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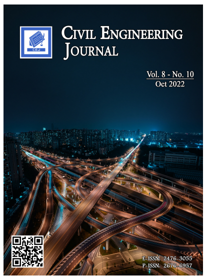

Maximum Strain Effect and Secant Modulus Variation of Hemic Peat Soil at large Deformation due to Cyclic Loading

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Abstract

This study presents the findings obtained in post-cyclic behaviour and degradation of shear strength from the static triaxial test, cyclic triaxial test and post-cyclic monotonic triaxial test to study the dynamic loading relationships with the degradation of shear strength after cyclic loading to the maximum strain effect due for Hemic peat soil and aim of this research was to assess the post-cyclic loading condition that brought to the understanding of secant modulus by using dynamic triaxial apparatus. It begins with a visual inspection of fibre characteristics. This is followed by an analysis of static, cyclic, and post-cyclic loading with stress-strain behaviour. Shear strength decreased and notched lower strength than its initial strength. As a matter of fact, PNpt-25 kPa from 1, 2, and 3 Hz are accumulated in the adjacent maximum strain. With regards to this maximum strain, the undrained shear strength ratio shows sequent decreases from higher to lower frequency applied. For instance, PNpt-25 kPa-1Hz to PNpt-25 kPa-3Hz recorded 1.16 to 1.13 undrained shear strength ratios, respectively. The secant modulus (Esec) for all specimens reflects decrement. The secant modulus for BSpt at an effective stress of 100 kPa in static monotonic is about 18.74 MPa, while in post-cyclic, the secant modulus expanded to 19.630 MPa cyclically loaded with 1 Hz. Unfortunately, the secant modulus returned to decline position when higher frequency applied at 2 Hz, where the secant modulus is about 12.781 MPa and continues to decline with 3 Hz at 7.492 MPa.

Keywords: Strain; Post-cyclic; Secant Modulus; Dynamic; Shear Strength; Peat Soil.

1. Introduction

This study presents the post-cyclic behaviour of peat soil after being subjected to cyclic loading. Tests were carried out on samples from Beaufort-Sabah peat soil (BSpt), Parit Nipah-Johor peat soil (PNpt), and Penor-Pahang peat soil (PNpt) by allowing the cyclic pore pressure to develop during cyclic and post-cyclic loading. In dynamic loading, also known as "cyclic loading," past studies have concluded that cyclic loading is dependent on the stresses and frequencies imposed during the loading onto the soil.

A comparison of the stress-strain behaviour during the post-cyclic tests with the stress-strain behaviour during the monotonic tests has been plotted [1]. The post-cyclic undrained shear strength of the specimens is influenced by the cyclic loading and its amplitude. The tests were performed in this study to understand the dynamic loads that caused vibrations by machines, earthquake impacts, or explosions. The term "dynamic loading" consists of a system that exhibits a degree of consistency both in its magnitude and in its frequency [2]. It has been related to explaining non-static repetitive soil loading [3, 4]. Soil deposits are often subjected to cyclic loading due to wave action, traffic loading

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or earthquakes, machine operations, wind, and wave actions [5]. Thus, it should further be noted that the impact of these dynamic loads gives a transformation that needs to be investigated. The dominant feature of peat is when subjected to load, it is noted for its great compressibility, high moisture content, poor shear strength, and long-term settlement [6].

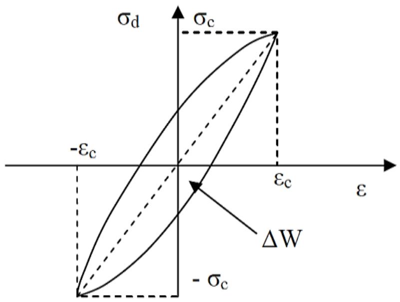
The dynamic loads will affect the soil behaviour and are particularly significant in soil shear strength, where pertinent parameters have to be observed. Complex and uncertain loading reactions are synonyms for dynamic stresses. It is vital that engineers have a good understanding of the context of dynamic loading and make a conscious effort to do so. There are two (2) categories in evaluating characteristics of dynamic loading behaviour [7]. The post cyclic yield shear strength of undisturbed peat soil is considerably lower compared to static shear strength [8].

In this study, the frequencies for the dynamic testing on the peat soil samples were focused and simulated on traffic vehicle loading frequencies, earthquakes, and machine operations. Thus, the application of cyclic triaxial in this study fulfills the requirement of cyclic loading, where the strain of amplitude applied is 0.1%, and as referred to Table 1, it is classified as a large strain amplitude response. This is in line with this research, where traffic loading, earthquakes, and machine operations are subjects of the loading applications. For this purpose, the frequencies and stress applications are reviewed in this research. It is vital to understand and study the strain response for both parameters. The loading frequencies and stress applications are the main parameters that determine the magnitude of the strain amplitude [2]. In cyclic triaxial test, there are some parameters to be taken into account in the analysis of dynamic loading characteristics are the dynamic shear modulus (G) and Young's Modulus (E). Table 2 shows the parameters obtained from dynamic loading behaviour with the aid of the stress-strain graph. From Table 2, it's clearly understood that the cyclic triaxial is the slope from the extreme points of the hysteresis loop from the deviator stress versus the axial strain graph, which gives the value for the modulus of elasticity or Young's modulus (E) as in Equation 1. In Equation 2, the determination of shear modulus using the equation. Unfortunately, it's requiring the knowledge of poisons ratio (μ). At low strain amplitudes, the shear modulus is high, but it decreases as the strain amplitude increases [9].

Table 1. Categories of dynamic loading characteristics

Type of cyclic loading	Strain Amplitude range (%)	Example of the loading applications	Type of dynamic loading test
Low strain amplitude response.	0.001 - 0.01	Effects from operation of machines, wind or sea waves and changing of water table.	Resonant column, ultrasonic pulse, piezoelectric bender element.
Large strain amplitude response.	0.01 - 0.1	Effects from strong motion earthquakes, blasts and fast-moving vehicles.	Cyclic triaxial, cyclic direct simple shear, cyclic torsional shear.

Table 2. Parameters obtained from dynamic loading behavior

<table>
<tr><th colspan="2">Cyclic Triaxial</th></tr>
<tr><td rowspan="2">
</td>
<td>Young's modulus, E (MPa)
$$E = \frac{Cyclic\ deviator\ stress, \sigma_c}{Cyclic\ axial\ strain, \varepsilon_c} \quad (1)$$</td></tr>
<tr><td>Dynamic shear modulus, G (MPa)
$$G = \frac{E}{2\,(1+\mu)} \quad (2)$$
Where, poisson's ratio μ = 0.5 for saturated undrained sand or clay specimens. μ = 0.3 for drained sand specimens [10].</td></tr>
</table>

The dynamic loads studies are continuous effort from various researchers. Various considerations and criteria are taken into consideration while making statement and procedures. With concerned to the environmental effects of earthquake, human artificial structures to risk assessment of infrastructures, the soil behaviour under dynamic conditions is a crucial component of several studies. Shear modulus, Young's modulus and damping ratio with cyclic shear strain have been substantially investigated in prior work as conducted [11, 12] studied on Mercer Slough peat and Shermand Island peat in California [13]. Testing performed on undisturbed sample with pre-sheared and found that, the modulus reduction and damping relations was small. Unfortunately, the specimens tested under re-consolidation level as and additional consideration to the prior work that was studied [14]. Cyclic loading is generally applied under either stress- or strain-controlled conditions. Strain controlled and stress controlled has different significant to measure the dynamic characteristic accordingly. Contrarily with clay soil, lower limit to the cyclic stress ratio below which cyclic loading has a negligible effect on clay softening [15].

From strain-controlled cyclic triaxial, post-cyclic behaviour of peat soil evaluated by monotonic tests is compared to static results. To illustrate their practical utility, the generalizations made about stress-strain curves are used to evaluate the relative accuracy of typical laboratory tests. Erken & Ülker [16] drew the stress versus strain graphs to show the correlation of stress-strain in response to applied frequencies. The undrained shear strength was determined to be half of the deviator stress at the critical state, at which there is no change in deviator stress with continued axial strain [17].

At the same point, Yasuhara et al. [18] also stated that the secant modulus determined from the ratio of deviator stress against axial strain. At the critical state, deviator stress measured is equal to one half of its deviator stress. From the stress-strain curve in Table 1, the secant modulus of soil can be determined. The key aspect discussed from the empirical correlations that has determined and obtained from the undrained triaxial test where the secant modulus generated from the Equation 2. E, defined as the ratio of the difference in deviator stress to the corresponding axial strain. From the secant modulus itself, it can be categorized by consistency or density of soil to the secant modulus values. Chen et al. [19] has categorized the secant modulus range according to the secant modulus values for selected soils such as silt, clay, loess sand, sand and gravel. A recent study, Sarkar & Sadrekarimi [20] stated that maximum shear moduli of the peat samples are determined from shear wave velocity measurements. The smaller the initial shear stress or the higher the vibration frequency, the smoother the curve after the turning point and the smaller the tangent slope [21].

The reason of this categorization is to classify the soil condition to its condition and physical strength. For instance, silt with a modulus value of 0.2 – 2 is categorized as very soft and clay soil with E, 25 – 250 MPa is categorized as sandy. Given these points, Chen et al. [19] stated, the field values are depended on stress history, water content and density. This instance classification can be used to indicate peat soil as well. Just in the same way, to understand the changes in post-cyclic behaviour of soil, extended from secant modulus, E and undrained shear strength, S_u, Kishida et al. [11] has compared the ratio between static and post-cyclic monotonic undrained shear strength. Kishida et al. [11] in their study of post-cyclic degradation of clay soil has indicated that a general degradation of strength and stiffness is noted as a results of cyclic loading effects. The relationship between maximum strain and post-cyclic undrained shear strength explained by Kishida et al. [11].

