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Comparative Behaviour of Soft Soil by Analysing The Parameters of Cone Penetration Test with Pore Water Pressure (CPTu) in Western Johor

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Abstract

Soft soil consists of marine clay, peat, and organic soil, characterised by low strength, high compressibility, and high water content. This soil type poses persistent challenges for contractors, consultants, and designers during the design, construction, and maintenance stages. Even with modern advancements, it remains challenging to fully comprehend the behaviour of soft soils in tropical areas. Significant environmental influence factors, such as high rainfall, warm temperatures, and complex soil compositions, make their behaviour unpredictable and difficult to study. Therefore, conducting thorough in-situ site investigation work is crucial for the development area located in tropical regions. In-situ high-end measuring devices, such as the Cone Penetration Test with Pore Water Pressure (CPTu), provide high efficiency in characterising sites, particularly those with distinct stratigraphic horizons. In this study, CPTu was performed to determine the CPTu parameters consisting of cone resistance (q_c), sleeve friction (f_s), and pore water pressure (u_2). Three and two of the CPTu points were conducted in Pontian and Sedenak, respectively. The CPTu parameters were analysed to determine the behaviour and subsurface profiling. This study also compares CPTu values with those from a prior investigation in Parit Nipah, to clarify the diversity of soil behaviour, and presents a range of CPTu parameters within the Western State of Johor. The findings exhibit the behaviour and identify the heterogeneous subsurface profiling, which consists of layers of peat, soft, and medium-stiff clay, by indicating the significant range of CPTu parameter values. Peat exhibits a range for q_c, f_s, and u_2 of 0.001–0.890 MPa, 0.0006–0.033 MPa, and 0.0001–0.079 MPa, respectively. Meanwhile, soft clay demonstrates ranges of 0.056–0.850 MPa, 0.0001–0.006 MPa, and 0.011–0.255 MPa. Medium-stiff clay reveals corresponding ranges of 0.150–6.480 MPa, 0.001–0.077 MPa, and 0.045–0.677 MPa. In conclusion, CPTu was able to identify the behaviour of soft soil and its characterisation, which is essential for designing safe, economical, and long-term buildings and infrastructure.

1. Introduction

Soft soil, including clay, peat, and organic soils, is recognised for its high compressibility and low bearing capacity, which has made the development of buildings, roads, and infrastructures challenging and complex for engineers, consultants, and contractors. Peat can significantly affect or become the primary factor contributing to the instability problem associated with non-uniform and excessive consolidation settlement [1]. Peat that exists in tropical areas is characterised by its high fibre, water, and organic content and can be categorised as a fabric or an amorphous type of material [2].

Consequently, when dealing with peat soil in any development work, determining index properties is essential, as they differ from those of inorganic soil. Index properties of peat include water, organic, and fibre content, as well as specific gravity and Atterberg limit. The water content of fibrous peat can range from 500 to 2000% due to the water held in the cells of plant remains [3]. Increases in moisture content result in a corresponding increase in organic content and a decrease in the specific gravity [4].

Meanwhile, fibre content can be determined as the quantity of plant pieces that have a diameter greater than 0.15mm, which influences the mechanical properties of peat, affecting its stability, compressibility, and susceptibility to subsidence. The strength of peat soil needs to be increased to support the foundation and prevent serious problems due to its unique characteristics [5]. The clay layer, which typically underlies the peat layer, also contributes to the feasibility of constructing any building in this area and is inevitably influenced by soil geotechnical factors that may lead to overestimation or underestimation of structural designs.

Additionally, an understanding of soil behaviour is essential in producing an effective design to provide a structure that will endure over its designated lifespan. However, the design of any construction relies on the superior quality of data obtained during site investigation (SI) activities. SI permits exploration work consisting of site inspection, boring, sampling, and testing to acquire geotechnical information that makes a significant contribution to producing practical and cost-effective geotechnical evaluations or designs.

Despite current advances, understanding the behaviour of soft soils in tropical regions remains challenging. Substantial environmental conditions, such as high precipitation, warm temperatures, and complex soil structures, make the behaviour unpredictable and challenging to analyse. In certain circumstances, conducting physical and software modeling can provide a better understanding of soil structure interaction, especially when dealing with peat soil and soft clay [6].

The most common technique for sampling and testing involves obtaining samples of undisturbed soil and then conducting laboratory testing to determine various soil characteristics. Due to its high water content, peat exhibits a great degree of sensitivity and softness. As peat soil is identifiable by its soft texture, obtaining undisturbed samples through sampling work is extremely tough and unattainable [7]. The typical undisturbed sampler faced challenges in sampling hemic and fibrous peat [8]. The challenges are not only due to the excessive water content but also to the fibrous condition that makes it difficult to cut the sample without producing compression, especially when using a tube sampler. Furthermore, sampling in peat is complex and more challenging than in soft clay. Also, there is a potential for encountering a decrease in pore water pressure [9]. Therefore, the utilisation of in-situ experiments or testing methods, such as the Cone Penetration Test with Pore Water Pressure (CPTu), has become more prevalent in geotechnical engineering in recent years, offering data collection without the need for sample removal.

