Influence of cyclic loading on the secondary consolidation behavior of peats

Yosuke Yoshino[1*], *Taishi* Kochi[2], and *Satoshi* Nishimura[3]

[1] Graduate School of Engineering, Hokkaido University, Sapporo, Japan
[2] Department of Civil and Environmental Engineering, Institute of Science Tokyo, Tokyo, Japan, formerly Graduate School of Engineering, Hokkaido University, Sapporo, Japan
[3] Faculty of Engineering, Hokkaido University, Sapporo, Japan

1 Introduction

Peat ground is a soft, highly organic soil with high water content, of which long-term settlement continuing after the start of superstructure service is often a problem. When constructing river levees on peat, it is therefore necessary to design them by predicting long-term settlement to meet the height requirements. However, it is challenging to predict the behavior of peat ground after being subjected to seismic motion. Some settlement data of levees built on peat ground showed that the settlement rate was accelerated or maintained after the 2018 Hokkaido Eastern Iburi Earthquake, Japan, even after the apparent densification due to the dissipation of excess pore water pressure induced by the cyclic loading. Similar phenomena have also been observed by Shafiee et al. [1] and Shafiee [2], who interpreted the increase of the rate as partially resetting the secondary compression clock without increasing total stress.

Secondary consolidation due to viscosity is prominent in peat, which results in significant long-term settlement. The e-log$t$ relationship (e: void ratio, t: time) has been conventionally used in engineering practice to predict the long-term settlement. However, this method has a theoretical limitation due to the arbitrary definition of the time origin and thus fails to describe settlement systematically. The isotach law, proposed by Šuklje [3], can be an alternative approach to understand the settlement behavior of peat which introduces a unique relationship between the strain and the consolidation pressure corresponding to a given strain rate in association with viscosity. This concept enables the description of settlement behavior based on the soil state, independent of time setting.

The present study investigated the secondary consolidation behavior of peats before and after cyclic loading using cyclic triaxial tests. Three types of peats were used to comprehensively understand their secondary consolidation characteristics. This study aims to systematically interpret the changes in the secondary consolidation behavior of peat ground induced by seismic ground motion, using objective variables through the application of the isotach concept.

2 Cyclic triaxial tests

This study used undisturbed peats from three sites in Hokkaido, Japan; Yubari, Kitamura and Tsukisamu. Table 1 shows their basic engineering properties. The degree of peat decomposition was assessed according to the Von Post scale, which is a visual classification system consisting of ten classes from H1 to H10, where H1 represents the least decomposed peat and H10 represents the most decomposed.

Table 1. Engineering properties of peat samples (average).

Sample	Natural water content, w_n: %	Ignition Loss, L_{ig}: %	Density of soil particle, ρ_s: Mg/m^3	Von Post scale
Yubari	727	92.4	1.50	H5
Kitamura	329	41.9	2.08	H6
Tsukisamu	786	94.9	1.66	H4

The secondary consolidation behavior before and after cyclic loading was investigated using cyclic triaxial testing apparatus (Figure 1). The specimens were 50mm in diameter and 100mm in height, which were formed by trimming originally larger samples after pre-consolidating under K_0 conditions to approximately 50% of the target consolidation pressure. To ensure a normally consolidated state prior to cyclic loading, the specimens were consolidated in the triaxial apparatus at a sufficiently slow rate with drainage from both top and bottom ends. Either isotropic or K_0 consolidation was applied to compare the behavior under different stress conditions. After consolidation, the specimen was subjected to creep for approximately one week while maintaining a constant stress state. Subsequently, undrained cyclic loading was performed. Following the cyclic loading, the drainage line was reopened, and the creep behavior was observed while maintaining the same stress state as prior to the cyclic loading. To account for the reduction in strain rate, the duration of the post-cyclic creep stage was set to more than two weeks. Figure 2 shows the experimental procedures on the e-log p' plane (p': the mean effective principal stress).

