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Stress Path Behaviour and Friction Angle Transition Due to the Cyclic Loading Effects

Habib Musa Mohamad [1*], Adnan Zainorabidin [2], Adriana Erica Amaludin [1]

[1] *Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia.*

[2] *Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat Johor, Malaysia.*

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Abstract

In various aspects, peat soil is different from mineral soil. Peat is a biogenic deposit that emerged within the last 10,000 years, during the post-glacial (Holocene) era. Peat is a soft soil that is unable to support external loads without experiencing significant deformations. Tyre pressure from automobiles and/or aeroplane wheels on paved surfaces creates traffic load, which can manifest as static or dynamic types of loading. To resolve the problem with peat soils, a thorough understanding of the static and dynamic behaviour of peat is still required. Many people who live near regularly used highways feel traffic vibration, and it is important to comprehend the nature of this issue to make predictions about potential solutions to this problem. As such, this study aims to investigate the cohesion (c) and friction angle (φ) properties of peat soil after it has been subjected to cyclic stress. Monotonic triaxial tests are conducted to ascertain the initial shear strength characteristics of the soil. Cyclic triaxial tests are performed with half of their maximum deviator stress to simulate the behaviour of peat soil under various effective stresses and frequencies of loading that are applied with 100 number of cycles. After applying various numbers of cycles of dynamic loading, the post-cyclic monotonic shear strengths were subsequently evaluated. It has been noted that irregular behaviour tends to occur more frequently at higher frequencies, particularly between 2 and 3 Hz. With higher frequencies being applied, the reduction in cohesion and friction angle becomes more evident.

Keywords: Post-cyclic; Shear Strength; Triaxial; Peat Soil; Dynamic Loading; Cohesion; Friction Angle.

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1. Introduction

Peat soils are typically classified as problematic soils due to their very low bearing capacity. It is not uncommon practice to subject peat soils to remedial measures to improve their engineering properties [1], however it is crucial to establish the natural peat soil index and strength characteristics first before applying any soil improvement methods [2]. Several general properties and distinctive data were compiled as a result of the review of peat in this study, which was carried out through a series of tests. In this study, the researcher will perform various commands to observe and determine the shear strength of soil through the use of the triaxial test. According to Whitlow [3], the triaxial test is frequently used to assess the shear strength of soil and is suitable for all types of soil, apart from very sensitive clays.

Furthermore, it also allows a number of different test methods to be conducted in succession. For instance, the Consolidated Undrained (CU) triaxial test is considered a reliable method for this test for determining shear strength parameters, as suggested by Gosling & Keeton [4]. Moreover, Boylan & Long [5] noted that a primary controlling factor in peat failure is the inherent shear strength of the peat itself. Based on the findings of earlier research, Warburton et al. [6] observed various types of contacts at the peat-mineral soil interface, with the outcomes ranging from sharp contact

* Corresponding author: habibmusa@ums.edu.my

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to complex connections. Many of the mineral failures in Pollatomish, Co. Mayo, that were described by Boylan et al. [7] occurred on a plane of organic material beneath the mineral soil.

The stability of peat mass is indicated through an understanding of the strength variation through the said peat mass; however, knowledge of the shear strength behavior of peat soil remains an essential requirement in the design of any embankments, structures, or any infrastructures. Das [8] specifies that the strength of a material is generally equated to the greatest stress it can sustain. The significance of shear strength can be described in a few factors, particularly in the safety aspect of any geotechnical structure that is highly dependent on the soil strength itself, especially since any structure founded on peat may risk collapse if the soil fails. This is where understanding shear strength is the basis for analyzing soil stability problems to a comprehensible stage. Conversely, Das [8] intently emphasizes the comprehension of soil shear strength by explaining that soil shear strength is derived from its resistance to shearing stresses, while simultaneously highlighting the significance of shear strength.

The necessity of this study includes the behavioral observation of soil shear strength elements from a stress path perspective and changes in soil friction angle during the loading or unloading process. Peat specimens subjected to cyclic loading lead to changes in soil parameters, especially at a series of stress points. Therefore, a curve or a straight line is the locus of a series of in-situ elements showing the changes in stress behaviour. In terms of the shear strength parameter of soil, friction angle is measured during the loading and unloading processes. The changes are derived from the Mohr-Coulomb failure criterion, which is used to describe the friction shear resistance of soils together with the normal effective stress.