Thus, from this indicator, it can be concluded that shear strength of post-cyclic are degraded during cyclic loading. Further than that, the influence effects of drainage prior to the post-cyclic loading have consider in the undrained shear strength. Undrained shear strength during static compared to the undrained shear strength in post-cyclic monotonic in triaxial test. In consequence, to the cyclic loading behaviour, the researchers had concluded that the elastic modulus or secant modulus decreases significantly more than the undrained shear strength. With this intention, post-cyclic shear strength compared to the static shear strength against the peak cyclic strain (%) during cyclic loading. The same finding on the post-cyclic behaviour is noted as a result from the effect of cyclic loading. The effective stress decreased gradually with the increase of the cycle shear stress ratio [22].

1.1. Dynamic Loading Characteristics Based on Cyclic Triaxial Test

As stated in Table 1, in consequence of high strain level, frequency and stress applications a chain reaction from large strain amplitude or deformations. Triaxial test is a common procedure, as it allows mechanical properties and strength parameters to be determined for many deformable soil materials. The cyclic triaxial and cyclic simple shear test is relevant test apparatuses which can reproduce these kinds of stress conditions accurately [23]. In this context, the internal peat material frequency to simulate the dynamic loading in testing program are difficult to measure. Peat acknowledged with high water content with fibrous condition making it harder to predict. There is still a lack of knowledge in determining the natural frequency of soil [2]. In cyclic triaxial test, there are some parameters to be taken into account in the analysis of dynamic loading characteristics are the dynamic shear modulus (G) and Young's Modulus (E).

Various considerations and criteria are taken into consideration while making statement and procedures. With concerned to the environmental effects of earthquake, human artificial structures to risk assessment of infrastructures, the soil behaviour under dynamic conditions is a crucial component of several studies. Shear modulus, Young's modulus and damping ratio with cyclic shear strain have been substantially investigated. On Mercer Slough peat and Shermand Island peat in California [23-25]. Similar studies on methodology in this research. Testing performed on undisturbed sample with pre-sheared and found that, the modulus reduction and damping relations was small. Unfortunately, the specimens tested under re-consolidation level as and additional consideration to the prior work that was studied [26].

Peat has excellent water-holding characteristics, highly fibrous due to the presence of a lot of decomposed materials and organic matter, which makes it highly compressible, weak at shear strength, and low in bearing capacity. This characteristic makes it unsuitable for use as foundation or sub-grade since it would have a large impact on deformation and settlement if not treated very well [27]. However, Shafiee et al. [28] has investigated pre- and post-cyclic volume change properties of Sherman Island peat by using strain-controlled method. While the stress-controlled method had performed by various researchers, Erken & Ülker [16] in Dinar, Turkey, stress controlled are similar to load-controlled technique adopted [29, 30]. Despite of that, Das & Sobhan [31] also using the same technique on clay soil.

On the other hand, Erken & Ülker [16] have studied a post-cyclic shear strength of granular material behaviour from fine grained soils, applied with stress-controlled method. Obviously, the selection of controlled method is depended on the soil material used. On the grounds that, Das & Sobhan [31] stated that, stress controlled dynamic triaxial tests are used for liquefaction studies on saturated granular soils. While, modulus of elasticity and damping ratio evaluation tests are conducted using strain-controlled tests with a servo-systems is used to apply cycles of controlled deformation. By virtue of that, peat known as combination of humus, plants material and unidentified peat material, liquefaction does not happen in peat. Karaca et al. [32] Conducted study on liquefaction potential for Adiyaman peat stated that, liquefaction property of peat has not been fully researched yet, so it is a promising study on liquefaction properties of peat. As a result of earthquake motion in New Zealand, a studied conducted and found that, liquefaction happens in loose silt and sand that is below the water table. It does not happen in peat because it is made of plant materials [33].

A study has been conducted undrained cyclic strain controlled triaxial tests [28], when cyclic loading applied, the axial strain is constant with time. At the meantime, axial strain applied and the deviator stress reduced. This phenomenon affects the soil stiffness and degrades as evidenced to the reduction in the shear stress to achieve the uniform strain amplitude. This impression led to lost in stiffness and reduction in shear strength. Reviewed from many past dynamic loading tests, frequencies ranging from 0.1 Hz to 0.5 Hz was applied.

According to Zergoun & Vaid [34], this application in order to obtain reliable excess pore pressure measurements during cyclic loading, very low axial strain rates have been used. Wichtmann et al. [35] has conducted cyclic test and the samples were then sheared under undrained strain-controlled conditions. At this stage, cyclic shear strains would lead to strain softening, particle structure breakdown and a rapid deterioration of stress-strain-shear strength characteristics up to the plastic threshold. It is known that peat soil is highly compressible [36] thus, the compressible behaviour of peat soil seen as the major causes to the changes in shear strength which in line with the statement where peat is soft and easily compressed when load imposed [37].

2. Methodology and Testing Procedure

Sample decided have to be through five breakdown of testing, index properties, static test, dynamic test and post-cyclic Index properties with common test conducted and the soil extracted to determine the degree of decomposition, specific gravity, moisture content, loss of ignition, Atterberg limit, fibre content and pH test accordingly. The effective pressure 25, 50, and 100 kPa are performed to simulate the real site pressure condition and frequencies applied represents loading type as further discuss in literature review. Under static test, consolidated undrained (CU) test are conducted, cyclic triaxial test has been proceed immediately.

Undisturbed sample properly collected. Soil sampling are reflected the real conditions of soil sample on field and sample handled with care. Trends toward reduced the impact of placement and handling undisturbed samples is important and preferred to maintain the natural characteristic. Quality assurance, particulate sampling and sample handling a matter of concern to control the integrity of sample itself. Undisturbed soil samples keep the structural integrity of the in-situ soil and they have a higher recovery rate in the sampler. Undisturbed samples allow the author to identify the properties of strength, compressibility, as well as the fracture patterns among others. Due to high water content in peat soil, changes of the in-situ conditions are projected. The magnitude of the disturbance reduction varies considerably with the type of soil that depends on the soil condition, sampling method followed by the competencies of ground man. Additional care has been taken to ensure the sample go through minimal disturbances. The fibre and soil structure in peat soil itself with high compressibility factor is particularly phenomenon when dealing with low decomposed peat soil. Tube sampler is used and penetrated into the soil until reach the required depth. In this study, the depth requirement is up to 0.5 m depth. Tube sampler using PVC with size 50 mm diameter and 160 mm height. Drive samplers are pushed into the soil without rotation, displacing the soil as they penetrate. The tube has been sharpened to the cutting edge at their base. Figure 1 shows the illustration of tube sampler condition during undisturbed sampling on site. Prior to stripping the topsoil, the existing vegetation shall initially be sprayed and cleared and any dead aerial growth shall then be removed by close mowing and then proceeded by excavation.

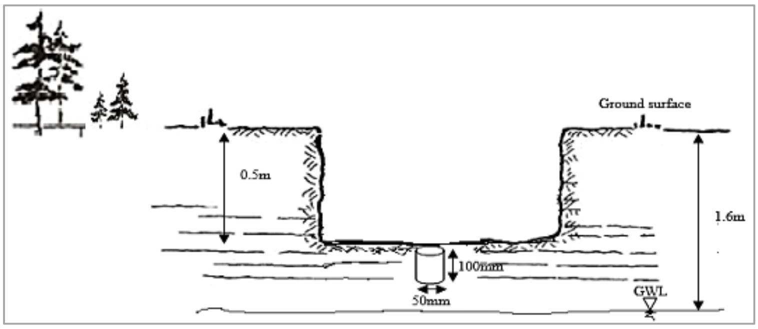


Figure 1. Illustration of the tube sampler setup condition

Tube sampler were placed shortly after top soil have been excavated in vertical position and penetrated to the soil immediately up to the required depth without twisting or rotation to avoid any disturbances as shown in Figure 2. Table 3 shows the summary of laboratory tests. This soil test summary represents soil samples that tested accordingly to guide references and explained the significant of each test and certified labs standard soil analysis. Figure 3 illustrates the schematic drawing of the methodology flowchart of this study. Figure 4 shows the Malaysia map and sampling site.

Figure 2. Tube sampler in vertical position and penetrate to the soil

Table 3. Summary of Laboratory Tests

Testing		Standards BS1377:1990/AASHTO/ ASTM/USDA	Method Approach
Site Sampling	Degree of Humification (Von Post scale)	[38]	On site determination
Index Properties	Particle Size Distribution	[39]	Wet Sieve Analysis
	Specific Gravity	[39]	Small Pycnometer (Kerosene liquid)
	Moisture content	[39]	Oven Dry Method
	Liquid Limit	[39]	Cone Penetrometer Test
	Organic Content	[39]	Loss of Ignition
	Fibre Content Test	[40]	Dry Weight of Fibre Retained
	pH Test	[39]	pH Meter
Static Test	Monotonic Triaxial Test	[39]	Consolidated Isotropic Undrained Triaxial. Effective pressure levels 25, 50 and 100 kPa.
Dynamic Test	Cyclic Triaxial Test	[40]	One Way Stress-Controlled. (Frequencies 1, 2 and 3 Hz)
Static Test (Post-cyclic)	Monotonic Triaxial Test (Post-cyclic)	[39]	Consolidated Isotropic Undrained Triaxial

