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Research Article

Investigating Peat Soil Stratigraphy and Marine Clay Formation Using the Geophysical Method in Padas Valley, Northern Borneo

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A geophysical survey including electrical resistivity tomography (ERT), induced polarization (IP), and seismic refraction (SR) was carried out to estimate peatland thickness in Beaufort District, Eastern Malaysia. Peatlands are important natural carbon storage and play a key role in the global carbon cycle. The ERT and IP studies were performed along three profiles over different peat thicknesses using Schlumberger configuration. The SR survey was carried out using vertical geophones along the same profiles. The peat soil material was characterized by low seismic velocity and high resistivity. Our results show that ERT and IP methods were able to clearly detect the interface between the peat soil and marine clay underneath. These layers differ greatly in geoelectrical characteristics showing clear contrast, thus enabling the delineation of peat soil stratigraphy, while the SR image obtained was not able to determine the base of the peat soil layer as the stiffness difference on the transition layer was very small. Overall, it was concluded that the ERT and IP method offer a useful alternative in delineating the peat soil stratigraphy. The combined application of ERT and IP method with the conventional boring method meets the demand for large volume peat stratigraphy mapping, which, moreover, has various ecological conditions and undulating strata.

1. Introduction

Peatlands play an important role in the global carbon cycle and impact greenhouse gas concentrations in the atmosphere. In their natural state, peatlands store a large amount of carbon [1–3]. Due to the large amounts of soil organic carbon stored in peatland, they act as a source or sink of carbon dioxide depending on their present condition. The peat volume, their specific stratigraphy, and peat properties, such as bulk density and organic content matter, determined the carbon storage of peatlands [4]. The peat thickness determination is vital information on peat stratigraphy to properly estimate the peatland volume, while investigation on the organic matter content was critical for the estimation of ongoing peat degradation. The organic matter content decreases as bulk density and degree of decomposition increase [5]. The amount of organic content contributes to the estimation of carbon content in peatlands.

In Malaysia, there are 2.4 million hectares of peatland which is about 7.45 % of Malaysia's total land area. Overall, the peatland depth in Malaysia is mostly undulating and varies from 1 to 20 m depth [6], which results in difficulties in estimating the volume of peatland accurately. These areas are part of the large global carbon stored in peatlands. Thus, the accurate determination of the peatland volume is important to accurately estimate the amount of carbon stored in peatlands. Commonly, peatland thickness for the estimation of peatland volume is determined by the conventional boring method. This method has been widely used, as the direct measurement provides certainty on the results.

The geophysical survey method, however, provides localized results and actual positions which required a large number of tests conducted to allow approximate mapping of peat stratigraphy in larger areas. The method is also expensive and intrusive and needs longer investigation time. In tropical conditions, limited accessibility further complicates the investigation process. The application of the geophysical method for soil investigation such as peat thickness estimation has been long suggested by several researchers. In particular, ground-penetrating radar (GPR) has been successfully applied to peatlands to estimate peat thickness since the 1980s [4, 7–9]. However, the depth of investigation using GPR is depending on the electrical conductivity of the peat soil, and it is widely accepted that GPR can only penetrate up to 10 m in peatlands using 50 to 200 MHz central antenna frequency [10, 11]. The dielectric constant of peat varies from 5 to 70 depending on the bulk water content [11, 12]. This makes the method less popular for the investigation of deeper peat soil thickness (>10 m). Recently, the investigation of peatland stratigraphy by geophysical methods such as electrical resistivity tomography (ERT) and induced polarization (IP) to support the conventional boring method has gained popularity. Another potential method also includes the seismic refraction (SR) method. The application of these methods was previously limited to the determination of archaeological structure [13], investigation of seawater intrusion and liquefaction potential [14, 15], delineating alluvial aquifer [16], and landslide investigation [17]. However, due to the capabilities of these methods to delineate soil stratigraphy, the application for peatland mapping is introduced. The advantages of these methods include larger volume of investigation, deeper depth of investigation, and being economic and timely efficient. Consequently, integrated geophysical studies that provide information on the physical properties beneath the mineral contact may also improve understanding of the peatland stratigraphy.

