formula was proposed based on the experiment.

2 EXPERIMENT CONDITIONS

2.1 Samples

Thin-wall sampling using a fixed piston sampler was done at 5 locations in Hokkaido, Japan: Warabitai in Tobetsu Town; Shinotsu in Ebetsu City; Asajino in Sarufutsu Village; Riyamunai in Kyowa Town; Onobunai in Teshio Town. Seven types of undisturbed soil samples, with various physical properties, were collected, including from organic clay to fibrous peat (Table 1), and the cyclic torsional shear tests were conducted on them. The sedimentation condition of peaty ground is extremely heterogeneous. It is possible for samples from a single location to have
heterogeneous physical properties. Therefore, portions of samples that contained greatly differing amount of fibers and degrees of plant decomposition were eliminated. Further caution was taken by checking that the physical properties of the samples from a single location were mutually similar by measuring the $L_i$ of the samples after the tests.

### 2.2 Experiment method

Preparation and placement on the test device of the fibrous peat samples must be done carefully. The following were done in this study. The sample was carefully pushed out of the thin-walled tube and was cut into appropriate lengths by wire saw. The surface of the cylindrical sample was trimmed by wire saw and straight edge. When it was necessary to cut plant roots and stems on the surface, a pair of scissors and a utility knife were used. Then the sample was placed in the mold and the upper and bottom surfaces were carefully trimmed. A drill guide was attached, and a lead hole was made by drill in order to form an inner cavity. A wire was put through the lead hole, and the inside of the sample was carefully hollowed out bit by bit. A pair of scissors and a utility knife were used for cutting fibers during this process. Lastly, the inside surface was smoothed with a straight edge. The sample was 70 mm in external diameter, 30 mm in inner diameter and 70 mm in height.

To shorten the time for consolidation, 6 pieces of filter paper of 0.5 cm in width by 8 cm in length were stuck at regular intervals on the inside and outside surfaces of the sample before it was placed on the test device. To adjust the saturation, carbon dioxide was supplied to the sample. The voids of the sample were filled with deaerated water, and a back pressure of 100kN/m² was applied. The $B$ values from 0.98 to 1.0 were observed. A cyclic torsional shear test was done pursuant to the standards of the Japanese Geotechnical Society (JGS 0543) on the samples prepared as described above.

Peat has a pronounced structural anisotropy. It has been clarified that the dynamic properties of peat are hardly influenced by the anisotropic consolidation ratio of the $\sigma'_c$. Therefore, isotropic consolidation was done by applying a pressure of 30 to 150 kN/m² (Table 1). The consolidation was finished by using the 3-t method as an evaluation criteria. Cyclic torsional shear with a sine wave of 0.05 Hz under a undrained condition was applied, with 11 waves per stage of loading, by using the consolidation pressure as the $\sigma'_c$. The $\sigma'_c$ applied in this test was greater than the consolidation yield stress (Table 1), and all the samples were within the normally consolidated region.

### 3 EXPERIMENT RESULTS AND DISCUSSION

#### 3.1 Relationship between $G_0$ and physical index

Previous studies (e.g. Hardin and Richart, 1963; Kokusho, 1980; Kokusho et al., 1982): Dynamic Properties of Soft Clay for Wide Strain Range, Soils and Foundations, 22(4), 1-18.) on sand and clay often expressed $G_0$ by using a relational expression (Eq. (1)) between the $G_0$ and the $e$ and $\sigma'_c$. Where, $A$ is a constant, $F (e)$ is a function of $e$ and $n$ is also a constant.

$$G_0 = A F (e) \sigma'_c^n$$  \hspace{1cm} (1)

Noto and Kumagai (1986), and Ogino et al. (2010) noted that the applicability of empirical formulas that use $e$, such as Equation (1), is low because the voids in peat are much larger than those in sand and clay. The mechanical characteristics of peat are generally discussed in relation to $W$, and the relationship between $G_0$ and $W$ was investigated in these previous studies. Figure 1 shows the relationship between $G_0$ and $W$ after
The case of clay and peat are shown in Figs. 3 and 4 respectively.

![Fig. 1. Relationship between $W_c$ and $G_0$](image1)

![Fig. 2. Relationship between $L_i$ and $G_0$](image2)

![Fig. 3. Relationship between $\sigma_c^e$ and $G_0$ (organic clay)](image3)

![Fig. 4. Relationship between $\sigma_c^e$ and $G_0$ (peat)](image4)

consolidation ($H_v$), which was obtained in the experiment in this study and is expressed on a double-logarithmic graph. It is understood that at a constant $\sigma_c^e$, $G_0$ decreases almost linearly with increase in $W$. The slope of the $G_0$ line is within the range of -0.49 to -0.60. The slope does not greatly change even when the $\sigma_c^e$ changes.

The relationship between $L_i$ and $G_0$ on the double-logarithmic graph is shown in Fig. 2. At a constant $\sigma_c^e$, $G_0$ linearly decreases with increase in $L_i$. Similar to the case of $W$, the slope is hardly influenced by the $\sigma_c^e$.