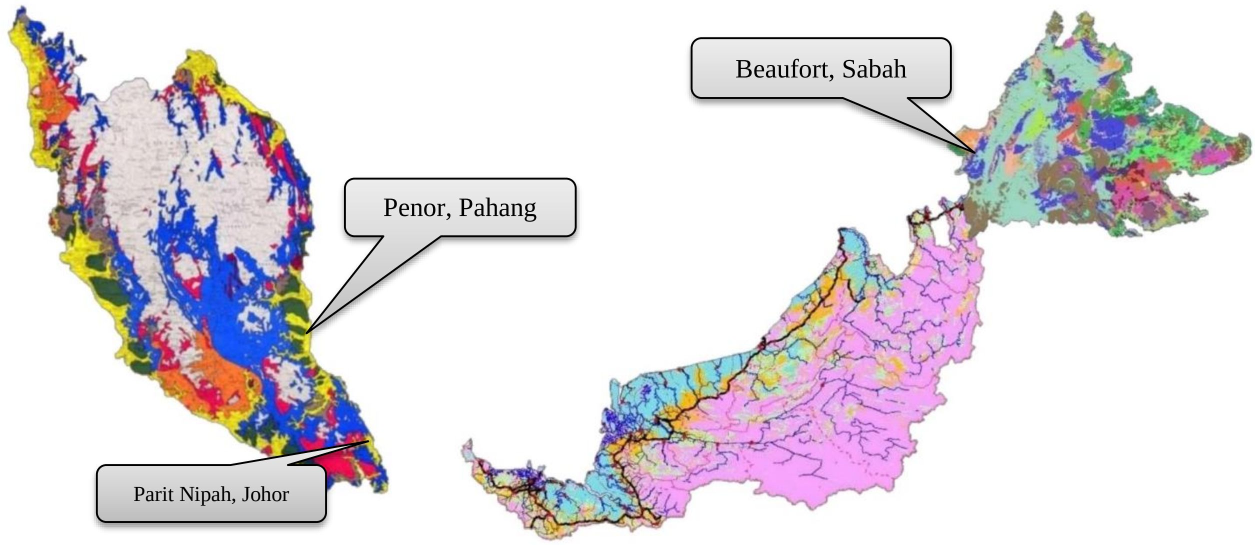


Figure 3. Malaysia peat soil distribution map

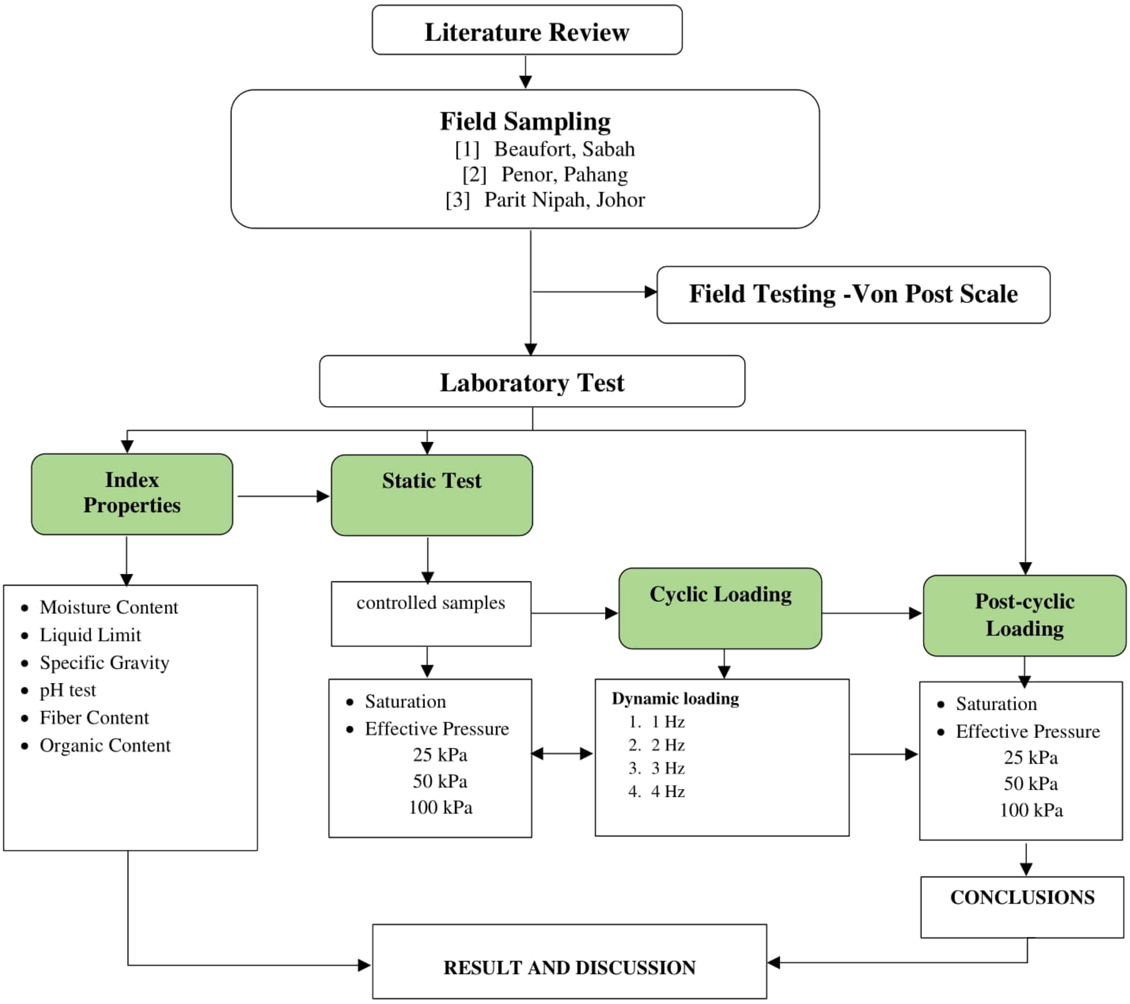


Figure 4. Flowchart of Research

Samples of peat soil taken from various location as mentioned earlier and tag with PNpt, PRpt and BSpt according to the location. Samples are managed according to the date, location and site number. Moisture content and density primarily measured before test being done. For the purpose of triaxial test, the specimen firstly prepared from undisturbed sample of peat soil before placing into the triaxial cell. The preparation of peat sample itself may involve extruding sample from the 50 mm diameter by 160 mm heights PVC tubes and trimming the undisturbed sample into required size at 50 mm diameter to 100 mm heights. The following steps has been followed for consolidated undrained shear strength in triaxial compression (CU) laboratory test sample preparation. A cylindrical rubber membrane is wrapped over the sample and then, a de-aired saturated porous disc takes from under water and will slide on to the pedestal without trapping any air.

Concurrently, the specimen coupled with porous disc at top and bottom of specimen. O-rings and a rubber membrane are placed together over the stretcher. Membrane placed to the sample while applying suction to the rubber tube, and then the suction released so that the membrane clings to the sample at the correct height. The lower end of the membrane is rolled over the base pedestal and seal it in place with both O-rings. Triaxial cell are fixed to the dock and chamber fixed tightly. Saturation test are carried out shortly. Then, triaxial cell are assembled with the loading piston slowly extended until the top cap and load cell makes contact at both surfaces. This ELDYN apparatus is using air pressure. Pressure is allowed to fill in the chamber when the software and saturation stage desired to start.

3. Results and Discussion

As seen in Table 3, the specific gravity values of the mentioned locations generally range from 1.14 to 1.56 correspondingly for peat soil. In connection with results of BSpt, PSpt and PNpt in this research, it ranges from 1.24 to 1.34 which is relevant to state that this values in the ranges and fulfil the articulation. The correlation of moisture content and liquid limit have significant value, where the study found the moisture content for BSpt, PNpt and PSpt is approximately 600% to 700% respectively while the liquid limit recorded 149% to 162% respectively. A correlation can be found as it is noted that there is a slight but significant increase in liquid limit with the increase in natural water content as highlighted [41]. The natural water content of peat in Table 3 ranges from 140% to 964.50%. Zolkefle [42] found that the moisture content in their findings was 710.44%. The liquid limit (LL) value is also higher as the sample that contains fibre within 33% to 66% or organic content and thus it has high water absorption capacity [43].

These variations of results are due to climate change that are manifested by changes in temperature, precipitation and rainfall which influences the intensity of soil saturation where, the water table formed in a relatively in horizontal plane and may rise to a level that is greater or less than the elevation of the actual water table. In the meantime, organic content and fibre content extracted from BSpt, PNpt and PSpt specimens in this study are found to be varied, for the organic content BSpt is 65.21%, PNpt is about 80.32% and PSpt 80.32%. From these results, it can be clearly seen that, the result is situated in the range as presented in Table 4 where the range of fibre content in Malaysia's peat varies from 65% to 98.50%. In addition, the fibre content is also determined as varying. BSpt has a lower fibre content compared to PNpt and PSpt, 40.51% and 53.23% respectively. It can be concluded that, the continuous agricultural activity contributed to the formation of ground fibre that derived from growth and dead plants or crops.

