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ORIGINAL ARTICLE

Shear Wave Velocity Measurements in Tropical Peat Using In-house Device

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ABSTRACT – Many people in the construction industry will agree that peat is a problematic material due to its compressibility behaviour. However, construction on these areas are inevitable because of the scarcity in space and suitable land for development. Hence, there is a need for proper in-situ testing on soil properties before any construction work can be carried out in peat. Shear wave (S-wave) velocity (V_s) used to compute the small strain shear modulus, (G_0) which is an essential parameter to design structures in earthquake and vibration prone areas. The most versatile method to assess G_0 is by measuring shear wave propagation through soil samples using bender elements tests (BET). Currently, BET is limited to laboratory environments, which can be time consuming and expensive. Therefore, a portable device of BET for peat has been proposed in this research which is simple to use and economical. The proposed setup consists of an oscilloscope, digital multimeter, signal generator, signal amplifier, direct current generator and a pair of piezoelectric bender elements. Peak-to-peak method from time domain (TD) technique is implemented as the method to analyse shear waves. To validate the function of the proposed device, different types of soil samples including Ottawa sand, Kaolin S300, Silty loam, Hemic, and Fibric peat were prepared. The peat samples for this study were collected from Pekan and Maran districts in Pahang, Malaysia. With a suitable frequency input from the sine wave generated, the V_s determined from the device was used to compute G_0. Results show there is only a less than 10% error in V_s when it was compared with the typical values of tropical peat. The proposed device is also effective to differentiate the type of soil sample when tested. In summary, the proposed in-house device can be used as an indicator and to find out the initial value of V_s and G_0 in tropical peat soil.

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INTRODUCTION

Insular of Southeast Asia have been undergoing serious climatic changes over the past few decades and are also believed to affect the peatlands in the region. Due to its location and extreme environmental conditions of this ground, it is estimated some 25 million hectares of peatlands in Southeast Asia (equal to 56% of all tropical peatland) were left undeveloped [1]. In Malaysia, peat has been identified as one of the important organic type of soil which is popularly used for the agricultural industry. To date, peat covers approximately 8% of the land or 3 million hectares. Sarawak has the largest area of peat in the country, constituting 13% of the state and covering about 1.66 million hectares [2] and the satellite data of peatland coverage of insular of Southeast Asia is shown in Figure (1). Typically Sarawak peat undergoes developments at a rate of between 2 to 5 mm per year.

Generally, peatlands in Malaysia are formed both in highlands and lowlands. Unlike the lowland peat, the highland peats are not extensively found. Only a limited area in Peninsular Malaysia for example in Cameron Highlands and mostly found in Kundasang, Sabah in Borneo. It is always a big challenge for engineers to use peatlands for construction purposes. Vulnerability of structures constructed on peat undergoes excessive differential settlements due to shringkage of pores during dewatering and compression. Hence, dynamic soil parameters such as the shear wave velocity V_s and the small strain shear modulus G_0 plays a vital role in understanding the behavior of peat. For example, in several earthquake related geotechnical engineering applications such as ground response analysis, soil-structure interaction analysis, liquefaction potential evaluation, and to design structures in earthquake prone areas require these parameters [3].

The common method to determine the shear wave velocity from a soil sample is by performing the bender element test [4]. Although the bender element test (BET) is readily available for engineers to determine the small strain shear modulus, G_0, the major issue encountered in this method is the tedious process involved throughout the test. Soil will be significantly disturbed in the process of transferring samples from site to the nearby laboratory. Currently available apparatus for the BET limit its usage to be a laboratory-based test [5].

Apart from that, results obtained from the laboratory test will be too time consuming and less accurate when compared to the in-situ properties measured. Furthermore, in a commercially available soil laboratory, BET test would be more expensive than any other basic soil property tests. Hence, the effort of developing an in-house device for the testing purpose is crucial and timely. This research is dedicated to design an in-house device that would be an alternative to the existing standard Bender Element Test (BET) commercially available. The idea is to enable in-situ testing, specifically for tropical peat by simplifying the procedure, low in cost, non-destructive approach with a reliable and accurate results.

