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The Small Strain Effects to the Shear Strength and Maximum Stiffness of Post-Cyclic Degradation of Hemic Peat Soil

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***Abstract*—**The laboratory tests for measuring the effects of small strain to the shear strength and maximum stiffness development of post-cyclic degradation of hemic peat are reviewed in this paper. A series of laboratory testing has been conducted to fulfil the objective of this research to study the post-cyclic behaviour of peat soil and focuses on the small strain characteristics. For this purpose, a number of strain-controlled static, cyclic and post-cyclic triaxial tests were carried out in undrained condition on hemic peat soil. The shear strength and maximum stiffness of hemic peat are evaluated immediately after post-cyclic monotonic testing. There are two soil samples taken from West Johor and East Malaysia peat soil. Based on these laboratories and field testing data, it was found that the shear strength and maximum stiffness of peat soil decreased in post-cyclic monotonic loading than its initial shear strength and stiffness. In particular, degradation in shear strength and stiffness is more sensitive for peat soil due to fragile and uniform fibre structures. Shear strength of peat soil, τ_{max} = 12.53 kPa (Beaufort peat, BFpt) and 36.61 kPa (Parit Nipah peat, PNpt) decreased than its initial 58.46 kPa and 91.67 kPa. The maximum stiffness, G_{max} = 0.23 and 0.25 decreased markedly with post-cyclic, G_{max} = 0.04 and 0.09. Simple correlations between the G_{max} and the τ_{max} effects due to small strain, ε = 0.1, the G_{max} values for post-cyclic are relatively low compared to its initial G_{max}. As a consequence, the reported values and patterns of both the West Johor and East Malaysia peat soil are generally the same.

***Keywords*—**Post-cyclic, strain, shear strength, maximum stiffness.

I. Introduction

THE deformational characteristics of peat soil at small cyclic and shear strength to maximum stiffness using dynamic triaxial test equipment were investigated. In geotechnical analyses, the stiffness characteristics of soils have been known to be significant with finite element method [1]. The predictions of the ground movements and field data interpretations related to the soil parameter to be deemed in the studies on the small strain effects characteristics [2]. A key aspect of this work was to measure the effects of small strain through stress-strain hysteresis loops at shearing stage and maximum stiffness of peat soil. The use of the post-cyclic analysis has become concentrated and broad in content in geotechnical practice as a means of controlling and optimizing engineering tasks. A stiffness degradation curve is normally explained, and was illustrated in Fig. 1, using the normalized stiffness degradation curve by comparing with the ground response to explain the shear stiffness for a wide range of shear strain and the measurement accuracy from laboratory investigation [3].

Strain levels are categorized into three groups, where the stiffness modulus is constant in the elastic range and known in very small strain level. Secondly, stiffness modulus varies non-linearly with the strain in small strain level and thirdly, large strain level, where the soil is close to failure and the soil stiffness is relatively small. This can be the case of cyclic study in peat soil, where the strain, γ level proposed 0.1 in small strain scale [4]. On the other hand, where peat shear strength degrades increasing soil deformations in post-cyclic, obviously the practiced small strain at 0.1 and the post-cyclic stress-strain curves of peat specimens were lower than its initial in monotonic test [5]. The results showed that the analysis with the small strain peat yielded a lower shear strength profile compared to the static tests.

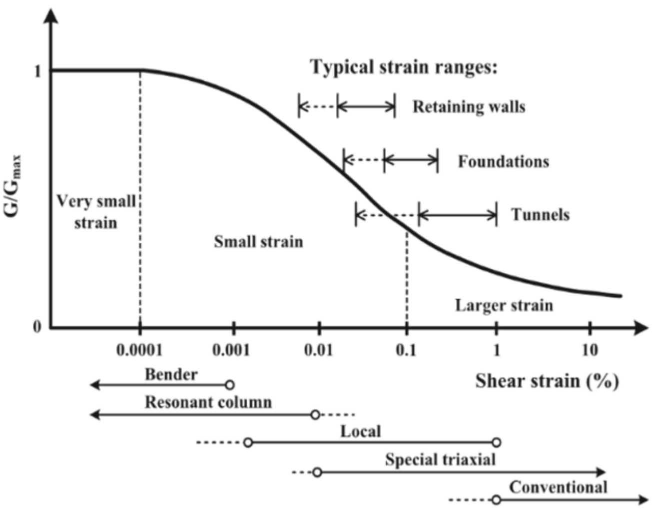

Fig. 1 Normalized stiffness degradation curve

Complex peat behaviour in post-cyclic condition stems from the nature of the multi-phase material contents that affects both shear strength and maximum stiffness. Thus, this study was conducted in a laboratory and was designed to determine the shear strength and maximum stiffness affects

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due to the small strain in triaxial testing.

