INTERNATIONAL CONFERENCE ON ADVANCES AND INNOVATIONS
IN SOFT SOIL ENGINEERING
24 – 26 August, Delft, NL

Interpretation of recompression of peats after unloading based on strain rate- and temperature- effect

Taishi Kochi[1*] and *Satoshi* Nishimura[2]

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

1 Introduction

Peat is common in cold regions and Southeast Asian regions. Being deposited in the subsurface, it exhibits large deformation against loads from superstructure in a relatively short-term. The long-term settlement continues in peat even after the service of infrastructure, resulting in its gradual deformation. Economical options to mitigate such a long-term behaviour are preloading method, including application of surcharge and vacuum, where the ground is brought into an "overconsolidated" state by unloading.

The precise prediction of recompression behaviour of soft soils, however, remains challenging due to the complex coupling of short-term swelling and long-term compression. The classic (compressive) rate-dependent approach (i.e., the isotach) is applicable only to cases with OCR values below 1.5 according to Yamazoe et al. [1]. Earlier, Den Haan [2] proposed a distorted reload isotach model to describe rate dependency in soft soils during reloading. These studies suggest that a modification to the classic isotach model is required when applied to the post-unloading behaviour of peat.

Another potential factor influencing the long-term behaviour of *in-situ* peat is temperature; our previous study (Kochi et al. [3]) reveal that the volumetric behaviour of peats is sensitive to temperature. A field measurement in cold region by Hanson [4] indicates that the temperature in peat fluctuates by 6-10°C within the upper 2m, due to seasonal air temperature changes, and the average temperature is approximately 10℃. The temperature fluctuations may be magnified under specific conditions, such as the use of energy-related infrastructure (e.g., energy pile: Van Lysebetten et al. [5]) and the surface albedo change due to urbanisation.

Accordingly, the combined effect of strain rate and temperature is addressed in this paper. This aims to develop a unified interpretation of post-unloading behaviour of peat under unsteady field thermal conditions.

2 Test specimens and experimental programme

The samples used in this study was collected from two locations in Hokkaido, Japan. They are named after their respective sampling sites: Teshio and Ebetsubuto peat. In the test cases, they are abbreviated as T and E, respectively. The engineering properties of the peat samples are summarised in Table 1.

For temperature control during the consolidation tests, the same two devices as those used in our previous study [3] were employed. The thermal biases in measurement are axial strain fluctuation of less than 0.001 and radial strain fluctuation of approximately 0.0003 during temperature changes between 10 and 50 °C. Only the straining that clearly exceeds these biases is considered in the discussion.

The strain measure adopted in the present study is the natural (logarithmic) volumetric strain ε_{nv}, instead of the typical measure of engineering volumetric strain ε_v. This strain measure accounts for the large deformation of peats.

The test paths employed in the present study consists of step-loading tests (T-OCR2 and T-OCR4) and constant rate of strain (CRS) tests, where unloading and heating are involved. In step loading tests, the total vertical stresses σ_z (=10, 20, 37, 73 144 kPa) were first applied at T = 10°C. It was then unloaded to either 73 or 37 kPa, to reach overconsolidation ratioof approximately 2 or 4. Subsequently, heating was applied stepwise: 10→20°C and 20→50°C. At each temperature stage after unloading, the specimen was kept under constant load for 10 days to monitor the post-unloading secondary consolidation (i.e., secondary compression) and thermal compression (i.e., recompression). In the CRS tests (E-mCRS-H20, E-mCRS-H50), the initial loading and unloading were applied at T = 10°C, followed by heating to either 20 or 50℃. Reloading was then applied under step-by-step strain rate changes. The controlled variable was engineering volumetric strain rate (i.e., linear displacement rate).

Table 1. Engineering properties of tested peat sample.

