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Determining the peat soil dynamic properties using geophysical methods

K. Basri*[a], A. Zainorabidin[a], H.M. Mohamad[b], B. Musta[b]
[a] Universiti Tun Hussein Onn Malaysia, Johor, Malaysia
[b] Universiti Malaysia Sabah, Sabah, Malaysia
*E-mail: hf170042@siswa.uthm.edu.my

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Abstract. The small strain dynamic properties of peat soil are a fundamental parameter related to the mechanical behaviour of a structure constructed on peat ground. These parameters are used in evaluation of the dynamic behaviour and seismic design in geotechnical structures. Determination of dynamic properties of peat soil is often done using laboratory-based tests that risk overestimation and underestimation due to sample disturbance. Since geophysical methods are proven to be able to obtain small strain dynamic properties with similar magnitude as the laboratory tests, it has become popular and is increasingly used in practice. Two geophysical methods known as multichannel analysis of surface waves (MASW) and seismic refraction were performed in this study to estimate the small strain maximum shear modulus ($G_{\max}$) and maximum elastic modulus ($E_{\max}$). The results showed the value of $G_{\max}$ and $E_{\max}$ were ranging from 1.01 to 6.83 MPa and from 3.88 to 10.9 MPa respectively. Correlations were also established to assist in estimating $G_{\max}$ and $E_{\max}$ on peat soil with bulk density. There appears to be a particularly good link between the $G_{\max}$, $E_{\max}$ and bulk density. Overall, the small strain dynamic properties determined shows significant increment with depth which could be governed primarily by the effective stress. Other parameters such as water content, bulk density, organic content and degree of decomposition also could significantly influence the dynamic properties of peat soil.

1. Introduction

The foundation vibrations analysis and the investigation of geotechnical earthquake engineering problems in civil engineering require the characterization of dynamic properties using geophysical methods. Dynamic soil properties are also important on dynamic structural analysis of the superstructure as the knowledge on the dynamic response of the soil structure is critical. According to L'Heureux and Long [1], the application of dynamic soil properties includes site characterization, seismic hazard analyses, settlement analysis, site response analysis, design application and soil-structure interaction. Geophysical methods are often used in the characterization of the subsurface dynamic soil properties as these methods focused on the very low strain tests that are not large enough to induce significant non-linear and non-elastic stress strain behaviour [2]. Multichannel analysis of surface waves (MASW) and seismic refraction had been increasingly popular among other geophysical methods due to the simplicity and non-destructive nature. MASW and seismic refraction method had been used to determine the soil's compression and shear wave velocities, as well as the soil's elastic and shear moduli which are the key stiffness parameters in the prediction of the response of soil and soil-structure systems to dynamic loading. The determination of stiffness parameters for deformation analyses also is one of the most important aspects of geotechnical engineering [3]. Despite the importance of these parameters, very limited studies are reported especially for soft soil such as peat soil. Most of the studies are laboratory-based test which includes triaxial and resonant column test [4–10]. Studies using geophysical methods are limited to SASW method [11], PS

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logging [12], MASW method [13, 14]. However, in recent years, the application of geophysical methods on soft soil such has peat soil had grown rapidly due to the challenges in obtaining high quality samples for laboratory test.

Investigation of peat soil small strain dynamic properties presents geotechnical engineers and researchers with many challenges arising from their problematic behaviour which includes, high compressibility, high organic content, high water content and relatively low shear strength [15]. Laboratory-based method required sampling of peat soil using tube and brought to the laboratory to be tested. This method raised major doubt on the risk of sample disturbance contributed by the peat soil characteristics. The laboratory testing also associated with the inability to reproduce the actual ground conditions (i.e. stress levels), heterogeneity and anisotropy of peat soil [16]. According to Matthews et al. [3], low stiffness values measured in the laboratory were generally attributed to sample disturbance. Thus, compared to laboratory-based tests, field measurement using geophysical methods provide alternative to measure the peat soil in its natural state. According to Seed and Idris [4] and Sauvin et al. [17], field measurement mitigates the effect of sample disturbance caused by boring, tube insertion, extraction, transportation, storage, trimming and reconsolidation.

