Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 11, November, 2024

A Formula for Predicting Primary Settlement of Tropical Highly Organic Soil and Peat in the Field

Ayu Prativi [1*], Noor Endah Mochtar [1], Indrasurya B. Mochtar [1]

[1] *Department of Civil Engineering, Institut Teknologi Sepuluh Nopember, 60117, Surabaya, Indonesia.*

Received 09 July 2024; Revised 25 September 2024; Accepted 11 October 2024; Published 01 November 2024

Abstract

Highly organic soil and peat are problematic soils due to their low bearing capacity and high compressibility. In tropical regions, the presence of woody material in these soils often affects the stress-compression and time-compression curves in load-increment consolidation tests, leading to unusual shapes. Consequently, conventional inorganic soil theory and the C_α/C_c concept are inadequate for analyzing their compression behavior. As an alternative, the Gibson and Lo model can be used to obtain compression parameters from single-load consolidation tests. However, this method introduces considerable discrepancies when predicting the primary settlement. To address this issue, this paper proposes a formula for predicting the primary settlement in highly organic soil and peat in the field, especially in tropical regions. Samples were collected from several locations in Indonesia. The formula was constructed from the stress-strain relationship during the primary compression stage, obtained from numerous single-load consolidation tests. Long-term field settlement is predicted by combining this empirical equation for primary settlement with the Gibson and Lo model for secondary settlement. The proposed formula was verified using field soil monitoring data, demonstrating reasonable accuracy in predicting the primary settlement of highly organic soil and peat.

Keywords: Consolidation; Field Settlement; Tropical Highly Organic Soil; Tropical Peat; Woody Peat.

1. Introduction

Highly organic soil and peat are composed of fragmented and decomposed plant materials [1]. These soils are classified according to their organic content. Peat soil has an organic content exceeding 75% [2], while highly organic soil has an organic content ranging from 50% to 75% [3]. The parent materials characteristics of highly organic soil and peat vary depending on the climate region. Highly organic soil and peat in temperate and cold regions are predominantly composed of *Sphagnum* moss [4]. Meanwhile, woody materials originating from rainforest trees are mainly found as the parent materials of highly organic soil and peat in tropical regions [5, 6]. The woody materials can be categorized into branches, stems, rootlets, roots, and rhizomes; each of them has a different rate of decomposition depending on the lignin content [4, 7]. Although leaves contribute significantly to peat accumulation, they have the lowest lignin content, which leads to rapid decomposition. In contrast, the high lignin content present in roots and stems results in a much slower rate of decomposition. Thus, roots and stems are reported as major components of peat in tropical regions [4, 8-10]. Tropical, highly organic soil and peat are widespread in Indonesia, covering approximately 13.43 million hectares across Sumatra, Kalimantan, Papua, and Sulawesi [11]. These soils are considered problematic due to their low bearing capacity and high compressibility [6, 12, 13]. Despite these challenges, constructing infrastructure on such soils is sometimes unavoidable. Therefore, soil improvement techniques should be employed to reduce compressibility and increase the bearing capacity of the organic layer.

* Corresponding author: ayuprativi@gmail.com

http://dx.doi.org/10.28991/CEJ-2024-010-11-03

To enhance the role of carbon storage systems, it is crucial to evaluate the impact of improving the engineering properties of highly organic soil and peat on carbon gas emissions [14]. Organic material in these soils is continuously decomposed by microorganisms under aerobic (oxygen-rich) and anaerobic (oxygen-poor) conditions, releasing carbon dioxide and methane gas, respectively. The decomposition rate increases significantly under aerobic conditions, which naturally occur near the soil surface, where oxygen from the atmosphere can diffuse into the highly organic soil and peat layer [5]. However, aerobic conditions can also occur when the groundwater table decreases, leading to significant land subsidence [5, 6] and releasing sufficient carbon gas emissions [15]. To avoid these environmental issues, soil improvement techniques should not involve the process of lowering the groundwater table in the organic layers or absorbing the natural water content of highly organic soil and peat. Therefore, preloading is considered a more sustainable technique for improving bearing capacity and reducing long-term compression in highly organic soil and peat.

Typically, highly organic soil and peat exhibit a short duration of primary compression and significant secondary compression [16-18]. Unlike inorganic soil, the void space of highly organic soil and peat is comprised of both macropores and micropores. Primary compression occurs due to water draining out from macropores. The primary compression is then followed by the secondary compression, which involves the drainage process of water from micropores into macropores [19]. The primary settlement of highly organic soil and peat in the field will be completed within a few weeks or months [17] and is followed by secondary settlement. Therefore, the long-term settlement of these soils must be considered to prevent infrastructure collapse due to excessive settlement [20].

Unfortunately, since highly organic soil and peat exhibit significant differences in compression behavior compared to inorganic clay, Terzaghi's one-dimensional theory developed for clay is almost not applicable to these soils [21, 22]. Several studies have indicated that the void ratio (e) versus logarithmic effective stress (σ') curve for highly organic soil and peat, obtained using the load-increment method in one-dimensional consolidation tests, often consists of two straight-line segments [1, 23–27], as illustrated in Figure 1. The unique compression behavior is also obvious in the void ratio (e) versus logarithmic time (t) relationship curve. The short period of primary compression followed by a high rate of secondary compression in highly organic soil and peat often causes the e-log time curve to deviate from the typical S-shape observed in clays [16, 28–30]. Consequently, determining the primary compression index (C_c) and secondary compression index (C_α) using conventional inorganic soil theory proves to be challenging.

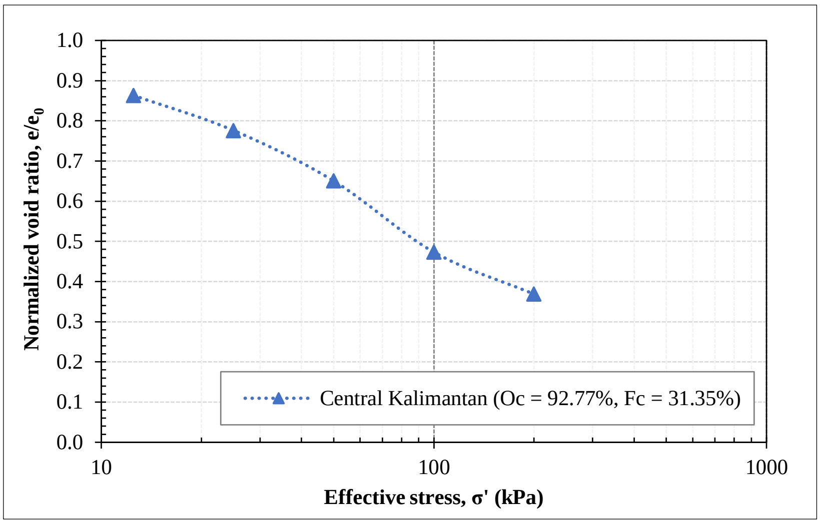


Figure 1. The unique shape of normalized void ratio versus effective stress curves of peat [31]

To address the challenge in predicting the compression of tropical highly organic soil and peat, C_α/C_c concept proposed by Mesri & Godlewski [32] and the Gibson & Lo model [33] proposed by Edil & Dhowian [20] are commonly used as alternative methods to predict the compression behavior of highly organic soil and peat. However, applying these methods to tropical highly organic soil and peat are challenging due to the influence of coarse fiber characteristics. For instance, Figure 2 illustrates the e-log time relationship of tropical highly organic soil from Riau, Indonesia under a load-increment consolidation test. The sample, with an organic content (O_c) of 72.40%, water content (w_c) of 213.68%, and initial void ratio (e_0) of 3.715, exhibits nearly linear e-log time relationship curves for each load increment. This curve shape indicates a very short duration of primary compression, followed by high rate of secondary compression. Additionally, several studies have reported that a linear e-log time relationship is also observed when the coarse fibers of the woody materials experience the apparent fiber reinforcement [29, 31]. The apparent fiber reinforcement refers to the temporary strength of the coarse fiber to retain the applied load. This phenomenon causes several stages of load increment to exhibit a short period of primary compression followed by a relatively small total compression magnitude.