Furthermore, Das [8] stated that in order to ascertain the static undrained shear strength of soil, it is correlated to the measure of the soil resistance to deformation by continuous displacement of its individual soil particles. As such, it is evident that shear strength in soils primarily depends on inter-particle interactions. The determination of static undrained shear strength plays an important role in this study since the primary objective is to systematically determine the post-cyclic undrained shear strength behaviour of peat soil and to compare the results with the pre-cyclic condition. As reported by Erken et al. [9], the static and dynamic study testing programme was conducted with the torque load at the desired values and rates that can be applied to the cylinder specimens in one direction in static tests. In triaxial shear strength determination, Erken et al. [9] described that the torque loading was applied monotonically in static tests after the consolidation process was completed. In their investigation, Erken et al. [9] utilized monotonic loading of 0.50 mm/sec loading rate, while the author used 0.10 mm/sec rates, which continued until the soil specimens exhibited a shear strain of 10%. As a comparison, peat material is classified as a highly sensitive and soft material [10]. Therefore, the loading rate imposed to the peat material must be applied slowly to prevent damage in the early stages of testing. Consequently, the stress-strain relationships and the shear strength properties of the soil specimens are determined under isotropic and anisotropic conditions by applying sinusoidal loads [9]. Various research findings have investigated the shear strength of peats through laboratory tests and have demonstrated that the peat behaviour is frictional with a high friction angle while also possessing relatively small cohesion intercepts as detailed by Edil [11] and reviewed by Yamaguchi et al. [12]. Accordingly, Cola & Cortellazzo [13] insist that these high friction angle values are linked to the presence of semi-decomposed fibres, which intersect the failure plane and constitute the internal reinforcement.

Yamaguchi et al. [12], which is then presently followed Cola & Cortellazzo [13] similarly assert that, due to the presence of fibre pull-out resistance, the shearing resistance is strongly influenced by the orientation of the failure plane that is relative to the general alignments of the fibre itself. At the same time, Yamaguchi et al. [12] discovered the idea that the friction angle values determined by means of compression triaxial tests for peats of Japanese origin resulted in normally consolidates that varied from 250 to 350 when major principal stresses coincided in a vertical and horizontal direction. The dynamic loads will affect the soil behaviour and are particularly significant for soil shear strength [14]. Principally, the effect of cyclic loading on post-cyclic shear strength increased the potential for reduction of shear strength. The stiffness ratio is 0.5, and the cyclic shear stress ratio is identified as lower than the shear strength of peat soil, which takes 0.082 caused by dynamic loads [15]. On the other hand, soil becomes increasingly nonlinear and inelastic, with significant permanent microstructural changes taking place under cyclic loading [16].

Due to the presence of fibre during the development of high excess pore pressure at failure, Farrell & Hebib [17], followed by Boulanger et al. [18], stated that the shear strength values can exceed the magnitude of confining pressure. Ultimately, this condition will result in complications when making any interpretation of the shear strength parameters. Farrell & Hebib [17] have conducted a laboratory test involving the shear behaviour of two types of peat. On both natural and remoulded samples, a series of undrained compression triaxial tests were carried out by monitoring pore pressure measurements with isotropic and anisotropic consolidation stages. In order to correctly assess the shear strength of peat soils, according to Farrell & Hebib [17], the shear strength results can be explained by means of analysing the fibres in shear behaviour that are evaluated and measured bilinear to the failure criterion. As stated by Gosling and Keeton [4], the physical properties and characteristics are influenced by shear strength factors. More specifically, Farrell & Hebib [17], through their investigation and field study had established the principal characteristics of peat soils. A reliable indicator to measure the effective friction angle (φ') and cohesion coefficient (c’) are applicable for stress path reaching the Kf line by generating the Mohr’s circle in order to characterize the post-cyclic monotonic behaviour.

After the transformation points were reached, all stress paths rose along one line (K_f line). Ishihara [19] clarifies that the transformation phase is defined as the state at which the reversal from contractive to dilative behaviour occurs. Subsequently, the effective friction angle is computed to be:

$$sin\emptyset = \frac{3M}{(6+M)} \tag{1}$$

This data should be interpreted accordingly with the observed stress-strain behaviour, where the deviator stress is plotted against the axial strain until failure occurs (otherwise known as softening behaviour) or there will be a condition where the deviator stress application results in the hardening behaviour on peat during static tests. The specimens predominately exhibit strain-hardening behaviour up to large deformations, while accompanied by a decrease in p'.

This phenomenon was further expounded by Yang and Sze [20] where the stress paths are all below this line, an indication that no tensile failure occurs for the WLP samples. When the specimens undergo deformation until the axial strain ε_a reaches approximately 20%, this occurrence is classified as Critical State Failure. The lack of a 'tension cut-off' failure or known as shear plane is possibly attributed to the relatively low fibre content. Even though some fibres may break in tension, the frictional shear component dictates the overall engineering behaviour of this fibrous peat.