* Corresponding author: yoshino.yosuke.f2@elms.hokudai.ac.jp

Table 2 summarizes the testing conditions. Stress-controlled cyclic loading was performed in the tests, and the stress amplitude was represented by the cyclic stress ratio (CSR), which is defined as the cyclic shear stress normalized by the effective vertical stress. In case Y1 (Table 2), for example, the specimen was consolidated to $\sigma'_a = 73$kPa (σ'_a: axial effective stress) under K_0 conditions and then subjected to creep for approximately one week while maintaining the stress. Subsequently, cyclic loading steps (1) to (4) were performed sequentially. Finally, the specimen was subjected to creep again at $\sigma'_a = 73$kPa under K_0 conditions.

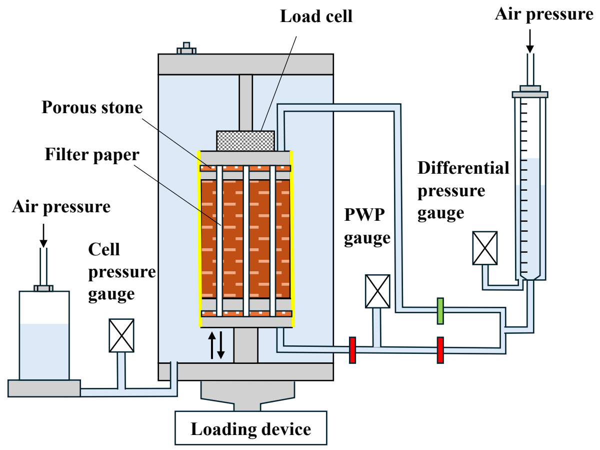


Figure 1. Cyclic triaxial testing apparatus.

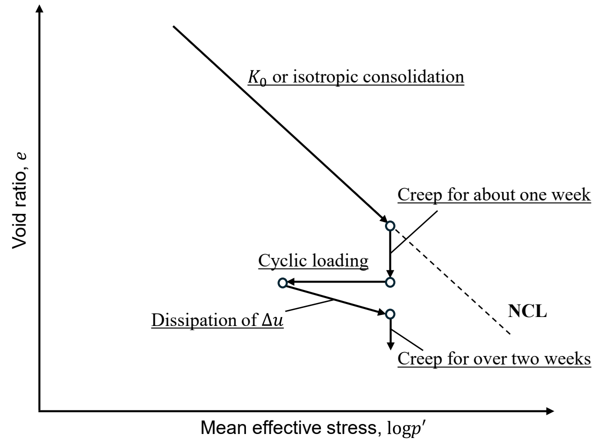


Figure 2. Experimental procedures plotted on $e - \log p'$ plane.

Table 2. Testing conditions.