With the aim of providing helpful information to designers and engineers for practical works on the dynamic properties of peat soil ground, this paper attempted to establish data on the maximum shear modulus ($G_{\max}$) and maximum elastic modulus ($E_{\max}$) of peat soil in Klias, Beaufort, Sabah. The shear-wave velocity (V_s) and primary-wave velocity (V_p) used to estimate the $G_{\max}$ and $E_{\max}$ are obtained using geophysical methods.

2. Methods

2.1. Overview of Sabah's peat soil

In Malaysia there are 2.4 million hectares of peat soil which is 7.45 % of Malaysia's total land area. Approximately 116, 965 ha were located in the state of Sabah. The Klias Peninsula and Kinabatangan-Segama Valleys contributed most of the peat areas. Fig. 1 shows the geological map for the location of the study, which is located near the Klias Forrest Reserve, Beaufort. As can be seen on the geological map, the peat deposits are found mainly in lowland area where the conditions are favourable for peat formation. Historically the Klias Peninsula supported 60, 500 ha of peat swamp forest, but in 2003, only 5, 500 ha remained [18]. The Klias forest Reserve contains approximately 3,630 ha of peat swamp forest and the remaining 1, 870 ha in Binsuluk Forest Reserve [19]. The Klias Peninsula peat swamp forest is the largest remaining piece in the Northern end of Borneo Island with peat layer as thick as 14 m [18]. While at Kinabatangan Valley, peatland forest comprise of 17, 155 ha and about 5, 000 ha between Batu Puteh and Bilit [19]. Sabah peatlands are tropical peat mainly discovered in a thick waterlogged that made up in decaying plant materials. The peat characteristics provides challenges especially from the engineering perspective as it is made up of mostly by decaying plant materials. Tropical fibrous peat causes the highest settlement followed by hemic and sapric peat when subjected to a load over a period of time [20].

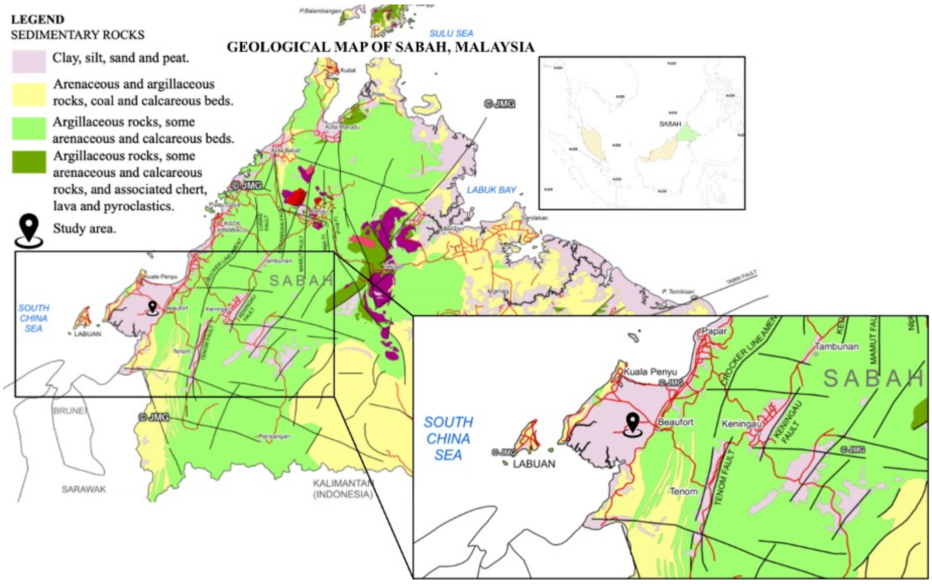

Figure 1. Geological map of the study area.

