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Post-cyclic Loading Relationship Effects to the Shear Stress and Cyclic Shear Strain of Peat Soil

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Abstract

Peats originate from plants and denote the various stages in the humification process. This condition renders the peat extremely soft and can be considered problematic soil. Thus, this study is conducted to examine and comprehend the particularities of peat engineering behaviour in respect to the relationship effects to the shear stress and cyclic shear strain of peat soil various characteristics to establish suitable correlation. This study carried out by using triaxial testing described by geotechnical test standards BS-1377: Part 8: 1990. Methods of Testing Soils for Civil Engineering Purposes: Shear Strength Tests (Effective Stress) that required for consolidated undrained and consist of five main stages: saturation, consolidation, static, dynamic, and post-cyclic loading using the GDS Enterprise Level Dynamic Triaxial Testing System (ELDYN). The parameters of shear strength were obtained in the peak deviator stress at a maximum of 20% of axial strain by using an undisturbed sample with an effective pressure imposed of 25, 50, and 100 kPa. In this study, all specimens are subjected to cyclic loading up to 100 cycles based on a one-way loading system with strain-controlled conditions. Based on the analysis conveyed, the post-cyclic shear stress decreased compared to its initial value of about 65.56 kPa (PNpt-100 kPa) in static and decreased to 14.9616 kPa in post-cyclic (PNpt-25 kPa-1 Hz). The principal stress ratio (σ'_1/σ'_3) shows the maximum values of this ratio that are located in the narrow zone of 1.61 to 1.12.

Keywords: Shear Stress; Cyclic Shear Strain; Triaxial; Peat Soil; Dynamic Loading; Post-Cyclic.

1. Introduction

The dynamic load studies are the result of a continuous effort from various researchers. Various considerations and criteria are taken into consideration while making statements 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 on Mercer Slough peat and Shermand Island peat in California [1-3]. Kishida et al. [1] have conducted similar studies on methodology for 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 the re-consolidation level were an additional consideration to the prior work that was studied [4]. 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. However, Shafiee et al. [5] have investigated the pre- and post-cyclic volume change properties of Sherman Island peat by using

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a strain-controlled method. While the stress-controlled method had performed by various researchers, Mohamad et al. [6] in Dinar, Turkey, stress controlled are similar to load-controlled technique adopted [7]. Despite that, Das [7] also uses the same technique on clay soil. The goal of this research is to advance the understanding of the behaviour of peat soil under specific post-cyclic conditions. At the end, this research will be able to establish the effect of peat soil stress-strain behaviour under static and post-cyclic loading. The history of cyclic loading preceding the post cyclic tests is found to influence the tangent modulus observed in the post-cyclic tests [8].

On the other hand, Erken et al. [9] have studied the post-cyclic shear strength of granular material behaviour in fine-grained soils, applied with a stress-controlled method. Obviously, the selection of the controlled method depends on the soil material used. On the grounds that Das [7] 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. [10] conducted a study on the liquefaction potential of Adiyaman peat and stated that the liquefaction property of peat has not been fully researched yet, so it is a promising study on the liquefaction properties of peat. As a result of earthquake motion in New Zealand, a study was 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 [11, 12]. Therefore, in this research, a strain-controlled approach has been used with various stresses and strains applied.

In these undrained cyclic strain-controlled triaxial tests, when cyclic loading is applied, the axial strain is constant with time. In the meantime, axial strain was applied and the deviator stress was reduced. This phenomenon affects the soil stiffness and degrades, as evidenced by the reduction in the shear stress to achieve the uniform strain amplitude. This impression led to a loss of stiffness and a reduction in shear strength. In many past dynamic loading tests, frequencies ranging from 0.1 Hz to 0.5 Hz were applied. According Zergoun & Vaid [13], this application in order to obtain reliable excess pore pressure measurements during cyclic loading, very low axial strain rates have been used. Mohamad et al. [6] conducted a 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.

The results represent an MHP peat sample. The author had performed the cyclic triaxial with strain controlled and established Young’s modulus of peat with various frequencies. Categorized as a large deformation, high frequencies level notched more reliable in this study. In this research high frequencies level are performed by author to relate and simulate the real vibrations from traffic loading. Farrell [14] followed Zolkefle et al. [15] reported that it is timely to note that the high frequency and large number of loading cycles are more applicable to pavement engineering than geotechnical engineering to achieve an equilibrium state. This statement in line with the objective of this research where simulation from vehicular loading used which is represent on road design. In that situation, Soltani-Jigheh & Soroush [16] found that, the value of Young’s modulus decreases when the effective stress is greater than 50 kPa. The same study was carried out [14], and they concluded that, in general, strain continued to build up even after 10th stress cycles. The aforementioned tests consisted of one-way cyclic loading at a frequency of 10Hz.