The CPTu comprises a cone and a surface sleeve that are consistently pushed into the ground, accompanied by the addition of a pore pressure transducer. The measurements obtained at depth include tip or cone resistance (q_c), sleeve friction (f_s), and pore water pressure (u_2), which reveal the measured value for different types of soil. CPTu can yield profiles of continuous data and obtain information regarding the behaviour and characteristics of the soil at the site, along with its depth, rapidly. The soil profiling and soil type, initial state parameters, strength parameters, deformation, and flow characteristics of soil can be determined by conducting CPTu [10].

Moreover, the characterisation of soft soil can also be determined by using undrained shear strength and pore pressure ratio methods in estimating the overconsolidation ratio (OCR) values [11]. CPTu can confirm the classification of the soil based on its behavioural aspects during SI work [12]. CPTu can measure in-situ pore water pressure and generate subsurface profiling in the construction area [13]. Bearing/pile capacities can also be justified by using CPTu data [14]. CPTU parameters and empirical correlations can be used to ascertain strength and stiffness parameters in clay [15]. The values obtained from CPTu can be correlated with other geotechnical soil tests, such as Dynamic Probing Heavy (DPH), particularly in coarse-grained soils [16]. The establishment of a correlation between data from the CPTu and the Flat Dilatometer Test (DMT) contributes to the estimation of settlement [17]. Besides, CPTu and DMT are advantageous for data collection at small intervals of 0.05 m and 0.5 m, compared to other tests such as the Standard Penetration Test (SPT) and the Field Vane Test (FVT) [18].

Furthermore, the q_c values recorded during the CPTu test will range between specific values, depending on the type of soil. In very soft clays, the q_c value obtained is relatively low [19]. In certain circumstances, the measured q_c value in fibrous peat may experience random fluctuations as a result of the cone penetrating the fibre [20]. However, the q_c value decreased with increasing depth in the peat [21]. Conversely, high values of q_t are typically associated with soils of coarse texture, such as sand [22]. The q_t is the corrected version of q_c that considers the unequal area effect [10] in terms of Eq. (1):

$$q_t = q_c + u_2(1-a) \tag{1}$$

where u_2 represents the pore water pressure behind the cone, and a denotes the cone area ratio. The cone area ratio, a, is defined as the ratio of the cross-sectional area of the load cell or shaft (A_n) to the projected area of the cone (A_c), as illustrated in Fig. 1.

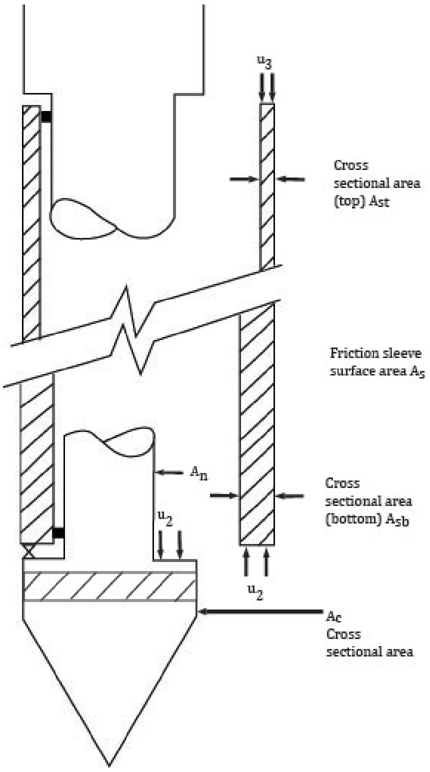

Fig. 1 *The cross-sectional area of the load cell or shaft (A_n) and the projected area of the cone (A_c) [10]*

In addition, values a range from 0.59 to 0.85, but sometimes may be as low as 0.38. A value of 0.38 should be deemed unacceptable when employing the CPT in extremely soft fine-grained conditions, as the correction becomes a significant contributor to q_t and may result in an increased accuracy loss. In granular soils, this correction is not as essential as in cohesive soils [10]. In the peat layer, the f_s value is also very high, in contrast to the minimal cone resistance [20]. The value of u_2 in fibrous peat is low, contrary to amorphous [10]. This low value is due to high hydraulic conductivity [20].

Accordingly, the present paper emphasises the investigation of soft soil behaviour by conducting in-situ high-end measuring device CPTu tests, which involve the measurement of q_c, f_s, and u_2 values at specified sites in Pontian and Sedenak. This study aims to obtain a significant range of q_c, f_s, and u_2 values and to reveal the reliability of CPTu in demonstrating various behaviours by comparing it with the CPTu parameter in a previous study in Parit Nipah. Ultimately, this study determines the subsurface profiling, including the existence of every type of soft soil layer in the Western State of Johor.

2. Materials and Methods

The data collection process involved conducting in-situ SIs using CPTu equipment, followed by a quantitative approach to analyse the gathered data. The subsequent subsection elaborated on the methods employed for data collection and analysis.

2.1 Data Collection

This study was conducted at two sites in Pontian and Sedenak. Parit Nipah site, previously investigated by Zainorabidin et al. [20], was selected as a comparative site for the study. All site locations were shown in Fig. 2.

