An overview on the Cyclic Loading Behaviour of Peat Soil

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Abstract: Recently, the reactions towards dynamic or cyclic loading has been of fear and concern to engineers mainly geotechnical and geophysicists for years. The significant parameters in Geotechnical Engineering which control the effect and reaction of soil towards the dynamic loading are shear modulus and damping ratio. Most of researchers conducted investigation on the dynamic loading of soft soils such as sand and clay but only a few had discovered the behaviour of peat in terms of static and dynamic loadings by using Cyclic Triaxial and Torsional Shear or Resonant Column tests. Hence, this paper present a critically review on the earliest work on the dynamic loading onto peat soil associated with Kramer [1], Wehling et al [9], Kramer, [13], Boulanger et al. [14] and Kishida et al [15]. The analysis and conclusions describes the influence of effective confining pressures towards dynamic peat soil behaviour at different locations. After considering these factors, additional testing is strongly advice to precisely evaluate the properties of peat and to study the reasons of increasing effective confining pressures due to the size of sample, organic content and fiber content as well as the percentage of vegetative in the sample.

Keywords: Cyclic loading, Peat soil, confining pressure.

1. Preamble

Recently, the reactions towards dynamic or cyclic loading has been of fear and concern to engineers mainly geotechnical and geophysicists for years. Most research has been devoted to the dynamic response of inorganic soils such as sand, clay, silt and gravel with significant organic content. However, there were increasing interests in dynamic response of highly organic deposits such as peat have been developed [1].

O'Reilly and Brown [2] described the term 'dynamic' as a system of loading which depicts a degree of regularity both in its magnitude and in its frequency, whereby the word 'cyclic' comes out to be something of a misnomer and usually used by engineers to explain non-static repetitive soil loading. On the other hand, Yang and Sze [3] defined 'cyclic' or 'dynamic' as the symmetrical loading which constitutes level ground conditions in the free field, where no initial static shear stresses act on the horizontal planes of the elements of soil. The researchers developed the simulation of cyclic loading condition in a laboratory with the condition of symmetrical loading, non-symmetrical loading with stress reversal and non-symmetrical loading without stress reversal.

Jarret [4] described 'peat' as a soft soil in an engineering concept and very compressible in terms of strength. This soil has long been recognized by geotechnical engineers as a problematic soil and is noted for its very low unit weight, very low shear strength, very high compressibility and rate-dependent behaviour [1]. Fig. 1 shows an example of road settlement caused by dynamic loading at Cerrigydrudion, North Wales. This road indicates some patches along the settlement that was eventually constituted towards the dynamic effects.

Fig. 1 : Road settlement at Cerrigydrudion, North Wales. [5]

Basically, engineers normally define static and dynamic problems concerning to the analysis and design of foundations. These types of problems may depend on the natural source which produces it [6]. Saran, [7] had compiled the features of static and dynamic loading towards soil and explain in detail the characteristics as shown in Table 1.

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Table 1 : Characteristics Features of Static and Dynamic Loading [7]

Types of Loading	Features	Examples
Static Load	A foundation carried a load of a structure in a constant magnitude and direction	Loads are caused by the dead weight of the structures
Dynamic load	Changes with time	Loads are caused by earthquakes, bomb blasts, operation of machines, pile driving, quarrying, fast moving traffic, wind or sea wave's action

2. Parameters of Cyclic Loading

It has been agreed that the significant parameters in Geotechnical Engineering controlling the response of soil towards the cyclic loading are shear modulus and damping ratio [8]. Besides, both static and dynamic loading depends greatly on the level of strain induced to it [8]. These parameters must be determined to accurately measure their expected and required response towards earthquake shaking [9] and also for the design of geotechnical engineering problems [10]. Most of the common equations and the expected stress-strain curve for dynamic loading parameters in Fig. 2 are elaborate below:

Young's Modulus, $E = \frac{\Delta\tau}{\gamma}$ (1)

Shear Modulus, $G = \frac{E}{2(1+\mu)}$ (2)

Damping ratio, $D = \frac{1}{2\pi}\left(\frac{\text{area of the hysteresis loop,}\Delta E}{\text{area of OD}\gamma c^2}\right)$ (3)

The value of μ in Eq. (2) refers to the Poisson's ratio in the range of 0.4 to 0.5 for saturated, undrained soil [11] and the Young Modulus values, E can be obtained from Eq. (1). The damping ratio in Eq. (3) defined from the area of hysteresis loop (ΔE) may also represented as λ instead of D as pointed in Fig. 3 [12]. Fig. 3 sketched the variation of cyclic parameters with cyclic shear strain both in modulus reduction (G/G_{max}) and damping ratio (λ). The value of Gmax was taken as the largest shear modulus which in general is a shear strain of about 0.001%. This is to avoid any possible mistake that would be introduced by extrapolating the data to smaller shear strains [9]. As expected in Fig. 3, the graph of modulus reduction over the cyclic shear strain (γ_c) decrease linearly as the percentage of strain increases. On the other hand, damping ratio characteristic expressed an increasing graph of linearity as the strain increased.

