Hydraulic conductivity assessment of tropical fibrous peat using CRS consolidation

Yu-Chiao Wang[1], *Ayu* Prativi[1,2*], *Louis* Ge[1], *Yudhi* Lastiasih[2], and *Noor* Endah Mochtar[2]

[1] Department of Civil Engineering, National Taiwan University, Taipei 106319, Taiwan (R.O.C)
[2] Department of Civil Engineering, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia

1 Introduction

The constant rate of strain (CRS) consolidation test offers several advantages for characterizing the consolidation behavior of soft soils. The loading process is initiated at a very low and controlled strain rate, which minimizes disturbance to the specimen, particularly under undrained conditions [1]. In this method, the specimen is subjected to a small, constant axial strain, resulting in a gradual increase in effective stress. Consequently, the CRS test not only reduces specimen's disturbance during the test but also provides a more complete and continuous stress-compression relationship compared to the conventional load increment (IL) consolidation test, making it particularly suitable for soft soils.

Despite these advantages, most existing CRS studies have focused on inorganic soils, particularly clays. The application of the CRS test to tropical fibrous peat remains challenging due to its highly organic, compressible, and anisotropic nature, as well as the lack of specific testing guidelines for such materials. Furthermore, the fundamental theories used to interpret compression behavior in CRS tests, originally developed by Wissa et al. [2], were formulated based on inorganic soils. As a result, the applicability of these theoretical frameworks to tropical fibrous peat has not yet been fully evaluated.

This study aims to evaluate the hydraulic conductivity variation of tropical fibrous peat during loading using the CRS consolidation test. The peat sample was collected from Palangkaraya, Central Kalimantan, Indonesia. Specimens were tested under different imposed strain rates. Both linear and nonlinear formulations suggested in ASTM D 4186 [3] were employed to quantify the behavior of hydraulic conductivity during loading. The results were compared and analyzed to evaluate the consistency and reliability of the observed trends.

2 Material properties

The investigation utilized tropical fibrous peat specimens sourced from Bereng Bengkel Village, located in Palangkaraya, Central Kalimantan, Indonesia. The physical characterization of the material was conducted in accordance with ASTM D2974-20 [4], ASTM D1997-20 [5], and the Peat Testing Manual [6]. The fiber size distribution test was conducted following the procedure proposed by Prativi et al. [7]. The peat sample has an organic content (O_c) of 92.77%, unit weight of 10.34 kN/m^3, water content (w_c) of 496.51%, void ratio (e) of 7.16, specific gravity (G_s) of 1.41, fiber content (F_c) of 31.35%, and coarse fiber content (fibers retained on sieve no.8) of 17.35%. Based on ASTM D4427 [8], the soil was classified as a sapric peat (F_c< 33%) with moderate absorbency (300 < w_c < 800), slight acidity (5.5 < pH < 7), and medium ash content (A_c< 5%). Furthermore, visual examination of the oven-dried fiber size distribution test (as shown in Figure 1) confirmed the presence of woody parent materials; therefore, the peat was further identified as woody peat.

(a) (b) (c)

Figure 1. Oven-dried undisturbed sample (a) foreign materials, (b) coarse fibers and (c) medium fibers.

* Corresponding author: ayuprativi@gmail.com

3 Testing method

The Constant Rate of Strain (CRS) consolidation testing apparatus utilized in this research is shown in Figure 2. Three undisturbed specimens were carefully prepared, saturated under a back pressure of 100 kPa, and subsequently subjected to consolidation testing using the CRS method to evaluate their hydraulic conductivity characteristics during consolidation. To investigate the influence of loading velocity, each specimen was subjected to a distinct constant strain rate. Based on the measured coarse fiber content of 17.35%, the strain rates were selected within the recommended range of 0.1% to 0.5% min^{-1} for fibrous materials [9]; accordingly, three specific rates of 0.1%/min, 0.25%/min, and 0.5%/min were employed in this study. The loading phase was continuously maintained until a target total vertical stress of 200 kPa was achieved, ensuring sufficient data points for the subsequent analysis of the consolidation process.

(a) (b)

Figure 2. Constant Strain Rate (CRS) test: (a) apparatus and (b) specimen after test.