As regards the Zainorabidin & Bakar [17] MHP records, effects from the strain that builds up during cyclic loading cause a larger Young’s modulus at higher frequencies to achieve the equilibrium state. In the current situation, there is a lack of understanding in the study of post-cyclic behaviour of peat soil due to the shortage of literature. Shafiee et al. [5] independently established a study of laboratory investigation for the pre- and post-cyclic volume change properties of Sherman Island peats. Unfortunately, their study focuses more on the changes in volume, and yet shear strength of these phenomena was not previously documented. While Zolkefle [18] only did some research for dynamic testing on peats as basic references to the post-cyclic study using an undrained triaxial test. Zainorabidin & Bakar [17], and Das & Lou [19] expressed that the dynamic loading, also known as cyclic loading, is dependent on the stresses and frequencies imposed during the loading onto the soil. Zainorabidin & Mohamad [20] presented that there are large strains and small strains in the amplitude response in dynamic loading, whereby the large strain amplitude responses are from strong motions such as earthquakes, blasts, nuclear explosions, and fast-moving traffic, which cause the strain amplitude to range from 0.01% to 0.1%. Zainorabidin & Mohamad [20] presented their results from the monotonic triaxial test results, where cyclic triaxial testing was continued based on the calculated amplitude values as well as the datum results obtained with different effective stress applications. From the results recorded, the effective stresses of 50 kPa were chosen as the example of cyclic triaxial testing. The results of half maximum deviator stress noted at 36.20 kPa was proceeded for cyclic loading test. Figure 4 shows the half-sheared specimen in an isotropic, undrained condition for the date of the cyclic triaxial test.

There are some changes that occurred as implication factors are due to cyclic loading. It is observed that the shear strength of the peats increases after cyclic loading. The shear strength before cyclic loading was recorded is about,

σ_{pre} = 72.40 kPa, and after cyclic loading it showed a dramatic increase of shear strength rate where the shear strength was increase to σpost 79.08 kPa at 14.12 % at the peak mood of failure. A study showed the results of the effective stress decreased gradually with the increase of the cycle shear stress ratio [21]. The dynamic elastic modulus decreased as the plastic deformation increased, while the dynamic elastic modulus increased as the consolidation stress increased [22].

The monotonic behavior after cyclic loading generally exhibited: (1) a dilative response (compared to contractive response for monotonic undrained compression tests); (2) a reduction in maximum shear modulus; and (3) a decrease in post-cyclic undrained shear strength of about 25% compared to the virgin undrained shear strength [23]. Cyclic behaviour of the peaty organic soil was found to be significantly influenced by number of cycles, normalized cyclic deviator stress (CSR) and static deviator stress. Distinct permanent axial strain and excess pore pressure were accumulated with the increasing number of cycles [24]. Peat's settlement behavior is a classic problem in construction [25], thus to understand the behaviour of peat soil shear strength is demanded to overcome the issue. Moreover, Prendergast & Igoe [26], and Sezer et al. [27] suggested that predicted frequencies are highly sensitive to choose of model and degradation method used. Compare to peat, it was understood that soil relative density and cyclic stress ratio amplitude has a significant influence on shear modulus and damping ratio of silts.

2. Materials and Method

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. The cylindrical peat sample with 50 mm diameter and 100 mm height is vertically sealed within a thin rubber membrane and placed into a cell that can be pressurised in between two porous discs at the top and bottom end. The effective pressure is set to be 25, 50, and 100 kPa. The undrained triaxial test stipulated in BS 1377 and sample normally consolidated in 24 hours. The undrained condition is remained to cyclic triaxial and post-cyclic triaxial test. In static and post-cyclic triaxial, the loading rate was set to be 0.1 mm/min for each specimen. Undisturbed sample method used for triaxial testing and preferred to maintain the natural characteristic. Shear strength and corresponding deformation characteristics were developed in consolidated undrained condition. Consequently, this study conducting to identify the behaviour of peat soil by using consolidated-undrained triaxial compression tests method. Triaxial testing described by geotechnical test standards BS 1377: Part 8: 1990. Methods of Test for Soils for Civil Engineering Purposes: Shear Strength Tests (Effective Stress) that required for consolidated undrained test typically consists of four main stages, specimen and system preparation, saturation, consolidation, and shearing. Static test was used a GDS Enterprise Level Dynamic Triaxial Testing System (ELDYN).

CU test is used since the term of 'unconsolidated' delineated of slopes rather than 'consolidated' reflecting physical condition of the soil in the ground. Thus, CU is considered and used in this research significantly to the method where the drainage is disallowed to maintain its nature behaviour that consist high water content. Maximum deviator stress (σ_{dmax}) defined as the difference between major and minor of principal stress in maximum state. The parameters of shear strength obtained in the peak deviator stress at maximum 20% of axial strain under five various effective stress from 25, 50, and 100 kPa. 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. Pressure is allowed to fill in the chamber when the software and saturation stage desired to start. In practical application, the cell pressure is controlled by an enterprise level controller and the back pressure is controlled by a pneumatic controller. This purposes as a water pressure source and volume change gauge for the precise measurement of fluid pressure and volume change.

