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Effect of cyclic loading on shear modulus of peat

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ABSTRACT

Peaty ground, which is widely distributed in Hokkaido, Northern Japan, is very soft ground that is characterized by high organic content and peculiar engineering properties. With the aim of quantitatively understanding the changes in the shear modulus of peaty ground that has been subjected to cyclic shear loading that simulates earthquake motion, a series of hollow-cylinder torsional shear tests was conducted. The test results show that the shear modulus of peat, which never undergoes liquefaction, is reduced after undergoing cyclic shear loading, and that greater cyclic shear stress results in a larger reduction of the shear modulus. It is also suggested that the degree of reduction in shear modulus is likely to be estimable based on representative soil indexes of peat, namely natural water content and ignition loss.

Introduction

Peaty ground, which is distributed in the cold regions of Japan, particularly in Hokkaido (Figure 1), is very soft ground that is characterized by high organic content and peculiar engineering properties. Several large-scale earthquakes in Hokkaido have caused major damage to earth structures built on peaty ground, such as road or river embankments. The mechanism of the behavior of peaty ground that has been subjected to earthquake motion and the strength and deformation characteristics of peaty ground immediately after earthquakes are largely unknown, and these should be urgently elucidated.

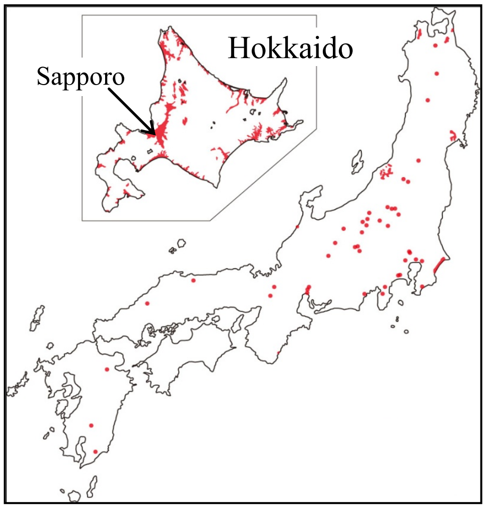

Figure 1. Distribution of peaty ground in Japan

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The authors have been conducting centrifugal model tests toward understanding the behavior of peaty ground during earthquakes and toward examining seismic reinforcement methods applicable to embankments built on peaty ground. It has been confirmed that overburden load causes a change in the attenuation rate of the response acceleration (Kajitori *et al.* 2013) and that embankment subsidence can be mitigated by installing stone-filled nets at the embankment toe (Kajitori *et al.* 2012).

This study reports on the results of hollow cylinder torsional shear tests conducted by using peat samples collected at various places in Hokkaido, toward understanding lateral flows and other behaviors of peaty ground during earthquakes. Specifically, the study focuses on the changes in the shear modulus of peat soil after cyclic shear loading that simulates earthquake motion.

Sample and Test Method

Peat Samples

The peat samples were collected at four sites of peaty ground by using a thin-walled sampler. The in situ density of all the peat samples as well as their physical and consolidation properties are shown in Table 1. Consolidation tests were performed by using a representative sample for each site. As shown in Table 1, the in situ density of each sample is lower than for conventional soil types, and the values of natural water content W_n and ignition loss L_i are notably large. The compression indexes suggest that these samples are highly compressible.

Table 1. Physical properties

Sample	Sample collection site	Wet density (g/cm^3)	Dry density (g/cm^3)	Nat. water content (%)	Ignition loss (%)	Consolidation yield stress (kN/m^2)	Compression index
R-0	Riyamunai	0.973	0.090	982.9	93.6	13.6	9.503
R-1		0.964	0.092	947.5	94.1		
R-2		0.991	0.112	785.9	73.3		
R-3		0.982	0.117	740.1	83.7		
O-0	Onobunai	0.992	0.088	1029.5	95.9	9.9	8.497
O-1		1.001	0.096	941.5	96.8		
O-2		1.015	0.103	882.5	91.1		
O-3		1.002	0.093	890.6	95.9		
E-0	Ebetsubuto	0.993	0.128	677.0	88.7	22.7	6.686
E-1		0.923	0.112	724.9	97.3		
E-2		0.984	0.163	505.0	91.8		
E-3		0.950	0.118	707.0	96.9		
E-4		1.011	0.173	484.0	70.9		
E-5		0.991	0.124	701.1	94.4		
T-0	Toyokoro	1.102	0.324	240.5	40.3	48.2	2.965
T-1		1.045	0.241	334.4	56.1		
T-2		1.062	0.277	283.5	51.4		
T-3		1.057	0.253	317.4	49.2		
T-4		1.064	0.253	320.9	55.7		