The instantaneous strain function (F_n) was employed as a critical criterion to evaluate whether the soil specimen had reached a steady-state condition during the CRS test. According to ASTM D4186, F_n represents the relationship between the increments of effective stress and total stress. A value of $F_n < 0.4$ indicates that the test is in an unstable transient phase, during which parameters such as hydraulic conductivity, coefficient of volume compressibility, and consolidation coefficient cannot be reliably determined. Therefore, to ensure data integrity, all measurements recorded while $F_n < 0.4$ were excluded from the analysis. The function is defined as follows:

$$F_n = \frac{(\sigma_{a,n} - \sigma_{a,l}) - (u_{m,n} - u_{m,l})}{\sigma_{a,n} - \sigma_{a,l}} \quad (1)$$

where $\sigma_{a,l}$ is the initial total stress of specimen; $\sigma_{a,n}$ is the total vertical stress at any time point; $u_{m,n}$ is the water pressure at any time point; $u_{m,l}$ is the initial water pressure of specimen.

The ratio of base excess pore water pressure to total axial stress, referred to as the base excess pressure ratio (R_u), constitutes a critical parameter for assessing the reliability of the CRS test. According to ASTM D4186, maintaining R_u within a range of 3% to 15% is essential to ensure a relatively uniform distribution of the void ratio and consolidation stress throughout the specimen, thereby yielding reliable results. For non-standard or unfamiliar materials like tropical peat, R_u serves as a benchmark for calibrating the appropriate strain rate. In this study, the R_u values generated under the previously selected strain rates (0.1%/min, 0.25%/min, and 0.5%/min) were evaluated to ensure they remained within the recommended limits. The ratio is calculated as follows:

$$\Delta u_{m.n} = (u_{m,n} - \sigma_{c,n}) \quad (2)$$

$$R_{u,n} = \frac{\Delta u_{m.n}}{\sigma_{v,n}} \times 100\% \quad (3)$$

where $\Delta u_{m.n}$ is base excess pressure; $\sigma_{c,n}$ is chamber pressure; $\sigma_{v,n}$ is the current total vertical stress.

In the Constant Rate of Strain (CRS) consolidation framework, k_{linear} refers to the hydraulic conductivity calculated based on linear theory. This formulation is derived from the assumption that the coefficient of volume compressibility (m_v) is constant, implying a linear relationship between strain and effective stress. According to the ASTM D4186 standard, the calculation of k_{linear} is performed once the test reaches a steady-state condition. The linear hydraulic conductivity at any given measurement point n is defined by the following equation:

$$k_{linear} = \frac{\dot{\varepsilon}_n \cdot H_n \cdot H_0 \cdot \gamma_w}{2\Delta u_{m.n}} \times \frac{1}{10000} \quad (4)$$

where k_{linear} is the hydraulic conductivity (m/s); $\dot{\varepsilon}_n$ is the axial strain rate (/s); H_n and H_0 are the current and initial specimen heights, respectively (cm); γ_w is the unit weight of water (kN/m^3). This linear solution applies only when F_n exceeds 0.4, excluding the initial transient phase where F_n is less than 0.4.

In contrast to linear theory, the nonlinear formulation ($k_{\text{nonlinear}}$) accounts for the nonlinear relationship between strain and effective stress. This approach is predicated on the assumption of a constant compression index (C_c), implying that the soil exhibits a linear relationship between strain and the logarithm of effective stress. This model is often utilized to describe the behavior of soft clays or organic soils under large-strain conditions, where compressibility typically decreases as effective stress increases.

The average axial effective stress ($\sigma'_{a,n}$) in the nonlinear theory is derived through an approximation considering the nonlinear stress distribution within the specimen:

$$\sigma'_{a,n} = (\sigma^3_{a,n} - 2\sigma^2_{a,n} \cdot \Delta u_{m.n} + \sigma_{a,n} \cdot \Delta u^2_{m,n})^{\frac{1}{3}} \tag{5}$$

According to the nonlinear solution provided in the Appendix of ASTM D4186, the hydraulic conductivity ($k_{\text{nonlinear}}$) under steady-state conditions is defined by the following equation:

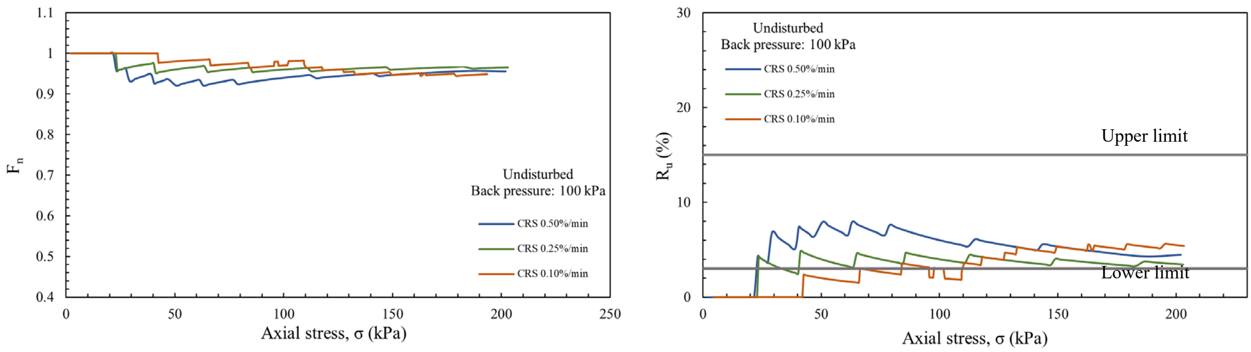
$$k_{nonlinear} = -\frac{0.434 \cdot \dot{\varepsilon}_n \cdot H_n \cdot H_0 \cdot \gamma_w}{2 \cdot \sigma'_{a,n} \cdot log\left(1 - \frac{\Delta u_{m.n}}{\sigma_{a,n}}\right)} \tag{6}$$

where $k_{\text{nonlinear}}$ is the hydraulic conductivity (m/s); $\sigma'_{a,n}$ is the average axial effective stress calculated from the nonlinear theory (kPa); and $\sigma_{a,n}$ is the total axial stress (kPa).

4 Result and discussion

The reliability of the Constant Rate of Strain (CRS) consolidation results was evaluated through the instantaneous strain function (F_n), as illustrated in Figure 3a. Throughout the loading phase up to an axial stress of 200 kPa, the recorded F_n values for all three strain rates (0.10%/min, 0.25%/min, and 0.50%/min) remained consistently within a high range, fluctuating between approximately 0.92 and 1.0. These values are significantly higher than the 0.4 threshold specified by ASTM D4186, indicating that the specimens effectively reached and maintained a stable steady-state condition shortly after the initiation of loading. Consequently, the reliability of the data obtained from the CRS tests is evaluated based on the R_u values.

Figure 3b illustrates the evolution of the R_u value as a function of axial stress for the three selected strain rates. It is observed that the R_u values for all specimens were initially below 3% during the early stage of loading, followed by an increase to a range between 3% and 15%. The specimens subjected to strain rates of 0.25%/min and 0.50%/min exhibited a distinct peak in R_u, which persisted for a short duration before gradually decreasing and approaching a steady-state condition. In contrast, the specimen tested at the lowest strain rate (0.10%/min) did not exhibit a clear peak within the duration of the test. Although the responses of the specimens under different strain rates varied slightly, it can be concluded that each applied constant strain rate yielded acceptable R_u values. Therefore, the obtained data that fall within the range of 3% to 15% are considered suitable for the determination of hydraulic conductivity.



(a) (b)

Figure 3. Effect of strain rate on (a) variations of instantaneous strain function (F_n) with axial stress (σ) and (b) base excess pore water pressure ratio (R_u) versus axial stress under different constant strain rates.

The hydraulic conductivity (k) variations interpreted through nonlinear and linear solution are illustrated in Figures 4a and Figure 4b, respectively. The hydraulic conductivity values obtained from the linear solution range from 10^{-6} to 10^{-8} m/s. Meanwhile, the values derived from the nonlinear solution range from 10^{-5} to 10^{-7} m/s. These values are consistent with the typical permeability range reported for fibrous peat by Mesri and Ajlouni [10]. However, given the significant discrepancy between the results obtained from the two solutions, further validation through comparison with field monitoring data is recommended.

In addition, a noticeable deviation was observed in the specimen subjected to a constant strain rate of 0.10%/min compared with the other test curves. Under the linear solution, the specimen produced relatively higher k values, whereas lower k values were obtained from the nonlinear solution. This behavior suggests that, although the R_u values remained within the recommended range, the applied strain rate of 0.10%/min may have been too low to produce consistent hydraulic conductivity values during the consolidation process of peat specimens.