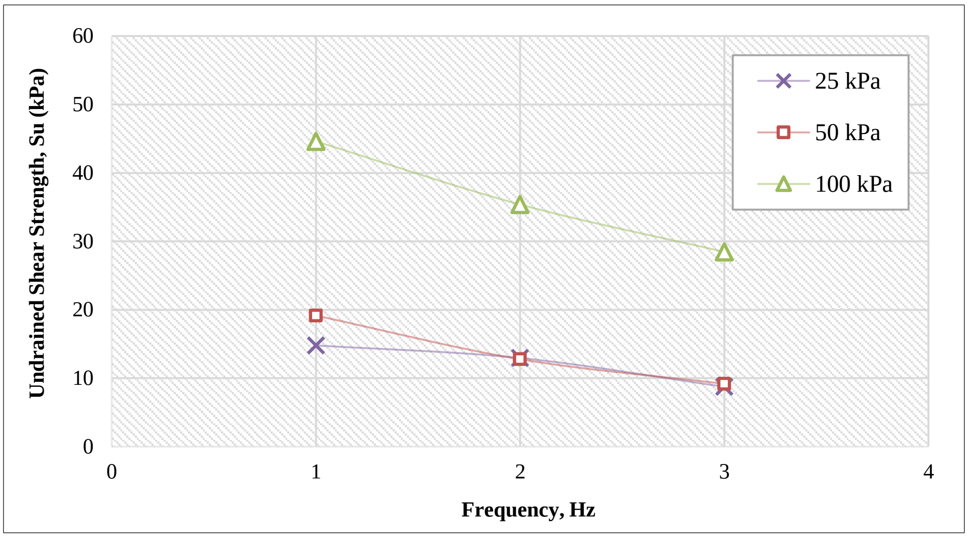
Table 4. Index properties of peat soil

Description	BSpt	PNpt	PSpt
Degree of Humification	H7	H6	H5
Specific Gravity, Gs	1.34	1.33	1.12
Moisture Content (%)	713.35	676.30	637.00
Organic Content (%)	68.21	80.32	87.49
Liquid Limit (%)	170	149	155
pH	4.5	3.68	3.77
Cu	3.85	6.00	7.30
Cc	0.42	0.54	0.66
Fibre Content (%)	37.72	40.51	53.23

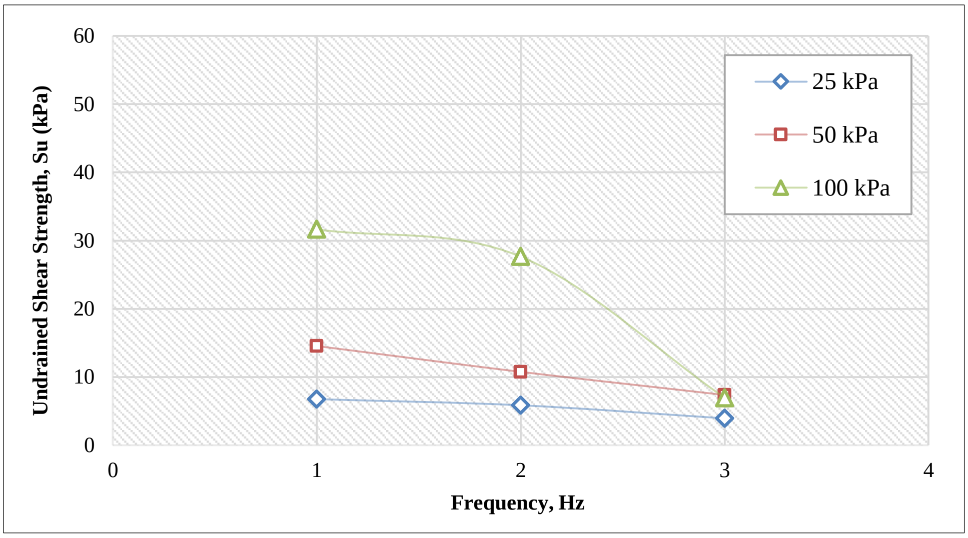
The pH is a value that measures of the acidity and alkalinity. A pH of 7.0 is considered neutral, below 7 indicates an acidic state while more than 7 is considered alkaline. Table 4 shows that peat can be classified as acidic as the pH value ranges from 3.0 to 3.72. This helps author to identify the PNpt and PSpt positions where the tests results indicate pH values as 3.68 and 4.28 respectively. For PNpt it may appear as in the range, but for PSpt it was recorded to be higher. It has been observed that the age of decomposition in soil fibre influences the acidic factors of soil. In PSpt site location, it can be observed that there are vital agricultural activities. Furthermore, the drainage system is in improper conditions, there is no artificial drainage and that situation causes the ground water to be entrapped for BSpt location. These enhances the possibility of ground water retention and naturally making peat soil more acidic. The challenges for the coming decade are the creation and maintenance of an artificial structure and infrastructure that is built on peat soil has to be resolved. From observations, peat has a high uncertainty margin. Uncertainties and difficulties of testing of peat soil to determine the strength with very high compressibility, which presents significant challenge in developing peat behaviour in research. Peat contains high water content hence causing the material to be very sensitive and soft. This is why many researchers described peat as a challenging soil.

Under those circumstances, from author observation there is no significant in liquid limit to this study. On the subject of soil behaviour, it is only a general measure of the critical water content that useful for peat soil identification only. Furthermore, author has observed that, the PSpt has lowest moisture content and showed that, the decomposition is moderate compare to PNpt and BSpt that has moderately high decomposition level. Referred to pH value, the PSpt also has the lowest. To put it in another way, the acidic becomes higher when the decomposition level is high.

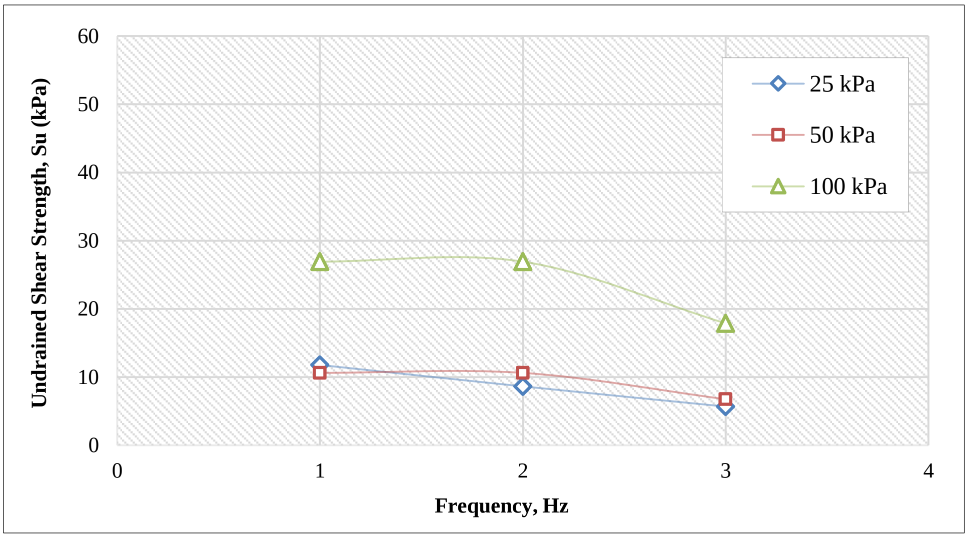
The relationship to the undrained shear strength, Figure 5 presents the relationship between undrained shear strength, Su (kPa) and frequencies, Hz applied at various effective stress, σ' level for (a) PNpt, (b) PSpt and (c) BSpt. Author has observed that, the undrained shear strength upon reaching maximum axial strain at 20%, the undrained shear strength decreased against frequencies that applied from lower to higher amplitude. Figure 5-a shows the undrained shear strength, Su for PNpt decreased orderly from 1, 2, and 3 Hz. To put it another way, the undrained shear strength also increased to the effective stress in multiples figure from lower to higher effective stress, 25 to 100 kPa uniformly. Based on Figures 3-b and 3-c, the undrained shear strength of PSpt and BSpt also depicted same behaviour. A similar regression results confirmed the undrained shear strength of peat after cyclic loading decreased to depend on frequency applied. On the contrary, higher undrained shear strength recorded for PNpt-100kPa-1Hz at 45 kPa, followed by PSpt at 31 kPa (PSpt-100 kPa-1Hz) and 28 kPa (BSpt-100 kPa-1Hz). On the other hand, the decreases are seen structured from lower to higher frequency and from higher effective stress to the lower. The post-cyclic undrained shear strength decreased, then after reaching a maximum value of deviator stress they follow a decreasing trend with increasing the axial strain. The undrained shear strength of the post-cyclic peat soil was 1.34 (PNpt-25kPa-1Hz) times smaller than that of the static undrained shear strength, compared to PSpt and BSpt, there are 1.76 (PSpt-25kPa-1Hz) and 1.26 (BSpt-25kPa-1Hz) times smaller. The reduction of undrained shear strength of PNpt varies from lower 25.56% to higher frequency and effective stress applied at about 69.89%. PSpt recorded highest reduction about 82.81% while some specimens in BSpt recorded lowest loss undrained shear strength at 20.98%. This variation of undrained shear strength results observably in line with the findings where, index properties of each sample from different locations are varied.