Test Method

Test Conditions and Method

A hollow cylindrical torsional shear test apparatus was used for testing. Peat soil, which consists of horizontally accumulated plant fibers, is structurally anisotropic; thus, questions have been raised about the validity of using a triaxial test in which maximum shear stress is applied to a sample plane inclined at 45 degrees (Noto and Kumagai 1986). In view of this, it seems appropriate to use a torsional shear test in which shear force is directly applied to the sample surface parallel to the fiber depositional surface. The preparation of samples and the test apparatus will be detailed later.

For examining the properties of the soil that underwent earthquake motion, the test method proposed by Yasuda *et al*. (1999) was used. The specific procedure is as follows. First, consolidation test results of the peat samples were used for conducting anisotropic consolidation in the normal consolidation range. The coefficient of earth pressure at rest was calculated by using equations obtained in previous studies (Hayashi *et al*. 2012). Then, cyclic shear stress with a constant vibration amplitude was applied in the undrained state. The total number of shear waves was 20. The cyclic shear loading was applied in the same manner as in a liquefaction test. Next, undrained monotonic shear loading was conducted at a shear strain rate of 10%/min. The stress-strain relationship during monotonic shear loading is regarded as the stress-strain relationship specific to soil subjected to earthquake motion (i.e., cyclic shear loading). This test method is hereinafter called the monotonic loading test after cyclic loading. The loading pattern is shown in Figure 2.

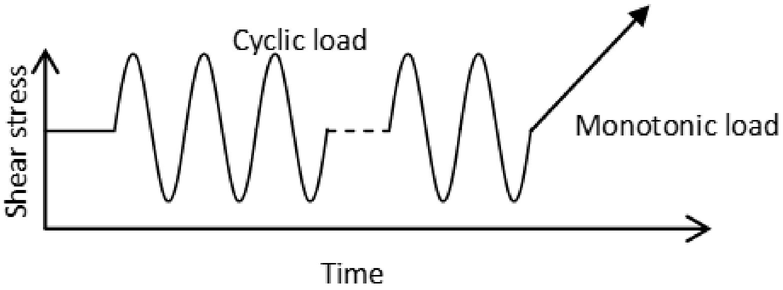

Figure 2. Test image

Besides the monotonic loading test after cyclic loading, monotonic torsional shear tests were conducted at a shear strain rate of 10%/min for the purpose of understanding the deformation characteristics of peat soil. The rigidity determined when the shear strain obtained in the monotonic torsional shear tests was 0.1% ($\gamma=0.1\%$) was regarded as the initial shear modulus (G_{0i}) and was compared with the rigidity determined after cyclic shear loading. The test conditions are shown in Table 2.

Table 2. Test conditions

Sample	Consolidation		Monotonic shear loading (undrained)		Cyclic shear loading (undrained)		
	Consolidation stress (kN/m^2)		Shear strain rate (%/min)	Initial shear modulus G_{0i} (kPa)	Shear stress ratio τ_d/σ_{ac}'	Frequency of loading (Hz)	No. of shear cycles Nc
	Axial direction σ_{ac}'	Lateral direction σ_{rc}'					
R-0	30.0	7.0	10	1114	-	-	-
R-1				-	0.41	0.1	20
R-2					0.34		
R-3					0.55		
O-0		8.4		770	-	-	-
O-1				-	0.38	0.1	20
O-2					0.33		
O-3					0.28		
E-0		7.4		1068	-	-	-
E-1				-	0.73	0.1	20
E-2					0.59		
E-3					0.38		
E-4					0.26		
E-5					0.49		
T-0	50.0	17.6		2357	-	-	-
T-1				-	0.303	0.1	20
T-2					0.528		
T-3					0.598		
T-4					0.430		