2. Materials and Methods

Tests were performed on collected specimens from (1) Parit Nipah, Batu Pahat, Johor, (2) Parit Sulong, Batu Pahat, Johor and (3) Beaufort, Sabah samples. The purpose of performing laboratory tests on the peat soil samples are to determine the physical characteristics, to classify soil samples, and to evaluate the basic index soil properties of samples designated for each location. Monotonic triaxial test are performed to establish the stress-strain curve with noted maximum moment peak failure to characterize the soil strength and to collect the proposed cyclic data. Meanwhile, the Cyclic triaxial test are performed at half of its maximum deviator stress to simulate the behaviour of peat soil under various effective stress and frequencies loading that are applied. A predetermined number of cycles of dynamic loading were applied to the peat soil samples in order to determine its post-cyclic monotonic shear strength values. The effective pressures of 25 kPa, 50 kPa and 100 kPa were utilized to simulate the real site pressure conditions and frequencies applied represents loading type as further discussed in the literature review section. Under the static test, the consolidated undrained (CU) test are conducted, and this was subsequently followed by the cyclic triaxial testing programme.

For this study, there were three chosen locations designated as the sampling site. The first location, Parit Nipah in Batu Pahat, Johor is considered as the main peat soil location. This location is well known as a peat deposit area based on some of problematic area in Malaysia that deals with peat soil, and has well-reported soil index and strength characteristics published in recent years [21, 22]. Parit Sulong, Batu Pahat, Johor is another location of peat soil deposit that was recently explored in the West Coast of Peninsular Malaysia [23]. The third and final location in Beaufort, Sabah peat is a newly discovered site, since there is no single study conducted for Sabah peat soil from an engineering perspective – hence making it a pioneering study in conducting peat soil research for Sabah region. Table 1 shows the symbol of peat specimens accordingly labelled based on their respective locations with longitude and latitude positions. The symbol is useful to tag every sample for identification reasons. These locations mainly consist of hemic peat soil. For undisturbed sample, a Dutch tube sampler is used for soil extrusion until the required depth was reached. In this study, the depth requirement is up to 0.5 m from soil surface. In addition, PVC tube samplers with size 50 mm diameter and 160 mm height were also used.

Table 1. Specimen label in symbol of peat based on Location

Location	State	Symbol	Latitude and Longitude
Parit Nipah	Johor	PNpt	1.829930, 103.182487
Parit Sulong	Johor	PSpt	2.002030, 102.833092
Beaufort	Sabah	BSpt	5.325761, 115.669575

According to the ASTM D5715-14 engineering standard, peat soils are classified based on their degree of decomposition. Degree of decomposition is the method used to describe the physical appearance of soil based on the Von Post scale. The degree of decomposition of peat materials is therefore an important property in relation to the classification and evaluation of the material for various uses [24-26]. Furthermore, O'Kelly [27] states that engineering behaviour of peat materials can be assessed with its Degree of Decomposition, since this parameter can be used to predict its peat shear strength, based on the correlation between its von Post classification and organic content with known shear strength values of peat [25].

In the present study, the Degree of decomposition test carried out by taking a representative sample in hand and firmly squeezing the soil. Two elements were noted upon the completion of the von Post test: (1) the colour of the water expelled between the fingers upon squeezing the sample, and (2) the amount of amorphous matter expelled and peat fibre passes between the fingers. Figure 1 illustrates the demonstration of the von Post test conducted via the squeezing technique in palm to generate some pressures onto soil. Through a visual observation, it is apparent that the PNpt, PRpt and BSpt peat soils are classified as different types of peat since they originate from various locations. This indicates that several factors played a role in the formation of the peat soil constituents, which includes the level of humification to temperature conditions, soil moisture, fibre content and obviously soil structure itself. Presence of external plants that were still growing near the soil sampling site had also influenced the content of peat from the presence of roots during sampling.

(a) Peat being squeezed (b) Remaining peat fibre in palm

Figure 1. Representative Sample of Peat Squeezed

The investigation of peat soil under the consolidated-undrained triaxial compression tests is done to inspect the element of soil shear strength. Shear strength and its corresponding deformation characteristics were developed in the consolidated undrained condition. Accordingly, this study was conducted to identify the behaviour of peat soil by using consolidated-undrained triaxial compression tests method. The series of planned tests are divided into the several phases. This research provides a detailed needs to the subject of triaxial testing stages. Triaxial testing was done as outlined by the geotechnical test standards BS 1377: Part 8: 1990. Methods of Test for Soils for Civil Engineering Purposes: Shear Strength Tests (Effective Stress) that required the consolidated undrained test which typically consists of four main stages: (1) specimen and system preparation, (2) saturation, (3) consolidation, and (4) shearing [28]. Static test was carried out using the GDS Enterprise Level Dynamic Triaxial Testing System (ELDYN). The Consolidated Isotropic Undrained test was executed under five various effective stress ranging from 25 kPa, 50 kPa and 100 kPa.

In this study, the peat soil undergoes shearing by applying an axial strain ε_a to the test specimens (in undrained condition) with a constant rate of axial strain slow enough to allow adequate equalisation of excess pore pressures. During consolidation, the drainage line is closed and the excess pore pressures were recorded. The frequencies used for this research are within the range of 0.5Hz, 1.0Hz, 1.5Hz and 2.0Hz for each specimen. Table 2 shows the cyclic properties that used in this study.