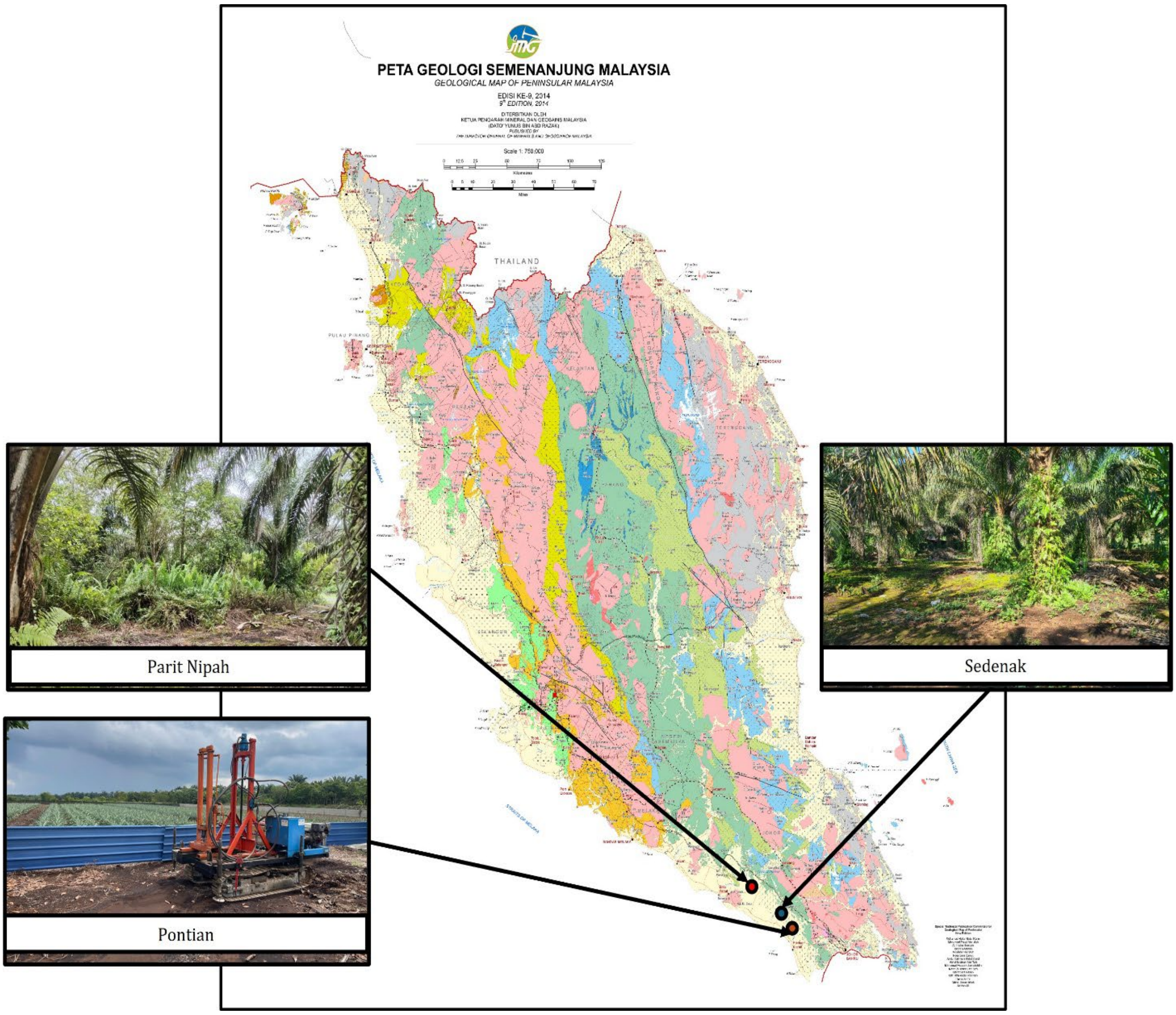

Fig. 2 *Location of sites studied in Pontian, Sedenak, and Parit Nipah, Johor, based on the geological map*

Table 1 summarizes the index properties of peat from these locations. Pontian and Parit Nipah sites comprised hemic peat. Meanwhile, the Sedenak site was classified as sapric peat. By conducting the Von Post Classification, the type of peat at the studied sites could be determined, with H4-H6, H6, and H8 classifications for the sites of Pontian, Parit Nipah, and Sedenak, respectively. Pontian site revealed a moisture content of 533%, while Sedenak and Parit Nipah exhibited higher values of 717% and 839.7%, respectively. The moisture content of peat varies between 500 to 800%, showing heterogeneity in water saturation levels across various areas. Liquid limit values, ranging from 189% to 345%, further demonstrated the heterogeneity of peat soils in Western Johor. The organic content in Pontian, Sedenak, and Parit Nipah reached 92.69%, 80.8%, and 81.8%, respectively. Fibre content also varies significantly, with Sedenak containing 30%, compared to 48% in Pontian and Parit Nipah, highlighting the diverse structural composition of these peatlands. All sites were underlain by a soft to medium-stiff clay layer.