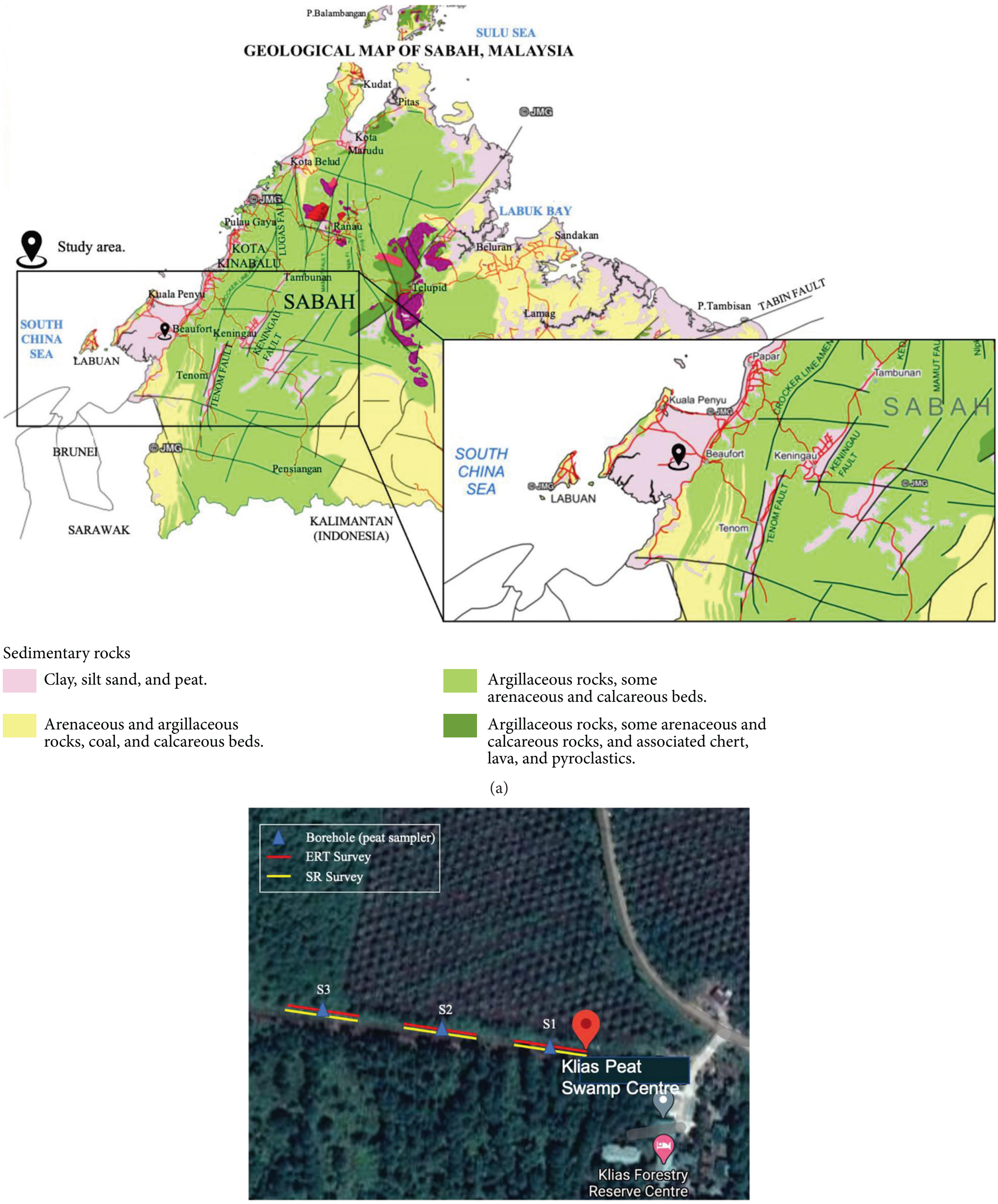
The ERT, IP, and SR methods may assist in peatland studies, particularly for examining the relation between mineral soil stratigraphy and peat properties. Compared to GPR, these methods are not restricted to studies above the mineral soil due to the limited depth of penetration. Bulk conductivity (reverse resistivity) measured in the direct current resistivity method depends upon fluid conductivity, moisture content, and surface conduction [8]. The electrical conductivity of peat soil pore water usually increases with depth as the mineral soil commonly underlying the peat soil is a source of organic solutes [8]. Highly decomposed peat soil also has a higher surface charge which suggests that surface conduction is likely to influence the bulk conductivity significantly [8] while the IP method measures the ability of the material to temporarily store charge or, in more complex, measure the magnitude of polarization of a material. The IP effect manifests itself as a frequency dependent resistivity or as a residual voltage following the termination of an applied current. The most common measure of IP is the time domain chargeability. The IP measurement is controlled mainly by the surface chemistry which includes charge density, surface area, and fluid chemistry [8]. The magnitude of polarization is also controlled largely by the cation exchange capacity (CEC) associated with the clay mineral [18]. Low decomposed organic material is commonly associated with a high surface charge density which results in a high CEC [19]. As the charge density is considered as one of the major controls on IP response, we expected the IP response on peat soil to be significantly different from the underlying mineral soil providing great contrast for layer separation. The SR method characterized the geologic structure by measuring the body waves and characterized the variations of thickness and velocity value [20]. By measuring the travel time of the seismic body waves, different subsurface layers with varied material composition and stiffness can be identified. As peat soil is a very soft material, it is expected that the stiffness contrast between the peat soil and underlying materials will differ greatly providing a clear separation of the peat base.

In this paper, we report the results of a field study to investigate the utility of geophysical methods (ERT, IP, and SR) for understanding the stratigraphy of a large peatland. Geophysical data are compared with a direct sampling of peat thickness using the conventional boring method. Our primary objective is to demonstrate the value of an integrated geophysical approach to peatland stratigraphy studies. We highlight the important information from the two electrical methods and show the value of resistivity and chargeability of the soil. The stiffness characteristic from the SR method was not in our intention in this study to investigate the controls on the electrical properties and stiffness of peat soil; further laboratory tests are required to do this. Instead, we show how field geophysical methods provide valuable insights into the stratigraphic on a large peatland.