### 3.2 Relationship between $G_0$ and $\sigma_c^e$

The relationships between $\sigma_c^e$ and $G_0$ in organic clay and in peat are shown in Figs. 3 and 4 respectively. The $G_0$ of organic clay is 6.8 to 13.9 MN/m² when the $\sigma_c^e$ is in the range of 50 to 150 kN/m², and the $G_0$ increases in proportion to the 0.64th power of the $\sigma_c^e$. The $G_0$ of peat is 2.2 to 10.4 MN/m², which is smaller than that of organic clay when the $\sigma_c^e$ is in the range of 50 to 150 kN/m². The relationship between $G_0$ and $\sigma_c^e$, which plots as a line with a slope that averages 0.86, is generally proportional irrespective of differences between samples.

It is known that the $G_0$ of sand increases in proportion to the 0.5th power of the $\sigma_c^e$ (e.g. Hardin and Richart, 1963; Kokusho, 1980). The $G_0$ of clay has been reported to be proportional to the 0.5th to 0.6th power of the $\sigma_c^e$ (e.g. Zen et al., 1978; Kokusho et al., 1982). Based on the above, $n = 0.5$ is generally used when the $G_0$ of sand or clay is expressed by Eq. (1). The experiments done in this study show that the $n$ for organic clay or peat is greater than that for sand and clay, and they reveal that the $G_0$ values of the organic clay and peat are more greatly influenced by the $\sigma_c^e$ than mineral soil is. Greater values of $n$ ($n = 0.55$ to 0.92) than those for sand and clay have been reported in previous studies on peat and other highly organic soils (Noto and Kumagai, 1986; Wehling et al., 2003).

Figs. 5 and 6 show the relationship of $n$ for each sample and $W_c$ and $L_i$ respectively. As discussed above, the value of $n$ for peat ($n = 0.79$ to 0.96; the average value is 0.86) is greater than that for organic clay ($n = 0.64$); however, a clear correlation was not found...
between the n value and \( W_c \) and \( L_i \) in the range of the result of the experiments in this study.

### 3.3 Formulation of \( G_0 \)

In this section, the formulation of the \( G_0 \) for organic clay and peat is discussed based on the experiment results described in the sections above. Since the \( G_0 \) values of organic clay and peat have a linear relationship with \( W_c \) and \( \sigma'_c \) on the double-logarithmic graph in Figs. 1, 3 and 4. The relation of the value obtained by dividing the \( G_0 \) by the \( \sigma'_c^n \) (\( G_0/\sigma'_c^n \)) and the \( W_c \) is shown in Fig. 7. Where, \( n \) was assumed as the average value for each soil type (organic clay: \( n = 0.64 \); peat: \( n = 0.86 \)) from Figs. 5 and 6. The relationship between \( W_c \) and \( G_0/\sigma'_c^n \) can be approximated by using the equation shown in the figure for each soil type. From the results of approximation, the \( G_0 \) values of organic clay and peat can be expressed in Eqs. (2) and (3). Where, \( G_0 \) is in units of MN/m\(^2\), \( W_c \) is in units of MN/m\(^2\), and \( \sigma'_c \) is in units of MN/m\(^2\).
is water content after consolidation (%) and $\sigma'_c$ is in units of kN/m$^2$.

Organic clay: $G_0 = 1.284W_c^{-0.17} \sigma'_c^{0.64}$ (2)

Peat: $G_0 = 0.725W_c^{-0.32} \sigma'_c^{0.86}$ (3)

Eqs. (2) and (3) are thought to be practically useful, because the $G_0$ can be estimated from simple index such as water content by using these equations. However, it is necessary to check the accuracy of these empirical formulas, because they are based on several assumptions and approximations. Fig. 8 shows the relationship between the $G_0$ values obtained in the result of the cyclic torsional shear tests and those estimated by using Eqs. (2) and (3). The values for organic clay and peat generally agree with the values obtained in the experiments, and the estimated values are within the range of 0.7 to 1.3 times the experiment values.

4 CONCLUSION

In this study, a series of cyclic torsional shear tests was conducted on normally consolidated samples with a wide range of physical properties, from organic clay to fibrous peat sampled in Hokkaido, Japan. The influence of the effective confining pressure ($\sigma'_c$) and moisture content ($W_c$) on the shear modulus at small strain ($G_0$) was investigated. The main results are summarized below.

(1) The $G_0$ of organic clay was 6.8 to 13.9 MN/m$^2$ when the $\sigma'_c$ was in the range of 50 to 150 kN/m$^2$, and the $G_0$ increased in proportion to the 0.64th power of the $\sigma'_c$.

(2) The $G_0$ of peat was 2.2 to 10.4 MN/m$^2$, which was smaller than that of organic clay when the $\sigma'_c$ was in the range of 50 to 150 kN/m$^2$. The $G_0$ and the $\sigma'_c$ were generally proportional, irrespective of the differences within the samples, and they plotted as a line with an average slope of 0.86.

(3) Thus, we propose an empirical formula that expresses the $G_0$ of organic clay and peat as a function of $W_c$ and $\sigma'_c$.

REFERENCES