Table 1 *Index properties of peat Pontian, Sedenak, and Parit Nipah from previous research*

Location	Type of peat	Von Post Classification	Moisture content (%)	Liquid Limit (%)	Organic content (%)	Fibre content (%)	Reference
Pontian	Hemic	H4 -H6	533	189	92.69	48	[23]
Sedenak	Sapric	H8	717	-	80.8	30.6	unpublished
Parit Nipah	Hemic	H6	839.7	345	81.8	47.6	[20]

The CPTu approach was selected in this study as an effective and efficient alternative for the site's conventional SI methods, such as drilling or SPT. The repeatable, accurate, and reliable approach with CPTu might indicate the heterogeneity of the soft soil layer in a very fast period, approximately 1 meter depth in 1 minute. A series of CPTu was performed following ASTM D-5778 standards, adopted in 1995 [24]. The tests were conducted using a 5-tonne Geomil Piezocone Penetrometer with a 10 cm^2 cone and an apex angle of 60°. The cone was continuously pushed and penetrated with a standard rate of penetration of 20±5 mm/s. This device could achieve a maximum penetration depth of 30 meters.

Three CPTu points in Pontian and two CPTu points in Sedenak were selected, with the distribution constrained by site-specific limitations. The CPTu points were strategically positioned at 10-meter intervals along a linear alignment to ensure systematic data collection and consistency in spatial analysis. In a previous study at the Parit Nipah site, three CPTu points were conducted. The q_c, f_s, and u_2 measurements were continuously recorded with depth, with data collected at intervals not exceeding 50 mm. During the tests, all readings were continuously monitored, including inclination, to prevent potential harm from encountering extremely resistant or hard layers. The deviation of push rods from the vertical axis was minimised, particularly in the rods adjacent to the penetrometer tip, to prevent significant directional drift of the penetrometer. The cone was penetrated until it reached the depth at which the cone could no longer penetrate the soil, and constant readings were achieved.

2.2 Data Analysis

A comparative analysis was conducted between the current sites and Parit Nipah, assessing trends in q_c, f_s, and u_2 values over the depth penetration of the cone. The purpose of the comparison was to identify differences or similarities in these trends, which revealed information about soil behaviour, geotechnical properties, or other relevant factors. Correlation analysis was used to examine the relationship between q_c, f_s, and u_2 at different locations. The q_c, f_s, and u_2 values were presented in a visual interpretation of graphs and plots with depth.

The q_c, f_s, and u_2 patterns and trends were analysed to interpret soil layer boundaries and internal heterogeneity. The significance range of q_c, f_s, and u_2, with minimum and maximum values for every thickness of type layers of soil, was revealed in this study. There were some limitations on data analysis at the soil layer transition zone that affected the q_c, f_s, and u_2 values. Data processing software CPTask was used in the study. CPTask could provide some other relevant derived geotechnical parameters for presentation, including the equivalent SPT N60 values, relative density, internal friction angle, and undrained shear strength. These details were computed automatically and presented in the layout. However, in this study, the CPTask software was not validated against other methods or standards.

3. Results and Discussion

3.1 Behaviour of Soil from CPTu in Pontian, Sedenak, and Parit Nipah, Johor

The q_c, f_s, and u_2 values for every site revealed the behaviour of the soil and characterised the type of soil layer. The results from each site were presented in Figs. 3 to 5.

3.1.1 Pontian

From Fig. 3, the q_c values varied significantly, indicating a heterogeneous subsurface profile. This heterogeneous subsurface profile could be divided into three types of soil layers. A variety of q_c values ranged from 0.011 to 0.270 MPa in the upper 2 meters, which exhibited a peat layer. The high value of q_c might be attributed to the existence of fresh fibre [20] when the cone penetrated the fibrous layer. Meanwhile, lower q_c values at depths between 2 and 8 meters were attributed to the presence of a soft clay layer, which recorded values with a range of 0.057 to 0.269 MPa. Due to the homogeneous nature of the clay material, the q_c values in this depth range remained relatively constant as the depth increased. The greater depths implied a medium-stiff clay layer with q_c values reaching 1.253 MPa. Similarly, the f_s measurement showed a significant variation in the subsurface profile.

Furthermore, values of f_s range from 0.0006 to 0.033 MPa, correlating with the presence of peat soil at a depth of 2 meters. As the depth increased, the f_s value increased, ranging from 0.0001 to 0.045 MPa, indicating the presence of soft to medium-stiff clay layers. For the u_2 measurement, the values showed an increasing trend with depth. The range of u_2 values, which ranged from 0.0001 to 0.079 MPa at a depth of 2 meters, indicated the presence of the peat layer. The u_2 values in the peat layer were slightly low due to high hydraulic conductivity, which caused the faster pore water pressure dissipation [20]. A reduction of hydraulic conductivity due to the decrease in the void ratio would also be correspondingly related to consolidation [25]. The u_2 values recorded ranged from 0.011 to 0.677 MPa, indicating the presence of soft and medium-stiff clay in the deep layers.

3.1.2 Sedenak

Similar to the Pontian site, the q_c values for the Sedenak site also varied significantly, presenting a heterogeneous subsurface profile, as shown in Fig. 4. The variations in q_c values ranged from 0.004 to 0.890 MPa in the upper 4 meters, indicating the presence of a peat layer. At a depth of 4 to 8.5 meters, the q_c value was low due to the presence of a soft clay layer. A high q_c value of 4.733 MPa indicated that the cone reached the medium-stiff clay layer. The f_s measurement also revealed the presence of peat soil at a depth of 4 meters, with a range of 0.003 to 0.028 MPa. The low f_s value, ranging from 0.0001 to 0.006 MPa, encountered between 4 and 8.5 meters, revealed the presence of soft clay layers. For the medium-stiff clay layer at greater depth, the high f_s value of 0.039 MPa was recorded. For the u_2 measurement, the values also showed an increasing trend with depth. The u_2 values ranged from 0.0002 to 0.039 MPa at a depth of 4 meters, indicating the presence of the peat layer. For soft and medium-stiff clay, the u_2 values recorded ranged from 0.029 to 0.379 MPa.