(a) PNpt



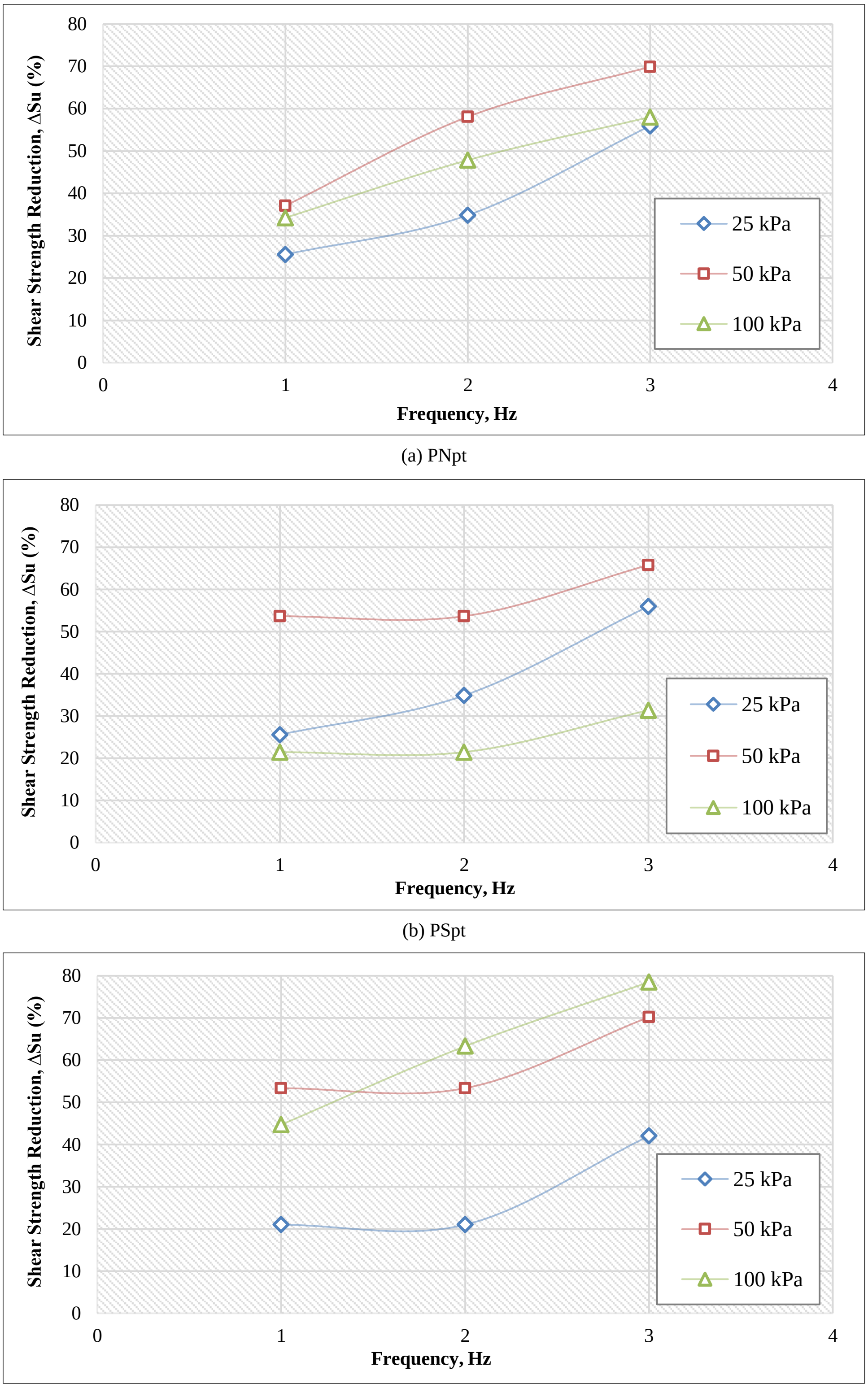
(b) PSpt



(c) BSpt

Figure 5. Relationship between Undrained shear strength, S_u (kPa) and Frequencies, Hz Applied at various Effective Stress, σ' level for (a) PNpt, (b) PSpt, and (c) BSpt

Relationship to the frequencies applied, which is frequency applied contributed to the undrained shear strength reduction in peat soil, the reduction of the undrained shear strength. This is observed and illustrated in Figure 6 where the relationship between undrained shear strength reduction, ΔSu (%) and frequencies applied, Hz for (a) PNpt, (b) PSpt and (c) BSpt are well illustrates to understand the occurrences of strength reduction is clearly understood. Based on Figure 6 shows that is when the frequency and effective stress becomes sufficiently applied, undrained shear strength ceased to increase, even under high frequency and effective stress applied. This is showed that, the specimens tend to react in higher reduction when higher frequency applied. The higher frequency applied; the higher undrained shear strength decreased. On the subject of this reduction undrained shear strength, PNpt, PSpt and BSpt indicates the similarities. For instance, the reduction in sequence ranging from 25.56% to 34.27% (PNpt-25kPa).



(a) PNpt

(b) PSpt

(c) BSpt

Figure 6. Relationship between Shear Strength Reduction, ΔS_u (%) and Frequencies applied, Hz for (a) PNpt, (b) PSpt and (c) BSpt

Relationship to the maximum strain, based on the findings and discussion in previous section on the relationship of undrained shear strength reduction, the maximum strain effects also studied in this research to understand the undrained shear strength ratio, Su(pc)/Su(c). Relationship between maximum strain due to cyclic loading and post-cyclic undrained shear strength are evaluated as illustrates in Figure 7 due to one-way loading cyclic loading and post-cyclic undrained shear strength for different peat soil origin from various places especially PNpt, PSpt and BSpt. These evaluations include static and post-cyclic undrained shear strength with effective stresses and frequencies that applied. Based on the work Diaz-Rodriguez et al. [44] that suggests post-cyclic behaviour of soil is generally considered to depend on the maximum strain developed during cyclic loading.

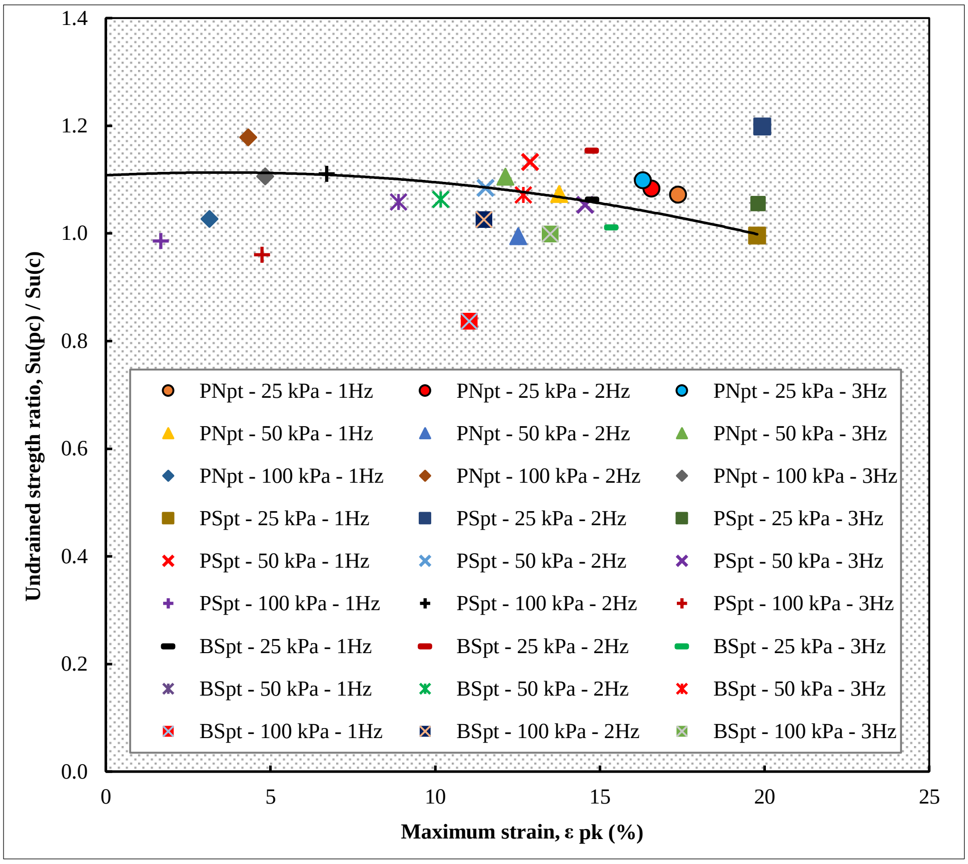


Figure 7. Relationship between Maximum Strain due to cyclic loading and post-cyclic undrained shear strength

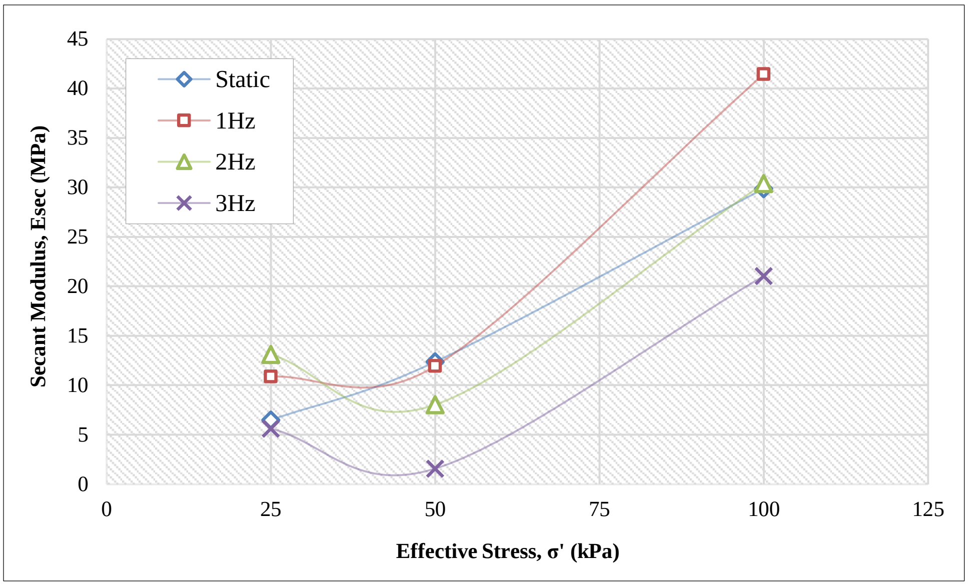
By all means, the maximum strain during one-way cyclic loading has an undivided effect to the post-cyclic undrained shear strength. As can be seen in Figure 7, it clearly showed that, the maximum strain influences the accumulation of maximum strain. Which is means that, for each sample has different strain level depended on the properties of peat soil itself. The maximum strain not accumulated merely scattered.

The undrained shear strength ration obtained from static and post-cyclic undrained shear strength. In relationship to the maximum strain applied, the undrained shear strength ratio seems to be independent and scattered. The maximum strain effect makes the undrained shear strength ratio differ for each specimen. This is observed due to frequency applied and datum difference during cyclic loading as a response to the amplitude size. Nonetheless, this relationship of undrained shear strength ratio of peat soil is applicable regardless of the manner in which the maximum strain was accumulated [34]. Correspondingly, the undrained shear strength ration relationship to the maximum strain is seen accumulated from each specimen. As matter of fact, PNpt-25kPa from 1 Hz, 2 Hz and 3 Hz are accumulated in the adjacent maximum strain. With regards to this maximum strain, the undrained shear strength ratio shows, sequent decreases from higher frequency to lower frequency applied. For instance, PNpt-25kPa-1Hz to PNpt-25kPa-3Hz recorded 1.16 to 1.13 undrained shear strength ratio respectively.