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Equation (1) and (2) shows the formula to determine G_0 and V_s, where ρ, L_{tt}, and t are the soil density, travel distance, and travel time of the shear wave respectively.

$$G_0 = \rho V_s^2 \tag{1}$$

$$V_s = \frac{L_{tt}}{t} \tag{2}$$

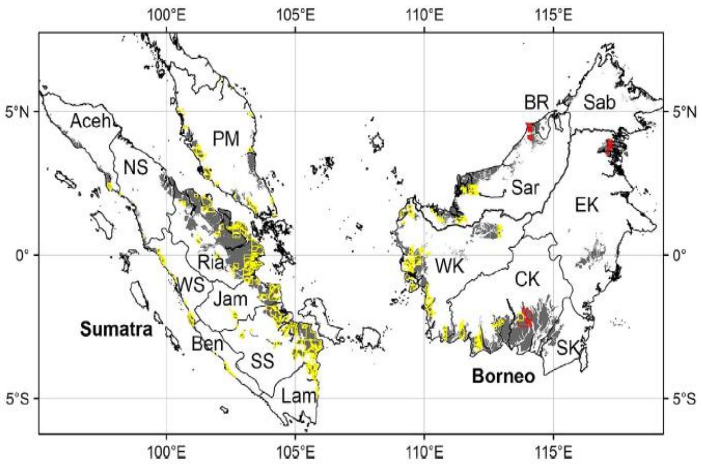

Figure 1. Satellite data of peatland coverage of Insular of Southeast Asia [1].

Table 1. Peat distribution in Malaysia [1]

State	Total peat, ha
Negeri Sembilan	6300
Kelantan	7400
Terengganu	81245
Sabah	86000
Perak	107500
Selangor	194300
Pahang	219561
Johor	228960
Sarawak	1657600

METHODOLOGY

An in-house device was instrumented and developed using do-it-yourself (DIY) concept. The idea is to perform bender element test (BET) to determine the shear wave velocity, V_s as well as small strain shear modulus, G_0 in peat using formula (1) and (2) respectively. In BET, bender elements transmit and receive S-waves through the soil [6]. Generally, two end caps each equipped with piezoelectric bender elements were used to generate and receive shear wave signals transmitted through the peat sample [7]. However, V_s travel across the sample will be subjected to various external disturbance including the near field effects that influence, P and S wave interference, and wave reflections which are challenges in performing BET [8].

The S-wave receiver bends when the shear wave arrives, propagating an electrical signal. When the shear wave reaches the other end of the piezoelectric bender element, a digital oscilloscope then measures the voltage-time histories of the transmitting and receiving bender elements [5]. There are mainly two techniques for determination of travelling time including time domain (TD) method and frequency domain (FD) method. TD technique includes methods such as the peak-to-peak, the zero-crossing, and the cross-correlation function. FD technique allows automation of signal processing and avoids difficulties associated with picking the first arrival or known as cross spectrum techniques. TD technique was adapted in this research for the ease of data analysis and simplifying the overall procedure.

Sample preparation

Peat samples were collected through excavation using shovel and spade from sites in Pekan and Maran districts in Pahang at approximately 0.5m deep into the ground. Hence, the retrieved samples are 100% disturbed samples. Laboratory testing including specific gravity (SG), organic content (OC), and fiber content (FC) is then conducted to identify the type of peat. The von Post scale is also used to classify the peat samples retrieved. However, in actual practice, a disturbed peat samples should be avoided for testing purpose. In future, a suitable auger can be fabricated to collect undisturbed peat samples. The auger should be able to extract peat samples that fits with the size of the designed PVC mould for the setup as in Figure (2). Due to limitations in the present scope of research, it is recommended to improvise sampling methods for the benefits of future works in order to reduce any degree of sample disturbance. Other than peat, samples including Ottawa sand, Kaolin S300, and Silty loam were also prepared for testing and data analysis.

Table 2. Basic properties of peat samples tested.

Sample	SG	OC (%)	FC (%)	Von Post scale	Type of Peat
1 (Pekan)	1.48	82	79	H3	Fibric peat
2 (Maran)	1.59	78	58	H6	Hemic peat

Theoretical data

The proposed in-house device is capable of obtaining information on shear wave velocity, V_s as the oscilloscope can read the arrival time of shear waves that travel across the sample. However, these readings have to be validated using some theoretical data. In order to compare and validate experimental results from proposed in-house device, some of the parameters from the literature was used. The small strain shear modulus as mentioned in Formula (1) requires soil density. Therefore, dry density value used in calculation was checked for similarity in terms of how the samples were prepared for laboratory testing. Only samples which have been air dried for several weeks before testing was conducted is used as a reference value. Table (3) shows the reference densities for various samples from different authors.