To check the degree of saturation is sufficiently high before moving to the consolidation stage, a short test is performed to determine Skempton's B-value. This stage requires 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. In this study, peat soil sheared by applying an axial strain ε_a to the test specimens at a constant rate with the specimen in undrained condition the rate of axial strain slow enough to allow adequate equalization of excess pore pressures. During consolidation, drainage is closed and excess pore pressures being recorded. In this study, the cyclic triaxial test are carried out to analyse and define the response of peat soil to dynamic loads. Dynamic testing carried out accordingly after shearing. The frequencies for this research using these ranges of 0.5, 1.0, 1.5, and 2.0Hz for each specimen. It is necessary to determine the effect of cyclic loads on monotonic shear test for peat soil and it is so called "*post-cyclic*". 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. Figure 1 shows the flowchart of this research. In static characteristic, consolidated undrained triaxial test (CU) has been carried out and proceeded with saturation and consolidation process. Figure 2 shows the peat soil sample erected in triaxial chamber.

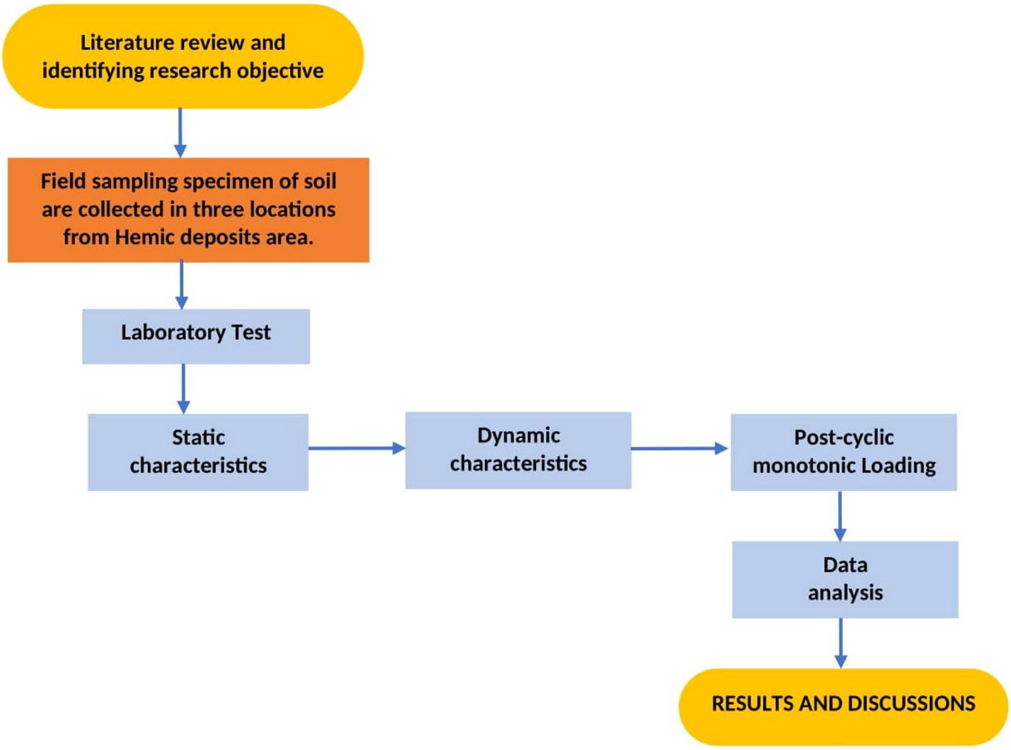
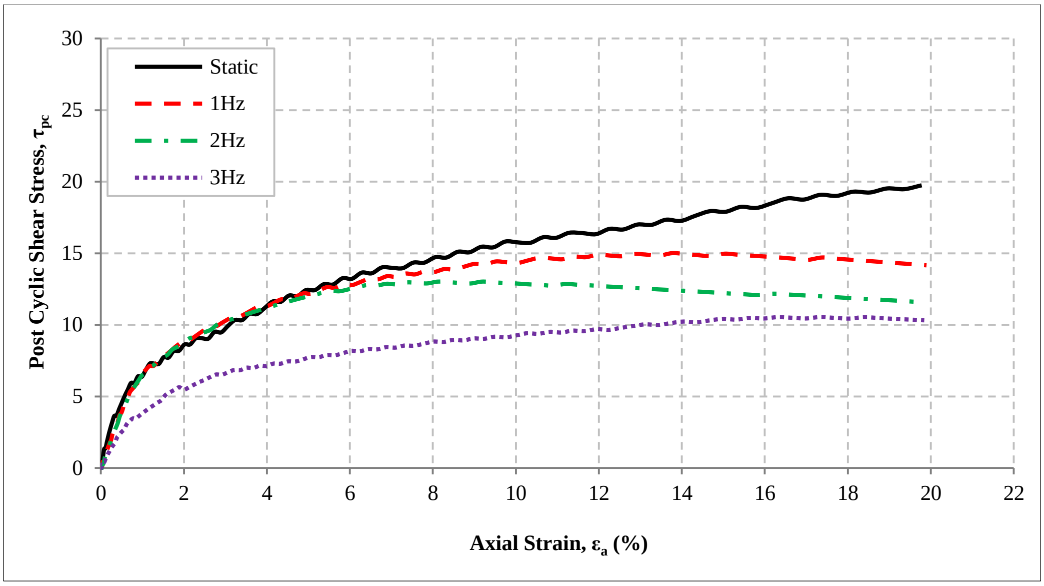