	Natural water content w_n: %	Ignition loss L_{ig}: %	Specific gravity G_s: -
T-OCR2	1188	91	1.43
T-OCR4	1154		
E-mCRS-H50	685	74	1.81

* Corresponding author: kouchi.taishi.h8@elms.hokudai.ac.jp

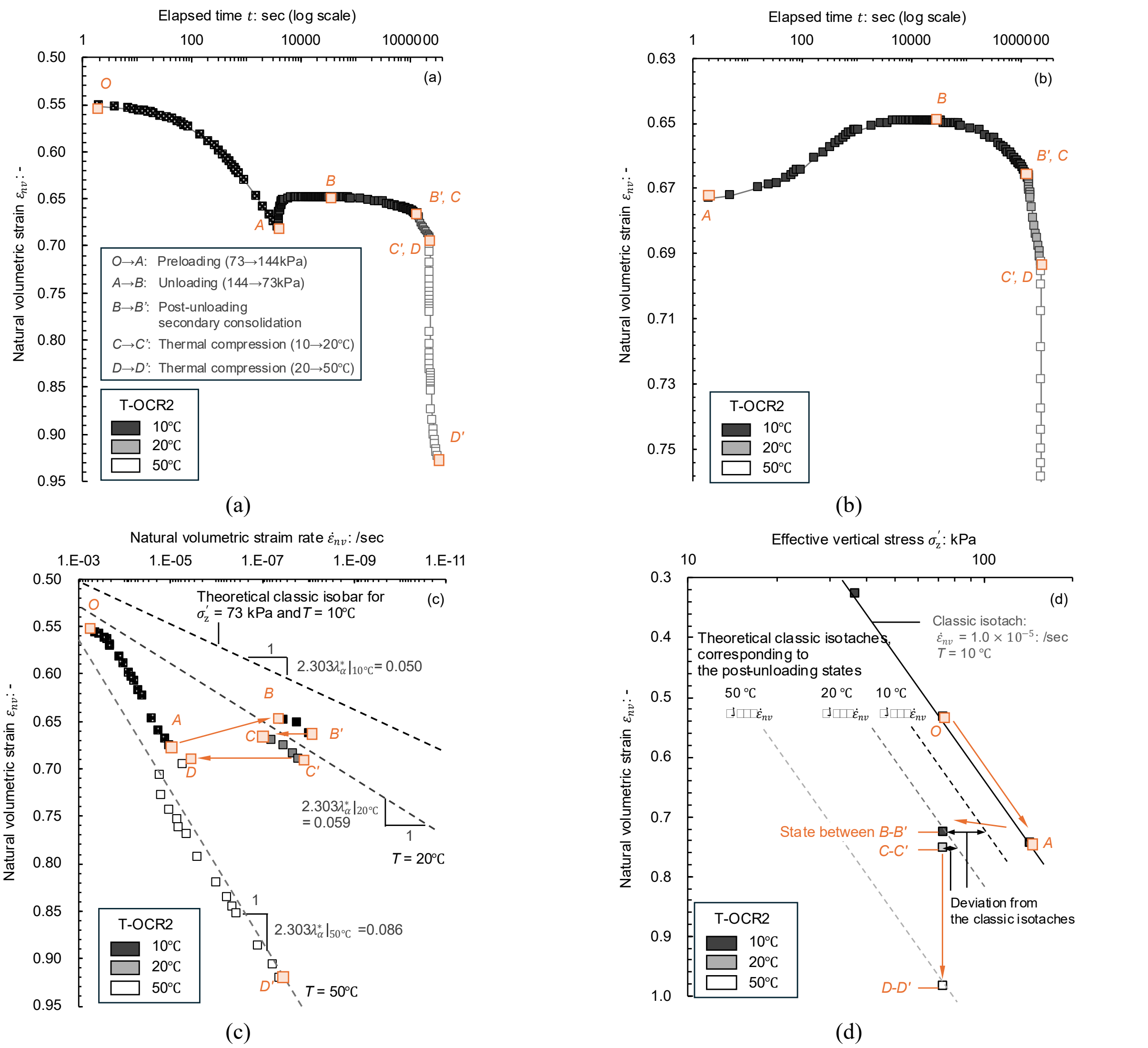


Figure 1. Comparative representations of recompression behaviour of Teshio, including thermal compression (a) time-strain: $t = 0$ for surcharge application, (b) $t = 0$ for its removal, (c) strain rate-strain, and (d) stress-strain.

3 Results and discussion

Several representations, both practical and constitutive, have been used in the literature to analyse the post-unloading behaviour (e.g., time-strain, strain rate-strain and effective stress-strain plots). It is, therefore, instructive to first review a set of representative forms of data presentation (regarding T-OCR2) to clarify how they correspond to each other.