Table 2. Cyclic Properties and Number of Sample

Peat Location	Effective Stress (kPa)	Frequencies (Hz)	Acceleration Rate (mm/min)	Number of Specimens Used	Total Number of Specimens Tested
PNpt	25	1.0, 2.0 and 3.0	0.1	9	21
	50				
	100				
PSpt	25	1.0, 2.0 and 3.0	0.1	9	21
	50				
	100				
BSpt	25	1.0, 2.0 and 3.0	0.1	9	21
	50				
	100				

The properties of values and frequencies were applied based on previous research, as recommended by other Malaysian and South-East Asian-based researchers, and by using the closest proposed values available in the literature [29]. The continued loading is affected by the changes in water level, traffic loading, and minor loads caused by earthquake activities in the nearest neighbouring countries [29]. Meanwhile, the frequency of 3.0 Hz was applied for the best representation of the minor effect of an earthquake in Malaysia, and the remainder comes from machinery and traffic loading.

A procedure known as the "post-cyclic" test is imperative to ascertain the impact of cyclic loads on the monotonic shear test for peat soils. The test is similar to the normal monotonic triaxial shear test. For the purpose of this research, which focuses on the behaviour of peat soil under cyclic loading, an axial strain limit, ε_a equal to 20% is applied to measure the shear strength after cyclic loading. A triaxial test is performed on a cylindrical core soil sample from BSpt, PNpt and PRpt to determine its post-cyclic shear stress and stress-strain behaviour. More specifically, the cylindrical peat sample with 50 mm diameter and 100 mm height was vertically sealed with a thin rubber membrane and placed into a cell that was pressurized in between two porous discs at the top and bottom end. The effective pressures were set at 25 kPa, 50 kPa and 100 kPa, respectively. The undrained triaxial test was conducted as stipulated in BS 1377, with the sample normally consolidated within the duration of 24 hours. The undrained condition was applied to the cyclic triaxial and post-cyclic triaxial test. In both the static and post-cyclic triaxial, the loading rate was set to be 0.1 mm/min for each specimen.

The undisturbed sample method was used for triaxial testing, and is a preferred sample preparation method in order to maintain the natural characteristics of the peat soil. Shear strength and its corresponding deformation characteristics were developed in the consolidated undrained condition. Consequently, this study was conducted to identify the behaviour of peat soil by using consolidated-undrained triaxial compression tests method. Triaxial testing was done as described in BS 1377: Part 8: 1990. Methods of Test for Soils for Civil Engineering Purposes: Shear Strength Tests (Effective Stress) which requires the consolidated undrained test, and it consists of four main stages: (1) specimen and system preparation, (2) saturation, (3) consolidation, and (4) shearing [28]. Static test was carried out using the GDS Enterprise Level Dynamic Triaxial Testing System (ELDYN).

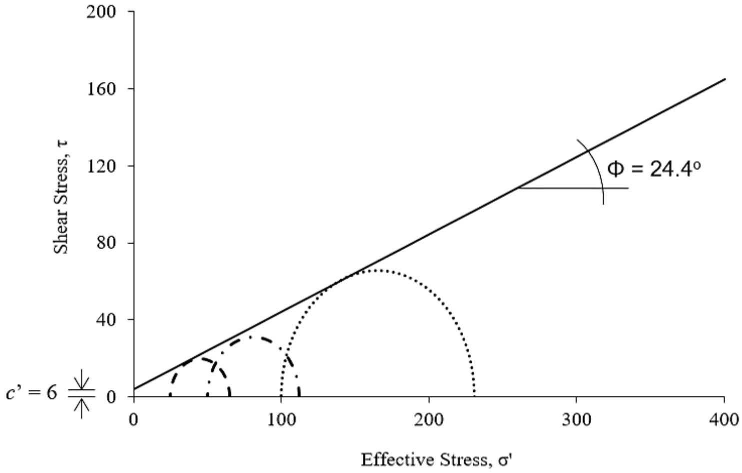
CU test is used since the term 'unconsolidated' is related to slopes, rather than 'consolidated' reflecting the physical condition of the soil in the ground. Thus, the term CU is considered and used in this research significantly to the method where the drainage is not allowed to maintain the peat soil natural behaviour that consists of high-water content. The Maximum deviator stress (σ_{dmax}) is defined as the difference between major and minor of principal stress in the maximum state. Meanwhile, the parameters of shear strength obtained in the peak deviator stress at maximum 20% of axial strain under five various effective stresses ranging from 25 kPa, 50 kPa to 100 kPa. The preparation of peat samples involves extruding samples from the 50 mm diameter by 160 mm height PVC tubes, and trimming the undisturbed sample into the required size at 50 mm diameter to 100 mm height. Pressure is allowed to fill in the chamber (pressure levels are indicated by the software) and the consequent saturation stage could therefore be allowed to start. In practical applications, the cell pressure is controlled by an enterprise level controller and the back pressure is controlled by a pneumatic controller. This functions as a water pressure source and volume change gauge for the precise measurement of fluid pressure and volume change.