Due to the linear shape of the e-log time relationship curve, identification of the end of primary compression (t_p) to determine C_α is only possible once the excess pore pressure has dissipated or becomes negligible [34]. As a result, determining C_α for tropical highly organic soil and peat with a conventional Oedometer apparatus is challenging, which limits the applicability of the C_α/C_c concept when excess pore pressure data is absent.

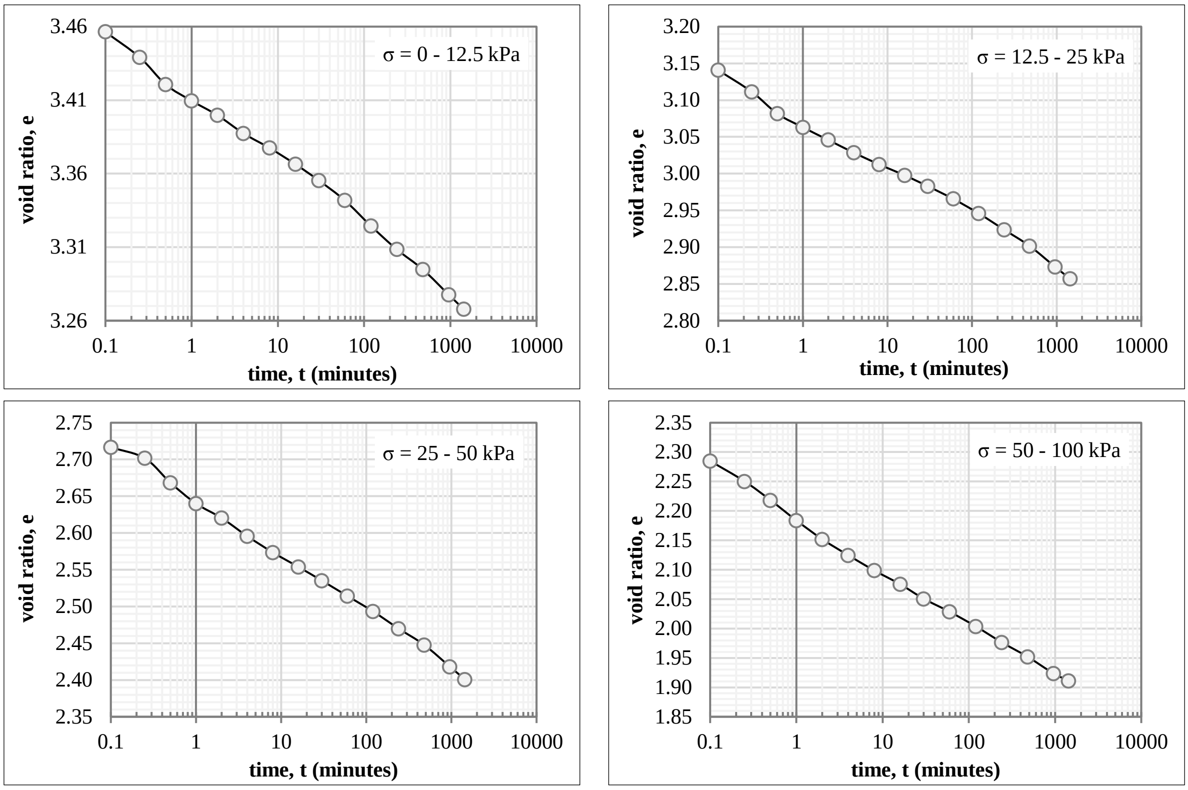


Figure 2. e-log time relationship of tropical organic soil from Riau under load-increment consolidation test

In 1979, the Gibson & Lo model [33] was first applied by Edil & Dhowian [20] to predict the secondary compression of peat. This model can be applied with both load-increment and single-load methods in one-dimensional consolidation tests. To address the linear shape of the e-log time relationship often observed in tropical highly organic soil and peat, the single-load method in one-dimensional consolidation tests appears to be more advantageous. Moreover, applying the Gibson and Lo model with the single-load consolidation test method for field predictions of long-term compression has yielded satisfactory results [35]. Unfortunately, this model assumes that primary compression occurs without considering the dashpot effect, which contributes to significant discrepancies during the early stages of compression and leads to an overestimation of primary compression [28, 35, 36]. Consequently, current methods for predicting the primary compression behavior of highly organic soil and peat in the field remain inadequate.

Considering the described problems above, this study aims to develop a rapid method for predicting the primary compression of tropical highly organic soil and peat in the field. To achieve this objective, time-compression data from single-load consolidation tests were collected. The samples used were tropical highly organic soil and peat from various locations in Indonesia. Subsequently, the stress-strain relationship in the primary compression stage, under numerous single-load consolidation test data, was analyzed to develop a new empirical equation. The applicability of the proposed formula is assessed by comparing settlement predictions with field settlement monitoring data. Additionally, the proposed formula's applicability is compared to the Gibson and Lo model to assess its performance.

2. Material and Methods

2.1. Laboratory Investigation Data

Figure 3 shows the peatland map of Indonesia [37]. Physical properties and single-load soil consolidation test data of tropical highly organic soil and peat were collected from several provinces in Indonesia, including Central Kalimantan, South Kalimantan, Riau, Aceh, and West Sumatra, as secondary data. Additionally, primary data samples were obtained from Central Kalimantan, Riau, and North Sumatra. The locations of sample collection sites are indicated by red points in Figure 3. The classification of organic soil and peat follows to ASTM D2487 [38] and MacFarlane and Radforth [39]. Initial physical properties such as unit weight (γ), specific gravity (G_s), fiber content (F_c), water content (w_c), and the void ratio (e), are presented in this paper.

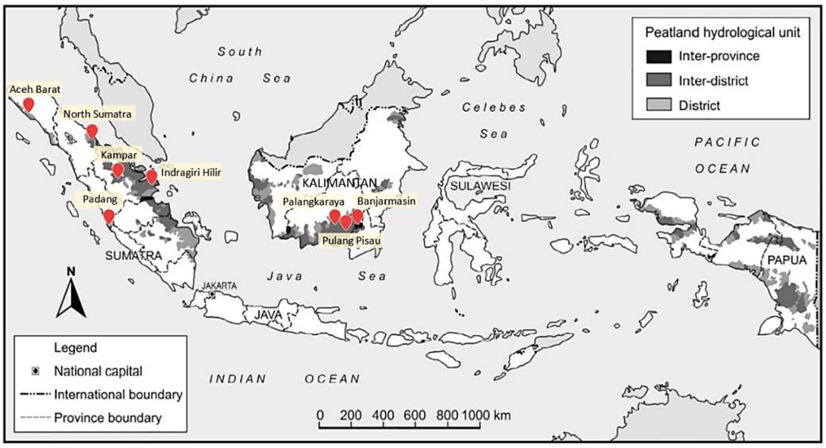


Figure 3. Locations of tropical highly organic soil and peat sample collection

The strain of primary compression (ε_p) was determined from the collected single-load consolidation test data as follows:

$$\varepsilon_p = \frac{\Delta e_p}{1+e_0} \quad (1)$$

where Δe_p is the magnitude of primary compression (excluding immediate compression) and e_0 is the initial void ratio. The strain of primary compression (ε_p) and the effective vertical stress (σ') are then plotted together. The plotted data will be analyzed using the least-square method, and a new empirical equation will be developed. When the thickness of tropical highly organic or peat layer in the field (H_{field}) is known from field investigations, the primary compression in the field ($S_{p,field}$) can be estimated using the following approach:

$$S_{p,pred} = \varepsilon_p \times H_{field} \quad (2)$$

The accuracy of the proposed formula for predicting the primary compression of tropical highly organic soil and peat in the field is then compared with that of the Gibson and Lo model. Predictions of strain at specific times are calculated using the procedures described by Edil & Dhowian [20], as detailed below:

$$\varepsilon(t) = \Delta\sigma\left[a + b\left(1 - \exp^{-\left(\frac{\lambda}{b}\right).t}\right)\right] \quad (3)$$

where $\Delta\sigma$ is the stress increment, t is time, λ/b is the factor of secondary compression rate, a is the parameter of primary compression, and b is the parameter of secondary compression. The empirical parameters (a, b, and λ) in the Gibson and Lo model are determined by plotting the logarithmic strain rate [log (Δε/Δt)] versus time (t). The resulting curve should form a straight line within the range corresponding to the secondary compression. The values of a, b, and λ are then obtained from the slope and intercept of this straight line as follows:

$$\text{Slope of the straight line} = -0.434\left(\frac{\lambda}{b}\right) \quad (4)$$

$$\text{Intercept of the straight line} = log_{10}(\Delta\sigma.\lambda) \quad (5)$$

$$a = \frac{\varepsilon_{tk}}{\Delta\sigma} - b + b.exp^{-\left(\frac{\lambda}{b}\right).t_k} \quad (6)$$

where t_k is the last time reading of compression taken in the laboratory.