Hollow Cylinder Torsional Shear Test

Basically, samples were prepared in accordance with *Methods for Preparing and Installing Hollow Cylindrical Samples for Soil Torsional Shear Tests* (JGS 2009), a standard proposed by The Japanese Geotechnical Society. First, a sample carefully pushed out of a thin-walled tube by using a device is cut with a wire saw to the proper length. The lateral face of the sample is finished by using a wire saw and a straightedge ruler. Plant fibers such as roots and stalks that are hard to cut are cut with scissors or a utility knife. Then, molds were fixed to the sample, both end faces were carefully shaped, a drill guide was attached and a hole was cut for shaping the inside surface of the hollow with a drill. The inside of the sample was carefully hollowed out in small steps with a wire saw that was inserted through the hole. Plant fibers were cut with scissors or a utility knife. The inside surface of the hollow was finished with a straightedge ruler. Although the fiber contained in peat is not usually easy to handle, by carefully and quickly following the procedure mentioned above, prescribed samples were successfully created. Each sample was 70 mm in outside diameter, 30 mm in inside diameter and 70 mm in height.

To ensure that each sample was saturated, air contained in the peat soil was replaced with carbon dioxide, deaired water was supplied to the sample and a back pressure of 100 kN/m^2 was maintained. It was confirmed that the pore pressure coefficient (i.e., the B-value) was 0.98 or greater. Using the samples prepared and maintained as explained above, anisotropic consolidation was conducted before monotonic loading tests, which were performed after cyclic loading and monotonic torsional shear tests.

Results and Discussion

Regarding the results of a monotonic loading test performed after cyclic loading for Sample T-2, the cyclic load-time history is shown in Figure 3. The excess pore water pressure of Sample T-2 is the highest among all samples. Figure 3 shows that the excess pore water pressure caused by cyclic loading was up to 7.5 kN/m^2; thus, the excess pore water pressure ratio is around 0.15 when the effective vertical stress (i.e., 50 kN/m^2) is taken into account. This result is consistent with the general knowledge that liquefaction does not take place in peat. At the same time, the result indicates that the shear strain steadily accumulates and that the axial stress is gradually reduced. Similar results were confirmed for all the other samples.

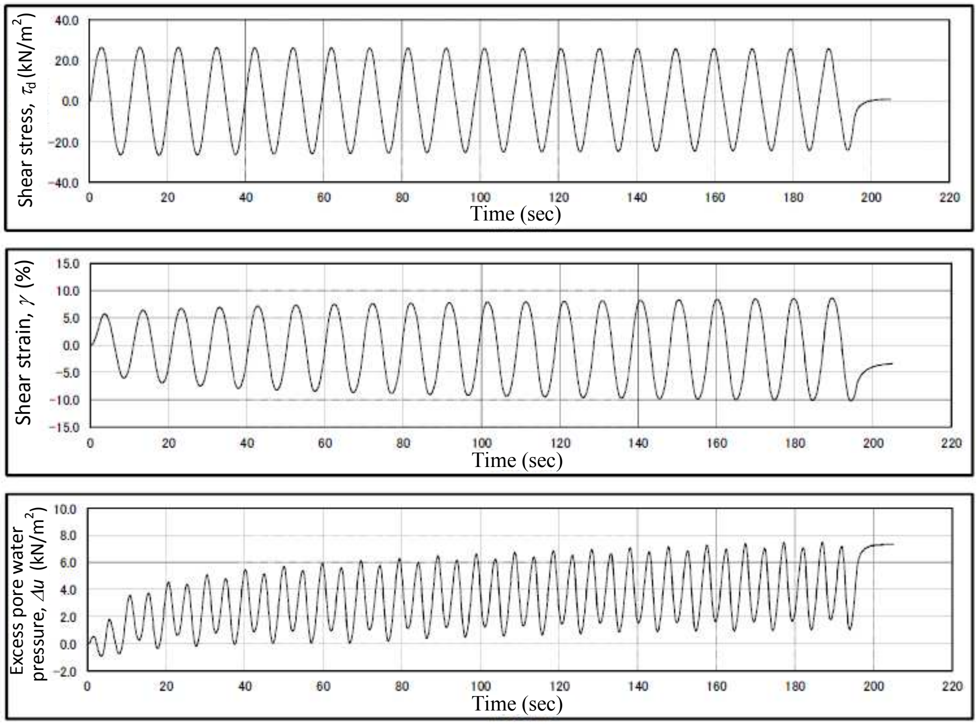

Figure 3. Cyclic load-time history (Sample T-2)