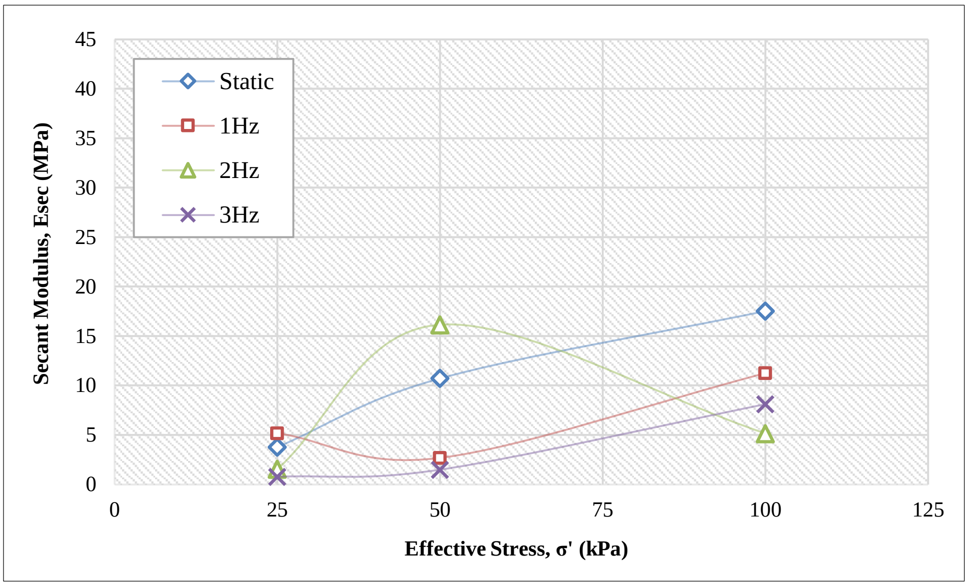
The other component of the post-cyclic parameters is the secant modulus at large deformation which is translated into a decrease in undrained shear strength subjected to cyclic loading. According to Erken and Ülker [16], the secant modulus is the ratio of deviator stress to axial strain, at which the deviator stress is equal to one half of deviator stress at critical state. The determination of secant modulus explains from stress-strain curve behaviour. Consequently, Table 5 summarized the secant modulus, Esec, effective stress and frequencies applied. The comparisons of the secant modulus against effective stress and frequencies applied are presented in Figure 8. The post-cyclic secant modulus obtained after cyclic loading, are designated by axial strain, ε_a = 20%. Post-cyclic secant modulus, E_{sec} than compared to the static secant modulus.

Table 5. Relationship of secant modulus, E_{sec} to the effective stress and frequencies applied

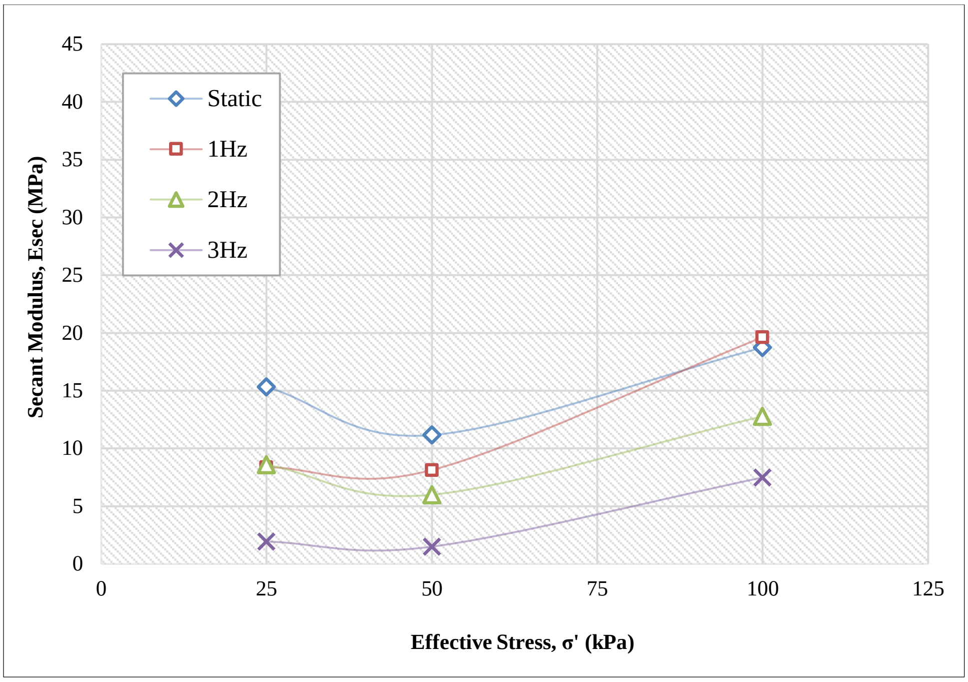
Test Condition	Effective Stress, σ' (kPa)	Frequency (Hz)	Secant Modulus, E_{sec}		
			PNpt	PSpt	BSpt
Post-Cyclic Monotonic	25	1	10.879	5.175	8.385
		2	13.113	1.529	8.594
		3	5.622	0.766	1.933
	50	1	11.952	2.668	8.125
		2	8.037	16.143	5.995
		3	1.577	1.488	1.49
	100	1	41.4671	11.242	19.630
		2	30.3915	5.147	12.781
		3	21.056	8.119	7.492
Static Monotonic	25	-	6.494	3.779	15.331
	50	-	12.375	10.716	11.159
	100	-	29.8670	17.531	18.7443



(a) PNpt



(b) PSpt



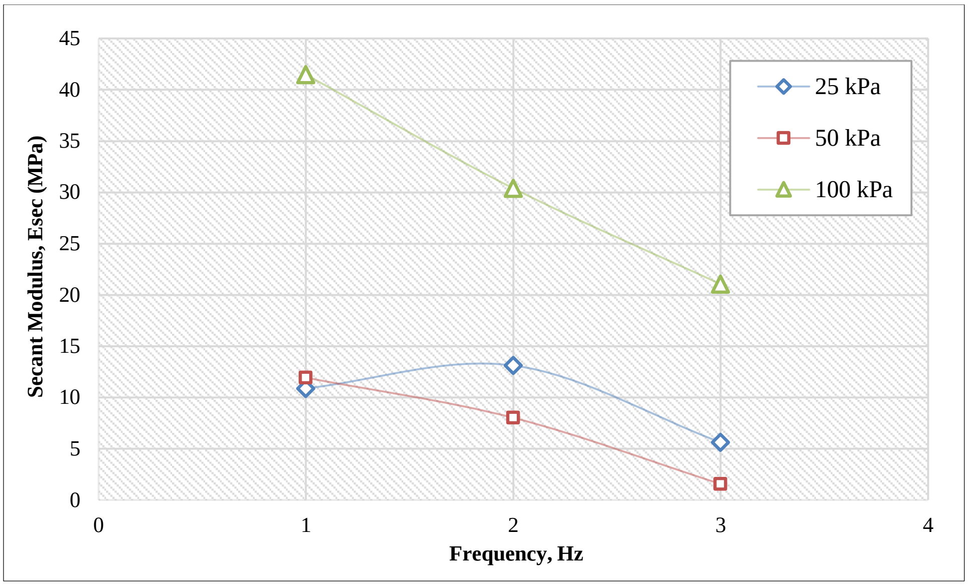
(c) BSpt

Figure 8. Variation in Secant Modulus with various Effective Stress, σ' (kPa)

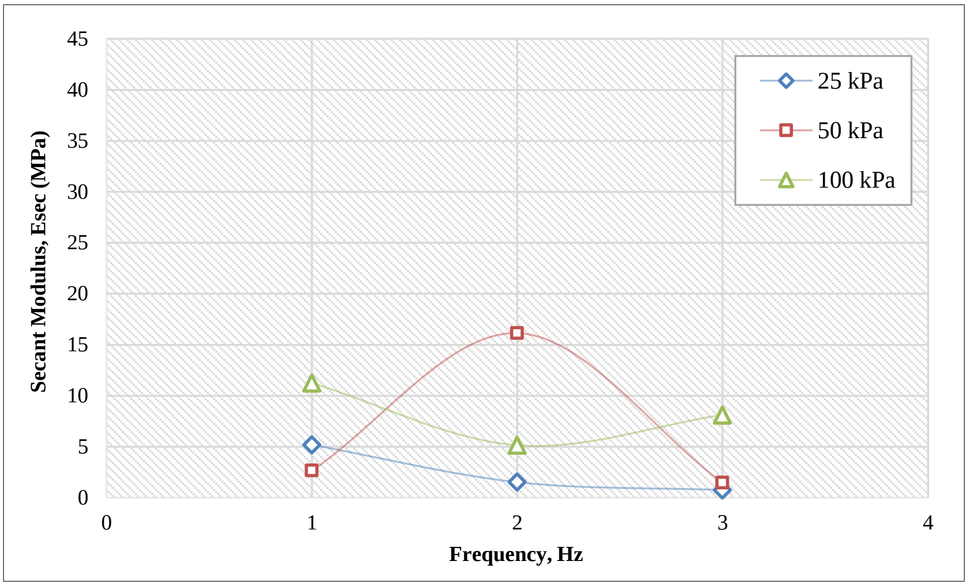
From Table 5, the secant modulus, E_{sec} of post-cyclic monotonic test shows a significant value, where for PNpt, at an effective stress 50 kPa, the secant modulus recorded contrary value compared to its initial secant modulus in static monotonic which is a higher secant modulus in post-cyclic compared to static. A same regime of secant modulus denoted in BSpt, at an effective stress 100 kPa, the secant modulus in post-cyclic also higher than its initial. This is showed that, there are enlargement and expansion occur in stress-strain behaviour curves that leads to the sharpness of gradient and automatically increase the secant modulus in post-cyclic.