2.2. Field Settlement Monitoring Data

Field settlement monitoring data were collected to assess the applicability of the proposed formula for predicting the primary settlement of tropical highly organic soil and peat in the field. Three sets of field settlement plate monitoring data were collected from Indonesia: one from a trial embankment constructed in Palangkaraya, Central Kalimantan, and two from the Padang-Sicincin highway project in Padang, West Sumatra. The geometry of the embankments and soil properties data are presented in this paper.

3. Interpretation of Result and Discussion

3.1. Physical Properties

The physical properties of tropical highly organic soil and peat samples are summarized in Table 1. All physical property data are presented as average values. As indicated in Table 1, the organic content (O_c) of the samples varies, with the lowest value being 48.48%. The unit weight of the tropical highly organic soil and peat studied is approximately 10 kN/m^3. The fiber content ranges from 31.35% to 74.92%, classifying these soils as fibrous highly organic soil and peat according to McFarlane and Radforth [39]. The presence of fiber in highly organic soil and peat contributes to its higher water absorbance capacity compared to inorganic soil. The water content of tropical highly organic soil and peat in this study ranges from 367.52% to 1171.36%, indicating a moderately to highly water absorbent capacity [2]. According to visual observations and previous research, the parent materials of each sample presented in Table 1 are classified as woody materials.

Table 1. Physical properties of tropical highly organic soil and peat samples

No.	Origin	Organic content, O_c (%)	Unit weight, γ (kN/m^3)	Spesific Gravity, G_s	Fiber content, F_c (%)	Water content, w_c (%)	Void ratio, e	Ref.
1	Palangkaraya, Central Kalimantan	98.91	10.00	1.44	53.33	536.33	8.17	[40]
	Banjarmasin, South Kalimantan	95.38	9.64	1.38	61.33	449.84	6.89	
2	Indragiri Hilir, Riau	-	10.04	1.50	37.61	612.83	10.70	[41]
3	Indragiri Hilir, Riau	95.54	9.80	1.50	44.48	715.44	11.52	[25]
4	Kampar, Riau	72.40	11.00	1.57	41.08	306.92	3.95	
5	Pulang Pisau, Central Kalimantan	97.46	10.06	1.42	-	641.73	9.45	[42]
6	Palangkaraya, Central Kalimantan	97.64	9.84	1.69	44.84	746.62	15.54	[43]
7	Palangkaraya, Central Kalimantan	99.14	9.81	1.51	50.91	511.27	7.51	[44]
8	Palangkaraya, Central Kalimantan	98.72	10.56	1.46	46.09	649.78	9.70	[45]
9	Palangkaraya, Central Kalimantan	92.77	10.97	1.41	31.35	657.01	9.19	
10	Aceh Barat, Aceh	92.27	9.98	1.36	46.13	1171.36	15.80	[46]
11	Serdang Bedagai, North Sumatra	88.21	10.13	1.45	67.44	513.87	7.50	
12	Padang, West Sumatra	48.48	10.7	1.64	42.00	367.52	5.30	[47]
13	Padang, West Sumatra	68.00	9.96	1.29	74.92	468.15	5.93	[48]

3.2. Relationship between the Strain of Primary Compression and Effective Stress

The analysis of the relationship between the strain of primary compression (ε_p) and the effective stress (σ') began by determining ε_p from each single-load consolidation test using Equation 1. Samples from North Sumatra that exhibited apparent fiber reinforcement were excluded. The values of ε_p were then plotted against the logarithm of σ' for 62 single-load consolidation tests, as shown in Figure 4, where the effective stress (σ') ranges from 10 kPa to 640 kPa. A positive relationship was observed, indicating that an increase in effective stress leads to a greater magnitude of primary compression. This linear relationship will be used to estimate the primary compression magnitude of tropical highly organic soil and peat in the field based on the design load. Using the slope and intercept parameters from Figure 4, the ε_p value can be determined using the empirical equation as follows:

$$\varepsilon_p = 0.1062 \ln(\sigma') - 0.238 \quad (7)$$

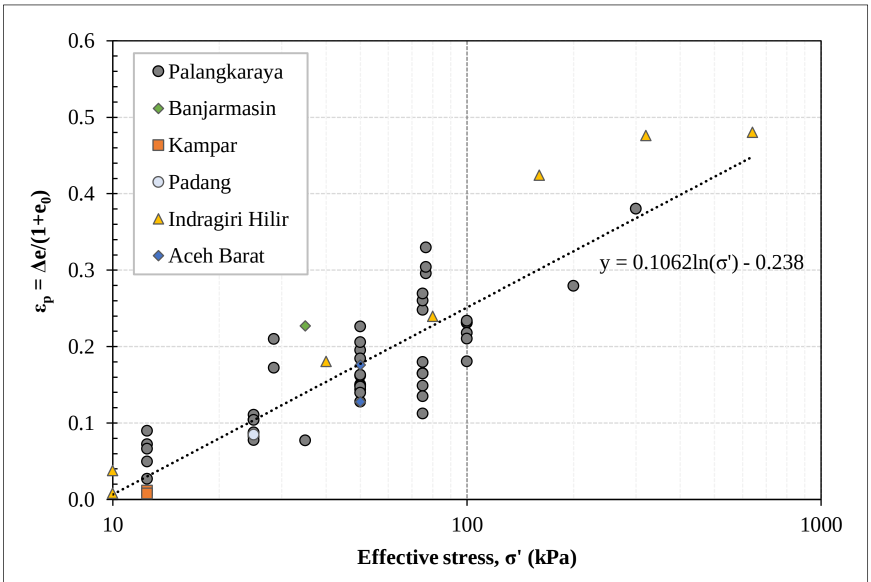
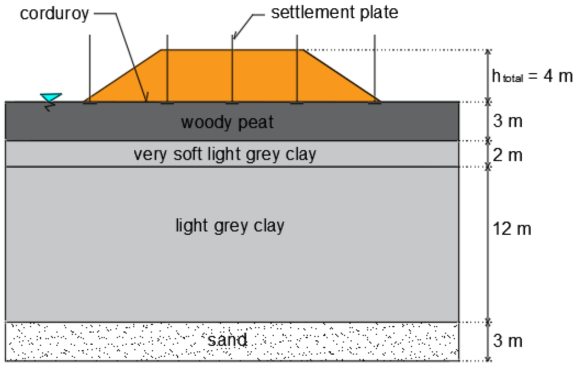


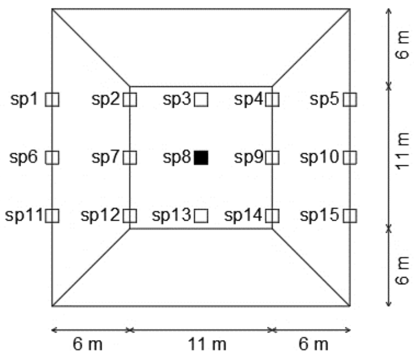
Figure 4. Strain of primary compression versus effective stress relationship (semi-logarithmic scale)

3.3. Field Investigation Data

The first field investigation data was collected from a trial embankment located between Tumbang Nusa & Bereng Bengkel (KM. 35+000 to KM. 42+000), Palangkaraya, Central Kalimantan, Indonesia. At this site, the natural soil layers consist of 3 meters thick peat layer at the top and clay underneath (Figure 5-a). The physical properties of the peat layer are presented in Table 2. According to ASTM D4427 [2], the peat at this site is classified as hemic peat with moderate water absorbent capacity. Visual observation in Figure 6 indicates that the peat studied is composed of leaves, roots, and stems, classifying it as woody peat.