Table 3. Basic properties of peat obtained from literatures.

References	Samples	Density, Mg/m^3	V_s, m/s	G_0, MPa
[9], [10], [12]	Sand	1.70	302.00	143.00
[9], [10], [11]	Kaolin clay	1.61	258.00	150.00
[13], [14]	Silty loam	1.35	150.00	70.00
[9], [15], [16], [17]	Hemic peat	0.24	54.00	0.70
[9], [15], [16], [17]	Fibric peat	0.17	44.00	0.50

Instrumentation setup

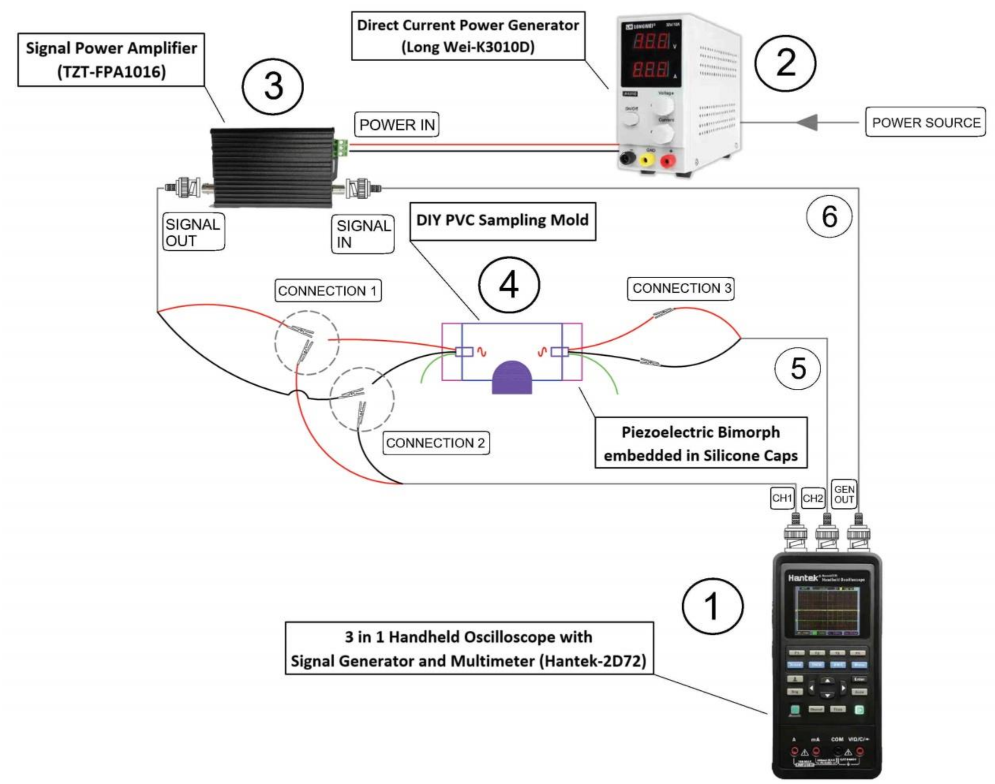

Figure 2. Schematic diagram of components proposed instrumentation setup.

Figure (2) shows the complete setup for the proposed in-house device in performing bender element test. Component "1" is the 3 in 1 handheld oscilloscope which also functions as the digital multimeter and signal generator. Component "2" is the direct current generator that supplies power to component "3" which is the signal power amplifier. Connection

"6" is the BNC-BNC cable that transmits signal from signal generator to the signal power amplifier. The amplified signal is then transmitted with connection "5" which is the BNC-Alligator cable. With connection "1" and "2", piezoelectric bender elements will receive the amplified sine wave signal. The signal then propagates through component "4", which is the PVC capsule containing the soil sample. Then, connection "3" will read the signal received by the piezoelectric bender element at the other end. Channel "CH1" and "CH2" will detect the signal transmitted and received respectively thus showing them on the screen of the oscilloscope proposed.