Table 1 summarizes some of the index properties for peat soil at Beaufort, Sabah. Overall, the peat type in the area are mostly hemic with Von Post classification of H6. However, some area with shallow peat (< 3 m) was categorized as fibric peat with Von Post scale H7. The classification also further supported by the fiber content value range from 61.61 to 79.4 %. As peat is classified into three groups according to their fibre content known as Sapric (< 33 %), Hemic (33–66 %) and Fibric (> 66 %) by US Department of Agriculture (USDA) classification. The water content recorded was among the highest ever recorded with almost 1000 %. The liquid limit and organic content range from 169.0 to 299.5 % and 53.97 to 95.82 % respectively. The peat soil is considered very acidic with pH value range between 4.0 and 4.9.

Table 1. Index properties of Beaufort, Sabah peat soil [21–23].

Properties	Value
Moisture content (%)	448.32 – 985.4
Liquid limit (%)	169.0 – 299.5
Organic content (%)	53.97 – 95.82
Specific gravity	1.25 – 1.44
Fibre content (%)	61.61 – 79.4
pH	4.0 – 4.9
Von post scale	H6 – H7
Peat type	Hemic – Fibric

2.2. Field survey

The study area was located in west Sabah within the Beaufort district that contain large area of peat soil. The location was as shown in Fig. 1. Three stations labelled as S1, S2 and S3 were investigated in the same area. Peat sampler investigation on all three stations revealed that the peat soil depth were 3.5 m, 5.4 m and 6.8 m for S1, S2 and S3 respectively. Thus, all the data obtained were limit to the depth of peat soil recorded as the main focused of this study is to study the peat dynamic properties. Two geophysical methods known as MASW method and seismic refraction were used to obtain the shear-wave velocity (V_s) and primary-wave velocity (V_p). The survey lines of the MASW method and seismic refraction were ensured redundant to allow comparison and correlation between both values. The in-situ V_s measurement was carried out at all stations. While, the V_p measurements were only conducted at S1 and S2. In addition, the peat soil density was collected for every 0.5 meter until peat soil layer ends using the peat sampler at all stations. The maximum shear modulus ($G_{\max}$) was obtained using Equation 1 from the relationship between V_s and bulk density. The relationship between V_p, V_s and ν was used to compute the maximum elastic modulus ($E_{\max}$) using Equation 2 and 3.

$$G_{\max} = \rho V_s^2 \tag{1}$$

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

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

$$E_{\max} = 2G_{\max}\left(1+\nu\right) \tag{3}$$

where ν is Poisson’s ratio, V_p is primary-wave velocity and $E_{\max}$ is maximum elastic modulus.

The MASW method and Seismic Refraction were conducted using ABEM Terraloc Pro II. The survey was planned for the dynamic properties determination with maximum depth ($Z_{\max}$) less than 10 m. Because the investigation was shallow in depth, a receiver spacing (dx) of 1 m with 24-channel acquisition system was adopted as the configuration seemed optimal to ensure the $Z_{\max}$ (> 10 m). A 14 Hz frequency of receiver sensor was used for both methods. The source offset (X_1) was fixed at half the total spread length to prevent interference of near-field and far-field effect. As the near-field and far-field effect results in either underestimation or overestimation of measurement [24]. Due to the characteristics of peat soil, which is very soft and high void ratio, weak seismic energy is expected. As mentioned by Said et al. [25], high attenuation in peat soil causes low signal-to-noise (S/N) ratio which lead to difficulties of data interpretation and processing. Thus, 5 stackings were used for every measurement to ensure sufficient seismic energy recorded and high S/N ratio data. Finally, the data obtained was processed using SeisImager and Plotrefa software.