(a)



(b)

Figure 5. Trial embankment in Palangkaraya: a). Cross section and soil stratigraphy, b). Settlement plate configuration

Table 2. Peat physical properties of trial embankment in Palangkaraya

Parameters	Unit	Average value
Unit weight, γ	kN/m^3	9.84
Water content, w_c	%	746.62
Specific gravity, G_s	kg/m^3	1.69
Organic content, O_c	%	97.64
Fiber content, F_c	%	44.84
Fiber Size Distribution		
Foreign	%	10.8
Coarse	%	19.1
Medium	%	1.8
Fine	%	68.3

Figure 6. Coarse fiber of peat from Palangkaraya

An embankment with a total thickness of 4 meters was constructed above the natural soil surface, as illustrated in Figure 5. Sand was used as the embankment fill material and compacted to achieve a unit weight of 19.15 kN/m^3. A corduroy was installed prior to embankment construction to reduce differential settlement. Fifteen settlement plates were installed on the embankment, with their configuration shown in Figure 5-b. The trial embankment was constructed to height of 4 meters, corresponding to a total load of 76.6 kN/m^2. The soil settlement was measured over a period of 590 days. The data recorded for settlement plate No. 8 (SP-8), as shown in Figure 7, indicate a total settlement of 0.994 meters at the end of the measurement period.

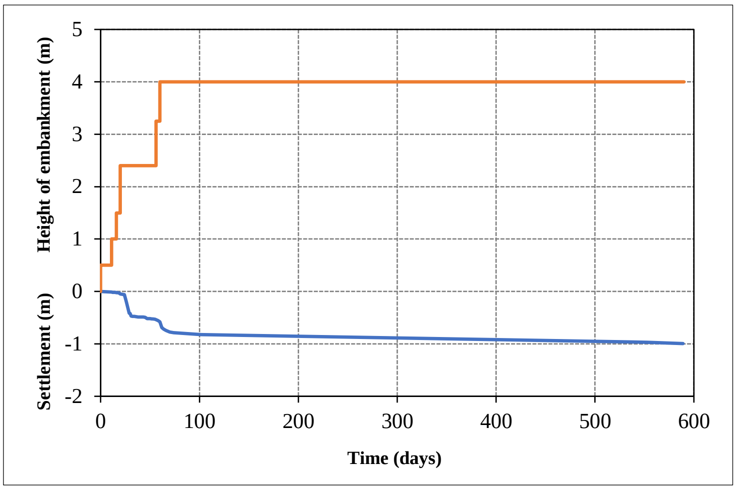
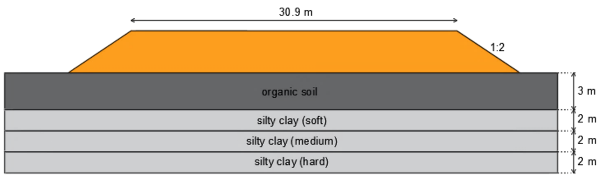
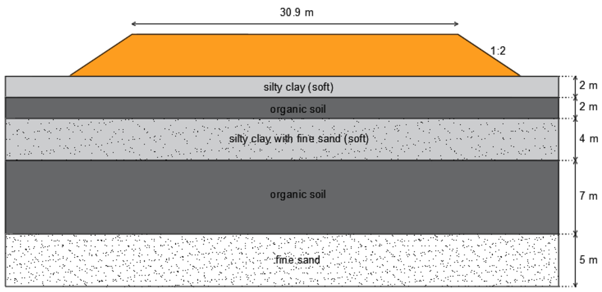


Figure 7. Step loading and recorded soil settlement at settlement plate No. 8 (SP-8) of trial embankment in Palangkaraya

Another field investigation was conducted at STA. 7+450 [47] and STA. 10+400 [48], Padang-Sicincin section of the Trans-Sumatra highway project. The soil stratigraphy for each section is shown in Figure 8-a and 8-b. According to Figure 8-a, the organic layer with a total thickness of 3 meters is laid above the silty clay. Meanwhile, Figure 8-b shows two layers of organic soil at STA. 10+400: 2 meters thick of top organic layer lies between soft silty clay layers, and 7 meters thick bottom organic layer. Table 3 presents the physical properties of the organic soil, taken at 1.5 meters depth for STA. 7+450, and 2 meters of depth for STA. 10+400. All physical property data are presented as average values. The fiber content at both locations is notably high, at 42.11% for STA. 7+450 and 68% for STA.10+400, respectively. This high fiber content is consistent with the presence of woody materials observed during on-site inspection, as shown in Figures 9 and 10. The noticeable stem on this soil also correlates with the high percentage of coarse fiber presented in Table 3.



(a)



(b)

Figure 8. Soil embankment cross-section and stratigraphy on the Padang-Sicincin Highway: (a) STA. 7+450, (b) STA. 10+400

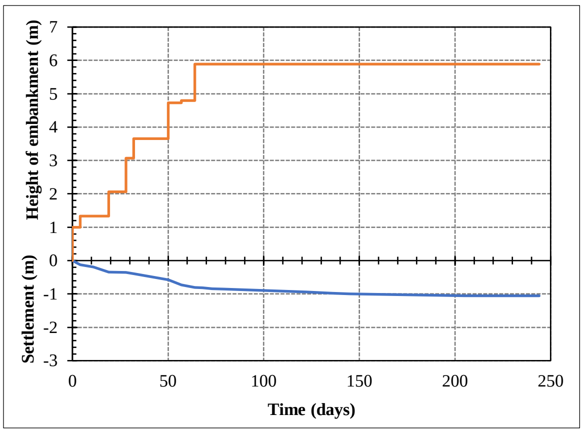
Table 3. Physical properties of highly organic soil in Padang-Sicincin Highway

Parameters	Unit	STA. 7+450	STA. 10+400
Unit weight, γ	kN/m^3	10.5	10.1
Water content, w_c	%	367.52	468.71
Specific gravity, G_s	kg/m^3	1.591	1.283
Organic content, O_c	%	48.48	68
Fiber content, F_c	%	42.11	76.69
Fiber Size Distribution			
Foreign	%	2.44	3.25
Coarse	%	70.39	40.64
Medium	%	23.43	27.27
Fine	%	3.74	28.84

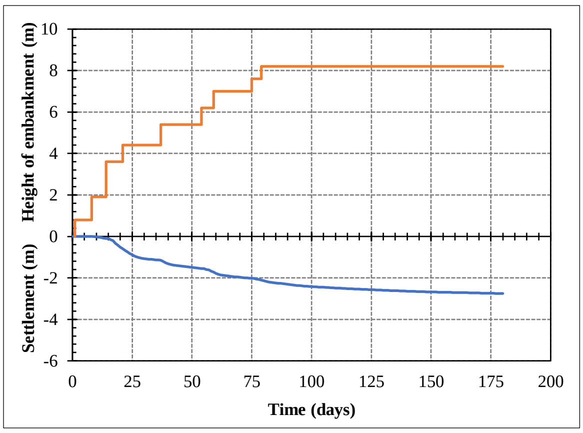
Figure 9. Woody materials of highly organic soil at STA. 7+450, Padang-Sicincin Highway

Figure 10. Woody materials of highly organic soil at STA. 10+400, Padang-Sicincin Highway

The embankment fill materials in each section have a density of 18.5 kN/m^3. Surcharge preloading was chosen as the soil improvement method. However, due to the thicker compressible organic layer at STA. 10+400, the surcharge preloading was combined with prefabricated vertical drain (PVD). The preloading at STA. 7+450 was completed in 64 days with a total height of 5.889 meters (equivalent to a total load of 108.95 kN/m^2). Meanwhile, the preloading at STA. 10+400 was completed in 180 days with a total height of 8.2 meters (equivalent to a total load of 151.7 kN/m^2). The settlement measurements were recorded at the centerline of the embankment. According to the recorded data, the final total settlement at STA. 7+450 and STA. 10+400 is 1.056 meters (Figure 11-a) and 2.752 meters (Figure 11-b), respectively.