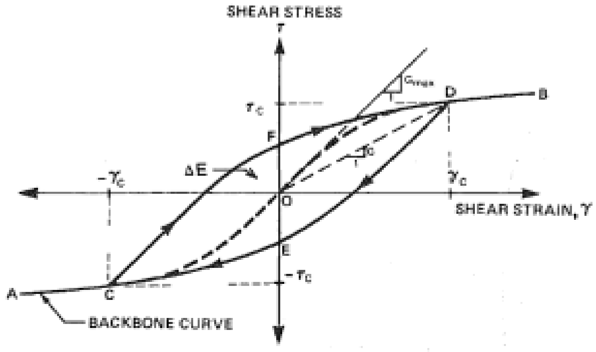

Fig. 2 : First cycle of stress-strain curve [12]

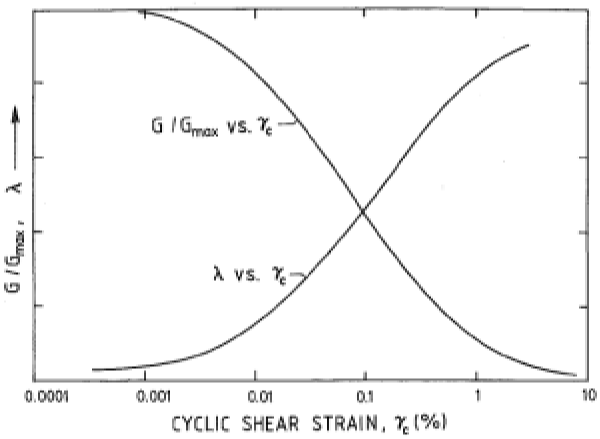

Fig. 3 : Variation of cyclic parameters with cyclic shear strain [12]

Cyclic Triaxial and torsional shear as well as resonant column tests can be performed to determine the modulus of elasticity, shear modulus and damping ratio of soils. Strain-controlled were used to evaluate the modulus of elasticity and damping ratio. Meanwhile, stress-controlled dynamic triaxial tests are mainly used for liquefaction studies on saturated soils [6].

3. Reviews of Past Literature on peat

Past research came out with different methods on investigating the dynamic loading on soft soils such as sand and clay. But, only a few researchers discovered the behaviour of peat in terms of static and dynamic loadings. The dynamic loading (or cyclic loading) is dependent on the stresses and frequencies imposed during the loading onto the soil [6] [11]. There are large and small strain amplitude response in dynamic loading and this has been categorized in Table 2 [11].

Table 2 : Examples of Strain Amplitudes [11]

Types of Strain	Example	Strain
Large Strain Amplitude	Earthquakes, blast, nuclear explosions and fast moving traffic	0.01% to 0.1%

Small Strain Amplitude	Operation of machines, wind sea or sea waves and changing of water table	0.01% to 0.001%.

Previous work identified in the literature on the performance of peat dynamic was associated with Kramer [1], Boulanger et al. [14], Kramer, [13], Wehling et al [9] and Kishida et al [15].

Kramer [13] who performed cyclic resonant column test investigated on the dynamic response of peat under strong earthquake in western Washington affecting three main characteristics mainly amplitude, frequencies and duration. The researcher performed his cyclic resonant column procedure by slowly increasing the load frequency until the response of peat reached its maximum value. Besides, he also executed the specimen on the normally consolidated condition by the used of wide ranges of effective confining pressures, strains and loading frequency. The samples used by Kramer [13] were obtained from Mercer Slough peat which was located in a peat-filled extension of Lake Washington. He added that Mercer Slough peat is fibrous at shallow depths and becomes less fibrous and more highly decomposed with increasing depth. As investigated by Kramer [13], the water content of the peat was approximately 500% to 1200%.

Kramer [13] concluded his findings by the effect of effective confining pressures on the relationships of shear modulus and damping ratio. Based on his data in Fig. 4, maximum shear modulus of Mercer Slough peat was pointed to increase with the increasing effective confining pressure but in an irregular pattern. The lowest maximum value of effective confining pressure results approximately 1.5 kPa as shown in the figure.

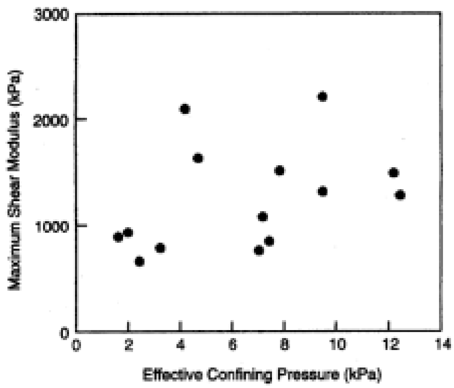

Fig. 4 : Relationship between maximum shear modulus and effective confining pressure for mercer slough peat [13].

Test data from Kramer [13] in Fig. 5 pointed the decreasing graph of modulus reduction with the increasing of shear strain on Mercer Slough peat. He did mention that the graph indicated that Mercer Slough peat behave essentially linear at shear strain of up to about 0.001 percent, but then the modulus reduction decrease quickly. Kramer [13] also stated in his conclusion whereby the modulus reduction of peat appeared to be influenced by the effective confining pressures.

