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Estimating the Small Strain Stiffness of Peat Soil Using Geophysical Methods

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Abstract- Geotechnical design commonly requires that the in-situ stiffness, strength and permeability of the ground be obtained. Laboratory based investigation often related with risk of sample disturbance and difficulties to replicate the in-situ stress condition which results in overestimation or underestimation. Application of geophysical methods in geotechnical investigation previously was limited to targeting and dimensioning sub-surface features due to lack of resolution. However, rapid developments of geophysical methods result in the application of these methods in providing geotechnical design parameters. Multichannel analysis of surface waves (MASW) and seismic refraction were among the geophysical methods capable of obtaining stiffness parameters including the maximum shear modulus (G_{max}) and maximum elastic modulus (E_{max}). The study revealed the efficiency of these methods to measure the small strain stiffness of peat soil with high accuracy as the results obtained were found to be similar to those obtained by previous researchers. Overall, the G_{max} and E_{max} values of peat soil obtained range from 0.50 to 1.92 MPa and 1.45 to 5.71 MPa respectively. The G_{max} and E_{max} values obtained shows significant increase with depth governed primarily by the effective stress. Other parameters such as degree of decomposition and peat thickness also shows potential influence on the G_{max} and E_{max} values obtained.

Indexed Terms- Peat soil, shear-wave velocity, primary-wave velocity, stiffness, active MASW, seismic refraction, maximum shear modulus, maximum elastic modulus.

I. INTRODUCTION

Traditionally geophysical method has been used as indirect means of investigating sub-surface features. The application for engineering site investigation has been only marginally successful in engineering site investigations. The reasons include lack of resolution, poor choice of geophysical method and underdevelopment of processing software. However, in recent years rapid development have taken place in geotechnical engineering investigation resulting in application of geophysical methods to provide design parameters. In particular, there is a growing admiration of measuring the small-strain stiffness, using seismic methods [1-5]. There are also increasing correlation between the seismic waves (i.e. V_s and V_p) with geotechnical parameters such as undrained shear strength [6-8], SPT-N value [9], cone penetration parameters [10-13], and 1D compression parameters [13, 14]. The growing interest of geophysical method application in geotechnical investigation has the advantages of not being affected by sampling disturbance and insertion effects. The stiffness parameters obtained in the laboratory were generally low due to sample disturbance [15]. Thus, excessive sample disturbance risk underestimation or overestimation of the geotechnical design. An example of application of stiffness parameters include deformation analyses and ground movements. In soft soil investigation such as peat soil, the effect of sample disturbance was critical due to the presence of fibre and very high water content. The peat soil also has high permeability and low shear strength causing difficulties maintaining high quality undisturbed sample [16]. Application of geophysical method provide alternative way of obtaining the peat soil parameters using field measurement which allows the investigation done in it's natural state. Field measurement allows the mitigation of the effect of sample disturbance caused by boring, tube insertion, extraction, transportation, storage, trimming and reconsolidation [17, 18]. Therefore, the determination of peat soil geotechnical parameters can significantly be improved for better design accuracy.

With the aim of providing helpful geotechnical information to engineers and designers for practical works on peat soil ground, this paper attempted to determine stiffness parameters which include G_{max} and E_{max} values in southern peninsular Malaysia. The G_{max} and E_{max} values were computed using shear-wave velocity (V_s) and primary-wave velocity (V_p) obtained using geophysical methods.

II. MATERIAL AND METHODS

2.1 Overview of peat soil in study locations

Overall there are approximately 2.4 million hectares of peatlands which covers about 7.45 % of Malaysia's total land area. The largest and thickest peatlands are located within the state of Sarawak which is around 69.08 % of the total peatlands in Malaysia [19]. The peat thickness can reach up to 20 m especially in the inland area [20]. The remaining peatlands are located in Peninsular Malaysia and Sabah with total land area of 26.16% and 4.76% correspondingly [19]. The state of Johor in Peninsular Malaysia covers around 143,974 ha of peatlands. The peatlands are mostly distributed near the coastal area (see Figure 1).