For instance, the secant modulus for BSpt at an effective stress 100 kPa in static monotonic is about 18.74 MPa, while in post-cyclic, secant modulus expanded to 19.630 MPa cyclically loaded with 1 Hz. Unfortunately, the secant modulus returned to decline position when higher frequency applied at 2 Hz, where the secant modulus is about 12.781 MPa and continues to decline with 3 Hz at 7.492 MPa. This phenomenon suggests that, cyclic loading causes the initial stiffness of the peat subjected to cyclic loading increased as the pore and void spaces removed after cyclic loading as discussed in previous section. Thus, the undrained shear strength decreased slightly more than increment of stiffness due to restructuring process of peat. That statement had been discussed [44] which is the researcher has explained, for a given shear strain, the secant modulus of peaty organic soils increased with decreasing organic content and degree of decomposition or with increasing confining pressure. With the further increasing number of cycles, the permanent axial strain of the peat organic soil would exceed than its initial due to higher deformation accumulation rate. Diaz-Rodriguez et al. [44] in their study also stated this condition under the same stress state, the post-cyclic secant modulus peat soil had lower due to the higher static strength, resulting in smaller permanent axial strain.

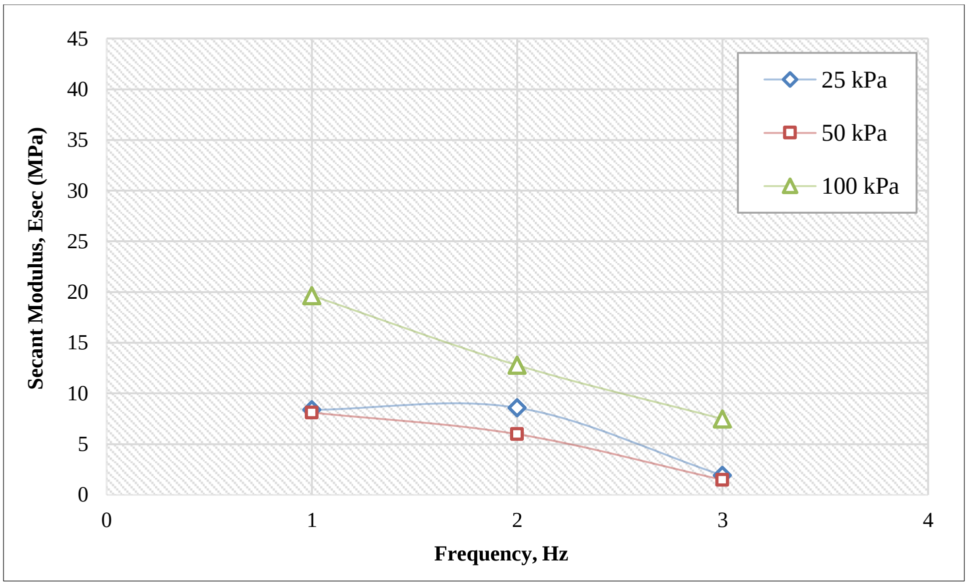
The initial stiffness is the initial tangential modulus, which is in turn the slope of the curve of deviator stress versus axial strain at the axial strain of 0% according to Shafiee et al. [28]. The yield shear strength was half of the deviator stress at an axial strain, in which those two tangential lines intersect [32]. Figures 9 to 12 demonstrates the comparison of variation secant modulus for post-cyclic condition with properties for PNpt, PSpt and BSpt. The secant modulus is equal to initial stiffness [28]. The secant modulus for PNpt is distinguishable and was smaller in static without cyclic loading and was greater in post-cyclic after cyclic loading. The $\Delta\sigma_{max}/2$ of PNpt-100kPa is 18.74 MPa and PNpt-100kPa-post-cyclic is 19.630 kPa. To further analysis of secant modulus, the variation of secant modulus is evaluated to understand the root causes of undrained shear strength degradation factors. In general, when specimen was imposed with 1 Hz cyclic loading, shear strength of PNpt, PSpt and BSpt gradually decreased. Thus, the small strain, 0.1% governs the deviator stress-strain behavior of post-cyclic [28, 34, 35].



(a) PNpt



(b) PSpt



(c) BSpt

Figure 9. Variation in Secant Modulus with Frequencies applied, Hz for (a) PNpt (b) PSpt and (c) BSpt

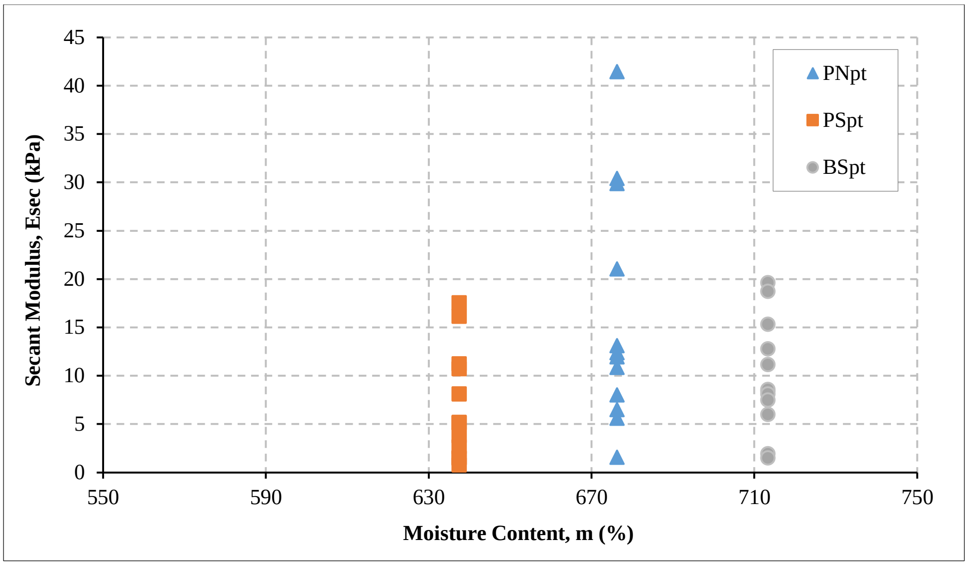
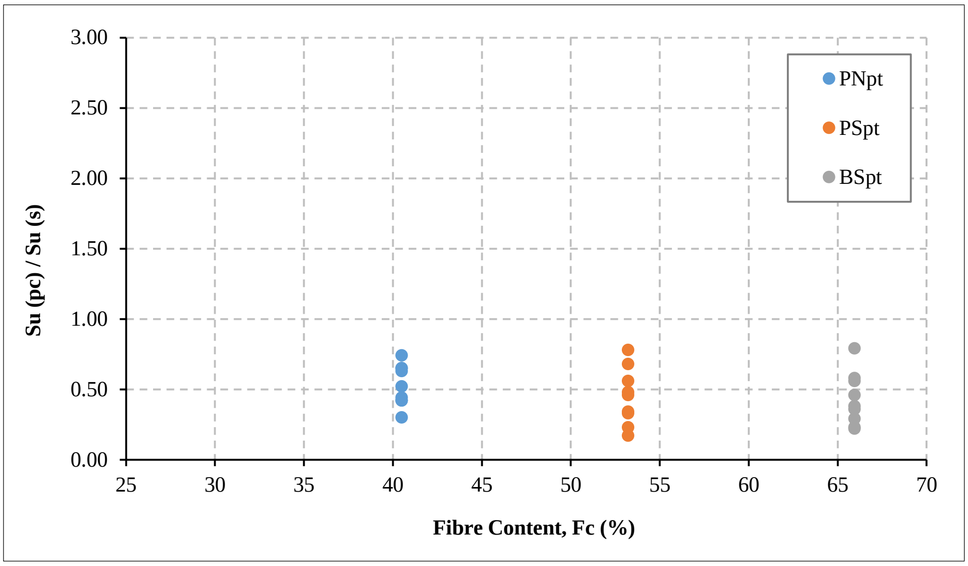
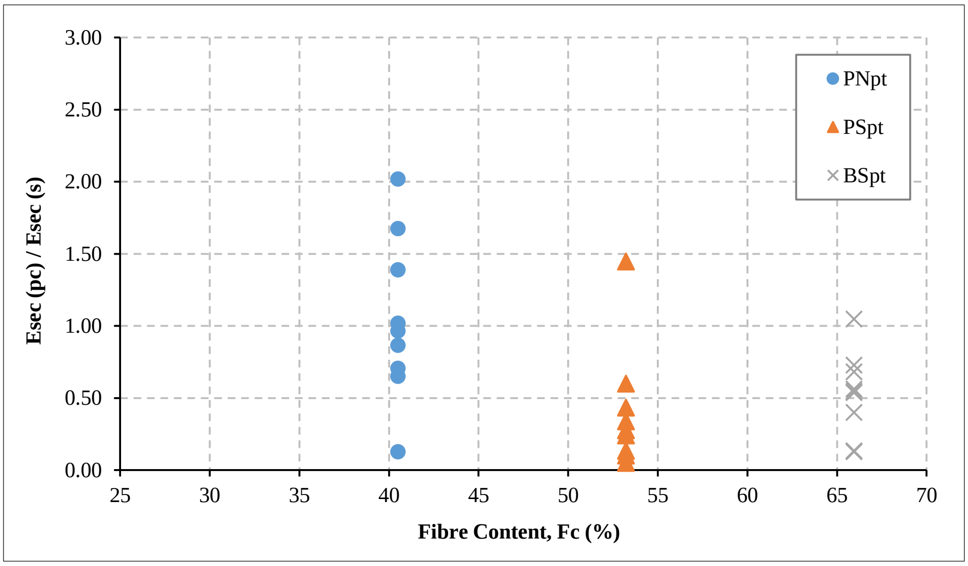