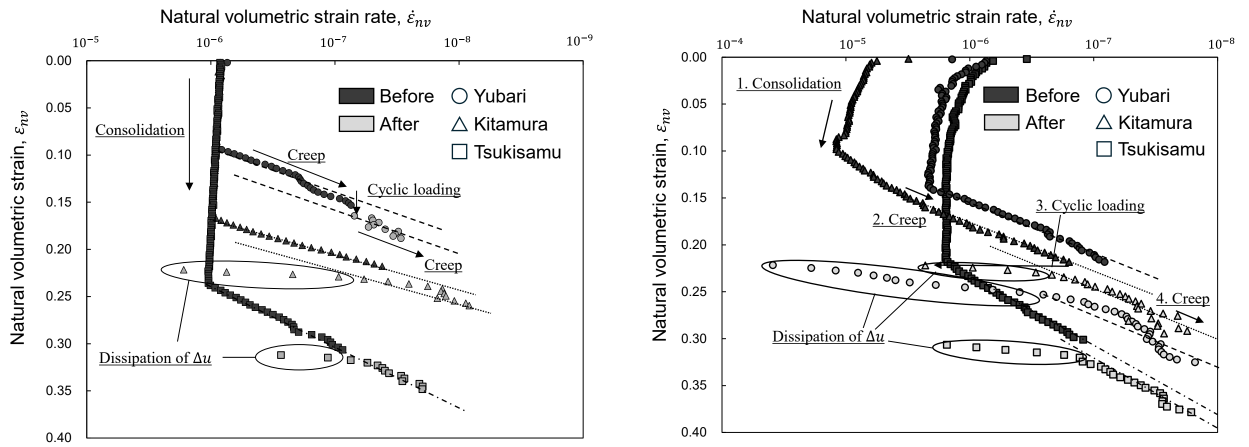
Case	Sample	Consolidation method	Consolidation pressure	Cyclic loading conditions (CSR, Frequency [Hz]) Number of cycles per stage: 10 (50 for Case T2)
Y1	Yubari	K_0	σ'_a=73kPa	(1)0.1, 0.004, (2)0.2, 0.004, (3)0.2, 0.008, (4)0.2, 0.03
Y2	Yubari	Isotropic	σ'_a=σ'_r=40kPa	(1)0.025, 0.02, (2)0.1, 0.02, (3)0.2, 0.02, (4)0.4, 0.02, (5)0.8, 0.01
K1	Kitamura	K_0	σ'_a=73kPa	(1)0.025, 0.01, (2)0.1, 0.01, (3)0.2, 0.01, (4)0.4, 0.01
K2	Kitamura	Isotropic	σ'_a=σ'_r=40kPa	(1)0.025, 0.01, (2)0.1, 0.01, (3)0.2, 0.01, (4)0.4, 0.01
K3	Kitamura	Isotropic	σ'_a=σ'_r=80kPa	(1)0.025, 0.01, (2)0.1, 0.01, (3)0.2, 0.01, (4)0.4, 0.01
T1	Tsukisamu	K_0	σ'_a=73kPa	(1)0.4, 0.01
T2	Tsukisamu	Isotropic	σ'_a=σ'_r=40kPa	(1)0.4, 0.01

3 Test results

The tests focused on the secondary consolidation behavior of the specimens before and after cyclic loading under constant effective stress conditions. Noting the observation by Butterfield [4] and Oikawa [5], who reported that the linearity of the e-log p' or the ε_v-log p' curve (ε_v: volumetric strain) does not hold under large deformations for highly compressible materials such as peat, natural strain was adopted in this study instead of nominal strain ε_n. Based on the isotach law, the natural volumetric strain ε_{nv} was plotted against the volumetric strain rate $\dot{\varepsilon}_{nv}$ on a logarithmic scale for the consolidation and creep stages, both pre- and post-cyclic loading (Figure 3). In addition, the test results for Case T2 were plotted on the ε_{nv}-logp' plane (Figure 4).

Given that the effective stress is identical before and after cyclic loading, the isotach law implies that the post-cyclic data points should theoretically lie on the extension of the pre-cyclic volumetric strain rate $\dot{\varepsilon}_{nv}$- volumetric strain ε_{nv} line. However, experimentally, the line defined by the post-cyclic plots is shifted relative to the pre-cyclic line in both isotropic and K_0 cases. This phenomenon is essentially same as the behavior reported by Shafiee [1, 2], suggesting that the conventional isotach law may no longer be valid when peat is subjected to cyclic loading. This shift results in a higher strain rate for the same strain, which can explain the phenomenon where the post-cyclic secondary consolidation rate is accelerated or maintained. It should be noted that in Case T1, no distinct shift was observed despite the application of a relatively large stress amplitude. Further investigation with retrial cases will be necessary to see how dependent the results are on peat characteristics.

For Case T2, the consolidation and creep processes are plotted as a v-log$t$ relationship (v: specific volume, $v = 1 + e$) in Figure 5, with the start of loading defined as $t = 0$. For plots after cyclic loading, two approaches can be taken: (i) resetting the time to define the end of cyclic loading as $t = 0$, and (ii) not resetting the time. Since which method to use is left to the observer, it is evident that this is unsuitable for a systematic interpretation of settlement behavior. It is known that the slope of the strain rate-strain line during creep corresponds to the coefficient of secondary consolidation defined in terms of strain, $C_{\alpha\varepsilon}$. It appears that $C_{\alpha\varepsilon}$ remains unchanged pre- and post-cyclic loading from Figure 3. However, the conventional practice of resetting the time upon loading (Figure 5(i)) results in an apparent increase in the coefficient of secondary consolidation after cyclic loading.