The study was conducted at Parit Nipah (PNPt), Pontian (PPt) and Medan Sari (MSPt), in the state of Johor as shown in Figure 1. The locations were chosen as all three sites represent different classification of peat thickness. According to the peat sampler investigation, the peat thickness at Medan Sari, Pontian and Parit Nipah were 1.5 m, 3.0 m and 4.0 m respectively [21]. The peat soil at Medan Sari, Pontian and Parit Nipah were classified as shallow peat (< 1.5m), moderate deep peat (1.5 to 3 m), deep peat (> 3m) correspondingly. The index properties of peat soil in the study areas were as shown in Table 1. Both Pontian and Parit Nipah peat were categorized as hemic peat with Von Post scale of H5 to H6. Similarly, Wahab *et al.* [22] also classified Parit Nipah peat as hemic peat with Von Post scale of H5. While, Medan Sari was grouped as fibric peat according to the fibre content classification by US Department of Agriculture (USDA). The classification however is based on the undisturbed samples obtained approximately 1 m from the surface. There are findings that shows the peat type might change with depth especially at thicker peat soil layer. As mentioned by Huat *et al.* [23] and Ulusay *et al.* [24], peat soil which is categorized as H3 and H4 near the surface, with increasing depth it would be classified as H5 to H7. The moisture content and organic content range from 839.7 to 913.2 % and 76.7 to 96.8 % correspondingly. Higher moisture content recorded at Medan Sari could be due to the lower decomposition rate compared to other locations. As mentioned by Kazemian [25], the more fibrous peat, the higher is the water content. The liquid limit and specific gravity range between 255 to 425 % and 1.24 to 1.34 respectively. The peat soil at the locations were acidic with pH value range between 3.7 to 4.0.

2.2 Multichannel Analysis of Surface Waves (MASW)

The surface waves investigation was conducted using active MASW method. The method is introduced in the late 1990s by researchers at the Kansas Geological Survey (KGS). The entire process involves three steps: acquisition of ground roll, construction of dispersion curve, and backcalculation (inversion) of the V_s profile from the calculated dispersion curve [26]. Three survey lines were investigated at Parit Nipah and Pontian with 5 m offset from each survey line. At Medan Sari, only a single survey line was investigated. The field surveys were conducted using 24 geophones with natural frequency of 4.5 Hz arranged linearly. Figure 2 shows the general field arrangement for the active MASW field survey. The receiver spacing (dx) used was 1 m, producing total spread length (L) of 23 m. Sampling time of approximately 4 s was used with 250 μs sampling interval and 16384 number of samples. A 7 kg sledgehammer was used as active source coupled with rubber plate. The rubber plate was chosen rather than the conventional steel plate to minimized the effect of plate penetrating the soft peat ground during impact and increase the resolution at lower frequencies [27, 28]. The distance of the optimum source offset (X_1) for the peat soil condition obtain from the preliminary investigation was half the total spread length (L/2) which was 11.5 m. Due to the characteristics of peat soil, longer source offset should be prevented due to rapid attenuation of seismic energy which contribute to low signal-to-noise ratio [29]. Park and Shawver [30] also mentioned that, longer source offset ensures the recording of long wavelengths, but results in lack of short wavelength due to excessive attenuation. The source offset distance was important to prevent interference of near and far-field effects which results in either overestimation or underestimation of measurements [31]. Five stackings were used for each dataset to increase the signal-to-noise ratio and suppress the ambient noise. The data obtained were processed using the SeisImager and WaveEq softwares.