Figure 10. Variation of Secant Modulus, Esec with Moisture Content, m for PNpt, PSpt and BSpt



(a) Undrained shear strength



(b) Secant modulus

Figure 11. Variation of Normalized post-cyclic (a) undrained shear strength and (b) secant deformation modulus versus fibre content

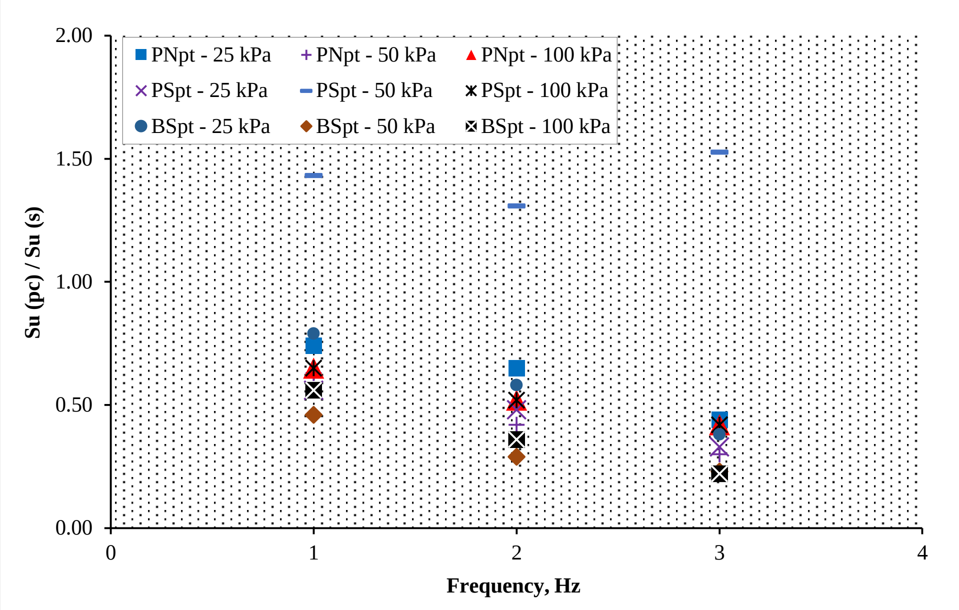


Figure 12. Variation of normalized post-cyclic undrained shear strength (kPa) versus frequencies, Hz applied

The secant modulus (E_{sec}) for all specimens reflects decrement. Shear strength decreased more with than secant modulus. The post-cyclic yield shear strength of undisturbed peat soil is considerably lower compared to static while cyclic loading is imposed to specimens after 100 numbers of cycles. The initial stiffness of post-cyclic for peat soil is governed by the softening behaviour that occurred when the specimen exhibited ± 1.5% axial strain [32, 36]. However, peat still showing the peculiarities behaviour consistently that showed, peat is not easy to handle and yet, challenging to the author. Figure 9 shows, a variation in secant modulus with frequencies applied for PNpt, PSpt and BSpt. For every stage of effective stress, there are similarities, the higher effective stress, the higher secant modulus, E_{sec}. In other words, it is also more pronounced where, the higher frequencies applied, the more secant modulus reduction responses.

Despite secant modulus (E_{sec}) for all specimens reflects decrement, it is also evidenced that the degradation of shear strength in post-cyclic loading is caused by cyclic loading. In addition, in this section widely discussed the variations of the post-cyclic undrained shear strength and deformation of secant modulus of peat soil are normalized to the corresponding values of moisture content as illustrated in Figure 10, variation of secant modulus, E_{sec} with moisture content, m for PNpt, PSpt and BSpt. Figure 11 shows the variation of normalized post-cyclic (a) undrained shear strength and (b) secant deformation modulus versus fibre content. In general, for the moisture content, the data are scattered and moderate positive correlation. In principle, there is no statistically significant result that's attributed to a reduction in shear strength, and no conclusion can be made. This is due to the regime of moisture content for all specimen according to the location where it took averagely same. Above all, the values of the secant modulus vary due to the effective stress and frequency applied, obviously. These applications during cyclic loading brought about the amplitude and maximum strain effects as discussed in the previous section. The causes of the decline in secant modulus have been explained previously; in this part, the effect of fibre content on the cyclic strain and amplitude imposed on the sample are discussed to explain the role of index properties towards post-cyclic stress-strain behaviour. For the fibre content, it is realized that in undrained shear strength (Figure 11-a), $S_{u(pc)}/S_{u(c)}$ does not change considerably. A similar result indicates that the secant modulus (Figure 11-b) toward fibre content function has no significant effect. The trend remained the same as the decreasing pattern in stress-strain behaviour and the root causes are related to the amplitude and maximum strain effects. This finding compared to the past studies conducted [34] and the results founds similarly where, there is no conclusion can be made and index properties does not change considerably in post-cyclic. The author emphasized that the strain-controlled method tends to apply to different stress levels.

4. Conclusions

The cyclic triaxial loading test, which simulates various dynamic loadings from traffic, waves, earthquakes, and machinery, is related to the fibrous condition of peat soil itself. In this research, image analysis observed and identified peat differences collectively across different locations. For particulate material, the micro-structurally of peat consists of organic material that is formed in fiber, woody material, roots, dead plants, and decomposable matter. In enhanced image, the peat clearly seen with woods and anonymous plant materials that formed peat from its nature condition. Averagely, the unrecognized material with moderate decomposition level is observed. The use of CT-scan technology affirmed soil investigation and showed that cyclic loading causes a reduction in pore and void spaces that leads to the solidification of peat. A comparison of the stress-strain behaviour during the post-cyclic tests with the stress-strain behaviour during the monotonic tests has been plotted and author observed that, the post-cyclic stress-strain behaviour of consolidated undrained peat soil from all samples and show diminution behaviour compared to its initial behaviour in static test with axial strain increasing as the specimens' heads towards the hardening and softening analogous under post-cyclic monotonic loading. Shear strength decreased and notched lower strength than its initial strength. Author also observed the decrease in pore pressure during post-cyclic loading has induced highly strength reduction and dilate upon loading to failure. The pore pressure generation seems to depend on the different loading frequencies and rely on amplitude levels that generated in the cyclic loading stage.

This reduction of excess pore water pressure is in line with the increases in loading frequencies and the decreasing trend with increasing axial strain. From static monotonic tests (Su(s)), compared to the post-cyclic undrained shear strength (Su(pc)). The post-cyclic undrained shear strength decreased, then after reaching a maximum value of deviator stress they follow a decreasing trend with increasing the axial strain. The higher frequency applied; the higher undrained shear strength decreased. The maximum strain effects were also studied in this research to understand the undrained shear strength ratio, Su(pc)/Su(c). The relationship between maximum strain due to cyclic loading and post-cyclic undrained shear strength is evaluated due to one-way loading, cyclic loading, and post-cyclic undrained shear strength for different peat soil origins from various places, especially PNpt, PSpt and BSpt.

The shear strain of peat in post-cyclic condition exhibit reduction for all specimens compared to its initial in static test. The main reasons that brought about the reduction in shear stress were also caused by the amplitude of the applied frequencies that applied and maximum strain in cyclic loading. Moreover, loading during post-cyclic increased the potential. Samples showed uncertainties data when pressurized in effective stress more than 25 kPa, the sample behave abnormally as pronounced unreliable data. This phenomenon believed and monitored as effects of water and pressure reaction in water are disturbing the peat structure to over pressured condition. The secant modulus, Esec of post-cyclic monotonic test shows a significant. There are enlargement and expansion occur in stress-strain behaviour curves that leads to the sharpness of gradient and automatically increase the secant modulus in post-cyclic. The causes of the decline in secant modulus and the effect of fibre content on the cyclic strain and amplitude imposed on the sample are discussed to explain the role of index properties towards post-cyclic stress-strain behaviour. For the fibre content, it is realized that in undrained shear strength, Su(pc)/Su(c) does not change considerably.

A similar result reflects the secant modulus towards fibre content function has no significant effect. The trend remained the same as the decreasing pattern in stress-strain behaviour and the root causes are related to the amplitude and maximum strain effects. The post-cyclic parameters have been observed to change relatively to the loading imposed, whether in static, cyclic, or post-cyclic loading. The author has observed that the shear strength degradation in post-cyclic is mainly caused by the cyclic loading history, which is related to the degradation in Young's modulus, E. The computed elastic parameter appears then to be a deceleration in the growth of Young's modulus that leads to a deficiency of stiffness and degradable elastic behaviour in the range of this research's peat soil. On the other hand, the pore pressure can be normalized since the stress-strain behaviour generated from triaxial stress gives relative behaviour to the pore pressure. It can be derived from the changes in excess pore water pressure to initial effective stress that was applied. To put it another way, the post-cyclic parameter changes observed and determination of undrained shear strength, Su and secant modulus, and Esec for PNpt, PSpt, and BSpt with effective stress studied. Upon reaching maximum axial strain at 20%, the undrained shear strength decreased against frequencies that applied from lower to higher amplitude. In general, the post-cyclic parameters affect the effective friction angle, cohesion of peat soil, secant modulus, and shear stress. However, while secant modulus (Esec) for all specimens reflects decrement, it is also evidenced that the degradation of shear strength in post-cyclic loading is caused by cyclic loading.

5. Declarations

5.1. Author Contributions

Conceptualization, H.M.M. and A.Z.; methodology, H.M.M.; investigation, A.Z.; writing—original draft preparation, H.M.M. and A.Z.; writing—review and editing, H.M.M. and A.Z. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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