3. Results and Discussion

3.1. Multichannel Analysis of Surface Waves (MASW)

The V_s profiles were determined using the MASW method. Three survey lines were investigated at three different stations marked S1, S2 and S3. The V_s profiles for all three points are shown in Fig. 2. Broadly speaking the V_s profiles can be divided into two layers. The first layer shows the decreasing value from the surface up to 2 meters. While the second layer shows significant increase with depth especially at depth greater than 3 meters. The slight drop in V_s value on the first layer was likely due to the change in decomposition rate of peat soil with depth. Based on the observation made on the peat profile obtained using the peat sampler, the peat soil shows the increasing decomposition rate with depths. As mentioned by Huat et al. [26] and Ulusay et al. [27], peats near the surface are less humified and with increasing of depth it became more humified. Lesser humified peat is more fibrous, and is likely to have greater strength than more humified peat at depth [28]. Thus, greater strength generally means higher stiffness and in turn higher V_s [4]. The slight variation of the V_s value on the first layer also could be contributed by a larger percentage error in timing over short distances or extreme variability of the material [29]. While on the second layer, the significant increase of V_s value with depth was primarily governed by the increase in effective stress. According to L'Heureux and Long [30], there was clear tendency of V_s to increase with effective stress. Comparison between all three stations shows lower V_s value especially on the top 3 meters at S3 compared to S1 and S2. As mentioned earlier, the peat soil depth at S3 was the thickest among all 3 stations which might suggest that thicker peat layer tend to result in lower V_s value near the surface (< 3 m). Overall, the V_s value determined for Klias peat soil range from 34.9 to 35.6 m/s, 34.4 to 49.0 m/s and 33.3 to 66.0 m/s for S1, S2 and S3 respectively.

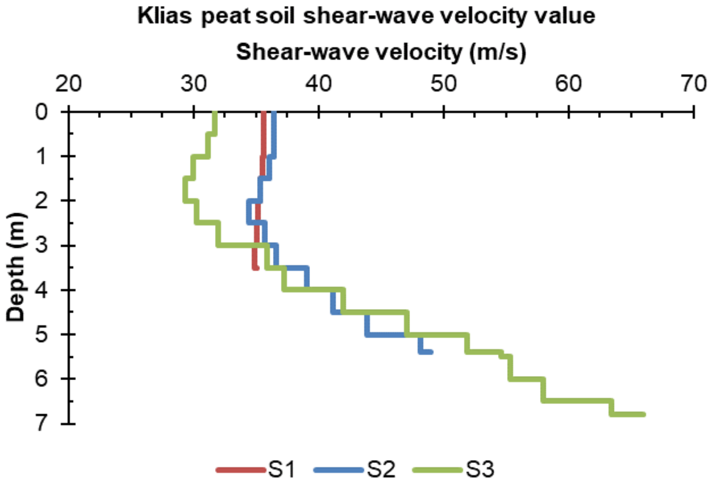

Figure 2. V_s profile of Klias peat soil.

3.2. Seismic refraction

The seismic refraction method is well suited for soil dynamics and earthquake engineering for general site investigation. This method determined the elastic wave velocities of a layered soil profile. The wave velocities and thickness of each layer are determined as long as the wave velocities increase with successively deeper layer. The V_p value was determined using seismic refraction. Two survey lines were investigated at a similar location as the MASW method with the exception of the S3. Fig. 3 shows the results obtained for the V_p value at Klias peat soil. Overall, the V_p value at both locations showed slight increases up to 3 meters depth. At the depth more than 3 meters the value increases more rapidly compared to the previous. The behavior observed was similar to the V_s profiles. The increase was primarily governed by the increases effective stress and decreasing void ratio [30]. The V_p value for peat obtained range from 316.7 to 335.5 m/s and 357.4 to 497.4 m/s for S1 and S2 simultaneously.

3.3. Comparison between V_s and V_p values

High accuracy determination of V_s and V_p value is important to allow estimation of $G_{\max}$ and $E_{\max}$ value accurately. According L'Heureux et al. [16] to geophysical method profiling has the advantage of to be able to obtain interval velocity accurately. This is important as inaccurate determination of V_s and V_p value will significantly affect the estimation of $G_{\max}$ and $E_{\max}$ value. As mentioned by L'Heureux and long [30], approximately 30 % of $G_{\max}$ and $E_{\max}$ value error will be contributed by 20 % error in V_s and V_p value used. Fig. 4 shows the comparison between the V_s and V_p value of Klias peat soil. From the graph, both V_s and V_p value behave differently at the top 3 meters where the V_s value was found decreasing and increasing simultaneously with depth. While, the V_p value increase slightly with depth and become significant at depth greater than 3 m. According to Foti et al. [31], the compressibility of the pore fluid strongly influenced the propagation of V_p compared to the soil skeleton. While, the propagation of V_s is linked to mass density rather than the pore fluid as it has no shearing resistance. This explained the fluctuating of V_s on the top 3 m as the dry peat soil had a lower mass density compared to saturated peat soil. As for the V_p, the slow increment was governed by the low compressibility of peat soil pore fluid especially for the top 3 m. Approaching the transition of soft clay layer the V_p increases drastically due to the effect of the high compressibility of the pore fluid of soft clay. Generally, the significant increase for both V_s and V_p value at depth greater than 3 m was likely due to the increment of effective stress. This finding suggests that for peat soil, the influence of the effective stress to the V_s and V_p value become significant only at depth greater than 3 meters. Although there was some drift in the results obtained especially for the top 3 m, the difference was extremely small and negligible.