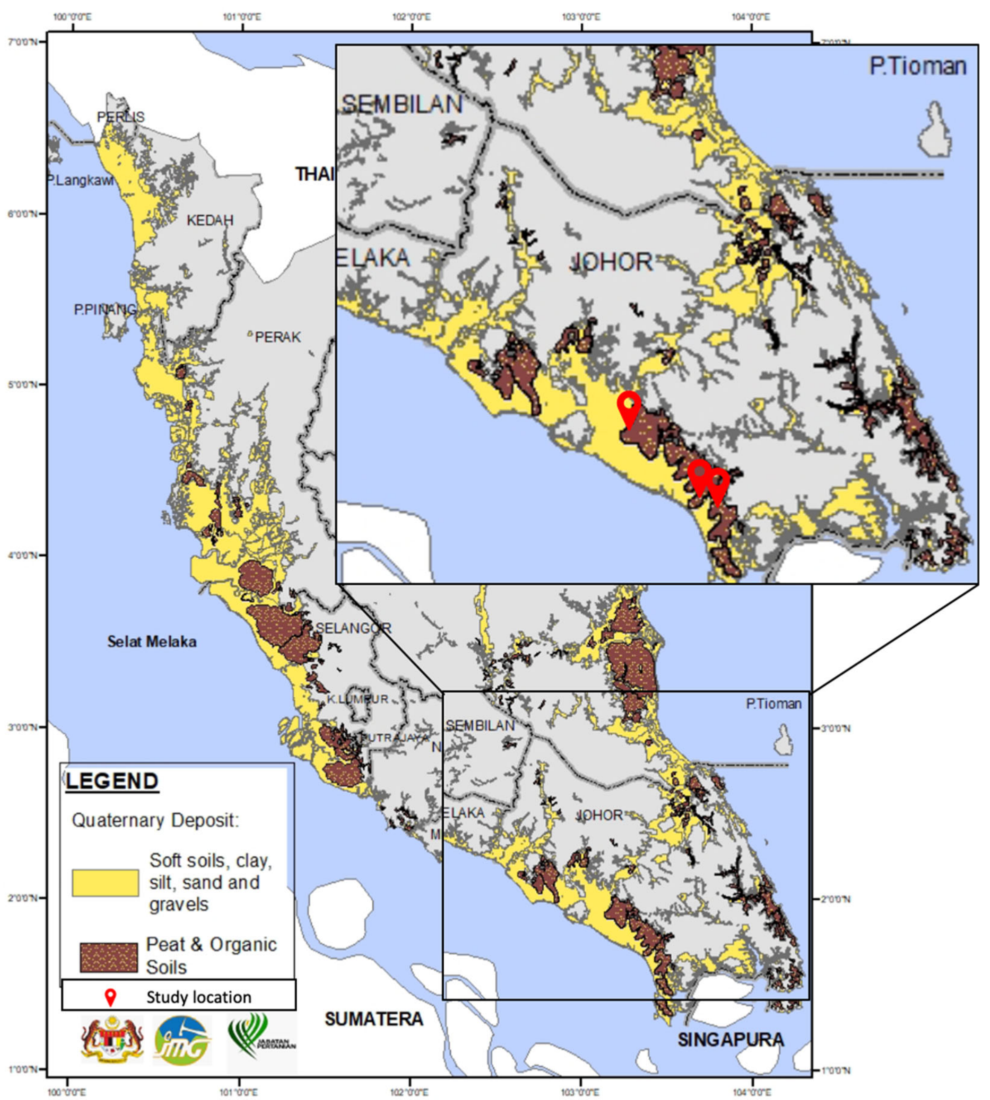

Figure 1: Geological map of the study area [32]

The shear-wave velocity (V_s) profiles obtained were than computed using Equation 1 to estimate the maximum shear modulus (G_{max}) value of peat soil at low strain levels (<0.001%). The bulk density (ρ) was obtained using the peat sampler equipment. It was recorded for every 0.5 m interval until the peat soil layer ends. The procedures of the peat sampler investigation follows the peat sampler operating instruction [33].

$$G_{max} = \rho V_s^2 \quad (1)$$

Where, ρ is bulk density, V_s is shear-wave velocity and G_{max} is maximum shear modulus.

Table 1: Index properties of peat soil at Parit Nipah, Pontian and Medan Sari, Johor

Properties	PNPt	PPt	MSPt
Moisture content (%)	839.7	898.9	913.2
Liquid limit (%)	345	255	425
Organic content (%)	81.8	76.7	96.8
Specific gravity	1.34	1.28	1.24
Fibre content (%)	47.6	43.6	73.9
pH	4.0	3.7	-
Von post scale	H6	H5	-
Peat type	Hemic	Hemic	Fibric
References	Author	Zainorabidin and Zolkefle [34]	Author