(a) (b)

Figure 3. Relationship between volumetric strain rate $\dot{\varepsilon}_{nv}$ and volumetric strain ε_{nv} during consolidation and creep stages before and after loading: (a) K_0-consolidation tests (Y1, K1, T1) (b) Isotropic consolidation tests (Y2, K2, T2).

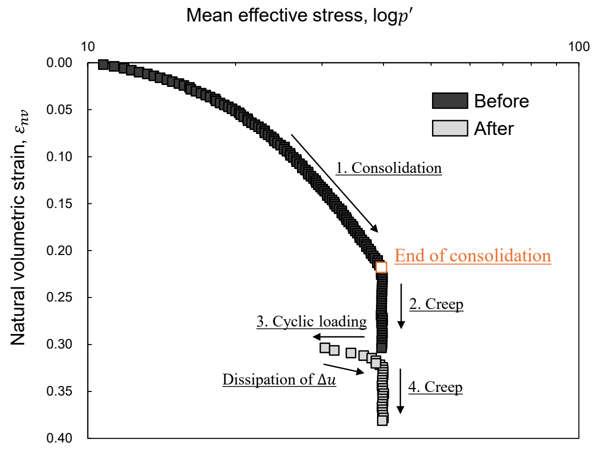


Figure 4. Relationship between mean effective stress p' and volumetric strain ε_{nv} (Case T2).

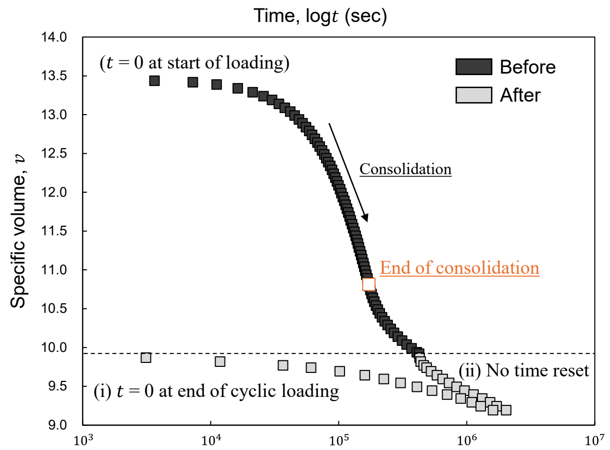


Figure 5. Relationship between time t and specific volume v (Case T2).

Figure 6 plots the excess pore water pressure Δu generated during cyclic loading against the energy input E. Note that this energy input E is calculated as the area enclosed by the hysteresis loop in the deviator stress q versus axial strain ε_a plot. The excess pore water pressure is normalized by the initial mean effective stress p'_0 ($r_u = \Delta u/p'_0$). While peat is known to exhibit higher cyclic shear resistance due to the reinforcing effect of fibers, Figure 6 shows that significant excess pore water pressure develops with high energy input. In other words, the generation of excess pore water pressure results in an overconsolidated state. The overconsolidation ratio (OCR) is obtained by the following equation:

$$\mathrm{OCR} = \frac{p'_0}{p'_0 - \Delta u} = \frac{1}{1 - r_u} \tag{1}$$

Yamazoe et al. [6] investigated the viscosity characteristics of preloaded peat through long-term consolidation tests, and reported that the peat behavior did not follow the isotach rule after unloading when the OCR is larger than 1.5. This finding implies that the viscous behavior of peat in the overconsolidated state differs from that in the normally consolidated state. It is inferred that this principle also applies to cases where the soil becomes overconsolidated due to the effective stress reduction caused by cyclic loading.