Figure 1. Research flowchart

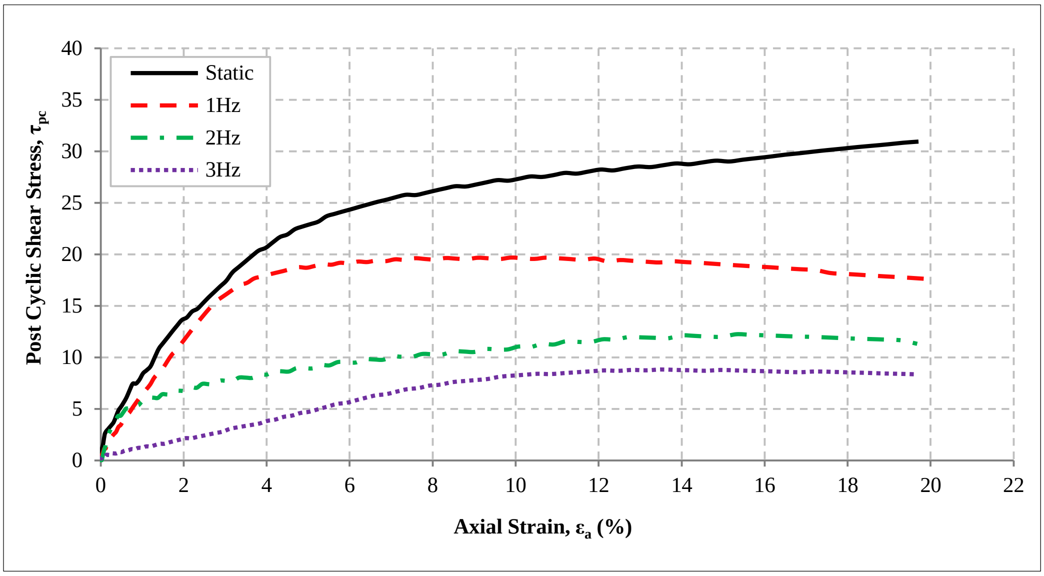
Figure 2. Peat soil sample pressurized in triaxial chamber for shear test

3. Results and Discussion

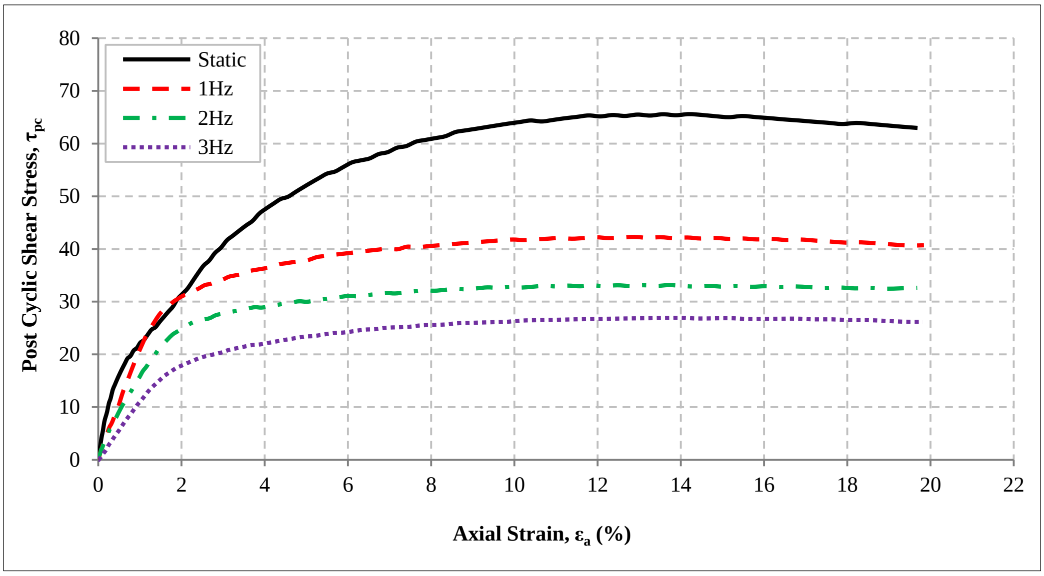
By conducting undrained triaxial tests on peat soil for PNpt, PSpt, and BSpt, it was found that the post-cyclic shear stress for the static test (τ_{pc}) decreased rapidly with an increase in normalized pore pressure ($\Delta u/p'c$) as shown in Figure 3. The rapid decrease in the post-cyclic, τ_{pc} shear stress began at a lower effective stress with a higher initial shear stress, τ_c as shown in Figure 3. The change in shear stress from its initial value was identified for all samples with identical axial strains induced by cyclic and post-cyclic loading, irrespective of the effective stress applied. The shear strain of peat in post-cyclic condition exhibit reduction for all specimens compared to its initial in static test. The reduction is noted as being similar to the downward trend in stress-strain behaviour in the previous section. The main reasons that brought to the reduction in shear stress were also caused by the amplitude of the applied frequencies and the maximum strain in cyclic loading. Moreover, loading during post-cyclic increased the potential.