Comparison of various effective confining pressures for the modulus reduction over the shear strain was developed by Kramer [13]. He compared his research of Mercer Slough peat at 1.5 kPa, 12 kPa and 19 kPa (from his early research) with peat soil from eastern United States with the effective confining pressure of 75 kPa. Fig. 6 explained the effect towards modulus reduction on Mercer Slough peat. Kramer [13] mentioned that the results show a distinct trend of increasing linearity with increasing effective confining pressures. He also added that peat soil would retained a higher portion of its original stiffness at a very large shear strains which is greater than 1 percent than typical inorganic soils. The results varied with increasing effective confining pressure which may cause the different properties of its original soil from various places. Kramer [13] declared that different types of test were used from previous research to produce this graph. For effective confining pressure of 19 kPa, cyclic triaxial test was used. Besides, resonant column and torsional shear test were used to implement the 75 kPa pressure.

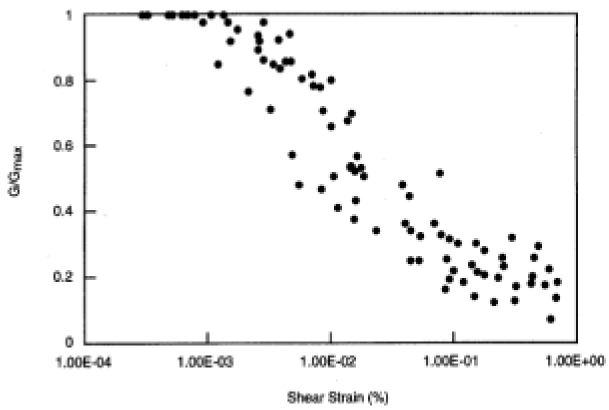

Fig. 5 : Modulus reduction behaviour for normally consolidated mercer slough peat specimens [13].

Fig. 7 expressed the relationships between damping ratio and shear strain on Mercer Slough peat by Kramer [13]. The figure pictured that peat had a high damping ratio at low strain levels. Besides, this result also expressed the decreasing of damping ratio at a particular strain levels with the increasing effective confining pressures. Kramer [13] did combine his results from Mercer Slough peat soil with other researchers for the determination of damping ratio over peat. Fig. 8 clearly shows the effect of effective confining pressure on the damping characteristics. Based on the figure, damping ratio from Mercer Slough peat tends to decrease when effective confining pressures was increased.

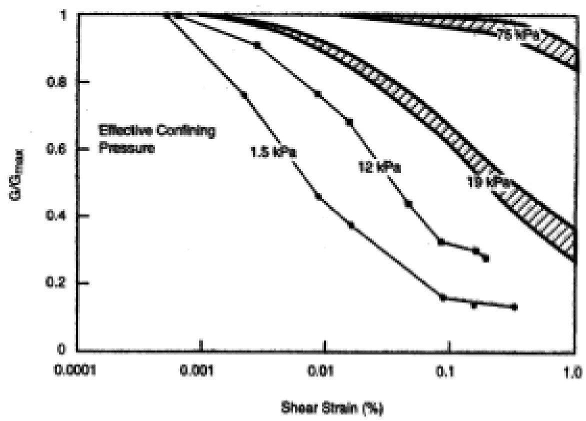

Fig. 6 : Comparison of modulus reduction behaviour with effective confining pressure curves [13]

Kramer [13] only compared his results with 75 kPa instead of both effective confining pressures (19 kPa and 75 kPa). The researcher reveals that this happened because of the effects of sampling disturbance and this trend could not be corroborated with the damping measurements from the cyclic triaxial test which used to determine the peat soil behaviour for 19 kPa. Besides, he also proved that peat was considerably softer than even the loosest sand and specifically exhibited more linear behaviour and lower damping at higher effective confining pressure.

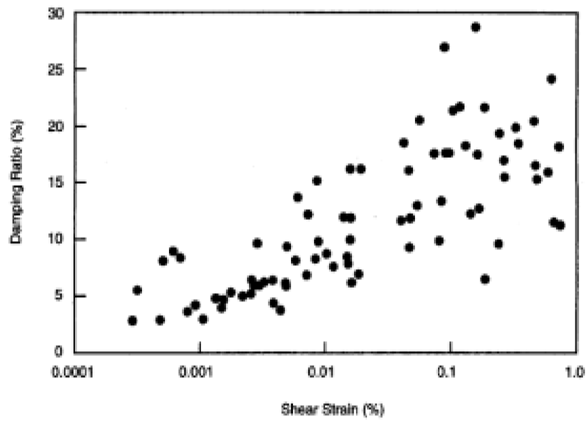

Fig. 7: Damping behaviour for normally consolidation mercer slough peat specimens at effective confining pressures of 1.5 kPa to 12.5 kPa [13]

Kramer [13] concluded that both effect on the effective confining pressures towards the shear modulus and damping ratio characteristics were caused by sampling disturbance whereby this disturbance would give a tendency to influence low-strain properties such as maximum shear modulus and low-strain damping ratio, more than properties at higher strains.