2. Materials and Methods

2.1. Site Description. The study area was located near the Klias Peninsular reserve forest, Beaufort Sabah (see Figure 1). The peat soil area in the state of Sabah is approximately 116, 965 hectares from the total of 2.4 million hectares in Malaysia. The Klias Peninsula and Kinabatangan-Segama Valleys contributed most of the peat soil areas. The peatlands are mainly discovered in thick undrained waterlogged conditions and made up from decompose plant materials. The soil moisture content was very high, between 448.32 and 985.4% [21]. The organic content and fibre content were between 53.97 to 95.82% and 61.61 to 79.4%, respectively [21–23]. The peat soil was classified as hemic to fibric according to the US Department of Agriculture (USDA) classification. The Von Post scale was between H6 and H7 [22], which also fall in the category of hemic to fibric.

2.2. Field Study. The determination of peat soil thickness on the field was done using conventional boring equipment. A total of 3 boreholes labelled as S1, S2, and S3 were investigated across the study area. Borehole locations were selected to represent a range of peat depths and geomorphic settings. The location of the boreholes was also fixed as the midpoint for the geophysical surveys for comparison. The



(a)

(b)

Figure 1: (a) Geological map of the study area. (b) Locations of the profiles.

borehole profiles were obtained with an Eijkelkamp peat sampler, which collects a semidisturbed sample with 0.5 m increment until the peat soil layer ends. During the sampling, images of the peat profile were taken, and the bulk density was evaluated and recorded.

The ERT and IP surveys were made using ABEM Terrameter LS with an automated data acquisition unit. A Schlumberger array configuration, with a 2 m electrode spacing was used to investigate the electrical structure of the peat basin and the underlying mineral sediments. The short takeout line with 41 steel electrodes was used to better resolve the near-surface electrical structure of the peat soil. The midpoint of all the survey lines was fixed on the borehole locations to allow comparison. The field procedures follow the 2D electrical imaging surveys practical guide prepared by Loke [24] and the data analysis using the RES2DINV software manual [25]. During the data analysis, the field setup was synchronized to ensure the correct configuration was used. Bad data observed on the pseudosection was removed to ensure low root mean square error (RMSE) was obtained. The data obtained were then inverted using the least-squares inversion technique in the RES2DINV software [26].

Subsequently, the SR surveys were conducted using ABEM Terraloc Pro II. The total spread length was 23 m with 1 m receiver spacing. The locations of the shot point were at both offsets, between 1st and 2nd, 6th and 7th, 12th and 13th, 18th and 19th, and 23rd and 24th geophone. For each shot location, 5 shots were stacked. 7 kg sledgehammer was used as the seismic source coupled with a steel plate as the impact absorber. Heavy source weight (i.e., 7 kg sledgehammer) provides a high amplitude energy band [27, 28]. Steel plate was used as an impact absorber to increase energy accumulation on the higher frequencies generated for better interpretation of the shallow profile [28, 29]. However, to minimise the risk of the source plate penetrating the peat ground during shot impact as reported previously [28, 30], a custom steel plate with a thinner size and smaller weight was used. 24 geophones with 14 Hz natural frequency were used to record the shots. The data processing was done using Pickwin and Plotrefa modules. The transverse resistance (T) for m-layer section has been calculated as [31]

$$T = \sum_{i=1}^{m} \rho_i h_i, \tag{1}$$

where ρ_i and h_i is the resistivity and thickness of i^{th} layer, respectively.

3. Results and Discussion

3.1. Soil Profile. The investigation of the peat profile was conducted using the peat sampler. The soil profiles obtained using the peat sampler delineated that the peat thicknesses at S1, S2, and S3 were 3.5 m, 5.4 m, and 6.8 m, respectively. Figures 2-4 show the images for the soil profiles obtained. From the images obtained, the presence of fibre scan is seen with bare eyes. Comparison made between all three boreholes shows that the distribution of the fibres was inconsistent. However, approaching the transition to the underneath soil layer (marine clay), the observed fibres started to diminish. This result could likely be governed by the changes in the degree of decomposition with depth. Peats near the surface had a lower decomposition rate and increases with increasing depth [32, 33]. Therefore, it is most likely that, at deeper depth, the peat soil is more decomposed compared to the peat soil near the surface as the fresh intact fibres were not seen. The degree of decomposition can affect the peat soil properties greatly [34]. Thus, it is of great interest to observe the rate of decomposition on peat soil. From the borehole results, a combine stratigraphy of the study area was produced as shown in Figure 5. It is observed that the peat soil thickness in the area was undulating which suggests that the peat soil in the area was basin-shaped peat.