Fig. 1 illustrates the post-unloading behaviour of the Teshio peat, including subsequent heating stages, using four representations: (a) time-strain referenced to preloading, (b) time-strain referenced to unloading, (c) strain rate-strain and (d) effective stress-strain. Stage transitions are labelled as O→A (preloading), A→B (unloading), B→B′ (post-unloading secondary consolidation), C→C′ (thermal compression by 10→20°C) and D→D′ (thermal compression by 20→50°C). The time-based plots in Fig. 1 (a) and (b), used in practice, illustrate that secondary consolidation continues after unloading (B→B′) despite being reduced at OCR = 2. The subsequent heating (i.e., 10→20°C), though modest in magnitude and comparable to *in-situ* seasonal temperature fluctuations, induces thermal compression (C→C′). This thermally induced compression becomes relatively significant under the post-unloading condition. The second heating (20→50°C), although extreme in magnitude, induces substantial compression (D→D′), comparable to the mechanical compression during preloading (A→B).

While the time-based representations discussed above are intuitive for describing the evolution of settlement, they depend directly on the choice of the time origin and thus lack objectivity; this is reflected in the different curve shapes in Fig. 1 (a) and (b). For objective interpretation, the strain rate is more appropriate. In the following, only the compressive strain rate is considered so that the post-unloading behaviour can be evaluated within the isotach framework, which assumes that the effective stress–strain relationship is uniquely determined by strain rate as well as temperature. Following Den Haan [2], the term *isobar* is also adopted to denote the equi-effective stress line obtained by projecting the isotach onto the strain rate–strain plane (i.e., dashed lines in Fig. 1c). Note that the slope of isobar corresponds to the coefficient of secondary consolidation defined in terms of strain rate, denoted as $\lambda_\alpha^*|_T$, with the subscript T indicates that the value is temperature dependent (Kochi et al. [3]).

Major findings on the post-unloading behvaiour of the Teshio peat under three temperatures (T=10, 20 and 50℃), shown in Fig. 1(c) and (d), are as follows:

- The post-unloading secondary consolidation (B→B′) does not follow the classic isobar (i.e., dashed lines in Fig. 1c, derived from test data under monotonic loading conditions in Kochi et al. [3]).
- The post-unloading isobar slope (i.e., secant slope between B and B′), is smaller than that of classic isobar, even when the temperature dependency of secondary consolidation, is considered. This aligns with the conventional understanding that unloading reduces the long-term settlement of soft soils. The post-unloading isobar slope approaches to λ_α^* due to heating (B→B′, C→C′ and D→D′ in Fig. 1c). Comparable behaviour has been reported under isothermal conditions at small OCRs, up to 1.5 by Yamazoe et al. [1], suggesting that the post-unloading behaviour eventually returns to the classic isobar, irrespective of whether the straining is thermally induced or not. Under the high OCR of 2 considered here, the test duration of 10days was insufficient to observe such a convergence.
- The post-unloading effective stress-volumetric strain states characterised by $(\dot{\varepsilon}_{nv}, T)$ (e.g., the state between B-B′ in Fig. 1d), deviates from a corresponding classic isotach (i.e., dashed lines in the figure). This deviation is here quantified as the stress ratio between the classic-isotach and the current state. By definition, $\xi \to 1$ when the response returns to the classic isotach. The deviation ratio from the classic isotach ξ computed for the current case is approximately 1.35 for 10℃, 1.09 for 20℃ and 1.0 for 50℃, indicating that the deviation converges by heating and simultaneous straining.

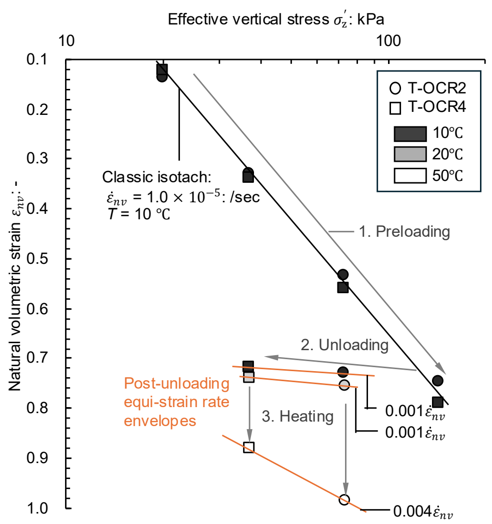


Figure 2. Equi-strain rate envelopes during recompression, constructed from T-OCR2 and 4.