On the other hand, Boulanger et al. [14] analyzed the dynamic properties of peat at Sherman Island, northern California. They had discovered that there was over 60 low-lying 'islands' gave ground levels below sea level at northern California. At the island, they were mentioned that there were levees which are constructed from uncompacted sands, silts, clays and peat.

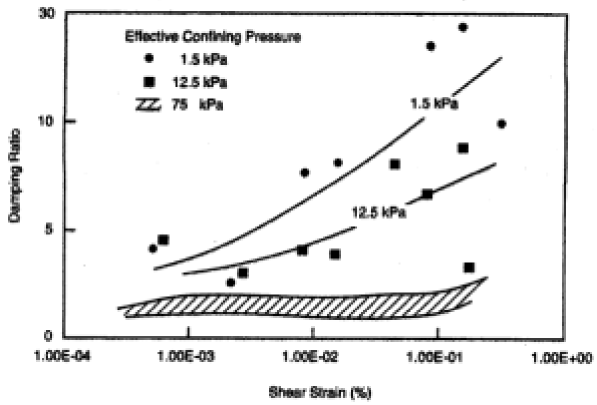

Fig. 8: Variation of damping ratio behaviour with effective confining pressure for peat soil [13]

The material contains in the levees depends on several factors such as subsurface stratigraphy, dynamic properties of the stratum, frequency content on the earthquake, level of shaking and duration of shaking as mention in Boulanger et al [14]. They investigated and focused on the layer of peaty organic soil under laying the south levee on Sherman Island near the western side of delta.

Boulanger et al. [14] implemented the index properties test towards peat soil on that island and found that the water contents of the sample ranges between 152-240% and ash contents of 35-56% which was then categorized as fibrous peat. The Shelby tube samples were used and obtained from depths of about 13m and the vertical consolidation stresses used were about 132 kPa. They also performed undrained, strain-controlled cyclic testing in stages on each specimen.

Boulanger et al. [14] summarizes the results for cyclic behaviour on Sherman Island peat in Fig. 9 and Fig. 10 indicating equivalent damping ratio and secant modulus over the shear strain respectively. This figure shows the fifth cycle of loading at frequency of 1 Hz. The result shows linear behaviour (insignificant with modulus reduction) and low damping ratios displayed for shear strains of up to about 0.1%. They also stated that the specimens that were consolidated to the effective confining pressures of 66 kPa and 200 kPa (closed symbols in Fig. 9 and Fig. 10) showed behaviour very similar to the specimens consolidated to their in situ effective confining pressure of about 132 kPa (open symbol in Fig. 9 and Fig. 10).

Furthermore, the researcher disclosed the effect of cyclic behaviour which was influenced by the strong cross-anisotropic behaviour of the peat and this behaviour was consistent with the visible layering of fibers within the specimens. Besides, they also added the possible causes of this including peat's highly fibrous fabric, high compressibility, scale effects such as specimen size versus characteristic particle for fiber size, boundary effects and other factors.

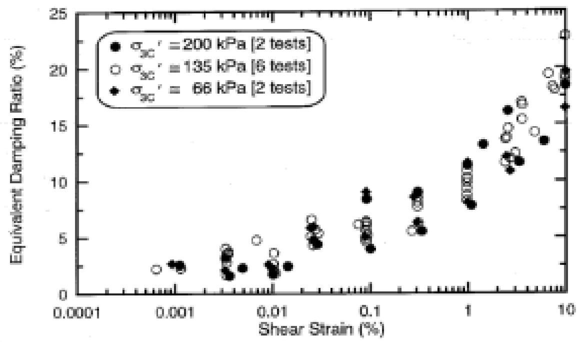

Fig. 9 : Summary of equivalent damping ratio versus shear strain at various effective confining pressure for Sherman Island peat [14]

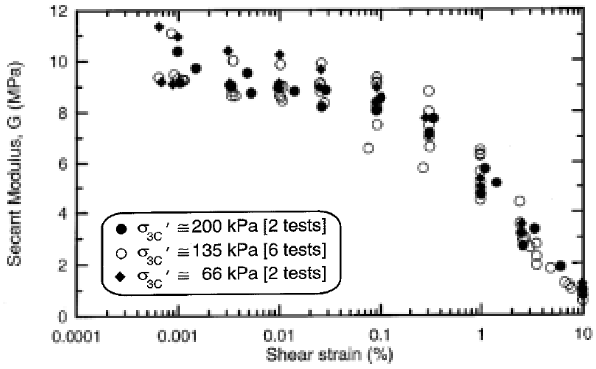

Fig. 10 : Summary of secant modulus versus shear strain at various effective confining pressures for Sherman island peat [14]

Kramer [1] reviewed past research on the dynamic response of mercer slough peat in Bellevue, Washington by using Cyclic Resonant column and Cyclic Triaxial test. The percentage of water content of the slough mention by Kramer [1] was generally between 500% and 1200% approximately.