3.2. Two-Dimensional ERT and IP. Resistivity and IP inversion results using 2 m electrode spacing are plotted in Figures 6 and 7 . The peat soil profile as determined from the peat sampler was superimposed for comparison. The resistivity inversion shown in Figure 6 contains a uniform upper resistive layer, underlain by a conductive unit of varying thickness. The underlain conductive unit identified as marine clay appears to provide a great contrast of resistivity values with the peat soil layer. The inversion images indicate a gradually decreasing resistivity with depth in the peat soil apart from the top 2 m. A similar finding was obtained [8, 35], where peat soil conductivity gradually increases with depth. Slightly lower peat soil resistivity values were observed on the top 2 m. This condition was mainly contributed by the wide electrode spacing as zero reading was obtained, causing extrapolation of the shallowest available values. As mentioned previously [36], the shallow profile is partially missing due to the wide electrode spacing. Higher resistivity values were determined on the peat soil layer compared to the marine clay layer. The low resistivity values on the marine clay layer were governed by the clay particles which facilitate surface conductance of electric current [37]. Comparison between the peat soil depth determined by the ERT method and borehole data shows a minimum discrepancy. However, extra care must be taken when analysing ERT surveys with wider electrode spacing. The spacing between electrodes exerts fundamental control on resolution. Decreasing the electrode spacing improves the resolution on the shallow part; however, risk of limiting the volume can affect the generated image. According to Slater and Reeve [8], the element size increases logarithmically with depth with the increasing distance from the current source but suffers a significant drop in resolution. Thus, the electrode spacing must be adjusted according to the purpose of the investigation or the target depth for better interpretation.

The IP inversion shown in Figure 7 resolves the peat as less chargeable, relative to the underlying marine clay. This behaviour could be contributed by the less chargeable organic material within peat soil. As discussed in a previous study [8], the IP response within peat is due to an increase in polarization, rather than the effect of a change in bulk conduction and the polarization presumably results from the surface charge density on the organic material. However, the chargeability value appears to be a good indicator of the peat soil thickness. The high chargeability values of the marine clay layer compared to the peat soil layer provide a clear separation between both layers, thus enabling the mapping of peat soil stratigraphy with high accuracy.

To further investigate the accuracy of the resistivity and chargeability values on the determination of the peat soil thickness 1D profiles were extracted from the midpoint for

Figure 2: Soil profile for S1.

Figure 3: Soil profile for S2.

comparison with the boreholes data. Figure 8 presents the resistivity values of peat soil extracted from the midpoint of the takeout lines. The graph revealed low resistivity values on the top 2 m contributed by the wide electrode spacing, making the reading less reliable as the values could be generated by the extrapolation of data. At a depth greater than 2 m, the resistivity values of peat soil decrease slightly with depth. As mentioned previously, the images of the peat profile obtained show an increase in the degree of decomposition with depth shown by the diminishing of peat fibres with depth. At a low degree of decomposition, fresh fibres exist in peat and become completely decomposed at a higher degree of decomposition [38]. The resistivity values of peat soil decreased with an increasing degree of decomposition [39] while, at the depth approaching the transition to the soft clay layer, the resistivity values decrease significantly. The significant increase in soil conductivity was most likely be governed by the presence of clay fraction. The clay fraction provides high cation exchange capacity (CEC) which contributes to high soil conductivity [6, 40]. Overall, the peat resistivity values ranged from 40.8 to 258.5 ohm·m, 62.5 to 315.7 ohm·m, and 59.8 to 302.8 ohm·m for S1, S2, and S3 simultaneously.

The chargeability values extracted from the IP image are as shown in Figure 9. The values determined show slight increases with depth on the peat soil layer while, near the transition layer and on the marine clay layer, the chargeability values increase significantly with depth. The results

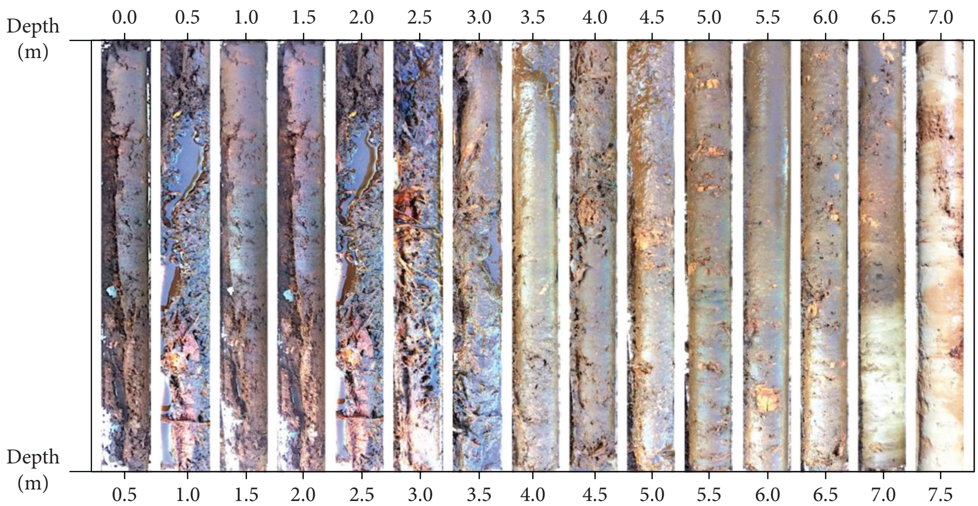


Figure 4: Soil profile for S3.