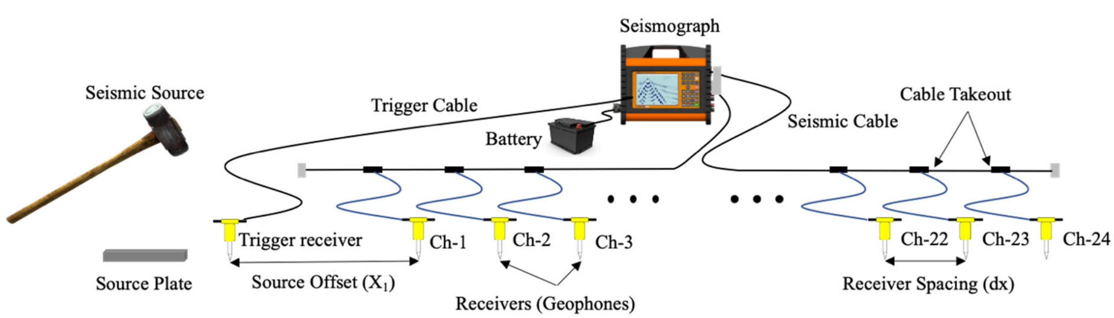

Figure 2: General field arrangement for active MASW survey

2.3 Seismic Refraction

The seismic refraction surveys were conducted only at Parit Nipah and Pontian. The field arrangements and equipment were similar as the active MASW method. However, some field parameters were changed which include the geophone sensors, impact source location and recording time. Higher natural frequency geophones which is 28 Hz were used instead of 4.5 Hz to allow recording of higher frequencies. The seismic refraction survey also requires 7 shot point locations, compared to a single shot point in active MASW method. The locations of the shot point are at both offsets, between 1st and 2nd, 6th and 7th, 12th and 13th, 18th and 19th and 23rd and 24th geophone. The sampling interval time and number of samples used were 500 μs and 2048 respectively, resulting a total recording time of 1.2 s. Shorter recording time was used compared to active MASW method as only the first arrival was needed for the data processing of seismic refraction method. The data obtained were processed using Pickwin and Plotrefa modules.

The data process using the software mentioned results in a 2-Dimensional primary-wave velocity (V_p). However, a 1-Dimensional primary-wave velocity was required for the computation of Poisson's ratio and maximum elastic modulus using Equation 2 and Equation 3. Therefore, a 1-Dimensional primary-wave velocity profiles were extracted from the midpoint of each survey lines. The midpoint of the survey line was chosen as all the other parameters were also extracted at similar location.

$$\nu = 0.5\left[\frac{\left(\frac{V_p}{V_s}\right)^2 - 2}{\left(\frac{V_p}{V_s}\right)^2 - 1}\right] \quad (2)$$

$$E_{max} = 2G_{max}(1 + \nu) \quad (3)$$

Where, ν is Poisson's ratio, V_p is primary-wave velocity and E_{max} is maximum elastic modulus

III. RESULTS AND DISCUSSION

3.1 Shear-wave velocity and primary-wave velocity profiles of peat soil

The shear-wave velocity (V_s) of peat soil obtained using active MASW method at all locations were as shown in Figure 3. There were three V_s profiles each for Parit Nipah and Pontian, including a single V_s profile for Medan Sari. Overall, the V_s values determined were very low which could be governed by the characteristics of peat soil which include very high water content, high organic content, high compressibility and low shear strength [35]. The graph also shows that, the V_s values of peat soil increases only slightly from the surface up until about 1 m before the transition layer to marine clay, where the V_s values increase significantly. This behaviour could be attributed by the low bulk density and high water table on peat soil. As mentioned by Huat [36], there is only slight tendency for an increase in peat soil strength with depth due to very low bulk density and high water table. The peat soil profiles obtained using peat sampler at all locations revealed that the highest bulk density of peat soil determined was only 1430 kg/m^3, while the water table was approximately 0.5 m from the surface. The peat soil profiles also delineated that the peat soil near the surface was less humified compared to peat soil at deeper depth. Thus, the V_s values of peat soil were expected to decrease with depth as lesser humified peat soil layer have greater strength and much more stiff compared to highly humified peat soil layer, thus, giving higher V_s value [17, 25, 37]. However, the graph shows otherwise as the V_s values shows increasing trend with depth. This behaviour could be governed by the increase of effective stress with depth. As the V_s value increases with the increase of effective stress [14]. This condition suggests that the in-situ V_s value was primarily governed by the effective stress rather than the degree of decomposition rate. While, the sudden significant increase near the transition layer could be governed by the rapid increase in effective stress approaching the marine clay layer.