A rapid check to determine the Skempton's B-value is conducted to ensure that required saturation level has been achieved before proceeding to the consolidation stage. This stage requires the specimen drainage to be closed whilst the cell pressure is raised by approximately 125 kPa, with $B \geq 0.95$ typically used to confirm full specimen saturation [30]. As previously mentioned, the peat soil is sheared by applying an axial strain ε_a to the test specimens at a constant rate, with the specimen in an undrained condition and the applied rate of axial strain slow enough to allow adequate equalization of excess pore pressures.

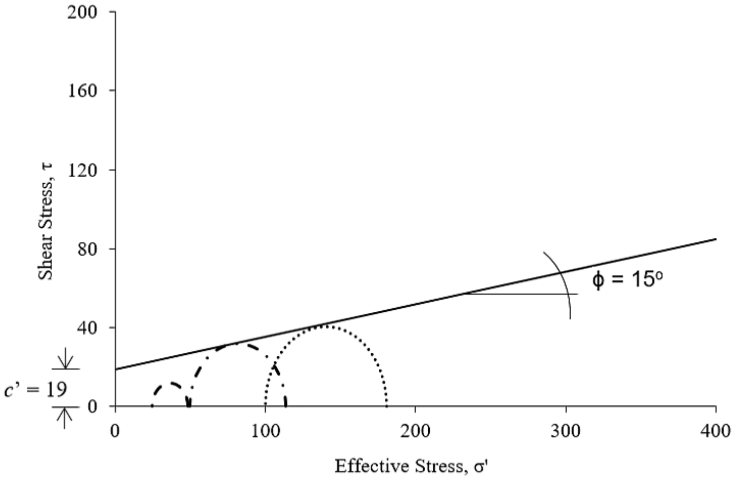
During consolidation, the drainage is closed, and the excess pore pressures are recorded. In this study, the cyclic triaxial tests are carried out to analyse and identify the response of peat soil to dynamic loads. Dynamic testing were carried out accordingly after shearing. The frequencies used for this research fall within the range of 0.5Hz, 1.0Hz, 1.5 Hz and 2.0 Hz for each specimen. The test is similar to the normal monotonic triaxial shear test. For the purposed of this research for behaviour of peat soil under cyclic loading, it is to be set up for axial strain limit, ε_a equal to 20% after cyclic loading to measure the shear strength after cyclic loading. In this research, which focuses on peat soil behaviour under cyclic loading, the axial strain limit ε_a equal to 20% (applied after cyclic loading) was imposed to measure the shear strength.

3. Results and Discussion

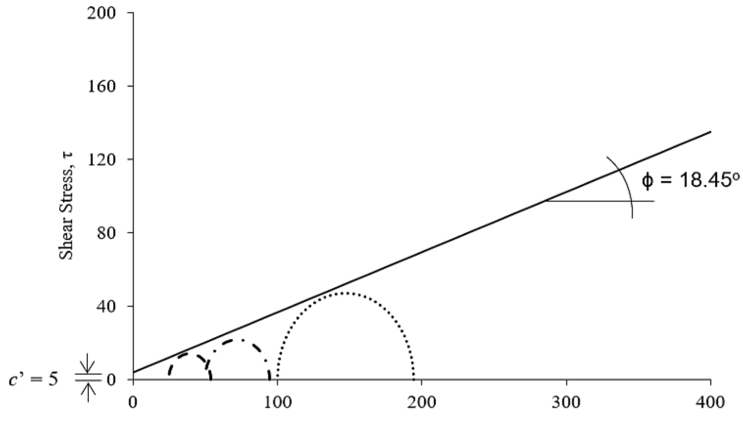
In this section, the undrained triaxial test on peat soil for PNpt, PSpt and BSpt samples are described, along with the explanation on the determined failure criterion used to compute effective friction angle. This section is the outcome of the experimental program methodology detailed from previous section, which was done to study the effects of cyclic loading on the post-cyclic effective friction angle. Generally, the dynamic response of a soil is presented in two forms, as (1) shear modulus degradation, and (2) damping curves for a wide range of shear strains [31], but the dynamic properties of Johor and Sabah peat soils were published by the author in several recent works [32, 33]. The total parameters to be studied is two (2), both of which are related to Mohr-Coulomb. The bounding parameters are cohesion, c' and effective stress friction angle, φ', respectively. To demonstrate the individual effects of static and post-cyclic conditions, Figure 2 illustrated the cohesion and effective friction angle for static monotonic tests using failure criterion of 20% axial strain.