3.1.3 Parit Nipah

The q_c, f_s, and u_2 values from the Parit Nipah site were shown in Fig. 5. The peat layer was identified within the upper 2 meters, with q_c ranging from 0.001 to 0.859 MPa. Soft and medium-stiff clay layers, found at depths exceeding 4 meters, exhibited q_c ranging from 0.056 to 6.480 MPa. For the peat layer, f_s ranged between 0.001 and 0.19 MPa, while the soft and medium-stiff clay layers recorded f_s values between 0.001 and 0.077 MPa. The u_2 values for the peat layer varied from 0.0002 to 0.0578 MPa, whereas for the soft and medium-stiff clay layers, u_2 values ranged from 0.047 to 0.548 MPa at depths greater than 4 meters.

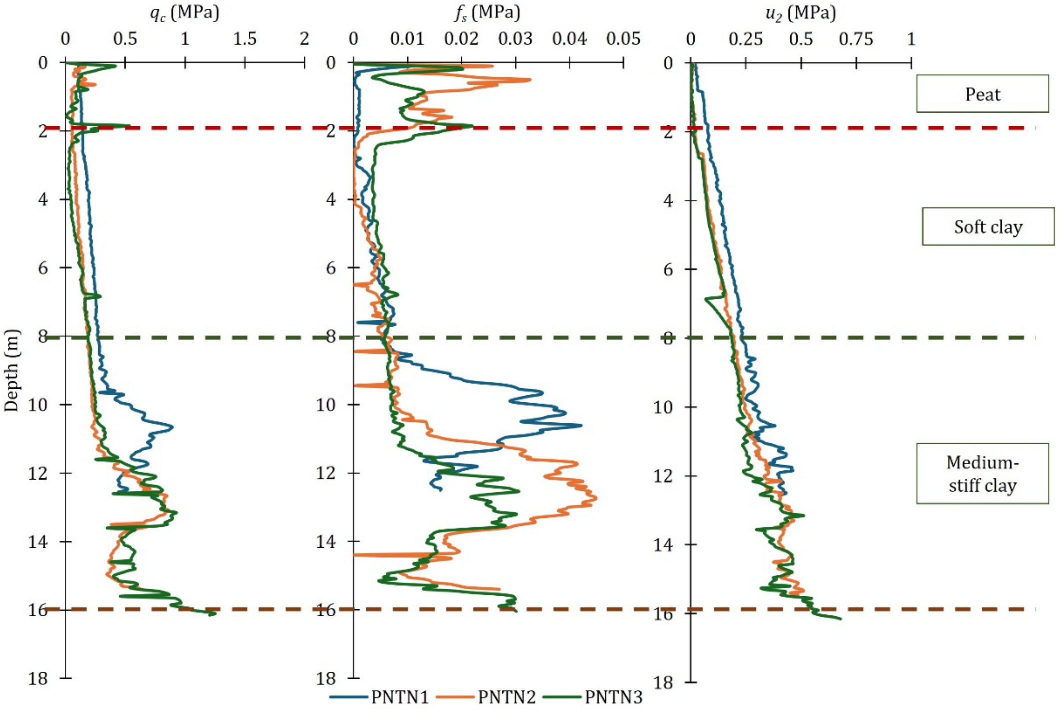

Fig. 3 *Values of q_c, f_s, and u_2 in Pontian, Johor*

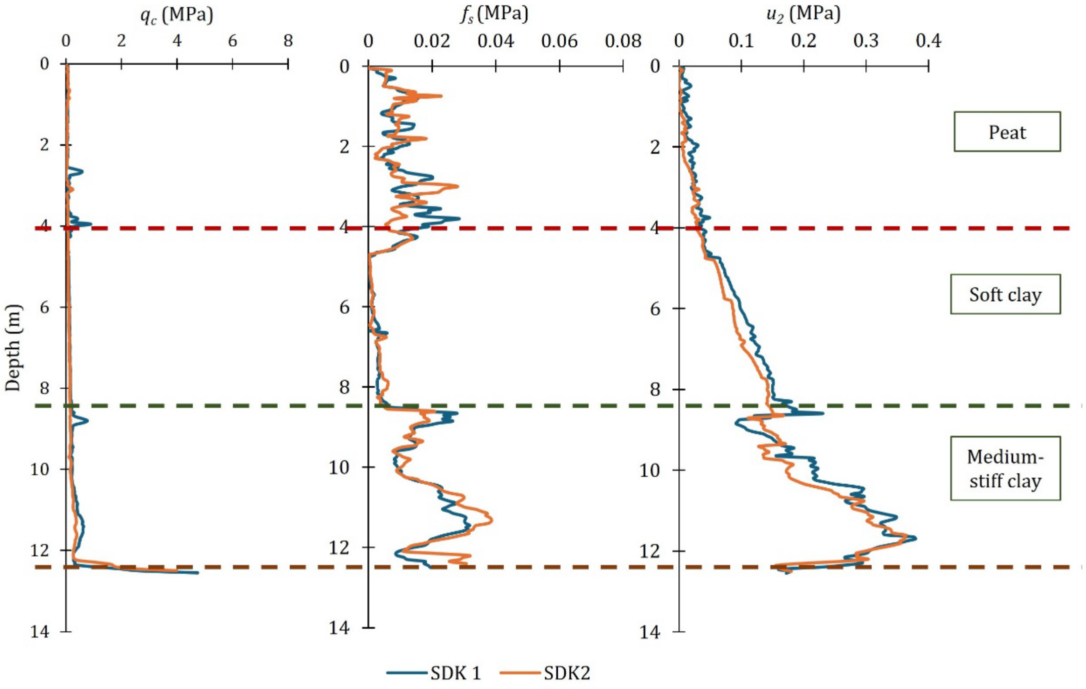

Fig. 4 *Values of q_c, f_s, and u_2 in Sedenak, Johor*