Maximum stiffness and shear strength was determined by static test and Fig. 2 shows the definition of post-cyclic shear strength, τ_{max} and maximum stiffness, where G_{max} is the maximum equivalent stiffness in static tests [6] and was determined using (1).

$$G_{max} = \frac{\tau_{max} - \tau_{min}}{\gamma_{max} - \gamma_{min}} \quad (1)$$

The shear strength of peat soil is determined at any potential of strain required and the maximum shear strength, τ_{max} is determined at the maximum yielding point [7]. In this case, the strain level used at 0.01% is considered small.

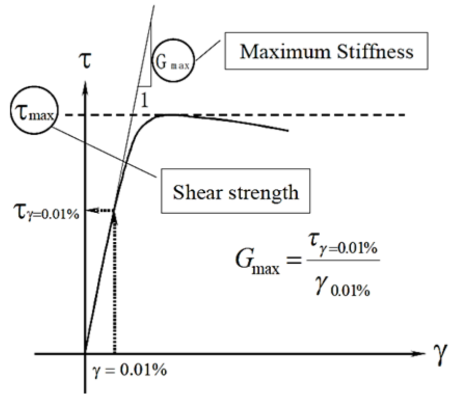

Fig. 2 Definition of shear strength and maximum stiffness

The post-cyclic behaviour of peat soil was evaluated by monotonic tests after cyclic loading and compared to static results [8]. A previous study on the pre- and post-cyclic behaviour on the monotonic shear strength of Penor peat, found the shear strength of peat soil decreased after the 100^{th} cycle of dynamic loading and post-cyclic shear strength decreased substantially with the frequencies applied compared to its initial in static tests, and thus cyclic loading has reduced the shear strength of peat soil [5]. It is also commonly known that peat soil behaviour is not simple like other soils.

Peat is a material that usually occurs when organic matter is preserved below high water tables like in swamps or wetlands [9]. Peat is known as a one of the most problematic soils in the construction industry.

Construction on peat soils has proven to be a challenging task to civil engineers since this soil type has very low shear strength, with high settlement. This study examines whether peat has potential changes in shear strength and maximum stiffness due to cyclic loading, evaluated under post-cyclic condition and compared to its initial strength and stiffness in static test.

II. Material and Experimental Method

A. Peat Soil Samples

Peat is a type of soft soil composed from high contents of fibrous organic matters and is produced from partial decomposition and disintegration of mosses, sedges, trees, and other plants that grow in marshes and other wet places in a condition where there is a lack of oxygen [10]. In general, it accumulates whenever the conditions are suitable; that is, in areas where there is an excess of rainfall and the ground is fully undrained, irrespective of latitude or longitude. Thus, this study was carried out on peat soil to examine the essential value of peat itself.

There are two locations stated for the sampling site, Parit Nipah in Batu Pahat, Johor (PNpt) and Lumadan in Beaufort, Sabah (BFpt). Both exhibit locations are well known as peat deposit areas in Malaysia. Beaufort, Sabah, has recently explored in the East of Malaysia. Both samples were compared in this study, and both samples are classified as hemic peat soil.

Specimens were prepared with undisturbed peat sample. The ground water table was found at the depth of 0.8 m during the sampling and soil was excavated to a depth of 0.5 m below the ground surface.

As seen in Table I, the index properties of PNpt are shown to be fairly significant with natural moisture content at 523%. The natural water content of peat in Malaysia ranges from 200% to 700% and with organic content in the range of 50% to 95% [11]. Specific gravity recorded 1.3 was within the range as reported previously. On the other hand, BFpt clearly showed moisture content at about 493% lower than PNpt. Moreover, BFpt has slightly more significant fibre content compared to PNpt. In organic content, PNpt is higher than BFpt. PNpt and BSpt has unique index properties even though there are some differences are seen depending on its location.