Operation of setup

The proposed in-house device is first setup as shown in Figure (2). Sine wave pattern is chosen as the wave generated by signal generator and set with amplitude around 1V. The direct current (DC) generator will supply 28V and 2.8A of DC current to power the signal power amplifier. The signal power amplifier then switched to 10 times gain multiplication. At this point, the signal power amplifier will be able to amplify sine wave signals from the signal generator. With the help of BNC-Alligator cable, the amplified sine wave can be transformed into applicable positive and negative signals that polarize the piezoelectric crystals of piezoceramic bender elements. The piezoelectric benders start to vibrate, and the vibration signals then propagate through the sample within the PVC capsule. Piezoelectric bender element on the other end will then detect the received signal and generate alternating current in sine wave forms. Again, BNC-Alligator cable will transmit the signal into the oscilloscope. With the transmitted signal shown in channel "CH1" and received signal in channel "CH2", the built-in cursor function from the oscilloscope can be used to study the arrival time of signal, disturbance, amplitude, and frequency of signals transmitted and received.

In the very first phase of this research, the proposed device was installed and tested in laboratory scale. The entire process was carried out to understand the mechanism and the feasibility of the proposed device. The setup was made to run smoothly and assessed for any serious limitations. Data was also analysed and checked for errors and mistakes using reference data. In the second phase of this research, a full scale field scale test would be carried out. Starting with field installation and followed by in-situ data monitoring and analysis.

Validation of setup

For the validation purpose, Ottawa sand was chosen as the control sample as it is uniformly graded with constant basic properties compared to other samples prepared. With different frequencies shown in Table (4) established, time taken for shear waves to travel across the sample is also recorded. Using Formula (1) and (2), the shear wave velocity and small strain shear modulus of Ottawa sand was calculated in reference values in Table (3). Based on the results in Table (4) and values in Table (3), the Ottawa sand shows similar trend of shear wave velocity and small strain shear modulus values as the ratio of travel length to wavelength increases with frequency. This trend certainly validate that the instrumentation setup can measure the time for signal waves to travel across a soil sample which then can be used for shear wave velocity and shear strain modulus calculation. The instrumentation setup is also able to detect near-field effects by calculation of ratio of travel length to wavelength.

Furthermore, when the Ottawa sand results from Table (4) is plotted with that of Table (5), it was observed that when the frequency is low, the shear wave velocity tends to show high error. When these results are compared with Toyoura sand data in Table (3) from the literatures, it is found that both experimental and the validation results are in line with the theoretical data. The proposed in-house device shows a reasonably matching results with the theoretical data when more than 2000Hz of signal frequencies are set for testing.

Table 4. Validation of setup with Ottawa Sand.

Frequency, Hz	Time, μs	V_s , m/s	G_0 , MPa	L/ λ
500	116	517	455	0.06
2000	332	181	56	0.66
8000	218	275	129	1.74
10000	223	269	123	2.23

RESULTS AND DISCUSSIONS

Figure 3 shows the best fit line plotted for both experimental and theoretical shear wave velocity data. The results from in-house bender element testing devices show a similar trend with the theoretical result. Shear wave velocity (V_s) measured decreases from sand, clay, silt, hemic peat, to fibric peat. When the testing comes to peat samples (hemic and fibric peat), drastic drop in shear wave velocity is obtained. Hence, the experimental results obtained from the device is proven to be reliable as the device is sensitive enough to detect the differences in soil properties and therefore able to distinguish the type of soil based on variances in V_s.

When referring to Table (10), it is known that the data errors in percentage was calculated by comparing the theoretical data in Table (3). The shear wave velocity is greater when it comes to coarser soil samples, meanwhile a drastic drop was observed in both the shear wave velocity and small shear strain modulus of hemic and fibric peat. From the results obtained, it confirms the behavior of peat as a problematic soil. Its stiffness is low and highly sensitive to the slightest change that occurs in physical properties.

These changes can be due to factors like moisture content, organic content, consolidation pressure, confining pressure, and many more. When these factors vary on peat samples prepared, results obtained for V_s will contribute to great errors. Hence, it was anticipated from the beginning that results measured can be very much different from the theoretical data mentioned in Table (3). Table (8) and (9) shows the results of peat samples using the in-house BET device. A frequency of 500Hz was applied as the control variable for the proposed instrumentation setup. Referring to the results obtained in Figure 4, it shows that when a low frequency is used for shear wave propagation, the received signal happened to be an outlier in the data collected and is pointed out with arrow in Figure 3.

Other than that, it is also observed that hemic peat shows a greater shear wave velocity compared to that of fibric peat. By using the proper analysis method on shear wave velocity obtained from the proposed in-house device, any outlier data from the setup can also be detected and removed.

Table 5. Bender element test with in-house device on Ottawa Sand.