The influence of decomposition rate was further investigated by comparing the peat soil V_s value of hemic peat (Parit Nipah and Pontian) and fibric peat (Medan Sari). The results exposed that the V_s values at Medan Sari peat were slightly higher compared to Pontian peat, which in good agreement with the previous assumptions where lesser humified peat soil has higher V_s value. The higher V_s values could be governed by fresh (intact) fibres in lesser humified peat compared to completely decomposed (amorphous) material in more humified peat [38]. As mentioned by Sarkar and Sadrekarimi [39], strength of peat is largely associated with the presence of organic fibres. However, the V_s values of Parit Nipah peat soil was slightly higher compared to Pontian and Medan Sari which raised speculation that the peat thickness could also affect the V_s value determined. The results however were very limited to fully understand the influence of decomposition rate and peat thickness on the generated V_s value. Overall, the effective stress shows more prominent influence on the generated V_s value of peat soil with depth. The V_s value obtained for Parit Nipah, Pontian and Medan Sari were range from 28.7 to 33.9 m/s, 25.4 to 36.6 m/s and 27.3 to 34.2 m/s.

The seismic refraction investigation allowed the determination of primary-wave velocity (V_p). The 2-Dimensional V_p profiles obtained from the investigation were further analysed by extracting the 1-Dimensional V_p profiles on the centre line. For this investigation, only Parit Nipah and Pontian peat soil were included with three V_p profiles for each location. Figure 4 shows the V_p profiles obtained on both locations. Generally, the V_p values increases slightly with depth for both locations. This behaviour was governed by the increasing effective stress and decreasing void ratio of peat soil with depth. As mentioned earlier, peat soil layer at deeper depth was more humified compared to the peat soil layer near the surface. According to Kazemian [25], the more fibrous the peat soil, the higher the void ratio. This suggest that the void ratio of peat soil decreases with depth which contribute to increases in V_p value with depth. While, slightly lower V_p values were recorded near the surface which was due to the layer was on top of the ground water table. The measured ground water table on both locations were approximately 0.5 m from the surface. According to Foti [3], other than the soil skeleton, the V_p value was more influence by the compressibility of the pore fluid. This suggest that dry peat soil have lower V_p value than saturated peat soil. Furthermore, approaching the transition layer to marine clay, the V_p values increases significantly. This behaviour was similar with the trend shown by the V_s value which suggest that the effective stress at the transition layer increases drastically shown by the rapid increase in both V_s and V_p value. Overall, the V_p value obtained for Parit Nipah and Pontian range from 99.1 to 291.6 m/s and 98.2 to 244.1 m/s correspondingly,

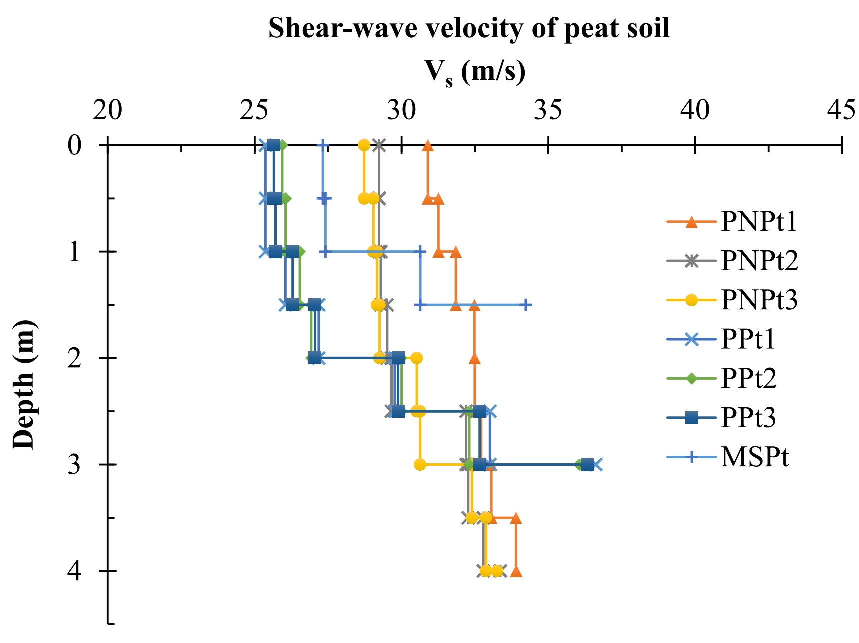

Figure 3: Shear-wave velocity profiles of peat soil at Parit Nipah, Pontian and Medan Sari