TABLE I
Index Properties of Peat Soil

Properties	Lumadan, Beaufort, Sabah	Parit Nipah, Batu Pahat, Johor
Moisture content	493	523
Liquid limit	211	243
Specific gravity	1.3	1.4
pH test	3.1	3.2
Fibre content	65	38.5
Von Post Scale	H7	H6
Organic content	95.44	96.64

B. Consolidated Undrained Triaxial

An experimental investigation of the post-cyclic shear strength and maximum stiffness characteristics of peat soils at small strain was conducted using dynamic triaxial equipment. Static test has been conducted as a bench mark to the comparisons data between post-cyclic to its initial characteristics. Sample preparation for the cyclic triaxial test is similar to that of the monotonic test. The specimens were mounted on the base of the pedestal sealed with a rubber membrane and ends with filter paper and porous stone at each end. All samples were consolidated to 100 kPa effective confining stress and cyclic tests were performed under different frequency at 1.0Hz in order to determine the shear strength. In addition, cyclic loading are set to be constant for both specimens at 100 cycles with small strain level at 0.01%. The effect of number of loading cycles on the deformational characteristics of peat soils was not investigated in this study. A transitional zone from elastic to plastic behaviour was also studied.

To develop a reliable post-cyclic testing system, specimens were developed and tested by using consolidated undrained (CU) method. The stiffness specimen of peat acquired is 1, with the cyclic loading rate determined at 0.01 mm/minute.

C. Laboratory Studies

In this study, the strain-controlled method is used. Strain-controlled is a more fundamental parameter because of its ability to control pore pressure generation and volume change [12]. It has been compared with previous research and it was found that there are some significant behaviours in shear strength after cyclic loading, where the post-cyclic behaviour of peat soil in the first study are established using strain-controlled method [8].

The investigation of peat soil under the consolidated-undrained triaxial tests and generally to inspect the element of shear strength characteristics were developed in consolidated undrained condition.

Shear Strength Tests (Effective Stress) that is required for consolidated undrained test, typically consists of four main stages, specimen and system preparation, saturation, consolidation, and shearing [13]; the parameters of shear strength obtained in the peak deviator stress at maximum 20% of axial strain. In this study, the soil has been 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 was slow enough to allow adequate equalization of excess pore pressures.

The multi-stage element of the test indicates that a single specimen has been used and consolidated to three effective stress stages. The reason for using the multi-stage approach is that fewer samples require less time in the field, and that issues of non-uniformity between samples are removed [14].

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III. Determination of Shear Strength

Shear strength and corresponding deformation characteristics were developed in consolidated undrained condition. The specimen is compressed in the axial direction by applying a deviator stress and identified as the maximum deviator stress. Maximum deviator stress (σ_{dmax}) is defined as the difference between major and minor of principal stress in maximum state. The shear strength parameters of peat soil are obtained from the deviator stress curve against 20% of axial strain. This is achieved by subjecting a right cylindrical specimen to several stages of saturation, followed by consolidation, and finally, shearing by application of an additional axial strain and deviator stress. The shearing process was allowed to continue until a specified failure criterion was reached. The identification of the peak deviator stress, peak effective principal stress ratio, observation of constant stress and excess pore pressure or volume change values, or simply a specific value of axial strain was reached or test terminated at 20% of axial strain.

As shown in Fig. 3 for the static shear strength for PNpt and BFpt, there are variances between these two samples. PNpt has higher shear strength at 91.67 kPa compared to BFpt is about 58.46 kPa; both samples reached maximum shear strength at 19.09% and 18.87% axial strength, respectively. The intrinsic factors of each of the sample properties are believed a major governing influence in the differences of the results. Obviously, PNpt is mainly found in agricultural areas, where BFpt origin is near to forest reserves and has been found abundantly in watery and soaked area. BFpt has higher fibre content, but is lower in organic content, as this is where voids are believed to have been formed.

The initial maximum stiffness in static test is derived from the shear strain, τ (kPa) versus strain rate, γ (%) curve, as shown in Fig. 4. It has been observed that, the initial maximum stiffness is noticeably high in static condition prior to cyclic loading. The maximum stiffness in static condition, the maximum stiffness, and Gmax for PNpt is higher than BFpt. A regression model to evaluate peat stiffness in the laboratory and in the field recorded as 0.35, where organic content is included as a predictor variable, and 0.30 for a regression model that included organic content and density as predictor variables [4]. PNpt and BFpt are samples from tropical peat soils.

Deformational characteristics of soils are affected by numerous factors [15]. Factors affecting the response of soil at small strain, $\gamma < 0.1$ % are reviewed with effect of various factors on G_{max} such as confining pressure, void ratio, geologic age, plasticity index, strain rate and number of cyclic loading cycles [16].