(a) PNpt



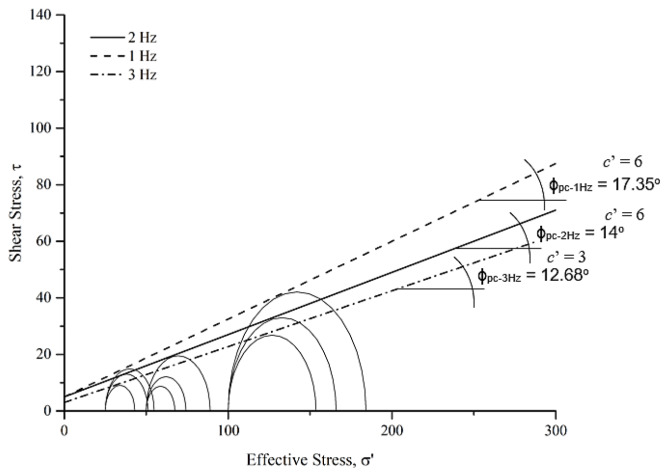
(b) PSpt



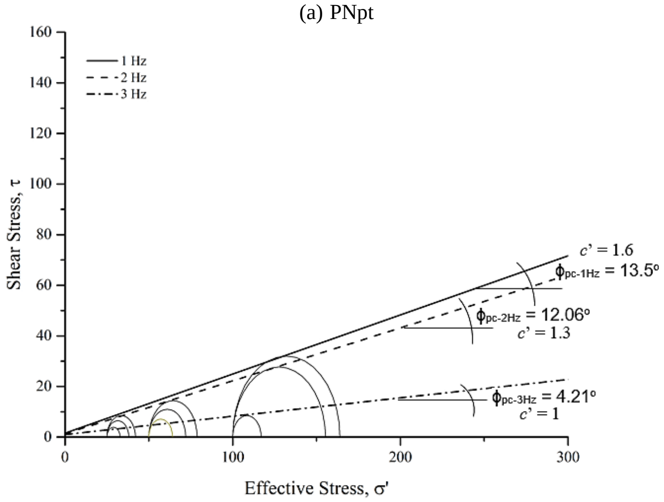
(c) BSpt

Figure 2. Effective friction angles of static monotonic for: (a) PNpt, (b) PSpt and (c) BSpt using failure criterion of 20% axial strain

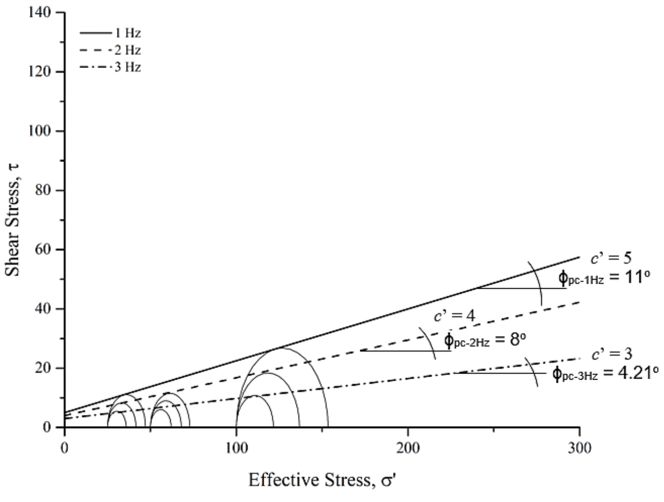
On the other hand, Figure 2 shows the post-cyclic effective friction angle for the consolidated undrained condition of (a) PNpt, (b) PSpt, and (c) BSpt peat samples. On account of the degradation in the stress-strain behaviour after 100 load cycles, the specimens produce cohesion and an effective friction angle. From Figure 3, it can be observed that the cohesion, c' for PNpt is about 6 kPa, while the cohesion for PSpt and BSpt is 19 kPa and 5 kPa, respectively. To that end, the effective friction angle for all specimens from PNpt, PSpt, and BSpt was instantly evaluated and shows varying values: for PNpt, the value is 24.40°, PSpt is 15°, and BSpt is about 18.45°. Under post-cyclic triaxial conditions, the specimens work-softening to the degradation of Mohr-Coulomb parameters. Figure 3 shows the post-cyclic monotonic failure criterion. When the peat soils were imposed with cyclic loading, the specimen response diminished as a result of an increasing effect on the maximum strain, as previously discussed. In comparison with static testing, it was found that the cohesion of PNpt in post-cyclic tests shows a consistent degradation, along with other parameters.