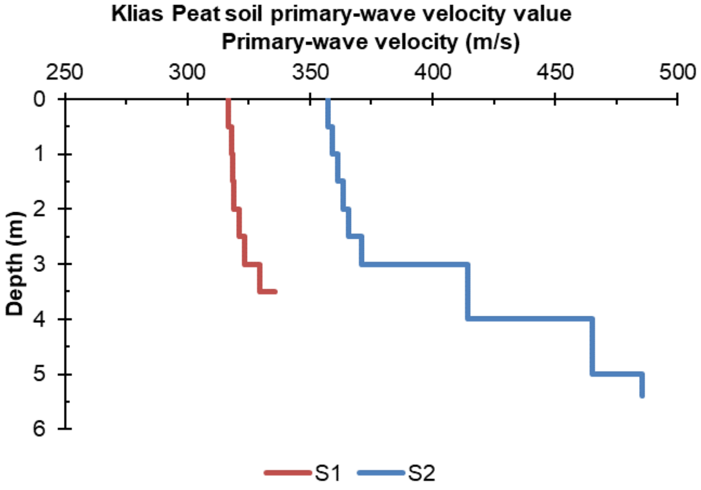

Figure 3. V_p profile of Klias peat soil.

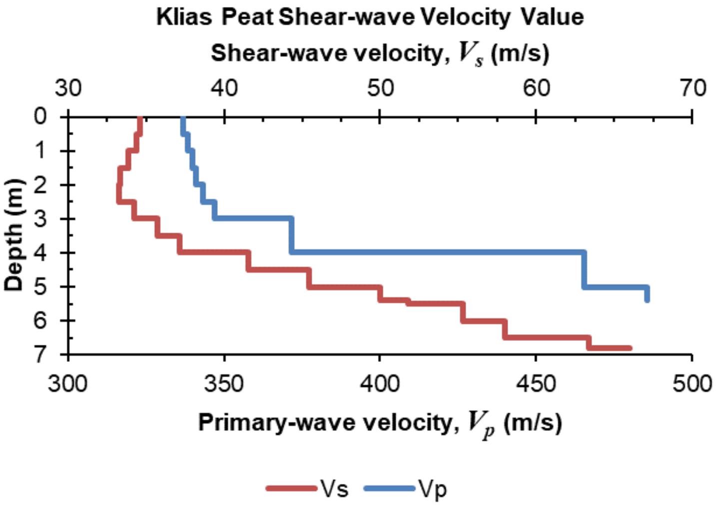

Figure 4. V_s and V_p value of Klias peat soil.

The V_s value obtained on Klias peat soil are plotted against V_p value in Fig. 5. The results show an increase in V_s with increasing V_p. The best fit is given by Eq. 4 with regression coefficient (R^2) of 0.80.

$$V_p = 12.144 V_s - 85.281 \tag{4}$$

Equation 4 can also be used to assess V_s from V_p measurements by rewriting the relationship and solving for V_s as follow:

$$V_s = \frac{V_p + 85.281}{12.144} \tag{5}$$

Combining the V_s and V_p value obtained, a relationship between both values was established for estimation of V_s or V_p value when either value was not available. The relationship showed good potential with the R^2 value determined at 0.80.