The researcher obtained samples by pushing thin-walled with open ended Shelby tubes, sharpened cutting edges in a piston sampler. The samples were tested on cyclic triaxial test and were backpressured to 200 kPa and consolidated isotropically due to their in situ vertical effective confining pressure prior to cyclic loading. The tests were performed on strain-controlled cyclic triaxial at a loading frequency of 1 Hz as mentioned in his research.

Kramer [1] did compare the results from previous research which investigated on peat sample from Queensboro Bridge and Sherman Island. Fig. 11 pointed the comparison data from past researchers. Mercer Slough peat with 11 kPa to 30 kPa effective confining pressures were resulted from Cyclic Triaxial test meanwhile for Mercer Slough peat with the effective confining pressures of 1.6 kPa to 12 kPa were results from Resonant Column test from prior research [1]. The other two were peat soil from Sherman Island and Queensboro Bridge. Based on the figure, Kramer [1] concluded that the relationships between G/Gmax and shear strain shows a general trend of increasing linearity with increasing effective confining pressure. The Sherman Island peat had higher modulus reduction than Mercer Slough peat which was studied by Boulanger et al. [14] and a bit lower than Queensboro Bridge.

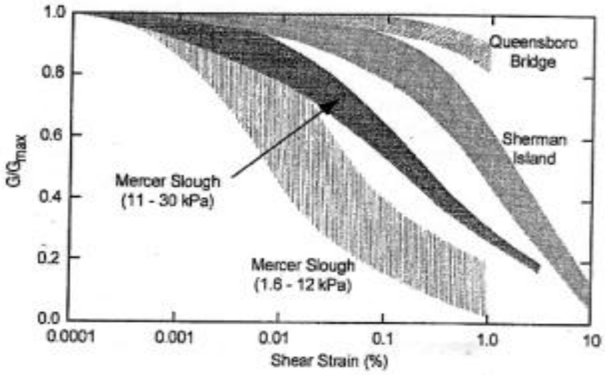

Fig. 11 : Modulus reduction behaviour for mercer slough peat [1]

Fig. 12 expressed the trend of damping ratio versus the shear strain for Mercer Slough peat, Sherman Island and Queensboro Bridge. The test results indicate that the damping ratio increase with increasing shear strain amplitude. He also stated that the damping data was characteristically scattered in Fig. 12. But, the researcher had observed the general trend of decreasing damping with increasing effective confining pressures in Fig. 13 and it was proved. Based on Kramer [1], the line in Fig. 13 indicated the results from Linear Regression Analysis.

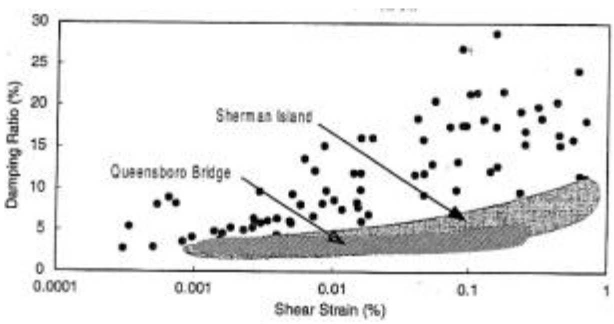

Fig. 12 : Comparison of the effect on confining pressure towards the damping ratio behaviour on peat. [1]

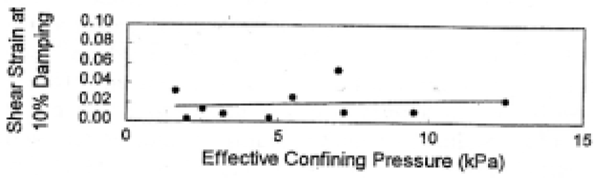

Fig. 13: Effect of effective confining pressure on damping behaviour [1]

Kramer [1] summarizes his investigation by giving the influences towards the increase in effective confining pressures. He said that the influences may arise from the variable nature of the peat and the effects of disturbance during sampling and specimen preparation.

Another researcher, Wehling et al [9] conducted an investigation on confinement and disturbance effects on dynamic properties of fibrous organic soil obtained from beneath a levee of Sherman Island in the Sacramento-San Joaquin Delta in California. Wehling et al [9] did reviewed past research on dynamic properties of Sherman Island peat and supplement the results testing reported by Boulanger et al [14]. The researcher described the levees on the Sherman Island which includes 7.5m to 10.5m thick peaty organic soil stratum. They also stated that this organic soil stratum has been compressed and the peat stratum is underlain by a 4.2m to 4.6m thick layer of medium plasticity, medium stiff clay which is underlain by dense sands and stiff to very stiff clays. Besides, the researcher had discover the percentages of water content and ash content on peat samples which was an average of 189% to 440% and 35% to 79% respectively. All the specimens used by Wehling et al [9] were highly fibrous with individual fibers ranging from fine, hair-like threads to 7mm-wide leaf blades.

In cyclic triaxial testing, Wehling et al [9] used nine samples including two samples from beneath the bench, three samples from beneath mid-toe and four samples from beneath the free field. All samples were consolidated isotropically to their estimated in-situ vertical stress. Furthermore, the researcher performed only 5 uniform cycles of undrained and strain-controlled loading at a frequency of 1 Hz.