3.2 Maximum shear modulus and maximum elastic modulus profiles of peat soil

The stiffness parameters which include the maximum shear modulus (G_{max}) and maximum elastic modulus (E_{max}) were determined using geophysical investigation combine with mathematical equations. The maximum shear modulus (G_{max}) was obtained through the relationship between the shear-wave velocity and bulk density as shown in Equation 1. While, the maximum elastic modulus (E_{max}) was obtained by the relationship of Poisson's ratio and G_{max} as described in Equation 3. The Poisson's ratio was generated by Equation 2 by the relationship between V_s and V_p values. The bulk density of peat soil was obtained using peat sampler at the midpoint of the survey lines at all locations. The bulk density of peat soil at Parit Nipah, Pontian and Medan Sari range from 734 to 1255 kg/m^3, 770 to 1430 kg/m^3, and 1100 to 1330 kg/m^3 respectively. The bulk density was obtained at the midpoint of the survey line because the generated V_s value was also located at similar location. As mentioned by Luo *et al.* [40], the inverted 1-Dimensional V_s profile should be located at the midpoint of the survey line. Figure 5 and Figure 6 summarizes the G_{max} and E_{max} values of peat soil at Parit Nipah and Pontian. Overall, the graph shows slight increases of G_{max} and E_{max} values with depth on both locations. Similar finding was obtained by Abbiss [1] and Donohue *et al.* [41], where the stiffness modulus tend to increase with depth. Slight variations were also observed especially on the top 1 m which could be due to the heterogeneity of peat soil. The variations however were small and negligible as clear increasing pattern with depth was observed. The degrading effects and increases of decomposition rate with depth also contributed to the increasing G_{max} and E_{max} values with depth. According to Matthews *et al.* [42] and Kishida *et al.* [43], degrading effect of weathering, decrease in organic content, increase in effective stress and stress relief will generally cause the G_{max} and E_{max} values to increase significantly. The G_{max} values obtained for Parit Nipah and Pontian range from 0.63 to 1.40 MPa and 0.50 to 1.92 MPa respectively. While, The E_{max} values were ranging from 1.82 to 4.17 MPa and 1.45 to 5.71 MPa for Parit Nipah and Pontian correspondingly.

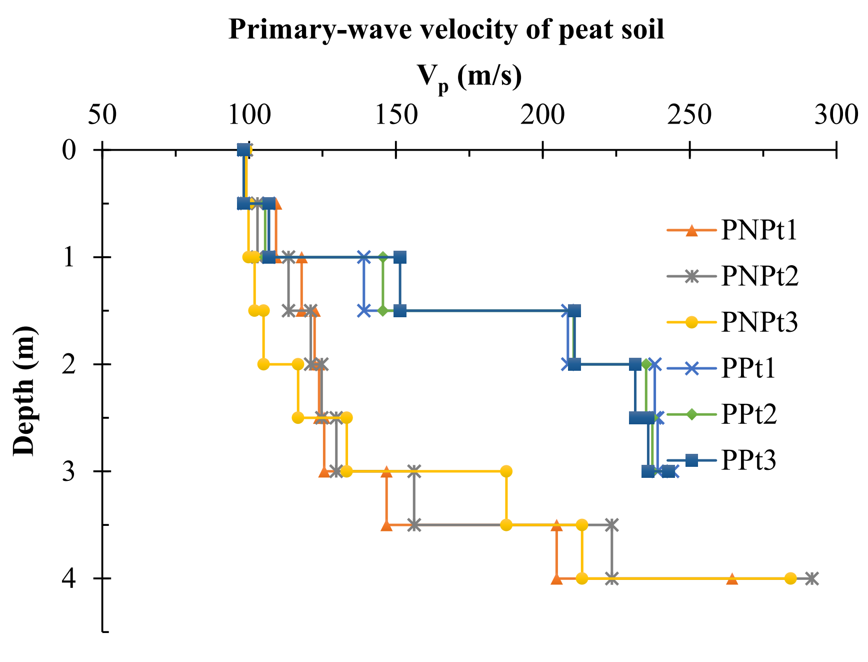

Figure 4: Primary-wave velocity profiles of peat soil at Parit Nipah and Pontian

IV. CONCLUSIONS

The application of geophysical methods for the determination of stiffness parameters such as the G_{max} and E_{max} values shows promising findings. The ability of the geophysical methods to investigate the geotechnical parameters in-situ eliminates the risk of sample disturbance commonly face for laboratory