(a)



(b)

Figure 11. Step loading and recorded soil settlement on the Padang-Sicincin Highway: (a) STA. 4+750, (b) STA. 10+400

3.4. Assessment of The Proposed Formula

The applicability of the proposed formula is assessed by comparing the predicted settlement magnitudes of tropical highly organic soil and peat with those obtained from field measurements. Additionally, the predicted primary settlement magnitudes from the proposed formula are compared with those predicted by the Gibson and Lo model. In order to determine the settlement of tropical highly organic soil and peat, the total settlement recorded on the settlement plate shown in Figures 7 and 11 is subtracted by the predicted primary settlement of clay, as shown in Figure 12. The resulting settlement data for tropical highly organic soil and peat (indicated by the ash dashed line in Figure 12) is then re-plotted as settlement versus logarithmic time for the purpose of analyzing its primary settlement magnitude, as shown in Figure 13.

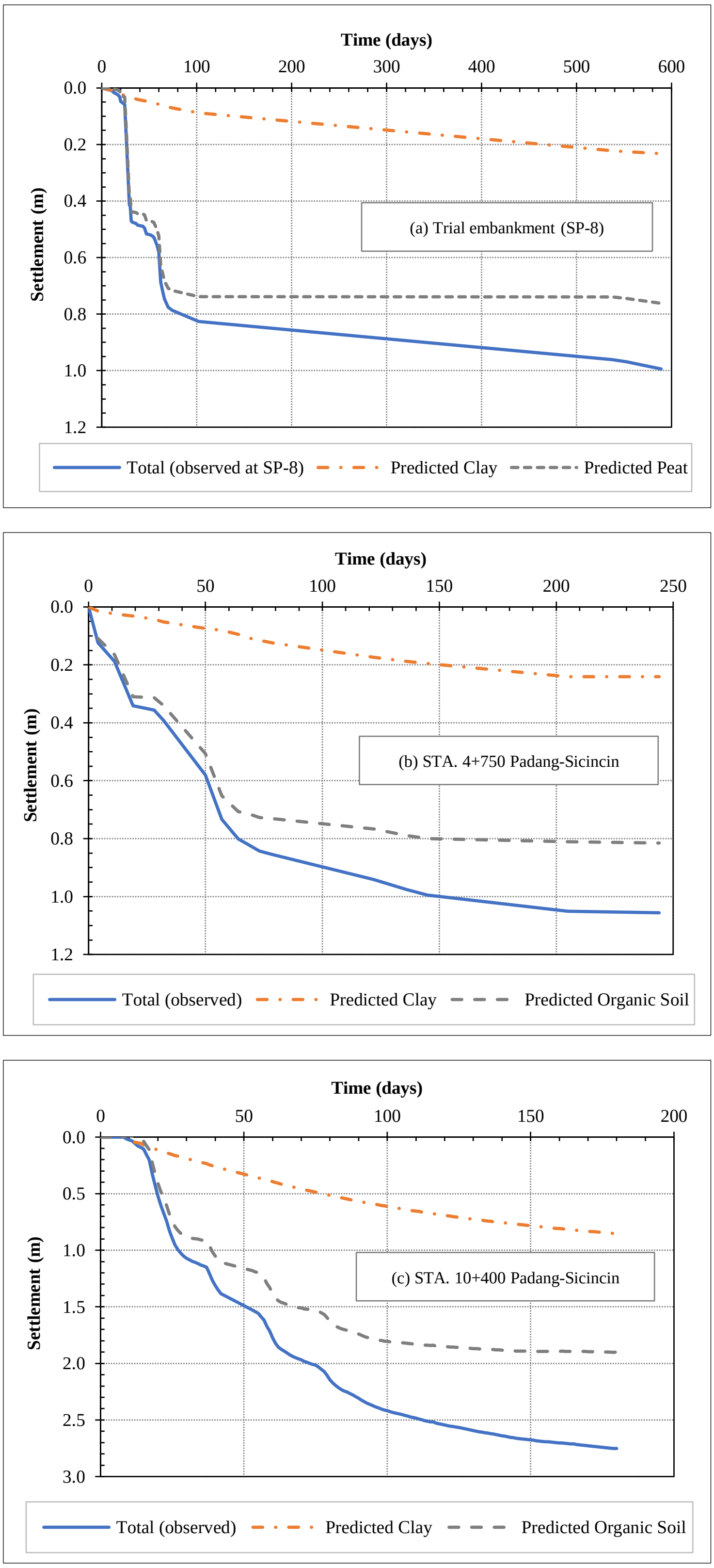


Figure 12. Recorded total field settlement, predicted clay settlement, and predicted organic or peat settlement: trial embankment in Palangkaraya and Padang-Sicincin Highway

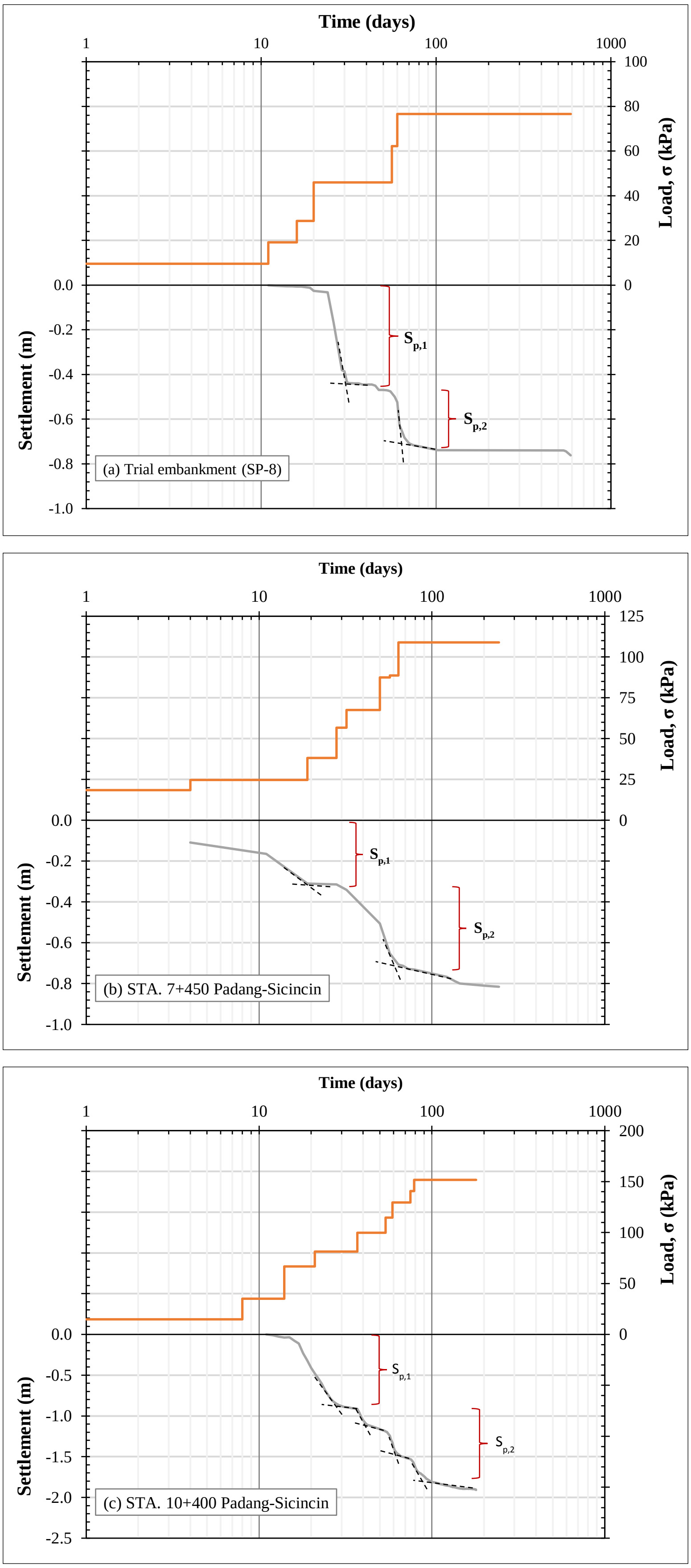


Figure 13. Determination of field primary settlement ($S_{p,meas}$) for the trial embankment in Palangkaraya and Padang-Sicincin Highway