Wehling et al [9] had plotted the results of normalized shear modulus and equivalent damping ratio for sample at free field in Fig. 14 by using the cyclic triaxial test. The effective confining pressures used by the researchers were about 13 kPa to 14 kPa for simulation of in-situ stresses and 22 kPa which were twice of their in-situ values. Based on their results, they had proved that the higher consolidation stress would cause the sample to behave more linear compared to those original soft peat samples with the in-situ effective confining pressure of 13 kPa to 14 kPa. Wehling et al. [9] also compared the results with Kramer [13] for the trends on modulus reduction and damping ratio on the effect of effective confining pressures towards the Mercer Slough peat which the results were approximately similar. Moreover, Wehling et al [9] did mentioned that the aspect of modulus reduction behaviour may represent the effect of sample bedding plane characteristics instead of the effect on differences in consolidation stress. However, the researchers had concluded that modulus reduction and damping properties of Sherman Island peat were relatively dependent on the consolidation stress.

Prior researchers, Kishida et al. [15] had developed the dynamic properties of highly organic soils from Montezuma slough and Clifton court. They had summarized the dynamic properties of highly organic soils from levee sites in Montezuma Slough and Clifton Court in the Sacramento-San Joaquin Delta, California. The organic content of their samples ranged from 14% to 61%.

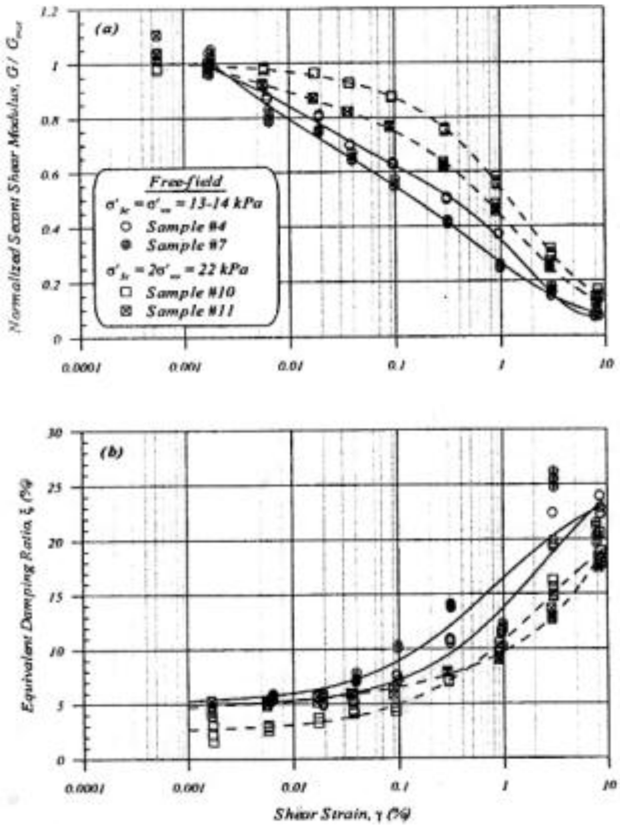

Fig. 14 : Effect of consolidation stress on samples from the free field: (a) normalized secant shear modulus and (b) equivalent damping ratio [9]

Kishida et al [15] stated the samples from Montezuma Slough were tested in a cyclic triaxial meanwhile for samples from Clifton Court, they used both cyclic triaxial and resonant-column devices. Also, Kishida et al [15] did explained that isotropic consolidation stresses were applied to each sample using total stresses and pore pressures equal to the estimated in situ total vertical stresses and pore pressures. They also used each sample to a sequence of cyclic loading stages, with each stage typically consisting of five uniform cycles of undrained, strain-controlled loading at a frequency of 1Hz.

The dynamic behaviour has been expressed in Fig. 15 for the samples from Montezuma Slough. The shear modulus, modulus reduction and damping ratio relationships shown in Fig. 15 are due to the different sample location, organic content and effective consolidation stress. Based on the figure, Kishida et al [15] concluded that the relations showed dependence on the organic content and effective consolidation stress. They also proved that the relative changes in consolidation stress and shear modulus are consistent with prior studies indicating that shear modulus will generally decrease with increasing organic content at the same consolidation stress. Besides, the researcher also explained that peaty organic samples had higher modulus reduction and generally had lower damping characteristics than organic clays. For the comparative of organic content, Kishida et al [15] concluded that differences in organic content had greater effect than did the differences in consolidation stress in these samples.

Meanwhile, Kishida et al [15] compared these results with Sherman Island investigated from previous researchers, see Fig. 16. They stated that the Montezuma Slough samples which had an organic content of 42% to 45%, were almost equal to those samples from Sherman Island (Fig. 16). They also added about the effect of effective consolidation stress on modulus reduction for Montezuma Slough and Sherman Island peat which had same organic content. Montezuma Slough showed smaller effect on modulus reduction than Sherman Island peat but achieved higher modulus reduction and lower damping characteristics.