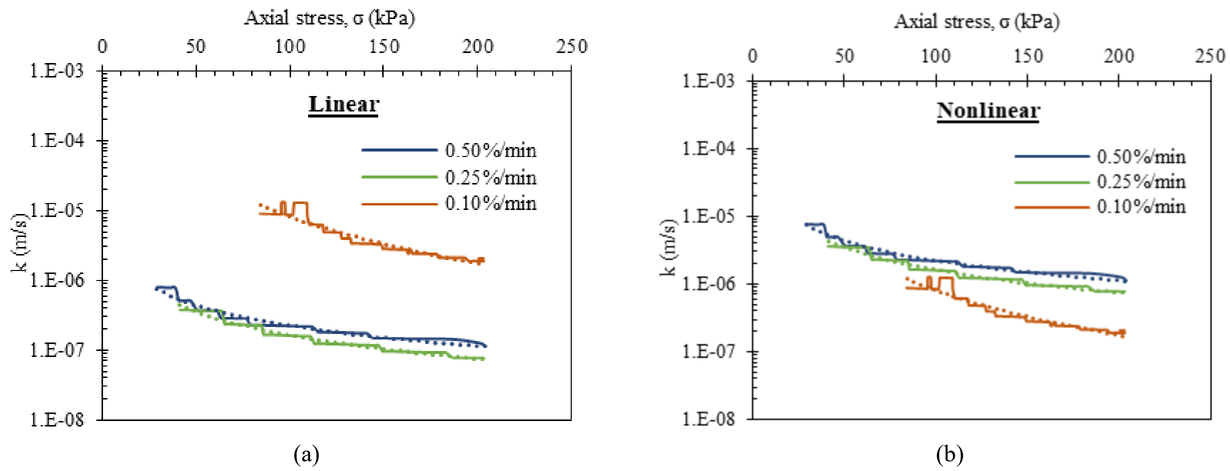


Figure 4. Interpreted hydraulic conductivity (k) during consolidation using different formulations: linear formulation (a), and nonlinear formulation (b).

5 Conclusion

This study evaluates the interpretation of hydraulic conductivity (k) in tropical fibrous peat from Palangkaraya, Indonesia, using CRS consolidation tests. The specimens, tested at strain rates from 0.10%/min to 0.50%/min, maintained steady-state conditions ($F_n > 0.4$) and optimal pore pressure ratios (R_u) of 3% to 15%, confirming the data's suitability for analysis. The findings indicate that both linear and nonlinear solutions are consistent with the established permeability range of fibrous peat reported in the literature. However, caution is required when interpreting results from the specimen subjected to a strain rate of 0.10%/min due to instability in hydraulic conductivity behavior derived from both the linear and nonlinear solutions. Further studies are needed, and validation through comparison with field monitoring data is recommended.

References

1. Y. Umehara & K. Zen, Constant Rate of Strain Consolidation for very Soft Clayey Soils. Soil Found., **20**, 79–95 (1980). https://doi.org/10.3208/sandf1972.20.2_79
2. A.E.Z. Wissa, J.T. Christian, E.H. Davis, S. Heiberg, Consolidation at Constant Rate of Strain. J. Soil Mech. Found. Div. **97**, 1393–1413 (1971). https://doi.org/10.1061/JSFEAQ.0001679
3. ASTM D4186, Test Method for One-Dimensional Consolidation Properties of Saturated Cohesive Soils Using Controlled-Strain Loading. ASTM Int. (2012).
4. ASTM D2974-20, Standard Test Methods for Determining the Water (Moisture) Content, Ash Content, and Organic Material of Peat and Other Organic Soils. ASTM Int. (2020).
5. ASTM D1997-20, Standard Test Method for Laboratory Determination of the Fiber Content of Peat and Organic Soils by Dry Mass. ASTM Int. (2020).
6. J.H. Day, P.J. Rennie, W. Stanek, G.P. Raymond, Peat Testing Manual, Technical Memorandum No. 125. (Sponsored By Muskeg Subcommitee, 1979).
7. A. Prativi, N.E. Mochtar, The Effect of Coarse Fiber on Long-Term Compression of Tropical Fibrous Peat in Indonesia. in Proceedings of the 4th International Civil Engineering and Architecture Conference - CEAC 2024. 439–448 (2025). https://doi.org/10.1007/978-981-97-5477-9_36
8. ASTM D4427, Standard Classification of Peat Samples by Laboratory Testing. ASTM Int. (1992).
9. A. Prativi, N.E. Mochtar, I.B. Mochtar, Assessment of Primary and Secondary Compression Parameters of Tropical Fibrous Peat Using Improved-CRS Consolidation Test. Civil Eng. J. **11**, 1756–1771 (2025). https://doi.org/10.28991/CEJ-2025-011-05-03
10. G. Mesri, M. Ajlouni, Engineering Properties of Fibrous Peats. J. Geotech. Geoenviron. Eng. 133, 850–866 (2007). https://doi.org/10.1061/(ASCE)1090-0241(2007)133:7(850)