Due to the step loading in the field, which causes the soil to undergo multiple phases of primary and secondary settlement, each settlement phase of the tropical highly organic soil and peat is identified separately. For practical purposes, the step loading is simplified into two loading stages for each site. Subsequently, the primary and secondary settlement phases of tropical highly organic soil and peat are separated by identifying an intersection point on the projection of the two straight lines, as indicated by the dashed line. The magnitude of primary settlement in the field ($S_{p,meas}$) is determined based on these step loadings, and the results are presented in Table 4.

Table 4. Comparison of primary settlement magnitude: field measurements versus predictions

Load, σ (kPa)	H_{field} (m)	Field measurement, $S_{p,meas}$ (m)	Predicted Field Primary Settlement			
			Proposed formula (m)	Error (%)	Using Gibson & Lo, 1961 (m)	Error (%)
A. Trial Embankment in Palangkaraya (SP-8)						
45.96	3	0.44	0.506	14.9%	0.929	111.1%
76.6		0.69	0.668	3.1%	1.561	126.3%
B. STA. 7+450, Padang-Sicincin Highway						
24.75	3	0.3	0.308	2.8%	0.273	9.1%
108.95		0.7	0.781	11.5%	1.022	45.9%
C. STA. 10+400, Padang-Sicincin Highway						
81.40	9	0.86	2.048	138.1%	2.255	162.2%
151.70		1.33	2.610	96.2%	2.984	124.4%

The comparison of the primary settlement predictions from the proposed rapid method and the Gibson and Lo model with observed field settlement measurements is presented in Table 4. The influence of the depth factor is considered to determine the load distributed in each soil layer. The strain of primary compression (ε_p) and the magnitude of predicted primary settlement ($S_{p,pred}$) for the proposed formula are calculated using Equations 7 and 2, respectively. The Gibson and Lo compression parameters (a, b, and λ) for samples from trial embankment in Palangkaraya and Padang-Sicincin Highway are shown in Tables 5 and 6, respectively. These parameters are determined based on the load-increment consolidation tests. Since soil consolidation data for organic soil at STA. 10+400 in Padang-Sicincin Highway are only available for the top organic layer, the Gibson and Lo compression parameters for the bottom organic layer are assumed to be the same as those for the top layer.

Table 5. Gibson and Lo compression parameters of peat at trial embankment in Palangkaraya

Parameter	Effective Stress, σ' (kPa)				
	5	10	20	40	80
λ (m^2/kN)	2.05×10^{-6}	2.07×10^{-6}	2.00×10^{-6}	2.00×10^{-6}	1.51×10^{-6}
b (m^2/kN)	0.0016	0.0021	0.0015	0.0016	0.0009
a (m^2/kN)	0.0029	0.0060	0.0063	0.0074	0.0065

Table 6. Gibson and Lo compression parameters of highly organic soil in the Padang-Sicincin Highway

Parameter	Effective Stress, σ' (kPa)			
	25	50	100	200
A. STA. 7+450, Padang-Sicincin Highway				
λ (m^2/kN)	1.38×10^{-6}	4.65×10^{-7}	7.55×10^{-7}	6.55×10^{-7}
b (m^2/kN)	0.0010	0.0007	0.0005	0.0003
a (m^2/kN)	0.0037	0.0074	0.0058	0.0041
B. STA. 10+400, Padang-Sicincin Highway				
λ (m^2/kN)	1.25×10^{-6}	3.12×10^{-6}	1.99×10^{-6}	1.13×10^{-6}
b (m^2/kN)	0.0011	0.0019	0.0012	0.0005
a (m^2/kN)	0.0039	0.0080	0.0076	0.0055

The error percentage value in Table 4 indicates that the proposed primary settlement prediction method yields results closer to field measurements than the Gibson and Lo model. The proposed formula has an error percentage of less than 15% for trial embankment in Palangkaraya and STA. 7+450 in the Padang-Sicincin Highway, while the Gibson and Lo model shows an error percentage of up to 126.3%. Notably, significant errors are observed at STA. 10+400 in the

Padang-Sicincin Highway for both methods. Although the proposed formula demonstrates a smaller error overall, caution should be exercised due to a large discrepancy between predicted and field-measured settlements at STA. 10+400 in the Padang-Sicincin Highway.

The overestimation of primary settlement predictions at STA. 10+400 in the Padang-Sicincin Highway can be caused by two factors. First, the settlement of the bottom layer of the organic soil is predicted using data from the top layer, in which the top organic layer is more compressible due to lower overburden pressure. Second, the substantial amount of large woody materials in the organic soil at STA. 10+400 in the Padang-Sicincin Highway (as shown in Figure 10) contributes to apparent fiber reinforcement, which reduces compressibility. Therefore, field investigations, such as boring and sampling, are essential to identify the presence of large woody materials in tropical, highly organic soil and peat.

The long-term settlement prediction of the tropical, highly organic soil and peat studied is shown in Figure 14. The primary settlement is predicted using the proposed formula, while the secondary settlement is predicted using the Gibson and Lo model. The secondary settlement is calculated as the difference between total settlement and primary settlement predicted by the Gibson and Lo model. Figure 14 indicates that the secondary settlement predictions closely match field measurements. The slight difference between the settlement predictions and field measurements arises because the prediction method assumes that primary compression occurs without any time delay effect. Overall, the long-term settlement can be predicted by combining the proposed formula for primary settlement with the Gibson and Lo model for the secondary settlement.