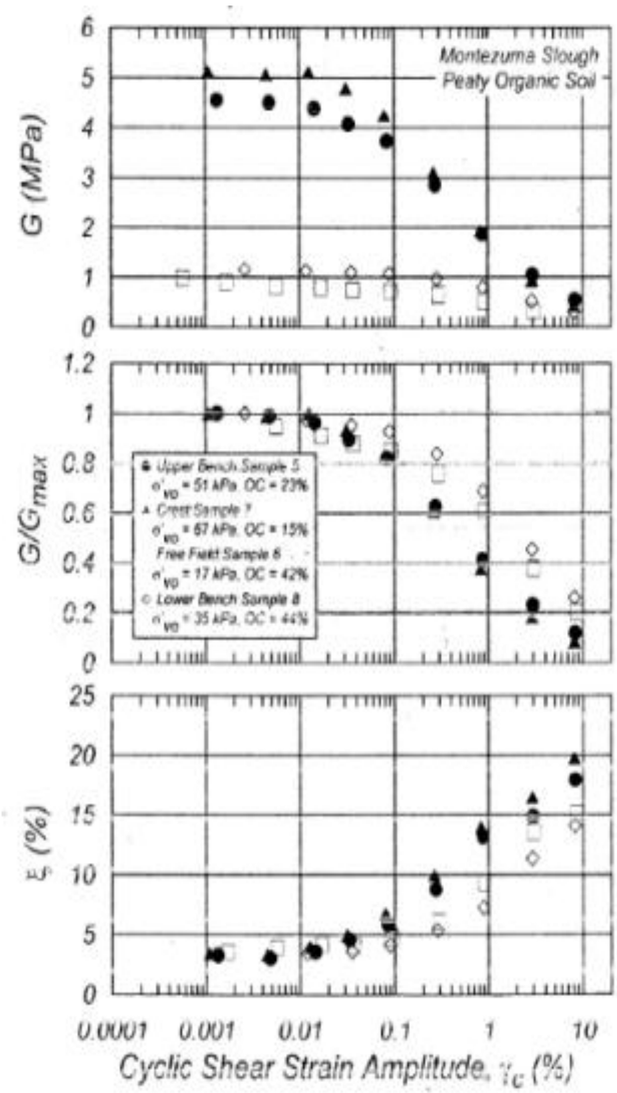

Fig. 15 : typical results of G, G/Gmax and ξ for highly organic soils from Montezuma slough [15]

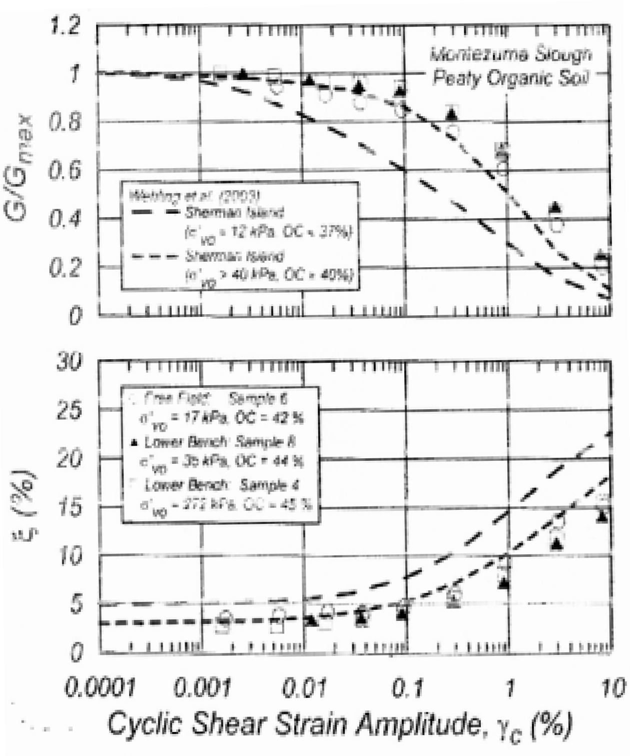

Fig. 16 : Comparison of results for peaty organic soils from Montezuma Slough and Sherman Island [15]

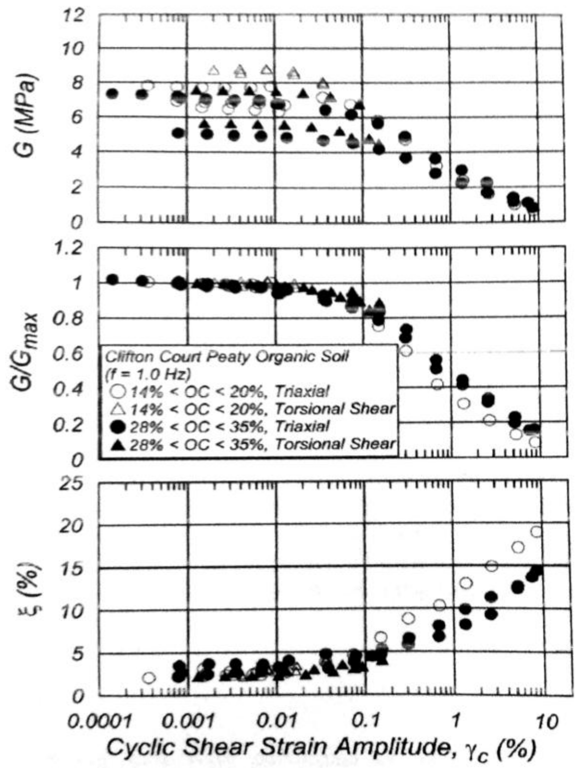

Fig. 17 : Effect of OC on G, G/Gmax and ξ observed by cyclic triaxial and torsional shear tests at 1 Hz and effective consolidation stresses of 55kPa to 69kPa for Clifton court peaty organic soils [15]