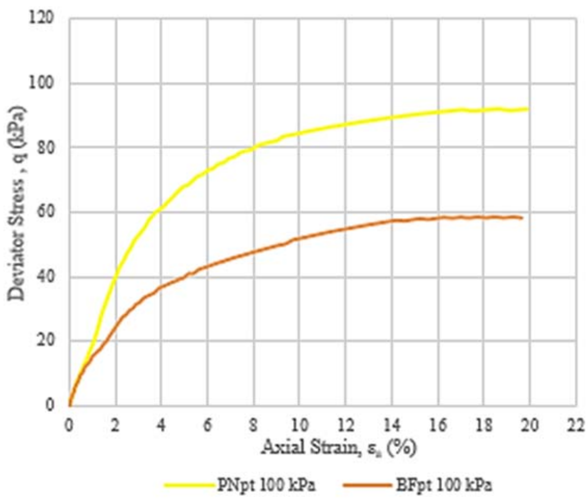

Fig. 3 Static shear strength of two peat soils

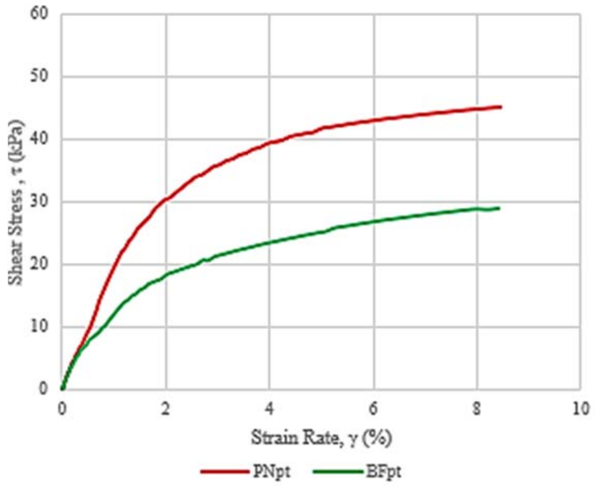

Fig. 4 Static shear strength and maximum stiffness

The shear strength and stiffness characteristics of peat soil are independent of strain amplitude at low amplitudes of strain. In addition to the parameters shown in Figs. 3 and 4, it has been observed that the static properties of soils are markedly high against axial strain. Much less research has been performed on peat material strength than on the shear small strain effects of peat soils.

IV. Determination of Maximum Stiffness

In this study, cyclic loading tests are carried out to analyse and determine the post-cyclic behaviour of peat soil.

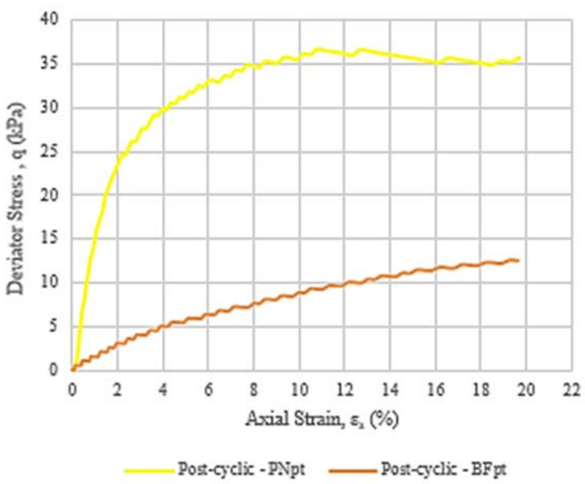

Fig. 5 Post-cyclic shear strength of two peat soils

The additional functionality for advanced research purposes that enables non-standard loading waveforms to be applied to test specimens referred to the time histories from earthquake acceleration records. Typical test frequency ranges of uniform monotonic loadings used in a cyclic triaxial test to approximate a range of dynamic loading situations are referred to in a previous study [17]. Meanwhile, the frequency of 1.0 Hz is applied for the best reflection of the minor effect of an earthquake in Malaysia. Additionally, cyclic loading test are carried out to understand the behaviour of peat soil and where the forces that are imposed on the soil are influenced in the reduction of shear strength. The magnitude is set at 0.5 from the datum in cyclic loading, which is line with other researchers [4].