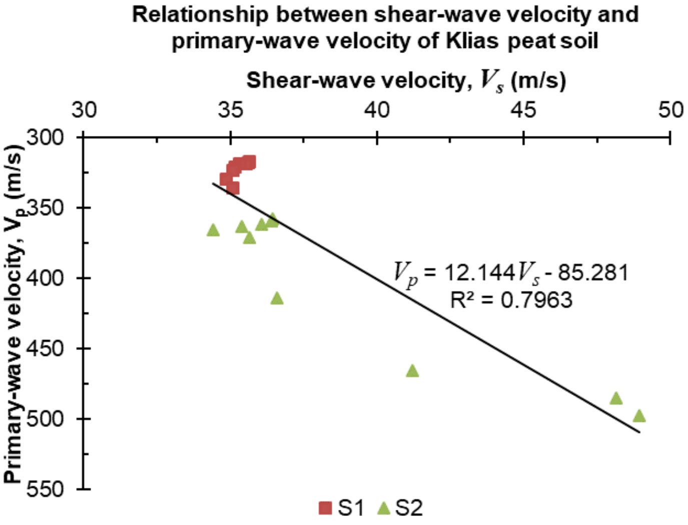

Figure 5. Relationship between V_s and V_p of Klias peat soil.

3.4. Maximum shear modulus ($G_{\max}$) and maximum elastic modulus ($E_{\max}$)

The relationship between V_s and density was used to compute maximum shear modulus ($G_{\max}$) as shown in Equation 1. While, the relationship between V_p and V_s was used to obtain the Poisson's ratio (υ) for peat soil which was then used to compute maximum elastic modulus ($E_{\max}$) using Equation 2 and Equation 3 simultaneously. The density of Klias peat soil range from 1071.7 to 1466.6 kg/m^3, 976.3 to 1521.9 kg/m^3 and 1005.8 to 1529.4 kg/m^3 for S1, S2 and S3 respectively. Fig. 6 and Fig. 7 presents the $G_{\max}$ and $E_{\max}$ value for Klias peat soil. Overall, the $G_{\max}$ and $E_{\max}$ value shows significant increase with depth especially at depth greater than 3 meter which similarly observed on V_s and V_p value. Similar conclusion was made by Abbiss [29] and Donohue et al. [31] which concluded that stiffness modulus tend to increase with depth. Minimum changes on the top 3 meters was likely due to the minimum changes in effective stress contributed by the very high-water table and low bulk density on-site. The water table measured on-site was approximately 0.8 m. According to Huat [33], there may not be a discernible increase of strength within the depth of the peat layer between 0.5 to 4 m due to low bulk density and high water table which implies low effective pressure. Thus, in this case the top 3 m of peat layer has low effective pressure which lead to lower stiffness. While, the significant increase of $G_{\max}$ and $E_{\max}$ value at depth greater than 3 m primarily governed by the increase in effective stress. As mentioned by Matthews et al. [34], stiffness of near-surface materials significantly increases with depth due to increases in effective stress and the degrading effects of weathering and stress relief. The increase in $G_{\max}$ and $E_{\max}$ value could also be attributed by the decrease in organic content. As mentioned by Kishida et al. [35], the decrease in organic content will generally cause the $G_{\max}$ and $E_{\max}$ value to increase. The $G_{\max}$ obtained were ranging from 1.36 to 1.80 MPa, 1.30 to 3.65 MPa and 1.01 to 6.83 MPa for S1, S2 and S3 respectively. The value showed good agreement with previous study which obtained $G_{\max}$ range from 1.5 to 12.3 MPa using laboratory based method [36]. While, the $E_{\max}$ value range from 4.07 to 5.39 MPa and 3.88 to 10.9 MPa for S1 and S2.

Comparison between the in-situ dynamic properties with laboratory-based dynamic properties by previous studies found that the values were in good agreement. Matthews et al. [34] found that the dynamic properties determined using oedometer and triaxial shows good agreement with the geophysical method, and the previous assumption that the value will be differs at least one magnitude seems incorrect. Clayton and Heymann [37] compared the measurement of dynamic properties between triaxial test and geophysical method and found the value to be almost similar. Kishida et al. [38] also found that the there is good agreement between the dynamic properties obtained in the laboratory using triaxial and from the field using geophysical method. Thus, the dynamic properties profile established on Klias peat soil using geophysical method could be safely used although comparison with any laboratory-based tests was still not available. The dynamic properties values obtained also was in good agreement with several studies includes Hayashi et al. [36], Zainorabidin and Said [14], Basri et al. [13], Zolkefle et al. [39] and Zainorabidin and Wijeyesekera [40]. This affirmed that the dynamic properties obtained using geophysical methods could be used to determine geotechnical parameters with relatively high accuracy.