Figure 4 shows the stress-strain relationships observed at the time of monotonic loading in the monotonic loading tests after cyclic loading as well as in the monotonic shear tests. Due to limitations of space, the stress-strain relationships shown are those for Sample E, which was tested more times than any other sample. τ_d/σ_{ac}' shown in Figure 4 is the cyclic shear stress ratio observed at the time of cyclic loading in the monotonic loading tests performed after cyclic loading. A tendency apparent in Figure 4 is that the strength of the sample is reduced as it undergoes cyclic shear loading. It should be noted, however, that this tendency is not shared by

Samples R, O, and T, in which reduction in the strength does not consistently correlate with the number of cyclic shear loadings. Yasuda *et al.* (2005) reported the following two experimental results. One is that a curve showing the stress-strain relationship at the time of monotonic loading after cyclic loading takes the form of a downward-facing convex curve regarding sandy soil such as Toyoura sand and decomposed granite soil in which liquefaction can take place. The other one is that the shape of the curve is convex upward regarding cohesive soil having a high fine fraction content in which liquefaction does not occur. The stress-strain relationship of peat soil is represented by upward convex curve.

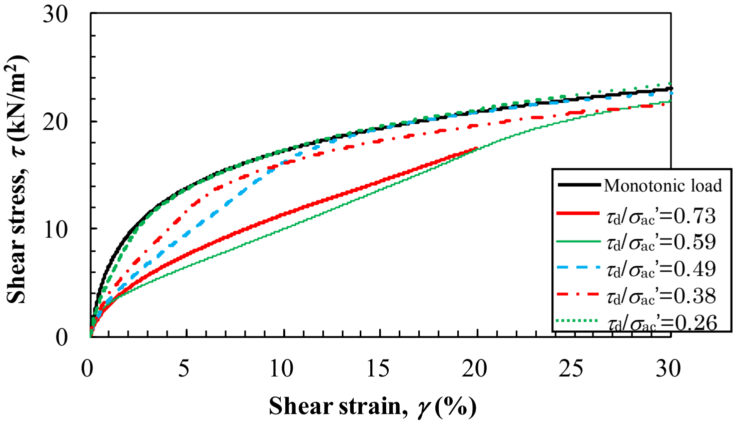

Figure 4. Relationship between shear strain and shear stress (Sample E)

Figure 5 shows the values of shear modulus G which were calculated by using the secant modulus at each strain level and were normalized by the initial shear modulus G_{0i}. It is verified that the cyclic shear loading applied to peat soil causes a decrease in the shear modulus, though the degree of decrease depends on the strain level. The greater is the cyclic shear loading applied to peat soil, the more the shear modulus decreases. In Samples R, O and T, the degree of reduction in the shear modulus and the magnitude of the cyclic shear loading are not as consistently correlated as in Sample E, but the inconsistency is not as noticeable as in the relationship between the strength and the cyclic shear loading. It is confirmed that the tendency in the reduction of the shear modulus regarding these samples is more or less similar to the tendency observed in Sample E (Figure 4). Concerning all samples, no obvious effects of cyclic shear loading are recognized at a shear strain of 10% or greater.

Focusing on the shear modulus, Figure 6 shows the relationship between τ_d/σ_{ac}' and G/G_{0i} based on the results shown in Figure 5 and also on the results regarding Samples R, O and T. G/G_{0i} is the reduction rate of the shear modulus calculated by normalizing the shear modulus obtained in the monotonic loading tests performed after cyclic loading (in which the strain was γ= 0.1%, 1% or 5%) by the initial shear modulus obtained in separately performed monotonic shear tests (in which the strain was γ=0.1%). τ_d/σ_{ac}' is the cyclic shear stress ratio. In Figure 6, although the rigidity of Sample O, depending on the strain, increases (i.e., G/G_{0i} exceeds 1) after undergoing cyclic shear loading, the rigidity of most other samples is reduced after cyclic shear loading, and the degree of reduction depends on the cyclic shear stress. At a greater strain, the reduction rate of the shear modulus in comparison with G_{0i} becomes larger.