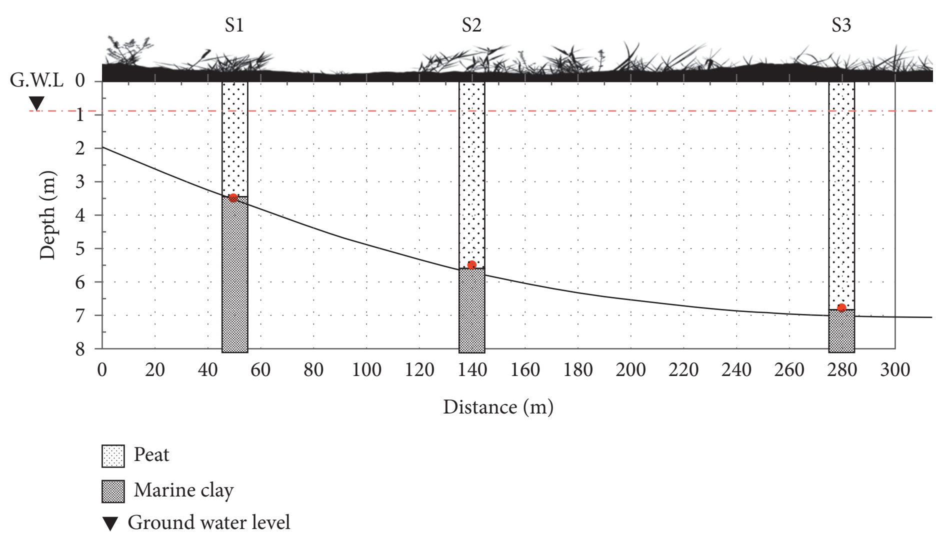


Figure 5: Soil stratigraphy delineated at the study area.

show that the peat soil was less chargeable compared to marine clay. The chargeability values for peat soil obtained ranged from 0.598 to 0.729 mV/V and 0.651 to 1.060 mV/V for S2 and S3 correspondingly.

3.3. Two-Dimensional SR. Three SR survey lines were investigated at all three stations. The midpoint was fixed at similar locations as the boreholes and ERT and IP method to allow comparison. The most important step in SR data analysis is picking travel times from shot gathers. Figure 10 shows the example of calculated and observed travel times. The image shows minor discrepancy between the calculated and observed travel times with RMS error between 3.8 and 4.5%.

The 2D V_p profiles obtained were as shown in Figure 11. Overall, unclear separation between the peat soil and marine clay layer underneath was observed. The contrast between the V_p values determined was small causing difficulties to determine the peat soil base, thus being unable to delineate the peat soil thickness. The small increase in stiffness with depth in peat soil was governed by the low bulk density and high-water table [41]. The SR images also show that the V_p values for peat soil vary laterally. This behaviour is most likely be governed by the heterogeneity of peat soil. The peat property varies laterally and vertically depending on the organic matter content [42]. Heterogeneity of peat soil caused lateral variation of stiffness [43]. Therefore, this finding suggests the importance of geophysical methods in investigating peat soil characteristics as the method was able to delineate the lateral variation which the conventional boring method failed to address. However, for the purpose of delineating peat soil stratigraphy, it is concluded that the SR method was less reliable compared to ERT and IP method. The finding was