(a) 25 kPa



(b) 50 kPa



(c) 100 kPa

Figure 3. Typical relationship between post-cyclic Shear Stress, τ_{pc} (kPa) and Shear Strain, $\acute{\varepsilon}_{pc}$ (%) for PNpt (a) 25 kPa (b) 50 kPa and (c) 100 kPa

Table 1 summarized the parameters effected in post-cyclic shear stress while in Table 2, shear stress ratio are summarized accordingly analysed from Figure 3. Cyclic shear strain, γ_c was analyzed at the N = 100th cycle during cyclic loading as suggested [9]. While the shear stress is the maximum value of shear stress for each sample. Undoubtedly, the post-cyclic shear stress decreased compared to its initial value of about 65.56 kPa (PNpt-100 kPa) in static and decreased to 14.9616 kPa in post-cyclic (PNpt-25 kPa-1 Hz). Compared to PSpt and BSpt, similar reductions were recorded. At 100 kPa, the initial shear stress for PSpt and BSpt is about 40.2782 kPa and 48.7443 kPa, respectively, and has decreased to about 6.9220 kPa (PSpt-100 kPa-3Hz) and 10.4817 kPa (BSpt-100 kPa-3Hz), respectively. By all means, the reduction of shear stress in post-cyclic is uniform for all specimens. Further observation is made in the next section, which analyzes the relation between post-cyclic shear stress and the shear stress ratio accordingly. Table 2 shows the shear stress ratios for PNpt, PSpt, and BSpt. In summary, the shear stress ratio in peat soil due to cyclic loading and reloading in post-cyclic shear strength tests is much lower. The shear stress ratio is post-cyclic shear stress divided by static shear stress (τ_{pc}/τ_s).

Table 1. Parameters effect of post-cyclic shear stress

Test Condition	Effective Stress, σ' kPa	Frequency Hz	Sample					
			PNpt		PSpt		BSpt	
			γ_c (%)	τ (kPa)	γ_c (%)	τ (kPa)	γ_c (%)	τ (kPa)
Post-Cyclic Monotonic	25	1	1.6124	14.9616	0.6348	6.7772	0.508	11.7798
		2	2.4099	13.0334	1.7303	5.8691	1.1825	8.6424
		3	3.983	10.5294	10.3081	3.9399	5.1735	5.6815
	50	1	1.6124	19.5924	1.4036	14.5545	1.4601	10.6147
		2	4.5236	12.0733	4.5183	10.7575	3.5283	6.7756
		3	13.3211	8.8026	9.2806	7.3491	5.4241	5.2997
	100	1	2.3339	42.1997	1.3762	31.3300	1.2866	26.9463
		2	11.7721	32.9762	4.0929	27.6606	2.5003	17.8888
		3	14.2839	26.9617	14.5832	6.9220	5.4483	10.4817
Static Monotonic	25	-	-	19.7590	-	11.9857	-	14.9082
	50	-	-	30.9179	-	31.3995	-	22.7534
	100	-	-	65.5622	-	40.2782	-	48.7443

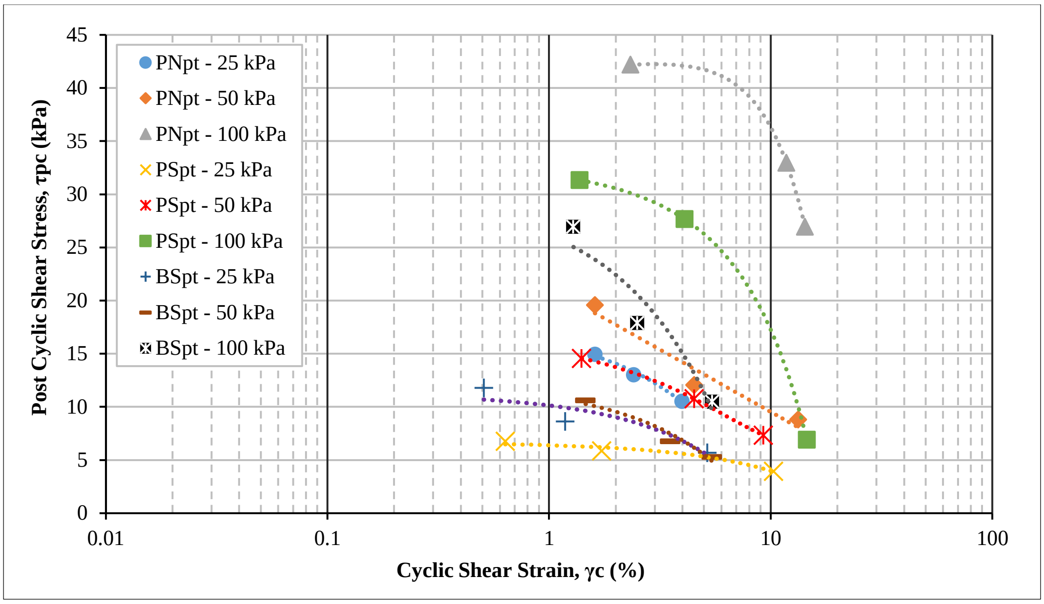
* Note; γ_c (%) = Number of Cycles, N at 100th cycle.