Maximum shear modulus (G_{max}) value of peat soil

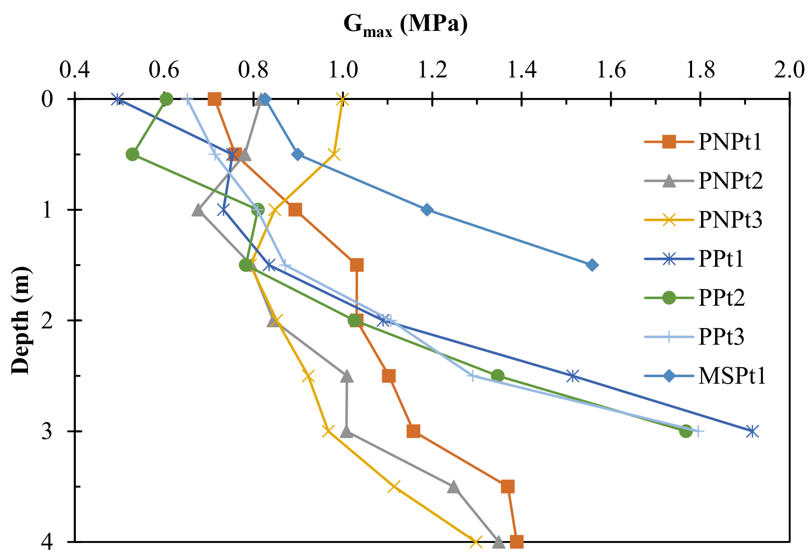

Figure 5: Maximum shear modulus profiles of peat soil at Parit Nipah, Pontian and Medan Sari

Maximum elastic modulus (E_{max}) value of peat soil

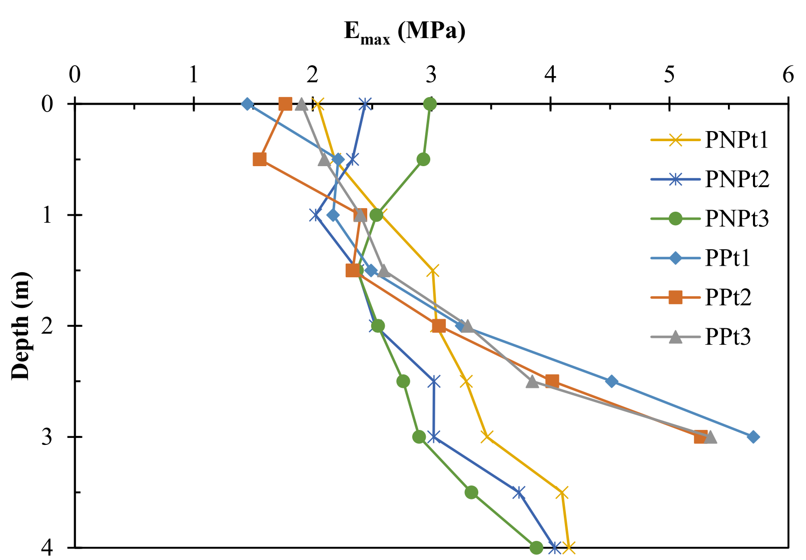

Figure 6: Maximum elastic modulus profiles of peat soil at Parit Nipah and Pontian

investigation. Problems usually encountered includes boring, tube insertion, sample extraction, transportation, storage, trimming and reconsolidation. The presence of fibre in peat soil further complicates the sample retrieval as the peat fibres usually interfere during tube insertion causing major sample disturbance. The excessive loss of water content also could affect the results as peat soil was well known to store very high water content. Although, there were still very limited data obtained, it is expected that these data could provide quantitative information for geotechnical applications or act as a preliminary data for further investigation on peat soil. Correlation between the seismic parameters with geotechnical parameters were also possible with the database obtained. Overall, the stiffness parameters of peat soil increase significantly with depth governed by the increase in effective stress. Furthermore, the change of decomposition rate with depth and different peat thickness also shows potential influence on the stiffness parameters of peat soil. However, further investigation was required to fully understand the effect of decomposition rate and peat thickness on peat soil stiffness value. Nonetheless, geophysical method provides sustainable investigation method due to its non-intrusive nature for investigation on peat soil.

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Nomenclature:

MASW	Multichannel Analysis of Surface Waves
V_s	Shear-wave velocity
V_p	Primary-wave velocity
G_{max}	Maximum shear modulus
E_{max}	Maximum elastic modulus
ρ	Bulk density
ν	Poisson's ratio

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