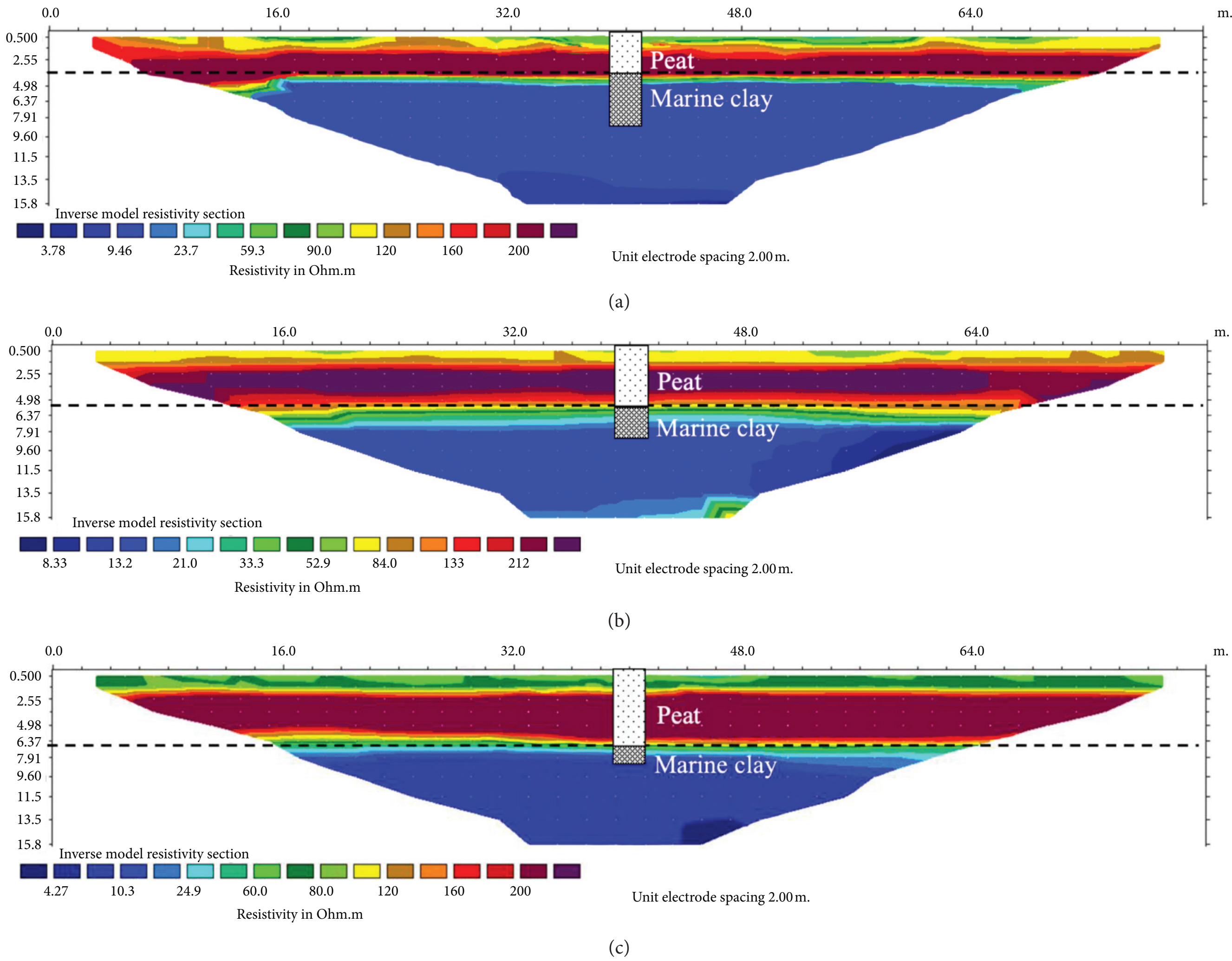


Figure 6: 2D resistivity images: (a) S1, (b) S2, and (c) S3.

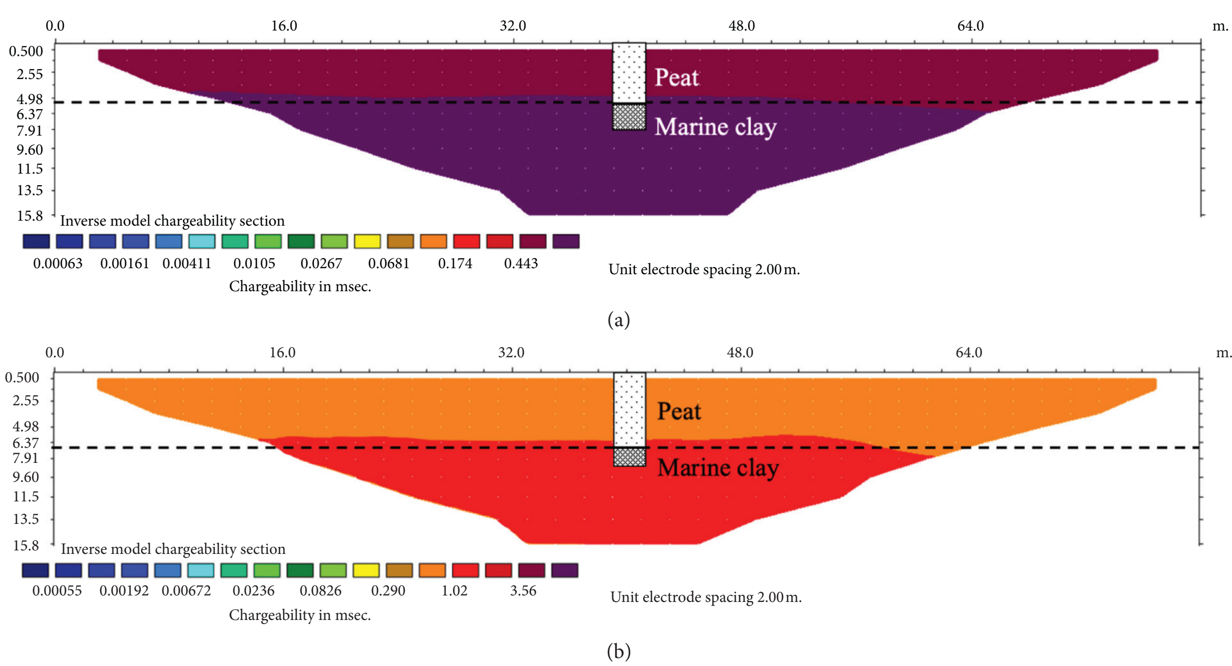


Figure 7: 2D chargeability images; (a) S2 and (b) S3.