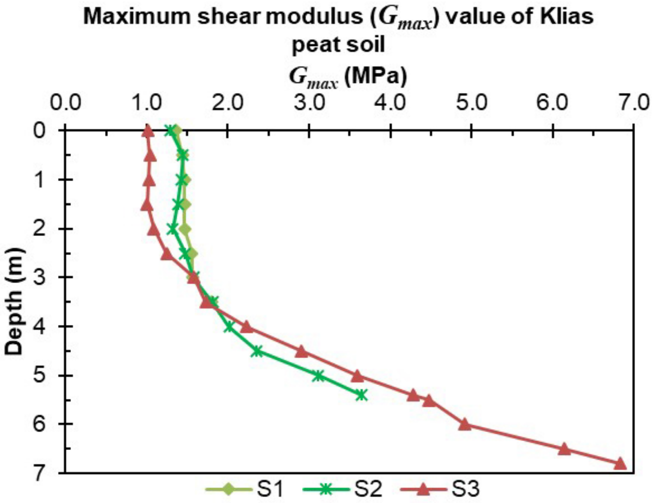

Figure 6. G_{max} value of Klias peat soil.

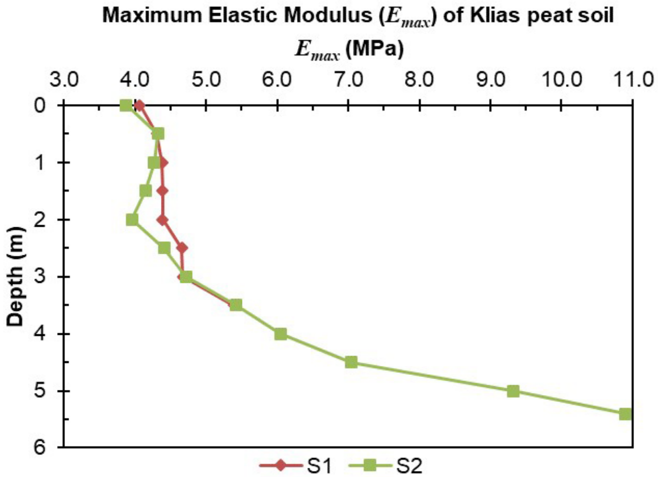

Figure 7. E_{max} value of Klias peat soil.

Fig. 8 and Fig. 9 show the relationship between the $G_{\max}$ and $E_{\max}$ value with the density value. The relationship was made to allow estimation of either density, $G_{\max}$ or $E_{\max}$ value when limited data available. Both $G_{\max}$ and $E_{\max}$ values show an increase with increasing density. The best fit is given by Equation 6 and Equation 7 with regression coefficient (R^2) of 0.83 and 0.72 respectively.

$$\rho = 241.71 \ln\left(G_{\max}\right) + 1072 \tag{6}$$

$$\rho = 341.57 \ln\left(E_{\max}\right) + 634.06 \tag{7}$$

Where, ρ is density, $G_{\max}$ is maximum shear modulus and $E_{\max}$ is maximum elastic modulus.