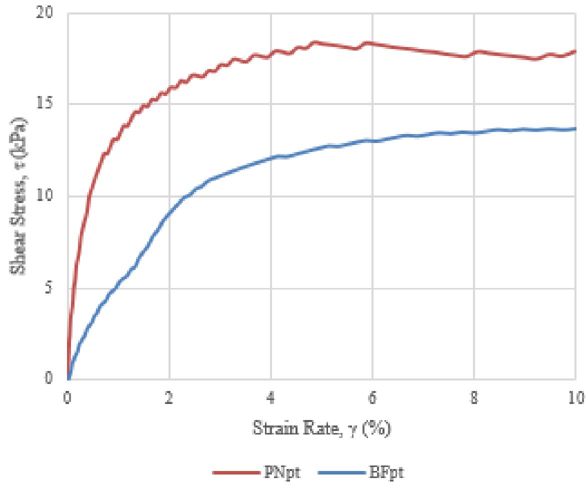

Fig. 6 Post-cyclic shear strength and maximum stiffness

Attempts to determine the post-cyclic behaviour of peat soil using dynamic analysis were performed with GDS Dynamic Cyclic combined with Dynamic Triaxial Testing using electromechanical actuation, which is also known as GDS Enterprise Level Dynamic Triaxial Testing System (ELDYN).

Static monotonic and cyclic tests have been conducted to provide the bases for comparison and evaluation of the results of the post-cyclic tests. Table II shows, the shear strength and maximum stiffness based on the results from Figs. 5 and 6.

TABLE II
Shear Strength and Maximum Stiffness

Properties	Lumadan, Beaufort, Sabah	Parit Nipah, Batu Pahat, Johor
	Static Test	
Shear Strength, τ_{max}	58.46	91.67
Axial strain, ε_a (%)	18.87	19.09
Strain Rate, γ (%)	0.1	0.1
Shear Stress, τ (kPa)	0.023	0.025
G_{max}	0.23	0.25
	Post-cyclic Test	
Shear Strength, τ_{max}	12.53	36.61
Strain Rate, γ (%)	0.1	0.1
Axial strain, ε_a (%)	19.65	11.09
Shear Stress, τ (kPa)	0.0035	0.0085
G_{max}	0.04	0.09
	Differences Percentage	
Shear Strength, (%)	66	60
G_{max} (%)	83	64

Effects of small strain to shear strength and maximum stiffness on post-cyclic behaviour have been monitored and a comparison of the static and post-cyclic behaviour, and presented in Figs. 5 and 6, respectively.

Significant changes and reduction of shear stress after cyclic loading was observed in comparison to the initial or static tests and the post-cyclic results for both samples.

Figs. 5 and 6 show the similarities in post-cyclic deviator stress and shear stress behaviour.

The shear strength of peat generally decreased after cyclic loading in the post-cyclic stage, and loses strength from its initial strength in static test. In post-cyclic, PNpt has 36.61 kPa, while BFpt recorded 12.53 kPa.

The differences between static and post-cyclic shear strength results are about 60% to 66% decrement. The results clearly show that shear strength gradually decreased with increases of axial strain. The graphs reflect the behaviour of peat soil in downtrend strength after cyclic loading. When comparing PNpt to BFpt, as can be seen in Fig. 5, the shear strength of PNpt is higher than BFpt. The shear strength behaviour of both peat samples showed significant values after cyclic loading when compared to static values.

The consistencies of downtrend patterns are governed by fibre content. Deviator stress curves are the pronounced peaks of its initial strength measured in static and post-cyclic tests for 100 kPa. It can be seen that after failure, the shear strength reduced to constant values with the increment axial strain and strain rate. Cyclic loading causes a reduction in the shear resistance of peat soil. Post-cyclic shear strength decreases with an increase of the axial strain. Thus, a large amount of deformation occurs in the soils due to the rapid increase of shear stress against strain rate.

Generally, the maximum stiffness, G_{max} decreased and notched lower than its initial stiffness; for PNpt, it is about 0.25, and for BFpt it is 0.23. In post-cyclic, the maximum stiffness of peat soil decreased to 0.09 and 0.04, respectively. There are great changes and decrement in maximum stiffness of peat soil from 64% in static test to 83% post-cyclic test. Moreover, the shear strength also reflected same decreasing behaviour patterns, the initial static deviator stress recorded 58.46 kPa and axial strain at 18.87%, these conditions change in post-cyclic monotonic tests, where the shear stress decreased manifestly with frequencies sequenced starting from 66% to 12.53 kPa. The observed decreases of maximum stiffness Gmax are caused by the high number of loading cycles.

V. Conclusion

The behaviour of the post-cyclic tests on PNpt and BSpt specimens showed downtrend curves. It was observed that the undrained monotonic shear strength and maximum stiffness of peat decreased significantly due to the cyclic loading and behaviour of peat in post-cyclic tests which show a significant deformation. During post-cyclic loading, the shear stress, τ are observed decreased and the soil strength degrades as evidenced by reductions in shear stress. On the other hand, Figs. 4 and 6, shows the relationships of shear stress, τ, and shear strain, γ, for PNpt and BFpt.

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