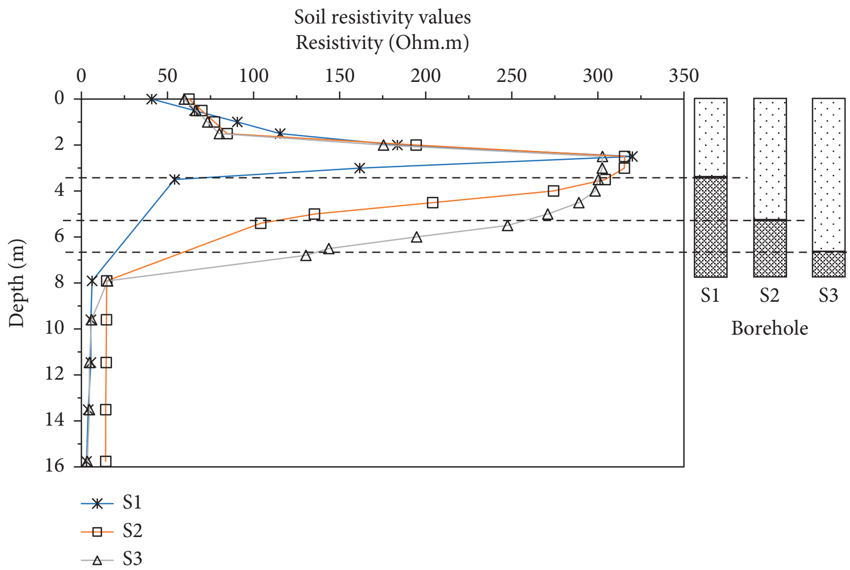


Figure 8: Soil resistivity values at Klias.

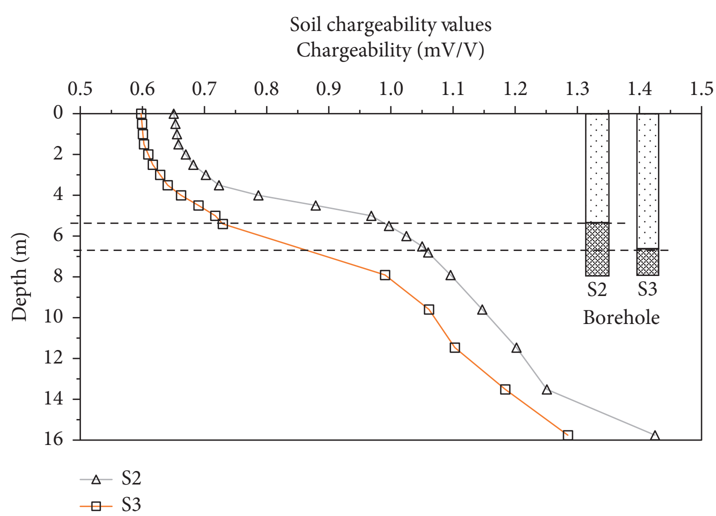


Figure 9: Soil chargeability values at Klias.

applicable for peat soil site with a soft underneath layer such as marine clay. In the case where stiffer underneath soil layer is present, the SR method could provide better stiffness contrast, thus being able to delineate the accurate thickness of the peat soil.

From the 2D SR image, 1D V_p values were extracted at the midpoint of the survey lines to be compared with the borehole data (see Figure 12). From the graph, the V_p values of peat soil near the surface show a slight increase with depth and become significant at a depth greater than 3 m. The slope of increment in V_p values greater than 3 m was consistently causing difficulties to determine the transition between the peat soil and marine clay especially for peat soil thicker than 3 m. The finding confirmed the conclusion made earlier that the SR method was unable to accurately determine the peat soil thickness due to the gradual increase of V_p values with depth. The existence of peat soil deposits in this area is classified as hemic peat and Klias peat classified as hemic peat with high organic content [44].