Table 2. Shear Stress Ratio

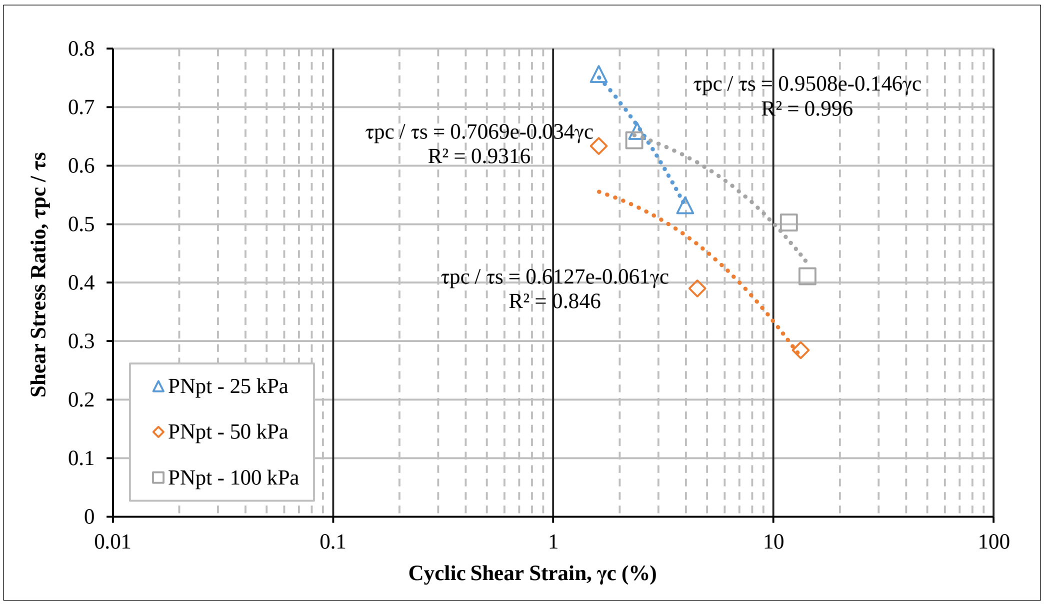
Test Condition	Effective Stress, σ' kPa	Frequency (Hz)	Sample					
			PNpt		PSpt		BSpt	
			γ_c (%)	τ_{pc}/τ_s	γ_c (%)	τ_{pc}/τ_s	γ_c (%)	τ_{pc}/τ_s
Post-Cyclic Monotonic	25	1	1.6124	0.76	0.6348	0.57	0.508	0.79
		2	2.4099	0.66	1.7303	0.49	1.1825	0.58
		3	3.983	0.53	10.3081	0.33	5.1735	0.38
	50	1	1.6124	0.63	1.4036	0.46	1.4601	0.47
		2	4.5236	0.39	4.5183	0.34	3.5283	0.30
		3	13.3211	0.28	9.2806	0.23	5.4241	0.23
	100	1	2.3339	0.64	1.3762	0.78	1.2866	0.55
		2	11.7721	0.50	4.0929	0.69	2.5003	0.37
		3	14.2839	0.41	14.5832	0.17	5.4483	0.22

* Note; γ_c (%) = Number of Cycles, N at 100th cycle.