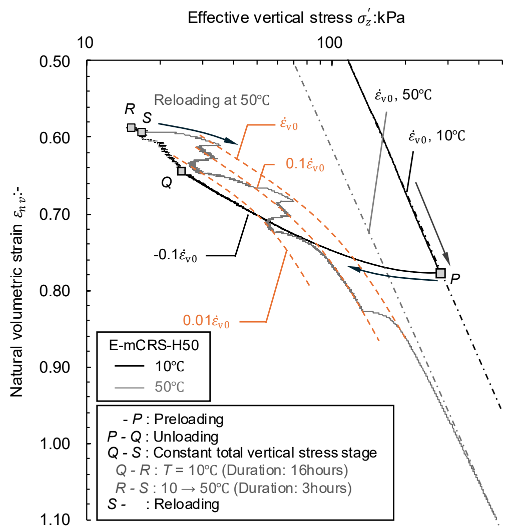
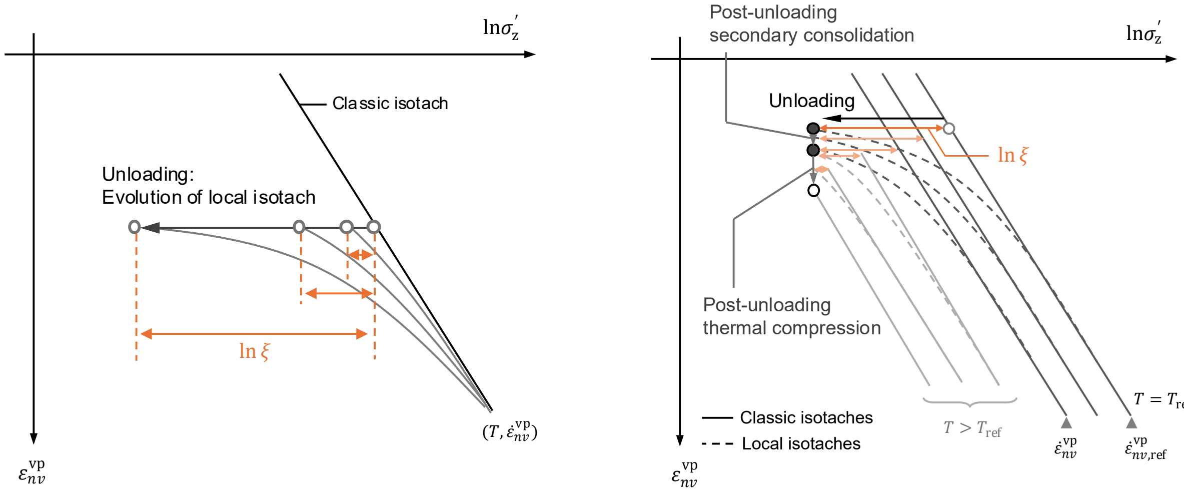


Figure 3. Strain rate dependency during reloading after heating from 10 to 50℃.



(a) (b)

Figure 4. Local isotach concept: (a) evolution of post-unloading rate-dependency, and (b) correspondence to recompression.

Fig. 2 presents the isotach during recompression, constructed by integrating the secondary consolidation and thermal compression stages under OCRs of 2 and 4. The results indicate that the slope of post-unloading isotach is smaller than that of the classic isotach (i.e., the compression index); the post-unloading isotaches are distorted, thereby deviating from the classic ones. Meanwhile, the slope progressively increases with heating (i.e., the decrease in the deviation ratio ξ). The multi-stage CRS test involving a heating stage (Fig. 3) demonstrates that the isotaches during reloading is also distorted and eventually converges to the isotherm at 50℃ not original 10℃, highlighting the coupled effect among unloading history, temperature, and strain rate.