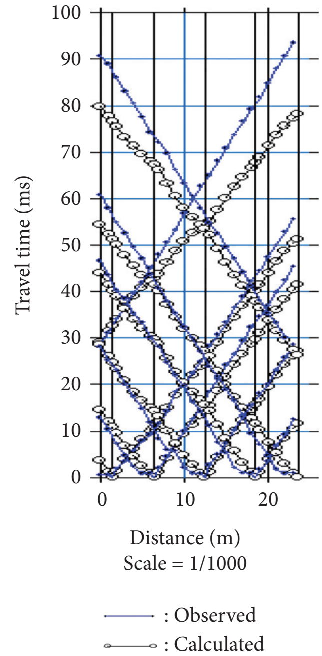


Figure 10: Example of calculated and observed travel time

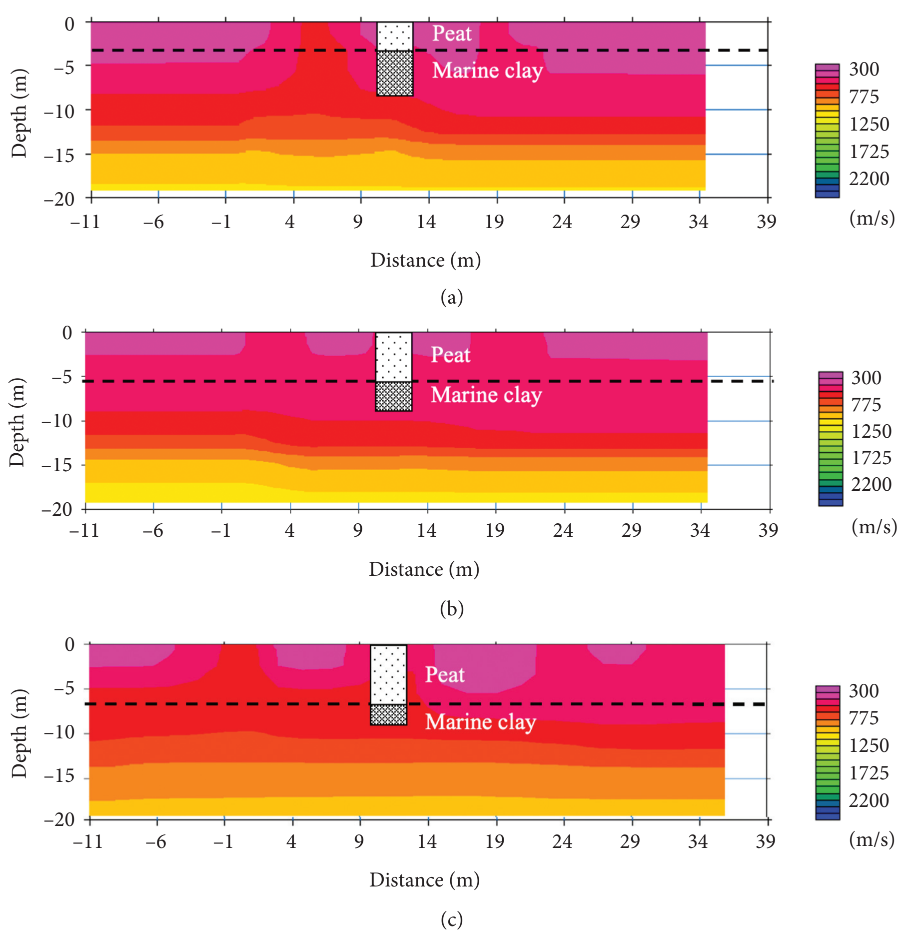


Figure 11: 2D V_p images: (a) S1, (b) S2, and (c) S3.

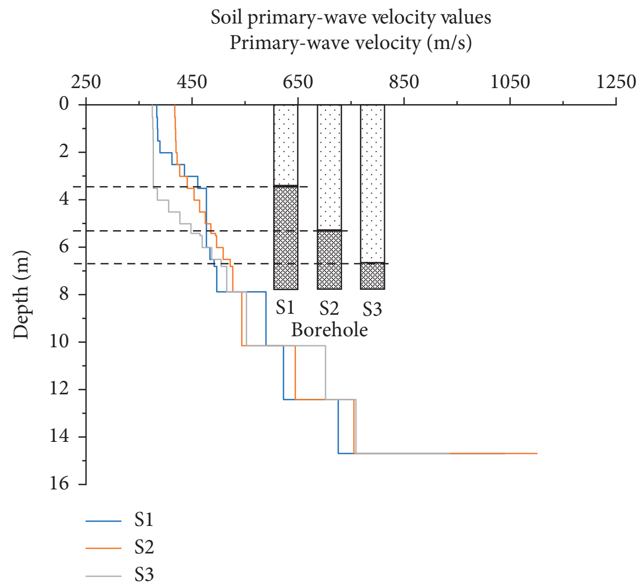


FIGURE 12: 1D V_p values compared with borehole data.

4. Conclusions

The integrated electrical and stiffness study of large peatlands in Klias, Sabah, demonstrates the value of ERT imaging, IP imaging, and SR imaging to studies of peatlands. Geophysical data were compared with direct sampling of peat thickness using a peat sampler. ERT and IP imaging are excellent methods for investigating electrical properties and stratigraphy of the peat soil. The resistivity and chargeability images resolved the variability in peat soil thickness, allowing better estimates of the peatlands volume. The resistivity values of peat soil show slight decreases with depth, governed by the increasing degree of decomposition while, near the transition to the marine clay layer, the resistivity drops significantly due to an increase in CEC. However, the SR images did not accurately define the base of the peatland, due to an observed gradual increase in stiffness with depth within the peat soil and marine clay. The low bulk density and high-water table in peat soil cause only a discernible increase in strength with depth. The small difference in stiffness values between both layers causes difficulty to determine the base of the peat layer, thus being unable to delineate the peat soil stratigraphy accurately. Despite the high quality of the 2D profile images, a good judgement and complementary of the borehole are required if preliminary data was not available. Overall, ERT and IP imaging provides valuable insight into peat soil electrical properties and delineate peat soil stratigraphy with high accuracy for better estimates of the peatlands volume.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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