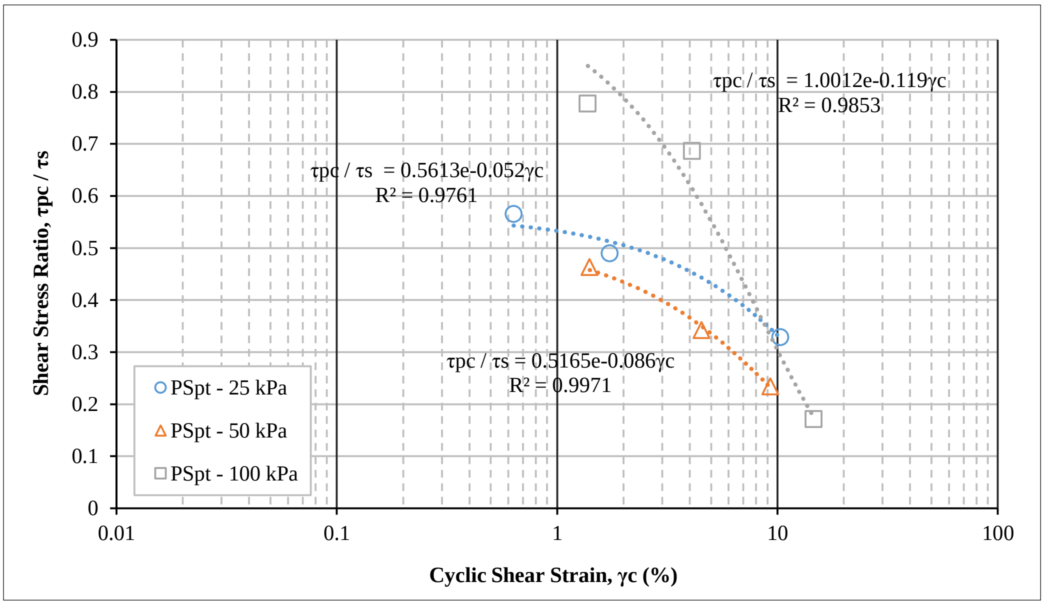
The relationship of post-cyclic shear stress and shear stress ratio are expressed in Figure 4 where reduction of undrained monotonic shear stress due to cyclic loading for PNpt, PSpt and BSpt clearly studied. Figure 4-a shows, the post-cyclic shear stress, τ_{pc} versus cyclic shear strain, γ_c history.



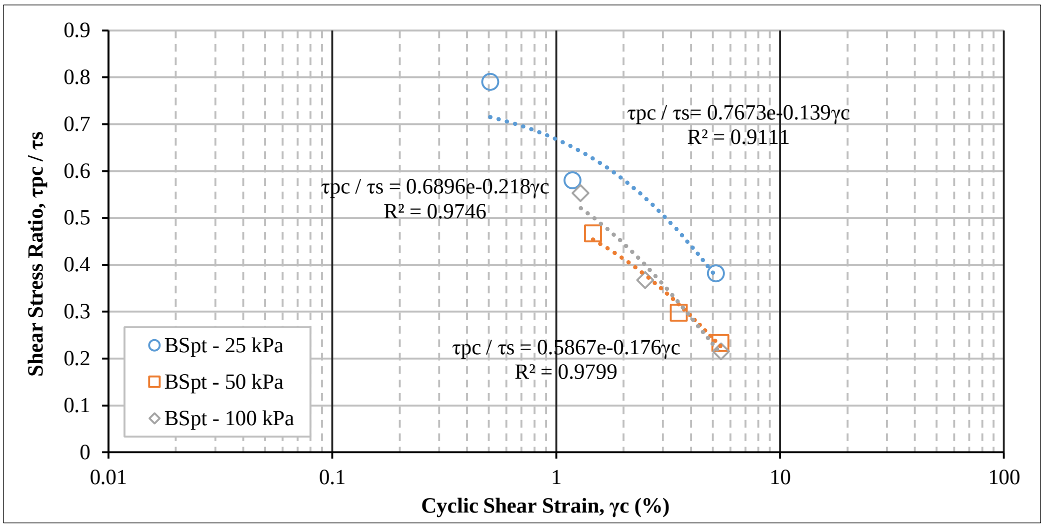
(a) Post cyclic shear stress versus cyclic shear strain



(b) Shear Stress Ratio versus cyclic shear strain - PNpt



(c) Shear Stress Ratio versus cyclic shear strain - PSpt



(d) Shear Stress Ratio versus cyclic shear strain – BSpt

Figure 4. Reduction of undrained monotonic shear stress due to cyclic loading for PNpt, PSpt and BSpt

When the peat soil imposed with cyclic loading, the induced cyclic shear strain causes a reduction in shear strength of peat soil. At frequency 1 Hz and effective stress, 100 kPa, the post-cyclic shear stress is about 42.1997 kPa (PNpt), 31.3300 kPa (PSpt), and 26.9463 kPa (BSpt). At the end of the tests, where 3 Hz of frequency was applied, the shear stress continuously decreased to 26.9617 kPa, 6.9220 kPa, and 10.4817 kPa, respectively.

The shear stress after cyclic loading controls the post-cyclic undrained shear behaviour of peat soil, irrespective of the initial shear stress and effective stress applied. These decreases have the characteristic of exponential trend lines. Further analysis in exponential is shown in Figures 4-b, 4-c, and 4-d. R-squared is statistically measured and shows the data are close to the fitted regression line. Shear stress ratio, τ_{pc}/τ_s for PNpt (Figure 4-b), shows a linear relationship when R-squared data points around the fitted regression line. Compared to PSpt and BSpt, the regression points show more precision near the 1 value. This shows that, the R-squared value of PSpt and BSpt is more reliable, which is the reduction in shear stress precisely caused by cyclic shear stress history during cyclic loading. The reduction of shear stress and shear stress ratio is significant when the peat soil specimen imposed with number of cycles (N = 100 cycles), which is enough to change the structure of peat soil and reach a certain yield strain level under the same stress amplitude as discussed previously. The reduction in shear strength and shear stress ratio considerably higher depending on the toughness of frequency and effective stress applied that formed amplitude and strain acts. In general, peat soil subjected to cyclic loading exhibit reduction in shear strength with the cyclic shear stress history.