This history-dependent, temporally evolving post-unloading isotach is, in this paper, referred to as the *local* isotach. It conceptually encompasses rate dependency during reloading (i.e., reload isotach) as well as that manifested in the recompression and the thermal softening. The local isotach concept is illustrated as follows; unloading invokes the evolution of local isotaches, increasing the deviation ratio ξ (Fig. 4a). The tangential slope of local isotach decreases for high deviation ratio. As schematically shown under a given effective vertical stress (Fig. 4b), the local isotaches align widening their spacing in the compressive direction. Just after unloading, this spacing is small, and hence the post-unloading secondary consolidation is reduced. With continued straining or heating, the spacing returns to the coefficient of secondary consolidation $\lambda_\alpha^*|_T$, being consistent with the recompression behaviour shown in Fig. 1 (c).

Note that unloading induces variations in the stress ratio and, consequently, in dilatancy. Although, in a strict multi-dimensional framework, predictions are also influenced by the choice of the viscoplastic potential and Poisson's ratio, their contribution has been shown to be minor (Kochi and Nishimura, 2025 [6]). Therefore, the interpretation based on one-dimensional compression (i.e., *local isotach*) provides a basis for developing the volumetric law of peat.

Meanwhile, the post-unloading behaviour of soft soils consists of both compression and swelling components (e.g., Vergote et al. [7]). The local isotach framework, however, captures only the post-unloading compression, while the swelling component remains an open challenge for peat. Incorporating this aspect will be essential for establishing a complete description of recompression behaviour of peat.

4 Conclusion

This study examines the post-unloading behaviour of peats under oedometer conditions, including thermal effects, with the aim of establishing an interpretation for recompression phenomenon in peat. The conclusions are as follows:

1. The strain rate-based representation of test data shows that the recompression of a peat under OCR of 2 does not follow the classic isotach / isobar; the slope of post-unloading isobar is smaller than the coefficient of secondary consolidation.
2. Heating after unloading produces compression. Even modest heating (10→20 °C), comparable to seasonal ground temperature changes, induces relatively significant thermo-plastic compression. Subsequent heating (20→50 °C) generates further compression.
3. The post-unloading secondary consolidation and thermal compression behaviour and the observation from multi-stage CRS tests show that the post-unloading isotaches are distorted, thereby deviating from the classic isotach. Such a history-dependent form of isotach is in the paper referred to as *local* isotach concept which encompasses the rate dependency during reloading (i.e., reload isotach) as well as the recompression.

This work was supported by JSPS Research Fellowship for Young Scientists (DC2), Grant Number 25KJ0490.

References

1. N. Yamazoe, S. Nishimura, H. Tanaka, T. Ogino and T. Kochi, Long-term settlement behavior of peat after unloading and applicability of isotach law. Soils Found. **65**(1), 101560 (2025). https://doi.org/10.1016/j.sandf.2024.101560
2. E.J. Den Haan, A compression model for non-brittle soft clays and peat. Géotechnique **46**(1), 1-16 (1996) https://doi.org/10.1680/geot.1996.46.1.1
3. T. Kochi, S. Nishimura and N. Yamazoe, Thermo-mechanical behaviour of peats under one-dimensional compression. Géotechnique **75**(8), 1064-1079 (2025). https://doi.org/10.1680/jgeot.23.00494
4. J.L. Hanson, Thermal precompression of peat, Ph.D. thesis, University of Wisconsin-Madison, Civil and Environmental Engineering, USA,1996
5. G. Van Lysebetten, M. Allani and N. Huybrechts, Real-scale test campaign on energy piles for Belgian practice and numerical modelling of their behaviour, in Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, Korea, September 17–22 (2017)
6. Kochi, T. and Nishimura, S., Revisiting classic isotach theory in unloading analysis for peat with extended viscoplastic potential, The 60th Japan National Conference on Geotechnical Engineering, Yamaguchi, Japan, July 22-25 (2025) (in Japanese)
7. T.A. Vergote, C.F. Leung and S.C. Chian, Modelling creep and swelling after unloading under constant load and relaxation with Bayesian updating. Géotechnique **72**(6), 496-509 (2022). https://doi.org/10.1680/jgeot.20.P.106