As previously mentioned, a shift in the strain rate-strain line during creep was observed due to cyclic loading. The vertical displacement of this shift is defined as ΔI. Figure 7 plots $\Delta I/\mathrm{C}_{c\varepsilon}$ against the OCR obtained from Equation (1). To account for the varying compressibility of each peat sample, ΔI was normalized by the compression index defined in terms of strain $\mathrm{C}_{c\varepsilon}$. It should be noted that the OCR corresponds to the value under undrained conditions after cyclic loading stages. In contrast, the creep line used to calculate ΔI was measured after the dissipation of Δu, when the stress state had returned to the same level as before cyclic loading. While additional data, particularly in the range of OCR > 1.5 are necessary for a more robust discussion, Figure 7 implies that there may be a positive correlation between the post-cyclic OCR and ΔI. If a significant shift occurs at OCR > 1.5, this would be consistent with the findings of Yamazoe et al. [6].

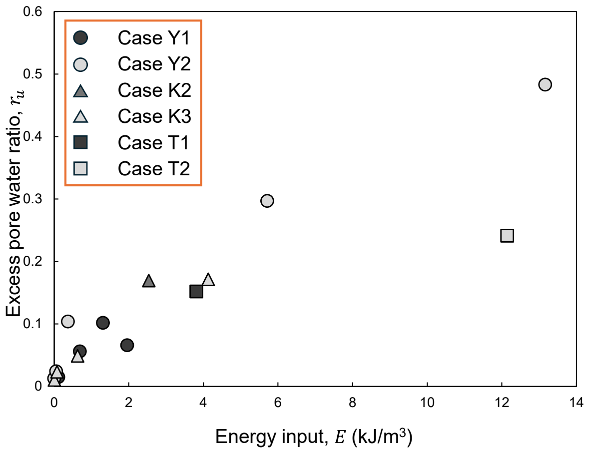


Figure 6. Relationship between energy input E and excess pore water ratio r_u.

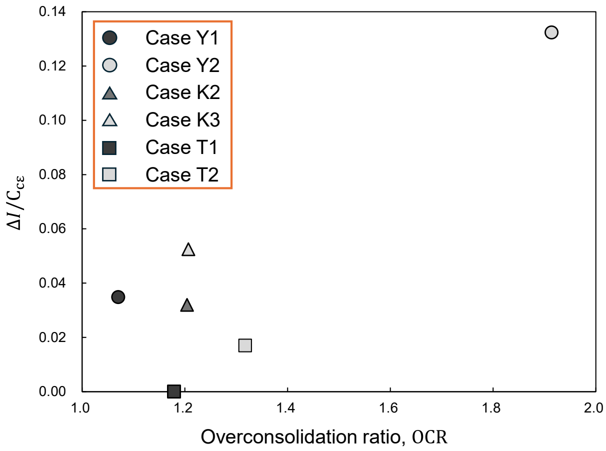


Figure 7. Relationship between post-cyclic OCR and $\Delta I/C_{c\varepsilon}$.

4 Conclusions

Motivated by settlement data of the levee during the earthquake, the changes in the secondary consolidation behavior of peats due to cyclic loading were investigated using cyclic triaxial tests. The main results of this study are summarized below:

1) The natural volumetric strain was plotted against the strain rate for the pre- and post-cyclic loading stages, and the plots suggest that the strain rate-strain line shifts due to cyclic loading, which means that the conventional isotach law may no longer be valid when peats are subjected to cyclic loading.
2) The coefficient of secondary consolidation remains unchanged between pre- and post- cyclic loading. The shift in the strain rate-strain line can explain the phenomenon where the post-cyclic secondary consolidation rate is accelerated or maintained.
3) Significant excess pore water pressure develops with high energy input to peat, and a possible correlation was observed between the vertical shift of the strain rate-strain line and the OCR defined based on the excess pore water pressure generated during cyclic loading.

Based on these findings, future work aims to extend the applicability of the isotach law to seismic conditions by introducing an additional model module [7].

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