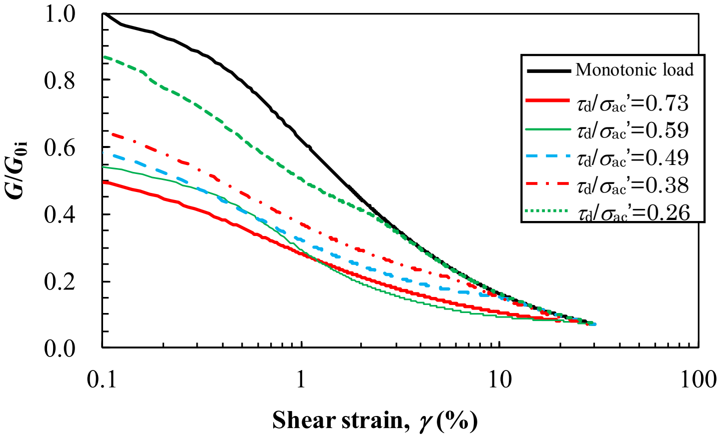

Figure 5. Relationship between shear strain and normalized shear modulus G/G_{0i} (Sample E)

The exact strain level which can be used for evaluating the shear modulus and thus for assessing the rigidity of motion-affected peaty ground are open for discussion. Regarding cohesive soil having a high fine fraction content, a study was conducted for evaluating the shear modulus at a strain of γ=1% after earthquake motion (Yasuda *et al*. 2005), but no similar studies have been done for peat soil. Numerical and other analyses will be conducted regarding the shear modulus of peat soil immediately after earthquakes.

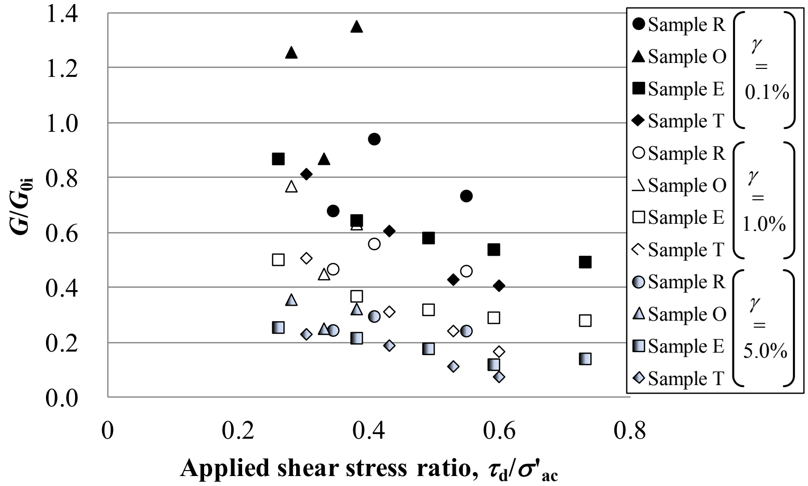

Figure 6. Relationship between τ_d/σ_{ac}' and G/G_{0i}

Method for Estimating Changes in the Shear Modulus

Figure 7 shows the relationship between the reduction rate of the shear modulus (G/G_{0i}) after cyclic shear loading and the natural water content (W_n), and Figure 8 shows the relationship between G/G_{0i} and the ignition loss (L_i). It is generally known that various physical properties and the compressibility of peat soil are highly correlated with natural water content and ignition loss (CERI 2011). Figures 7 and 8 show the values around the following values of shear stress ratio (τ_d/σ_{ac}'), which were given prior to monotonic shear loading: 0.30 (Samples R-2, O-2, O-3, E-4 and T-2); 0.40 (Samples R-1, O-1, E-3 and T-4); and 0.55 (Samples R-3, E-2, T-2 and T-3).