A curve of the shear stress ratio during the static and post-cyclic tests has been plotted as suggested [25], where the result plots the curve of shear stress, τ_{pc} against axial strain, ε_a (Figure 5). From the curves stated, it can be seen that after failure, the shear stress drops to a constant value associated with axial strain, and this condition is maintained right up to the end of the test. The maximum values of this result are located in a narrow zone ranging from 1.54 to 2.42 (PNpt-100 kPa), as illustrated in Figure 4-c. Notwithstanding, a typical result plots the curve of the principal stress ratio (σ'_1/σ'_3) against axial strain (Figure 5). The maximum values of this ratio are located in the narrow zone of 1.61 to 1.12. Wang [25] explained this condition as the failure criterion of $(\sigma'_1/\sigma'_3)_{max}$ can yield a relatively constant effective friction angle. Thus, this research further analyzed the relationship of effective friction angle effects to the post-cyclic undrained shear strength and will be discussed in the next section.

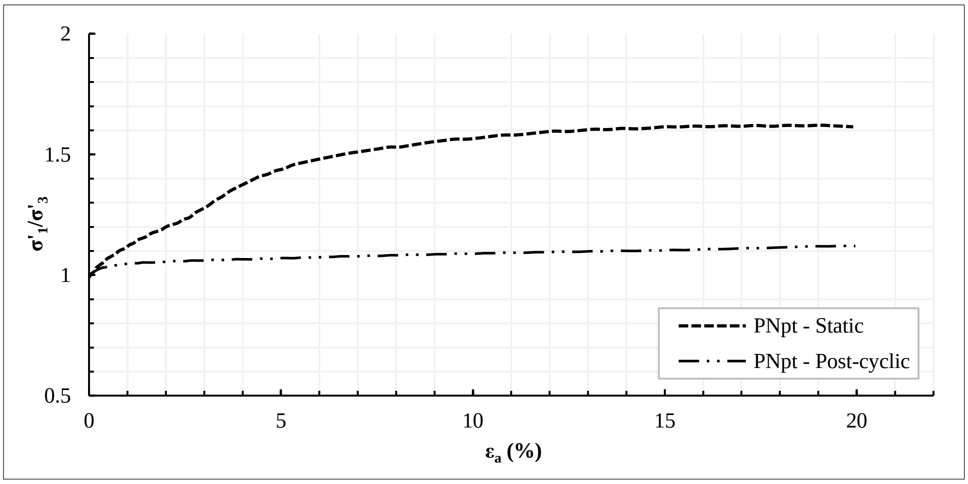


Figure 5. Typical principal stress Ratio versus axial strain of PNpt

4. Conclusions

The purpose of this research was to assess the post-cyclic loading condition that brought to the understanding of the relationship between post-cyclic Shear Stress, τ_{pc} (kPa) and Shear Strain, $\acute{\varepsilon}_{pc}$ (%) for PNpt (a) 25 kPa (b) 50 kPa and (c) 100 kPa, reduction of undrained monotonic shear stress due to cyclic loading for PNpt, PSpt and BSpt with principal stress ratio versus axial strain of PNpt by using dynamic triaxial apparatus. Based on the analysis conveyed, it can be concluded that there are multiple behaviors modifications in post-cyclic loading due to cyclic loading, as follows:

- After cyclic loading, in post-cyclic stress-strain behaviour of peat tends to softening behaviour. Due to cyclic and post-cyclic monotonic loading, the air-voids are removed and the restructuring phase of peat fibre occurs;
- The post-cyclic shear stress decreased compared to its initial value of about 65.56 kPa (PNpt-100 kPa) in static and decreased to 14.9616 kPa in post-cyclic (PNpt-25 kPa-1 Hz);
- At 100 kPa, initial shear stress for PSpt and BSpt is about 40.2782 kPa and 48.7443 kPa and decreased to about 6.9220 kPa (PSpt-100kPa-3Hz) and 10.4817 kPa (BSpt-100kPa-3Hz) respectively;
- The induced cyclic shear strain causes a reduction in the shear strength of peat soil. At frequency 1 Hz and effective stress 100 kPa, the post-cyclic shear stress is about 42.1997 kPa (PNpt), 31.3300 kPa (PSpt), and 26.9463 kPa (BSpt);
- The reduction in shear stress is precisely caused by the cyclic shear stress history during cyclic loading. The reduction of shear stress and shear stress ratio is significant when the peat soil specimen is imposed with a number of cycles, N = 100 cycles;
- The principal stress ratio (σ'_1/σ'_3) against axial strain shows the maximum values of this ratio are located in the narrow zone of 1.61 to 1.12. This condition as the failure criterion of $(\sigma'_1/\sigma'_3)_{max}$ can yield a relatively constant effective friction angle that could bring to the diminution of friction angle.

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 in the article.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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