Furthermore, Kishida et al [15] compared the Montezuma Slough peat by using different devices which are cyclic triaxial and torsional shear test, shown in Fig. 17. The tests were in the same loading frequency of 1 Hz and equal effective consolidation stresses which were about 55 kPa to 69 kPa. The researcher explained the results in Fig. 17 whereby the samples with higher organic content showed lower shear modulus, high modulus reduction and lower damping than the samples with lower organic content. They compared these results with previous test and proved that the results are consistent.

Kishida et al [15] stated about the differences between these two types of peat soil whereby this differences due to the organic components characteristics of peaty soil and they concluded that the organics at Montezuma slough were generally highly decomposed and often amorphous, whereas the organics at Clifton court were highly fibrous and only mildly decomposed. Thus, these reasons which induce the inherent anisotropy of peat may give the effect towards modulus reduction, damping characteristics and cyclic shear strain amplitude. Also, these relationships were clearly dependant on effective consolidation stress and organic content of peaty soil.

4. Conclusion

After the analyses, all conclusions were tabulated in Table 3. Based on the Table 3, tests and natural properties of peat seem to be difference for each testing. Therefore, the results on the effect of effective confining pressure were observed.

The modulus reduction and damping characteristics of peat may depend on numerous factors. Kramer [1] and Kramer [13] had concluded similar reasons that the effective confining pressures influences the shear modulus and damping characteristics because of the sampling disturbance of peat during the test. Meanwhile, Boulanger et al, [14] stated that its results was affected by the strong cross-anisotropic of the peat which influences the increasing in effective confining pressures.

On the other hand, Wehling et al [9] did not stated the reasons of the affect but the researcher had explained about the effects of sample bedding plane characteristics on the shear modulus and damping characteristics of peat instead of the effect on effective confining pressures. Besides, the increasing of effective confining pressures affected by the types of peat which were fibrous and amorphous, by the differences in organic content and the inherent anisotropy of peat. This was clearly stated by Kishida et al [15].

From the analysis made, it could be concluded that all effects were mainly influenced by the natural properties of peat such as the water content of that peat in different location. For example, the percentage of water content was 500% to 1200% on Mercer Slough peat. While it water content of 152% to 240% was observed in Sherman Island. The thickness of peat or depth of sample obtained also gives the difference on peat behaviour. Types of peat soil changes due to the increasing in depth. As mentioned by Kramer [13], “the mercer slough peat is fibrous at shallow depths and becomes less fibrous and more highly decomposed with increase depth”. Basically, number of confining pressures used as simulated the in-situ pressures such as earthquakes, blast, nuclear explosions, fast moving traffic, machines operation, wind sea and also the changing of water table.

The analysis and conclusions describes in this paper applies to the influence of difference effective confining pressures towards the peat behaviour on different location. After considering these factors, additional testing is strongly advice and precise properties of peat to cover the reasons of increasing in effective confining pressures such as the size of sample, organic content and fiber content as well as the percentage of vegetative in the sample.

For further research, the cyclic loading can be conducted with different confining pressure under various numbers of frequencies. It is most probably will give an increment of confining pressure on peat soils.

Table 3 : Summarized conclusion from past researcher

Prior Researcher	Location	Test	Sampling Types	Confining pressures	Water Content (%)	Peat thickness (m)	Conclusion
Kramer [13]	Mercer Slough	Resonant Column	Piston Sampler (Shelby tubes)	1.5kPa and 12kPa	500% to 1200%	80m	Affected by the sampling disturbance of peat during the test
Boulanger et al [14]	Sherman Island	Cyclic Triaxial	Shelby Tubes	135kPa	152% to 240%	12.8m to 13.7m	Affected by the strong cross-anisotropic of the peat soil
Kramer [1]	Mercer Slough	Cyclic Triaxial	Thin-walled tubes (Shelby Tubes)	11kPa – 30kPa	500% to 1200%	18m	Influenced by the variable nature of peat and the effect of disturbance during sampling

							and specimen preparation
Wehling et al [9]	Sherman Island	Cyclic Triaxial	Thin-walled tubes (Shelby Tubes)	11kPa to 14kPa (free field) and 78kPa (levee bench)	189% to 440%	7.5m to 10.5m	Does not give the reasons why but they had mentioned about the effects of sample bedding plane characteristics instead of the effect on effective confining pressures
Kishida et al [15]	Montezuma Slough and Clifton Court	Cyclic Triaxial and Resonant Column	Thin-walled tubes (Shelby tubes)	16kPa to 272kPa	189% to 440%	4m to 8m	Affected by the types of peat (fibrous and amorphous), differences in organic content and the inherent anisotropy of peat.

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