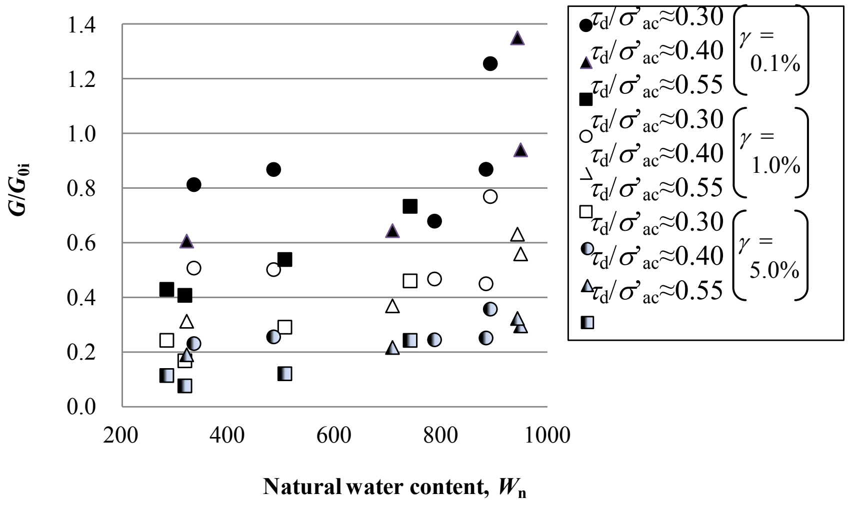

Figure 7. Relationship between W_n and G/G_{0i}

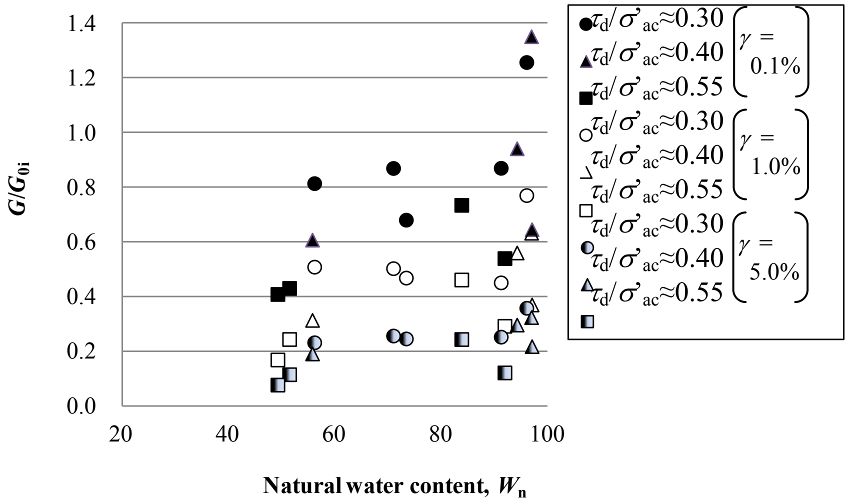

Figure 8. Relationship between L_i and G/G_{0i}

In Figure 7, the relationship between G/G_{0i} and the natural water content is not consistent when the value of τ_d/σ_{ac}' is as small as $\tau_d/\sigma_{ac}'\approx0.30$, and is fairly consistent when $\tau_d/\sigma_{ac}'\approx0.40$ or 0.55. As a general tendency, an increase in natural water content is associated with a smaller reduction rate of the shear modulus after cyclic shear loading. This result suggests the possibility that the natural water content can be used for estimating the reduction in rigidity of peat soil immediately after earthquakes. Similarly, an increase in the ignition loss (L_i) is associated with a smaller reduction rate of the shear modulus after cyclic shear loading in Figure 8. The reduction rates of the shear modulus after cyclic shear loading obtained in this study will be numerically analyzed toward assessing their validity.

Conclusions

A series of hollow cylinder torsional shear tests were conducted, focusing on the changes in the shear modulus of peat soil that underwent cyclic shear loading. The test results showed that cyclic shear loading causes reduction of the shear modulus even in peat soil, which never undergoes liquefaction. It was suggested that the degree of reduction in shear modulus can probably be estimated on the basis of the natural water content or the ignition loss. These findings are significant in understanding the lateral flow of peaty ground and the behavior of embankments built on peaty ground during earthquakes. Regarding peat soil that underwent earthquake motion, the authors will continue to accumulate experimental data for results complementing, and for the aim of appropriately evaluating the shear modulus of the peat soil in connection with the strain level. Numerical analysis will be also conducted that takes into account the reduction of shear modulus elucidated in this study.

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