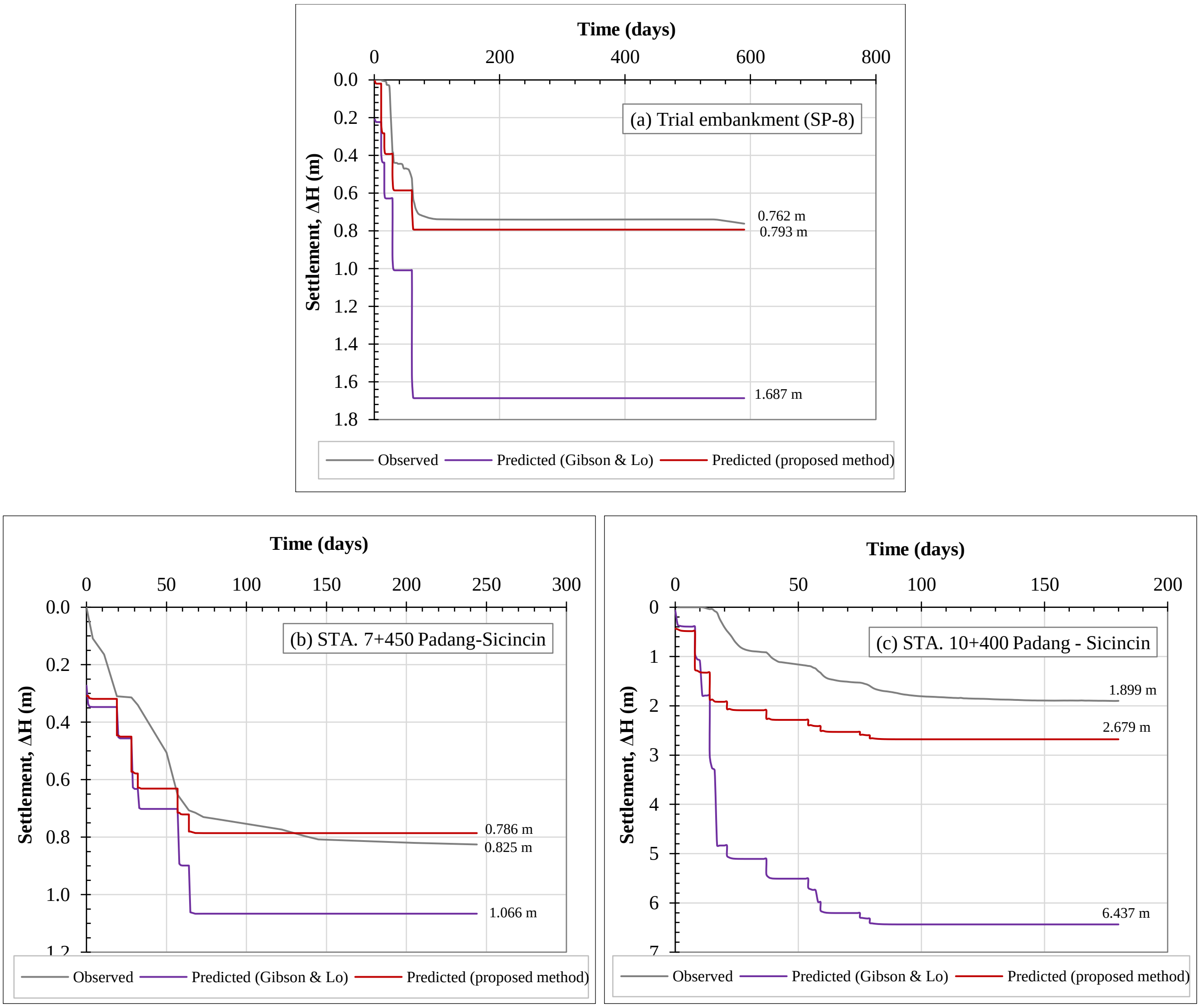


Figure 14. Evaluation of the proposed formula and the Gibson and Lo model for predicting long-term settlement of trial embankment in Palangkaraya and Padang-Sicincin Highway

4. Conclusions

Based on the analysis of numerous single-load consolidation test data and field settlement measurements of tropical highly organic soil and peat, several conclusions are made as follows:

- The parent materials of the tropical highly organic soil and peat samples studied are classified as woody materials. The organic content varies, with the lowest value being 48.48%. All samples are classified as fibrous highly organic soil and peat, with moderate to high water absorbance capacity.
- The proposed formula that describes the relationship between strain of primary compression (ε_p) and effective stress (σ') is given by: $\varepsilon_p = 0.1062 \ln(\sigma') - 0.238$.
- The field primary settlement can be predicted using the proposed formula (No. 2) if the thickness of the tropical highly organic soil and peat layer in the field is known.
- The field secondary settlement can be predicted by using the Gibson and Lo model. The empirical parameters (a, b, and λ) for this model are determined from the single-load method of one-dimensional consolidation tests, where the applied load must match the load applied in the field.
- The total settlement of tropical highly organic soil and peat can be predicted by combining the primary settlement predicted using the proposed formula with the secondary settlement predicted by the Gibson and Lo model.
- Caution should be considered when dealing with the tropical highly organic soil and peat containing large woody materials, as these factors can lead to an overestimation of primary settlement predictions.

5. Declarations

5.1. Author Contributions

Conceptualization, A.P. and N.E.M.; methodology, I.B.M.; validation, A.P.; investigation, A.P.; resources, N.E.M.; data curation, A.P.; writing—original draft preparation, A.P.; writing—review and editing, N.E.M.; supervision, N.E.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

This research is supported and funded by the Indonesia Endowment Fund for Education Agency (LPDP) of the Ministry of Finance, Republic of Indonesia (0001321/TRP/D/PDD-2020).

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Dhowian, A. W., & Edil, T. B. (1980). Consolidation Behavior of Peats. Geotechnical Testing Journal, 3(3), 105–114. doi:10.1520/GTJ10881J.

[2] ASTM D4427-18 (2023). Standard Classification of Peat Samples by Laboratory Testing. ASTM International, Pennsylvania, United States. doi:10.1520/D4427-18.

[3] Mankinen, GW., & Gelfer, B. (1982). Comprehensive use of peat in the U.S.S.R. DOE. Fifth Technical Conference on Peat. Bethesda, 28-29 April, 1982, Bethesda, United States.

[4] Chimner, R. A., & Ewel, K. C. (2005). A tropical freshwater wetland: II. Production, decomposition, and peat formation. Wetlands Ecology and Management, 13(6), 671–684. doi:10.1007/s11273-005-0965-9.

[5] Könönen, M., Jauhiainen, J., Laiho, R., Spetz, P., Kusin, K., Limin, S., & Vasander, H. (2016). Land use increases the recalcitrance of tropical peat. Wetlands Ecology and Management, 24(6), 717–731. doi:10.1007/s11273-016-9498-7.

[6] Den Haan, E. J. (1977). An overview of the mechanical behaviour of peats and organic soils and some appropriate construction techniques. Conference on Recent Advances in Soft Soil Engineering, 5-7 March, 1997, Kuching, Malaysia.

[7] Noor, M., & Masganti, A. F. (2014). Formation and characteristics of Indonesian tropical peat. Lahan Gambut Indonesia. Pembentukan, IAARD Press, Jakarta, Indonesia. (In Indonesian).

[8] Hoyos-Santillan, J., Lomax, B. H., Large, D., Turner, B. L., Boom, A., Lopez, O. R., & Sjögersten, S. (2015). Getting to the root of the problem: litter decomposition and peat formation in lowland Neotropical peatlands. Biogeochemistry, 126(1–2), 115–129. doi:10.1007/s10533-015-0147-7.

[9] Ratnayake, A. S. (2020). Characteristics of Lowland Tropical Peatlands: Formation, Classification, and Decomposition. Journal of Tropical Forestry and Environment, 10(1), 1-6. doi:10.31357/jtfe.v10i1.4685.

[10] Travis, K., Izzati Nazra, John Thor, & William Adam. (2023). Analysis of Land Subsidence in Peatlands in the Awareness Area of Pekanbaru, Riau, Indonesia. Journal of Geoscience, Engineering, Environment, and Technology, 8(1), 62–69. doi:10.25299/jgeet.2023.8.1.13461.

[11] Anda, M., Ritung, S., Suryani, E., Sukarman, Hikmat, M., Yatno, E., Mulyani, A., Subandiono, R. E., Suratman, & Husnain. (2021). Revisiting tropical peatlands in Indonesia: Semi-detailed mapping, extent and depth distribution assessment. Geoderma, 402. doi:10.1016/j.geoderma.2021.115235.

[12] Ahmad, A., Sutanto, M. H., Al-Bared, M. A. M., Harahap, I. S. H., Abad, S. V. A. N. K., & Khan, M. A. (2021). Physio-Chemical Properties, Consolidation, and Stabilization of Tropical Peat Soil Using Traditional Soil Additives — A State of the Art Literature Review. KSCE Journal of Civil Engineering, 25(10), 3662–3678. doi:10.1007/s12205-021-1247-7.

[13] Mochtar, N. E., Prativi, A., & Yogyanta, D. A. (2024). Behavioral Change of the Bacterially Decomposed Fibrous Tropical Peat Stabilized with Lime CaCO3 and Fly Ash. Advances in Civil Engineering Materials, ICACE 2023, Lecture Notes in Civil Engineering, Springer, Singapore. doi:10.1007/978-981-97-0751-5_70.