(a) PNpt



(b) PSpt



(c) BSpt

Figure 3. Post-cyclic Effective Friction Angle for Consolidated Undrained Condition of (a) PNpt (b) PSpt and (c) BSpt

The cohesion degrades from 6 to 3 kPa (PNpt-3Hz), while PSpt from 19 to 4.21 kPa (PSpt-3Hz) and 5 to 4.21 kPa (BSpt-3Hz). This clearly demonstrates that the cyclic loading is directly responsible for the reduction in cohesion of peat soil, in line with the degradation of stiffness found in previous section. This phenomenon occurs due to the dilative behaviour of peat during cyclic loading. The effective friction angle also overrides its initial effective friction angle accordingly. In contrast with the c' and φ', the loading effects during cyclic loading has considerable impact on the overall degradation in the shear strength, deviator stress, shear stress ratio and pore pressure. The effective friction angle in post-cyclic had also reduced compared to its initial value, as seen in Figure 3. The decreasing φ' corresponds to softening in stress-strain behaviour. As explained earlier, the loading phase shows more degradation in the effective friction angle. The suggested range of effective friction angle for PNpt is proposed 24.4 $\leqslant$ φ' $\leqslant$ 12.68, 15 $\leqslant$ φ' $\leqslant$ 4.21 (PSpt) and 18.45 $\leqslant$ φ' $\leqslant$ 4.21 (BSpt). Since the effective friction angle, φ' for static is higher than the post-cyclic value, a significant change in the effective friction angle can be correlated to the frequency applied. More specifically, the author has observed that with larger frequencies applied, more degradation of the effective friction angle value was recorded. The predicted stress-strain behaviour in this research leads to a progressive and correlated finding, which ultimately means that the major reduction in shear strength is caused by the shear plane that forms after cyclic and post-cyclic loading. The shear strength parameter changes were significantly correlated to microstructural modifications [34].

Conversely, the stress path behaviour of peat cyclic loading was monitored and produced significant behaviour to comprehend. The analysis of a *q-p'* stress path graph, which shows the changes in deviator stress (*q*) and mean effective stress (*p'*) will be used to evaluate the cyclic response of the PNPt, PSpt, and BSpt peat samples [35]. The PNpt-Static stress paths rose along one line to the left side, as shown in Figure 4, where the behaviour resembles the undrained stress path behaviour. However, contrasting behaviour apparently occurred in PNpt-Post-cyclic, where the phase transformation points were reached slightly short and ruptured to submerge their initial condition. Cyclic loading was largely responsible for the extensive behaviour changes to the post-cyclic behaviour, which rose from left to right side and behaved similar to the drained condition. The yielding surface is assumed to depend on the soil structure damage and is believed to have been entirely involved in wave action; this may cause repeated damage in the peat soil structure, hence weakening the soil strength. This failure transformation condition is otherwise known as damage to soil fabric, as clarified by Wang [36] and Wang et al. [37], which state that the damage to the soil fabric outstanding to cyclic loading is attributable to the reduced undrained shear strength and limited recovery of deviator stress with deformation demonstrated in silt [38].

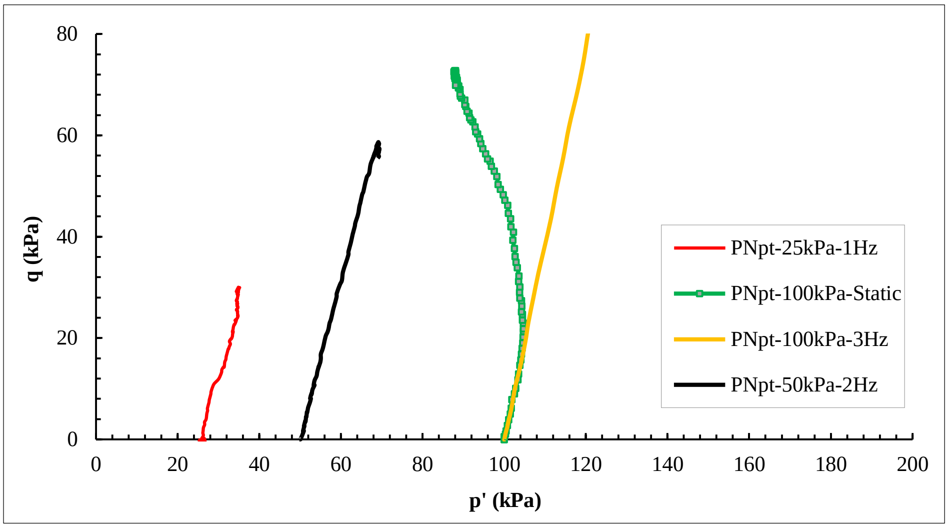


Figure 4. Typical effective stress paths behaviour of PNpt

Visual inspection of post-test peat specimens that had undergone static, cyclic, and post-cyclic loading indicates that the development of shear planes was more pronounced in the undrained triaxial test. Therefore, it is more apparent that shear zones formed by loading factors that are mainly attributed to cyclic loading facilitate the formation of a new regime of peat specimen shape in such a way that the undrained strength degradation is monitored. During the undrained loading that had localized drainage translating the volume changed in a small, specific region, although the overall volume of the specimen was constant [39, 40]. Figure 5 demonstrated that the formation of shear planes results in a reduction in shear strength.