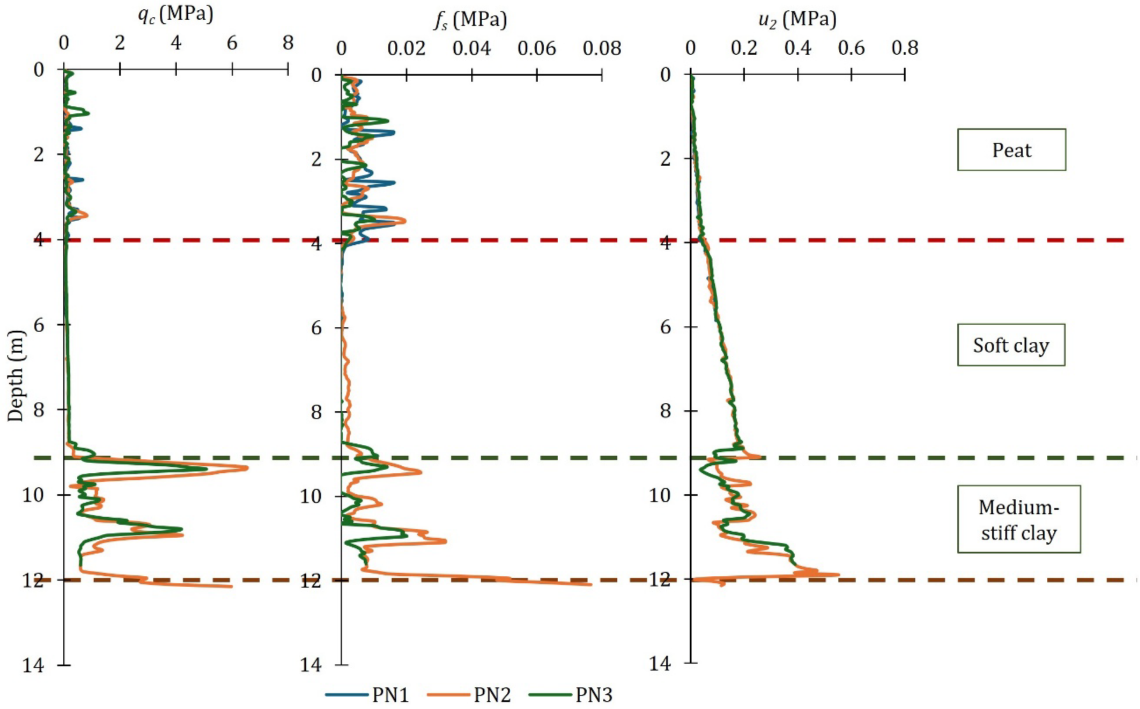

Fig. 5 *Values of q_c, f_s, and u_2 in Parit Nipah, Johor [20]*

3.2 Comparative Study on CPTu between Pontian, Sedenak, and Parit Nipah Sites

The comparative study between sites Pontian, Sedenak, and Parit Nipah showed a range of q_c, f_s, and u_2, with minimum and maximum values for every thickness of the soil layers, as demonstrated in Fig. 6 to Fig. 8. The CPTu profiles encountered across the three site locations displayed a complex subsurface structure in tropical soft soil in Western Johor. The maximum q_c values at sites Sedenak and Parit Nipah were recorded as almost three times higher than the q_c values from site Pontian in the peat layer, which was attributed to the disturbance effect on the original ground. Pontian might have been more disturbed compared to Sedenak and Parit Nipah as a virgin peatland.