4. Conclusions

The limited existence of dynamic properties of peat soil especially for Sabah's peat soil and risk of overestimation and underestimation of those values determined using laboratory tests initiated the need of investigation using geophysical methods. Therefore, a study was conducted to determine the V_s and V_p value to be used to estimate the dynamic properties of peat soil. The application of geophysical methods known as MASW method and seismic refraction allowed the determination of these parameters in its natural state and mitigate the risk of sample disturbance. In addition to providing stratigraphic information, V_s and V_p value yield quantitative information that can be used directly for geotechnical applications. The flexible system provides consistent results for characterizing the spatial and vertical variabilities of peat soil (up to about 6.8 m thick). Although there was still very limited data obtained, the data can have an important impact on future development on peat soil ground especially in Sabah. The database obtained was expected to assist geotechnical engineers in understanding peat soil dynamic behaviour. Overall, V_s, V_p, $G_{\max}$ and $E_{\max}$ shows consistent increase with depth governed primarily by the increment of effective stress. The V_s and V_p value for Klias peat soil range from 33.3 to 66.0 m/s and from 316.7 to 497.4 respectively. The $G_{\max}$ obtained were ranging from 1.01 to 6.83 MPa and $E_{\max}$ value range from 3.88 to 10.9 MPa. Some empirical correlations between in situ V_s and V_p with the $G_{\max}$, $E_{\max}$ and density were also developed. The relationship showed good potential with high regression coefficient value. Note that the relationship presented herein can be used either to evaluate $G_{\max}$ and $E_{\max}$, or the way around to evaluate density. The recommendations presented also should be used in conjunction with the engineer's own experiences and engineering judgement.

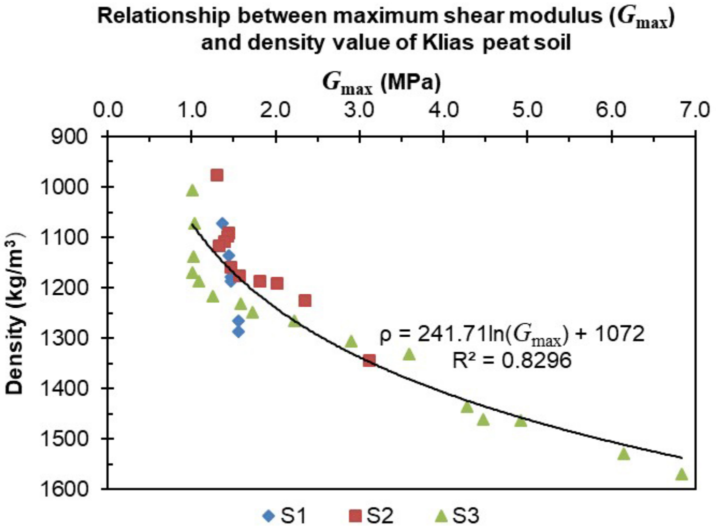

Figure 8. Relationship between G_{max} and density of Klias peat soil.

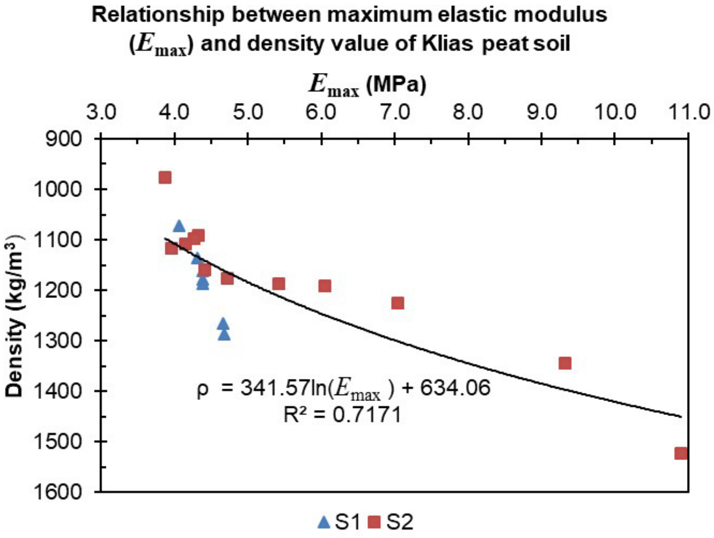

Figure 9. Relationship between $E_{\max}$ and density of Klias peat soil.

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Contacts:

Kasbi Basri, hf170042@siswa.uthm.edu.my
Adnan Zainorabidin, adnanz@uthm.edu.my
Habib Musa Mohamad, habibmusa@ums.edu.my
Baba Musta, babamus@ums.edu.my