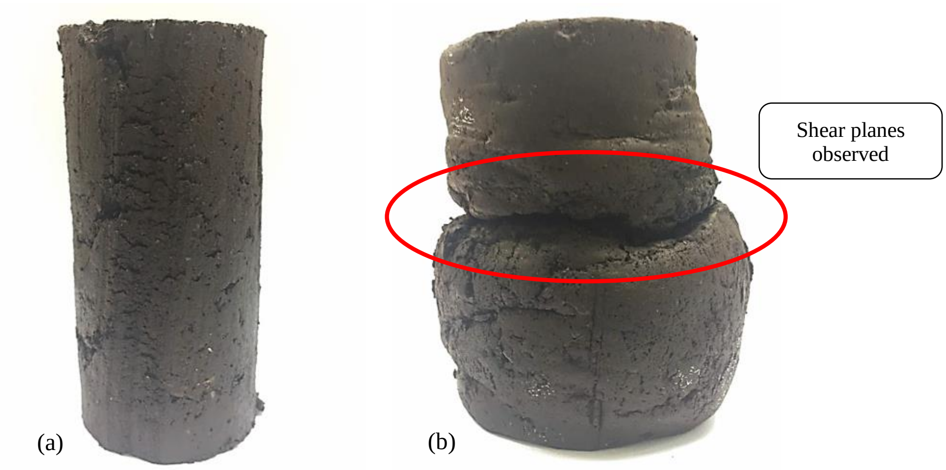


Figure 5. Peat specimen (a) undisturbed peat specimen without loading and(b) Shear planes observed after post-cyclic monotonic test (Cyclic loading condition: σ = 100 kPa, N = 100, 2 Hz)

Additionally, the cyclic loading played a major role in reshaping, in the context of the post-cyclic mode of failure condition. As a result of the reshaping, the final shape was observed to be rounder and more bulbous. It was noted that the cyclic loads gave more impression and stress to the peat soil. Specifically, physical changes in height, diameter, and volume were seen. Practically, the results of this research conducted with the undrained triaxial test on peat soil can therefore be accepted. It has been highlighted from these observed changes that the peat soil imposed with static and dynamic loading had responded accordingly by showing changes to the restructuring fibre and soil physical characteristics.

4. Conclusions

A more thorough understanding of the behavior of peat subjected to cyclic loading is now possible thanks to the contribution made by current research and recent studies conducted which focused on the post-cyclic parameter changes in peat soil. This research presents the findings obtained from the static undrained triaxial test and cyclic triaxial test behaviour to study the dynamic loading relationships with the studied loading phases, frequencies, and effective stresses applied. The results presented in this paper show the impact of cyclic loading in influencing the strength of post-cyclic shear in peat soil. The cyclic loading test, which simulates traffic loading frequency behaviour showed that the dynamic behaviour has a significant effect on the cyclic loading properties of peat soil. It has been observed that, at larger frequencies, more irregular and inconsistent cyclic behaviour were seen. In short, the higher the frequency applied, the more inconsistent behaviour occurs within the soil matrix, especially for frequency bands ranging more than 2 to 3 Hz. Based on the analysis, it can be concluded that there are multiple behaviors modifications in post-cyclic loading due to cyclic loading, listed as follows:

- The effective friction angle for all specimens from PNpt, PSpt, and BSpt is instantly evaluated and shows varying values, for PNpt is about 24.4°, PSpt is 15°, and BSpt is about 18.45°.
- Specimens PNpt, PSpt, and BSpt loaded with 100 cycles of dynamic loading caused fiber fragmentation and restructuring of the soil characteristics.
- Higher frequencies cause more irregular behaviour within the soil sample, especially for frequencies greater than 2 to 3 Hz. The reduction in cohesion and friction angle is more pronounced with higher frequencies applied.
- The cyclic loading test, which simulates traffic loading frequency behaviour showed that the dynamic behaviour has a profound effect on the post-cyclic loading shear strength parameters of peat soil.
- The cohesion of PNpt in post-cyclic compared to static shows a consistent degradation, along with the degradation of other soil parameters. The cohesion degrades from 6 to 3 kPa (PNpt-3Hz), while PSpt from 19 to 4.21 kPa (PSpt-3Hz) and 5 to 4.21 kPa (BSpt-3Hz).
- Contrasting behaviour occurred in the PNpt-post-cyclic test, where the phase transformation points were reached slightly short and ruptured to submerge their initial condition.
- It is more pronounced that shear zones formed by loading factors that are mainly attributed to cyclic loading facilitate the formation of a new regime of peat specimen shape in such a way that undrained strength degradation is monitored.

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., A.Z., and A.E.A. 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.

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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