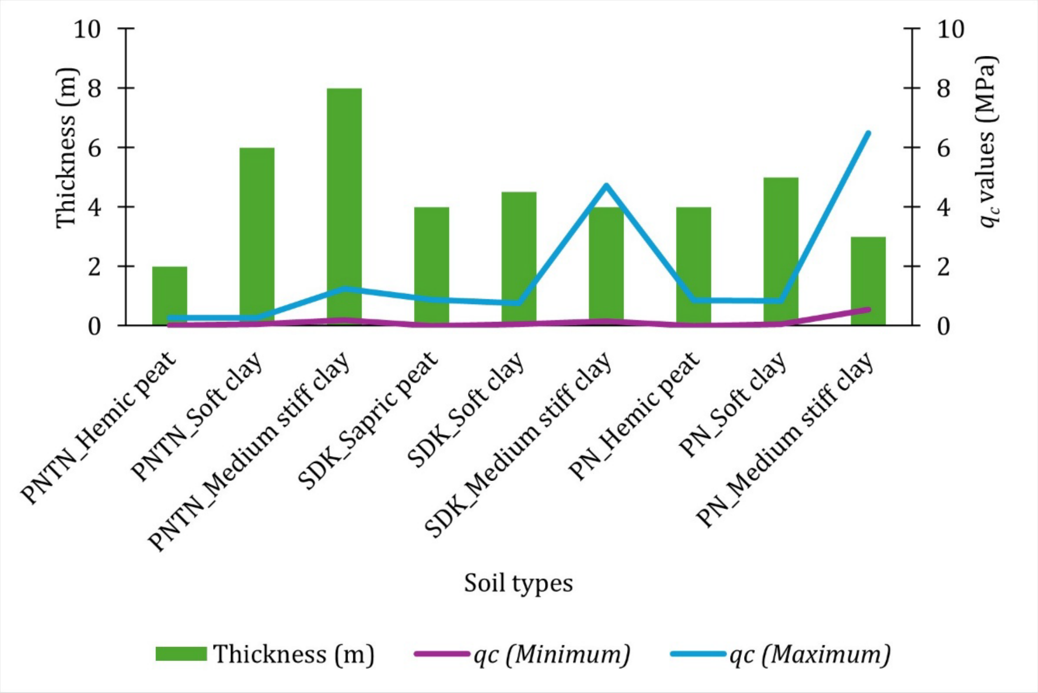

Fig. 6 *Range of q_c values for soil types and thickness across the sites*

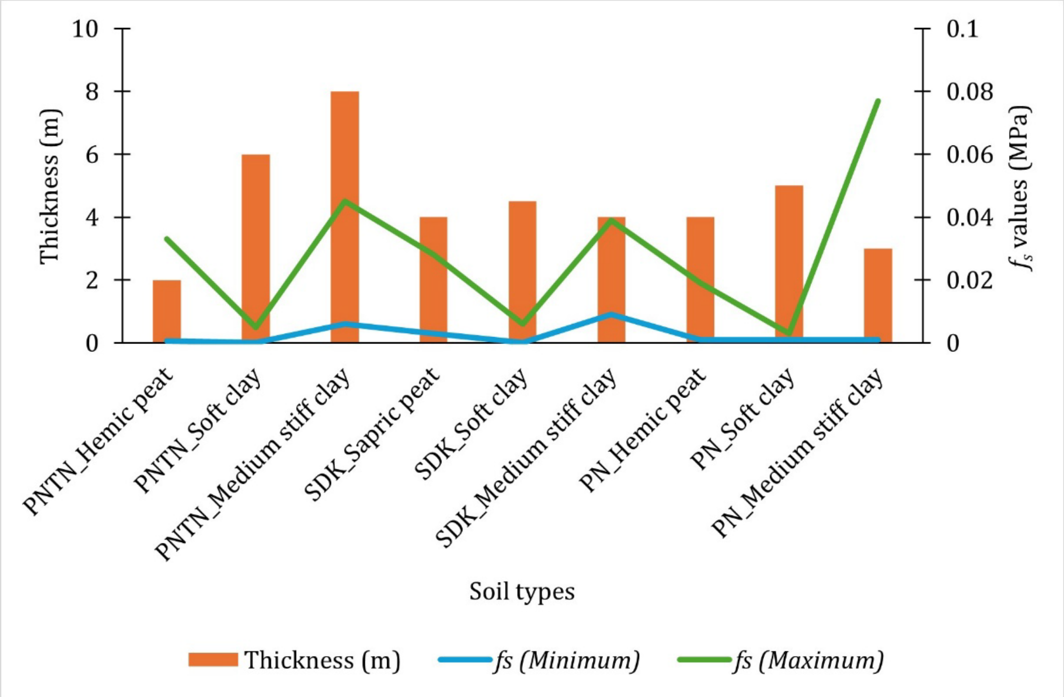

Fig. 7 *Range of f_s values for the soil types and thickness across the sites*

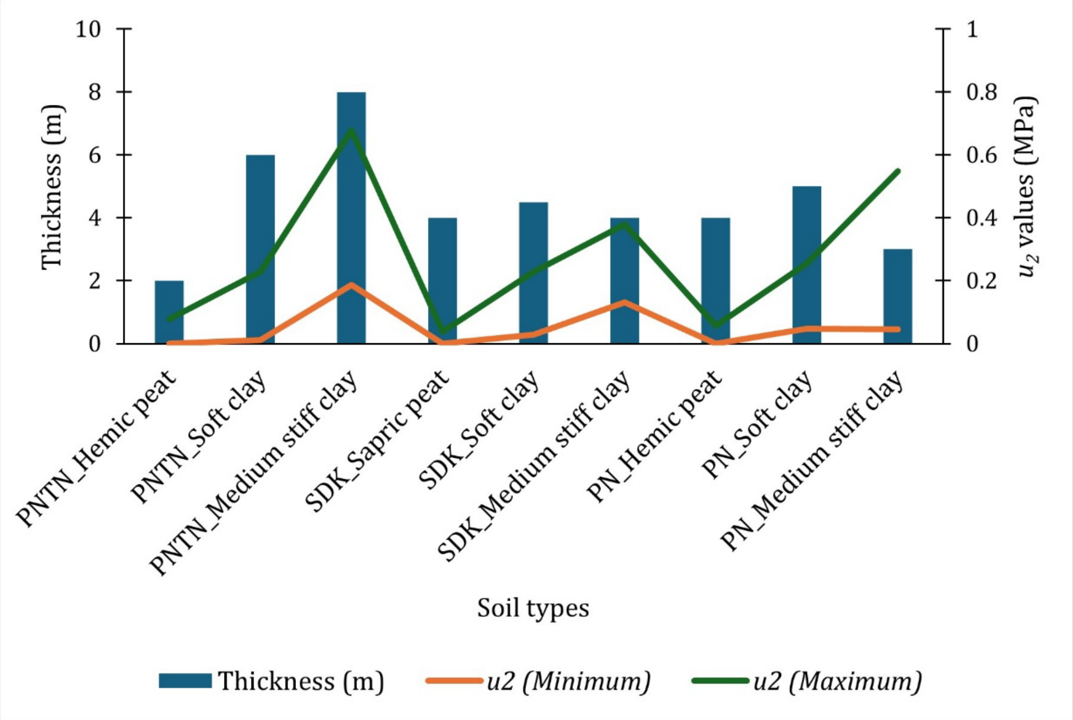

Fig. 8 *Range of u_2 values for the soil type and thickness across the sites*

Meanwhile, the maximum f_s values revealed similarity among all the sites. For the u_2 measurement, the values also showed an increasing trend with depth. The highest value of q_c at the Pontian site was almost attained, similar to the average value of q_c, indicating a peat layer from Chmielewska [21]. However, the patterns of increased values of q_c and f_s with increasing depth for all sites were contrary. Meanwhile, the increased values of u_2 demonstrated a similar trend. The q_c and f_s values in the peat layer were observed due to variations in fibre content and orientation, as these areas experienced ongoing decomposition or the humification process. Continuous biological decomposition caused a reduction in fibre content [26]. Decomposition would also reduce the compressibility and permeability of peat [27].

In the soft clay layer, the maximum q_c values in all sites were quite similar to those in the peat layer. Meanwhile, in medium-stiff clay layers, the maximum q_c values at the Parit Nipah site were recorded as 5.2 and 1.4 times those at the Pontian and Sedenak sites, respectively. However, the f_s value of the soft clay layer for all the sites exhibited low values. The identification of the clayey soil layer was contingent upon the q_c and f_s values being close to zero [18]. As the depth increased, and when the medium-stiff clay layer was reached, all the sites revealed higher values. The u_2 values in soft and medium-stiff layers also exhibited an ascending trend with depth.