Frequency, Hz	Time, μs	V_s , m/s	G_0 , MPa	L/ λ
500	116	517	455	0.06
8000	218	275	129	1.74
8500	194	309	163	1.65
9000	189	317	171	1,70
9500	218	275	129	2.07
10000	223	269	123	2.23
10500	210	286	139	2.21

Table 6. Bender element test with in-house device on Kaolin S300.

Frequency, Hz	Time, μs	V_s , m/s	G_0 , MPa	L/ λ
500	320	188	57	0.16
8500	224	268	116	1.90
9000	204	294	139	1.84
9500	208	288	134	1.98
10000	246	244	96	2.46
10500	253	237	91	2.66
11000	268	224	81	2.95

Table 7. Bender element test with in-house device on Silty Loam.

Frequency, Hz	Time, μs	V_s , m/s	G_0 , MPa	L/ λ
500	219	274	101	0.11
5000	353	170	39	1.77
5500	329	182	45	1.81
6000	342	175	42	2.05
6500	357	168	38	2.32
7000	341	176	42	2.39
7500	325	185	46	2.44

Table 8. Bender element test with in-house device on Hemic Peat.

Frequency, Hz	Time, μs	V_s , m/s	G_0 , MPa	L/ λ
500	629	95	1.27	0.31
930	1873	32	0.14	1.74
1000	1688	36	0.18	1.69
1500	1457	41	0.24	2.19
2000	1265	47	0.31	2.53
2500	1037	58	0.47	2.59
3000	983	61	0.52	2.95

Table 9. Bender element test with in-house device on Fibric Peat.

Frequency, Hz	Time, μs	V_s , m/s	G_0 , MPa	L/ λ

500	583	103	2.12	0.29
930	1928	31	0.19	1.79
1000	1872	32	0.21	1.87
1500	1531	39	0.31	2.30
2000	1332	45	0.41	2.66
2500	1174	51	0.52	2.94
3000	1077	56	0.62	3.23

Table 10. Average experimental data of samples and error in reference to theoretical data.

Sample type	V_s, m/s	Error, %	G_0, MPa	Error, %	Ratio L/ λ
Sand	276.67	8.39	130.21	8.95	2.17
Kaolin clay	234.98	8.92	89.01	40.66	2.69
Silty loam	176.02	17.35	41.87	40.18	2.30
Hemic peat	51.88	3.93	0.66	5.71	2.57
Fibric peat	47.76	8.55	0.39	22.00	2.78

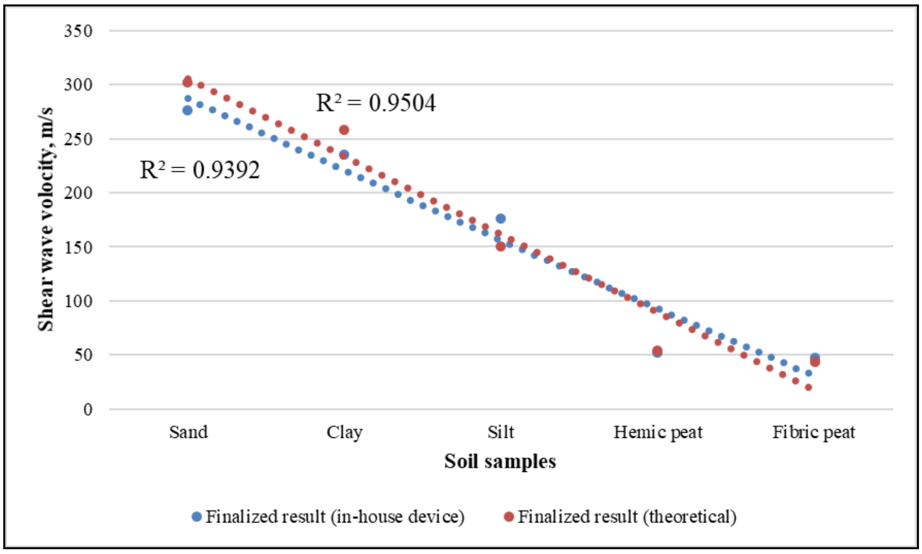

Figure 3. Theoretical and experimental data on various samples (best fit).