[14] Yulianto, F. E., Harwadi, F., & Wardani, M. K. (2014). the Effect of Water Content Reduction To Fibrous Peat Absorbent Capacity and Its Behaviour. 9th International Symposium on Lowland Technology, September 29-October 1, 2014, Saga, Japan.

[15] Laiho, R. (2006). Decomposition in peatlands: Reconciling seemingly contrasting results on the impacts of lowered water levels. Soil Biology and Biochemistry, 38(8), 2011–2024. doi:10.1016/j.soilbio.2006.02.017.

[16] Edil, T. B., Fox, P. J., & Lan, L. T. (1991). Observational procedure for settlement of peat. Geo-Coast 91, 3-6 September, 1991, Yokohama, Japan.

[17] Mesri, G., Stark, T. D., Ajlouni, M. A., & Chen, C. S. (1997). Secondary Compression of Peat with or without Surcharging. Journal of Geotechnical and Geoenvironmental Engineering, 123(5), 411–421. doi:10.1061/(asce)1090-0241(1997)123:5(411).

[18] O'loughlin, C. D., & Lehane, B. M. (2001). Modelling one-dimensional compression of a fibrous peat. Proceedings of the 15th International Conference on Soil Mechanics and Geotechnical Engineering, 223–226.

[19] Berry, P. L., & Poskitt, T. J. (1972). The consolidation of peat. Geotechnique, 22(1), 27–52. doi:10.1680/geot.1972.22.1.27.

[20] Edil, T. B., & Dhowian, A. W. (1979). Analysis of Long-Term Compression of Peats. Geotechnical Engineering, 10(2), 159–178.

[21] Acharya, M. P., & Hendry, M. T. (2019). A Formulation for Estimating the Compression of Fibrous Peat Using Three Parameters. International Journal of Geomechanics, 19(1), 4018187. doi:10.1061/(asce)gm.1943-5622.0001333.

[22] Edil, T. B., & Mochtar, N. E. (1984). Prediction of Peat Settlement. American Society of Civil Engineers (ASCE), San Franciso, California (1984), 411-424.

[23] De Guzman, E. M. B., & Alfaro, M. C. (2018). Geotechnical Properties of Fibrous and Amorphous Peats for the Construction of Road Embankments. Journal of Materials in Civil Engineering, 30(7), 04018149. doi:10.1061/(asce)mt.1943-5533.0002325.

[24] Elsayed, A., Paikowsky, S., & Kurup, P. (2011). Characteristics and Engineering Properties of Peaty Soil Underlying Cranberry Bogs. Geo-Frontiers 2011, 2812–2821. doi:10.1061/41165(397)288.

[25] Imananto, E. I. (1999). Application of the Hardin model (1989) and the Lan and Edil model (1992) for fibrous tropical peat soil from Riau, Indonesia. Institut Teknologi Sepuluh Nopember Surabaya, Indonesia. (In Indonesian).

[26] Roesyanto, & Nababan, V. N. A. (2021). Consolidation test on peat soil of Humbang Hasundutan regency, North Sumatera Province. IOP Conference Series: Materials Science and Engineering, 1122(1), 012022. doi:10.1088/1757-899x/1122/1/012022.

[27] Chmielewska, I. (2023). Effect of fibre content on the geotechnical properties of peat. Studia Geotechnica et Mechanica, 45(1), 133–143. doi:10.2478/sgem-2023-0003.

[28] Edil, T. B., & Mochtar, N. E. (1984). Prediction of peat settlement. Sedimentation consolidation models: predictions and validation: proceedings of a symposium, 1 October, 1984, San Francisco, United States.

[29] Prativi, A., & Mochtar, N. E. (2024). The Effect of Fiber Content on Long-Term Compression Behavior of Tropical Fibrous Peat. Proceedings of 6th International Conference on Civil Engineering and Architecture, ICCEA 2023, Lecture Notes in Civil Engineering, Springer, Singapore. doi:10.1007/978-981-97-5311-6_23.

[30] Mohamad, H. M., Zainorabidin, A., Musta, B., Mustafa, M. N., Amaludin, A. E., & Abdurahman, M. N. (2021). Compressibility behaviour and engineering properties of north Borneo peat soil. Eurasian Journal of Soil Science, 10(3), 259–268. doi:10.18393/ejss.930620.

[31] Prativi, A., & Mochtar, N.E. (2025). The Effect of Coarse Fiber on Long-Term Compression of Tropical Fibrous Peat in Indonesia. Proceedings of the 4th International Civil Engineering and Architecture Conference, CEAC 2024, Lecture Notes in Civil Engineering. Springer, Singapore. doi:10.1007/978-981-97-5477-9_36.

[32] Mesri, G., & Godlewski, P. M. (1977). Time- and Stress-Compressibility Interrelationship. Journal of the Geotechnical Engineering Division, 103(5), 417–430. doi:10.1061/ajgeb6.0000421.

[33] Gibson, R. E., & Lo, K. Y. (1961). A theory of consolidation for soils exhibiting secondary compression. Norges tekniske vitenskapsakademi, Trondheim, Norway.

[34] Fox, P. J., Edil, T. B., & Lan, L. (1992). Cα/Cc Concept Applied to Compression of Peat. Journal of Geotechnical Engineering, 118(8), 1256–1263. doi:10.1061/(asce)0733-9410(1992)118:8(1256).

[35] Mochtar, N. E., & Marzuki, A. (2010). Method to predict compression behaviour of tropical fibrous peat in the field. 7th International Symposium on Lowland Technology, 16-18 September, 2010, Saga, Japan.

[36] Prativi, A., & Mochtar, N. E. (2024). Application of Lan model to predict compression behavior of tropical fibrous peat soils in Palangkaraya, Indonesia. Proceedings Of The 4th International Conference on Green Civil And Environmental Engineering (GCEE 2023), 3110, 020056. doi:10.1063/5.0204846.

[37] Astuti, R. (2020). Fixing flammable Forest: The scalar politics of peatland governance and restoration in Indonesia. Asia Pacific Viewpoint, 61(2), 283–300. doi:10.1111/apv.12267.

[38] ASTM D2478-17. (2006). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, Pennsylvania, United States. doi:10.1520/D2487-17.

[39] MacFarlane, I. C., & Radforth. (1965). A study of the physical behavior peat derivates and compression. Proceedings of Tenth Muskeg Research Conference. Ottawa, Canada.

[40] Mochtar, N. E., Mochtar, I. B., & Indrasurya, B. (1991). Study on Physical and Technical Properties of Peat Soil in Banjarmasin and Palangkaraya and Alternative Handling Methods for Road Construction. Dipublikasi sebagai hasil penelitian BBI dengan dana dari DIKTI Jakarta, Indonesia. (In Indonesian).

[41] Rachman, A. (1998). The Effect of Load Increment Ratio, Loading Period, and Preloading on The Compression Behavior of Fibrous Peat. Master Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.

[42] Moeljawan, M. (2000). Planning of a highway on peat land KM. 19+500 to KM. 21+500 of the Palangkaraya - Pulang Pisau road section, Central Kalimantan. Bachelor Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia. (In Indonesian).

[43] Marzuki, A. (2004). The influence of the loading stage system on the results of peat soil layer compression forecasts in the field. Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia. (In Indonesian).

[44] Ma'ruf, M. A. (2012). The effect of water surrounding the stabilized peat area to the physical and engineering properties of the fibrous peat soil. Master Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.

[45] Wardani, M. K. (2012). The use of rice husk ash (RHA) and lime as a soil stabilization admixture of fibrous peat while subjected to drying. Master Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.

[46] Mardian, D. (2024). Comparison of three embankment reinforcement on soft soil, a Case study of Calang - Simpang Peut road section. Master Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.

[47] Arifanto, F. (2024). Analysis of embankment slope failure and effectiveness of reinforcement with full displacement column on soft soil. case study: construction of Padang Sicincin toll roal section STA 7+400 - 7+550. Master Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.

[48] Mulifandi, A. W. (2024). The influence of embankment construction stage on slope stability with varied heights on organic soft soil in the Sicincin-Padang toll road project STA 10+250 - 10+400. Master Thesis, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.