Additionally, the CPTu parameter values in soft clay layers agreed with those reported in a previous study by Duan *et al.* [13], which indicated low q_t and f_s values, as well as an ascending pattern over depth, due to the presence of a homogeneous clay layer. The q_c value of less than 0.5 MPa in the soft clay layer at the Pontian site was also in line with Selamat *et al.* [12], which was consistent with the presence of a soft marine clay stratum. Significant fluctuations in q_c and f_s values indicated the presence of interbedded soil layers in site studies. When the q_c and f_s values changed abruptly, it corresponded to a transition between different soil layers. These boundaries were critical indicators for geotechnical engineers, as they indicated areas where changes in soil type and strength could affect load-bearing capacity and settlement behaviour.

4. Conclusion

By analysing the CPTu parameters, determination and characterisation between sites can be investigated. The range variation in q_c, f_s, and u_2 values shows the influence of fibre content and orientation in the peat layer. In the soft clay layer, the q_c and f_s values are low. Meanwhile, the medium-stiff clay layer exhibits increasing values with depth. The constantly increasing value of u_2 over depth due to homogeneous material is revealed in soft and medium-stiff clay layers. The significant range of CPTu parameter values of q_c, f_s, and u_2 indicates a heterogeneous subsurface soil profile. Peat, soft, and medium-stiff clay layers indicate q_c, f_s, and u_2 ranges of 0.001–0.890 MPa, 0.0006–0.033 MPa, and 0.0001–0.079 MPa; 0.056–0.850 MPa, 0.0001–0.006 MPa, and 0.011–0.255 MPa; and 0.150–6.480 MPa, 0.001–0.077 MPa, and 0.045–0.677 MPa, respectively. This study displays the reliability of CPTu in demonstrating the heterogeneous nature and behaviour of soft soil.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Zuraini Zainal, Adnan Zainorabidin, Kasbi Basri;* ***Data collection:*** *Zuraini Zainal, Adnan Zainorabidin, Kasbi Basri, Amirzaki Salikin, Mohamad Johari Zainal, Ang Koh An ;* ***Analysis and interpretation of results:*** *Zuraini Zainal, Adnan Zainorabidin, Zeety Md Yusof, Kasbi Basri, Paulus Pramono Rahardjo, Ramli Nazir;* ***Draft manuscript preparation****: Zuraini Zainal, Adnan Zainorabidin, Kasbi Basri, Zeety Md Yusof All authors reviewed the results and approved the final version of the manuscript.*

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