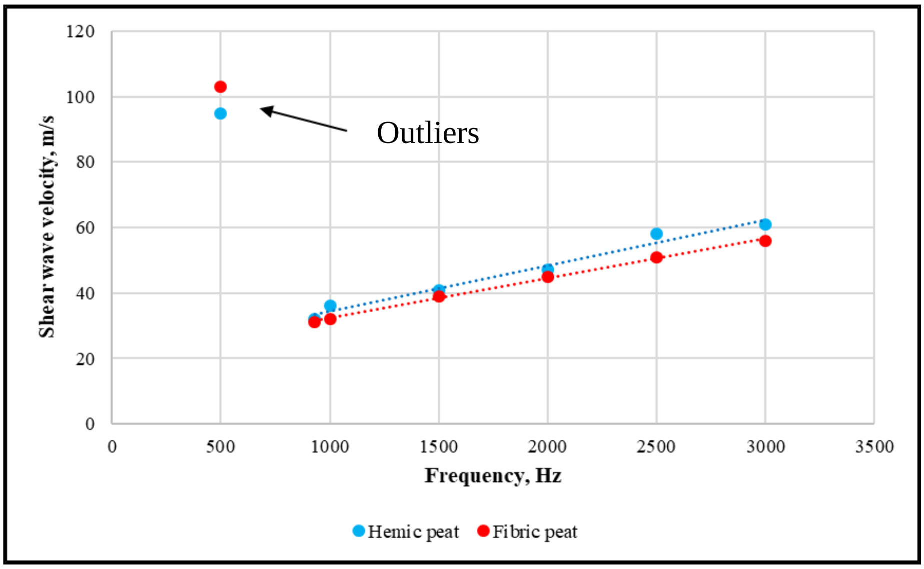

Figure 4. Shear wave velocity versus frequency on hemic and fibric peat sample.

After validating and verifying the results and the function of the in-house BET device, shear wave velocity measurements were analyzed along with the other soil properties. Analysis was done focusing on peat results from Table

(3) and (10). Graphs of shear wave velocity versus specific gravity, organic content, and fiber content were plotted. Figures 5-7 shows the best fit line of the data plotted. Then, a trendline was also plotted to equate the relationship between shear wave velocity with soil properties including specific gravity, organic content, and fiber content in tropical peat samples. The general trend shows that when the shear wave velocity in peat increases the specific gravity decreases too. Meanwhile the organic content and the fiber content increases along with the shear wave increment in the peat.

Tropical peat with the same specific gravity as the temperate peat recorded higher shear wave velocity values when tested using in-house device. According to the published research, data from Figure 5 also shows a wide scatter of V_s values of temperate peat due to poor data collection technique [17]. There is also a significant variance in the trend of shear wave velocity and specific gravity between the tropical peat collected from the east coast (Pahang) when compared to west coast of Peninsular Malaysia. Hence, there is a need for detail study to be carried out to find out the reasons behind this variance. Similar trend was also observed in Figures 6 and 7 showing there is a significant difference in dynamic properties measured in tropical peat obtained from the east and the west coast of Peninsular Malaysia.

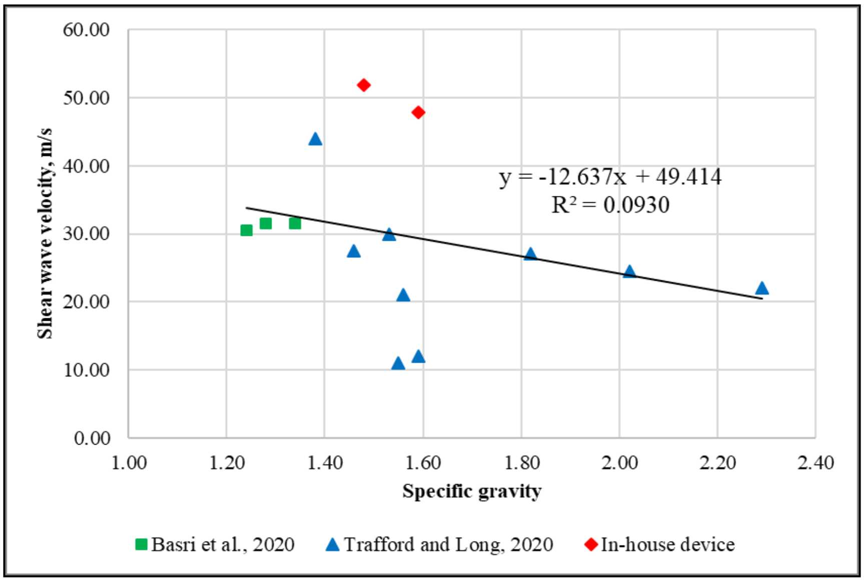

Figure 5. Shear wave velocity versus specific gravity of peat.

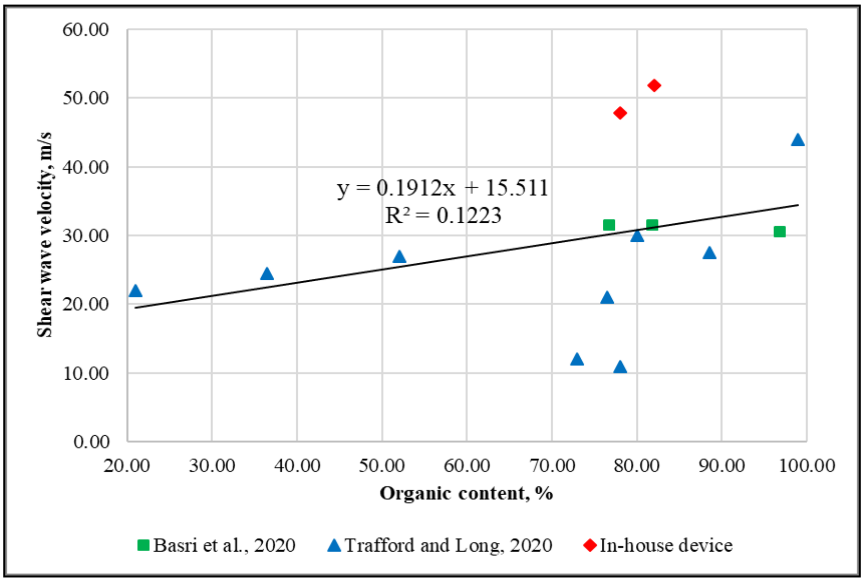

Figure 6. Shear wave velocity versus organic content of peat.

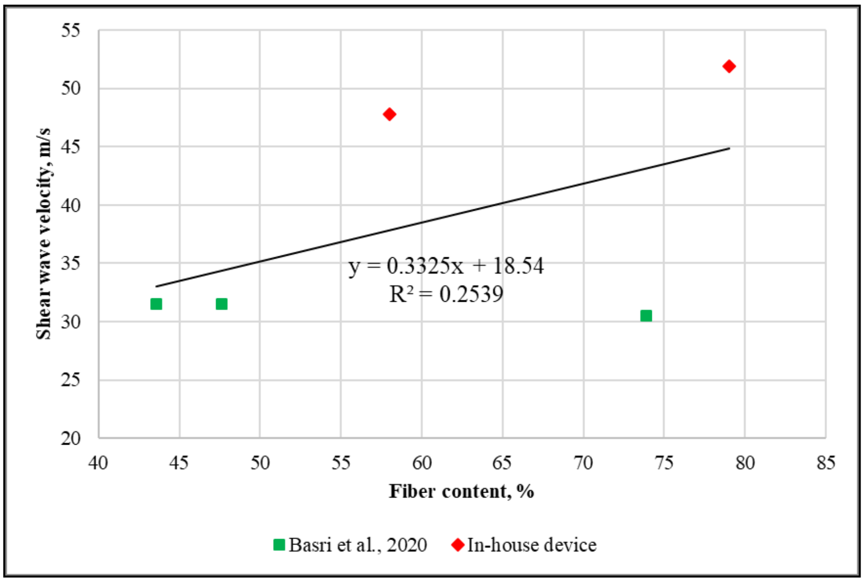

Figure 7. Shear wave velocity versus fiber content of peat.

CONCLUSION

As a conclusion, the proposed in-house BET device is an affordable and easy to use tool. This device can be used to conduct bender element test on peat, provide a reliable results on shear wave velocity and small shear strain modulus with small error in reference to results established in literatures. The suggested method of analysis for the proposed in-house device is the time-domain technique known as peak-to-peak method. Based on the analysis carried out between the experimental and theoretical data, the results are only valid when the ratio of travel length to wavelength is more than 2. This is because when the ratio is below 2, an unstable signal is received, and the near-field effect might be an issue when readings are done manually which further affects the quality of data. In spite of all the issues and challenges discussed, this device is still highly potential provided all the necessary precautions are taken. This is a portable and an alternative device for existing bender element tests on tropical peat as it can certainly provide measurements on dynamic soil properties of different soil types. This device needs fine tuning on automated data collecting system and further callibration works on minimising errors.

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