CYCLIC LIQUEFACTION BEHAVIOUR OF TORONTO PEAT

G. Sarkar [1], A. Sadrekarimi [2]

[1] *Graduate student, Department of Civil and Environmental Engineering, Western University, ON, Canada, e-mail: gsarkar2@uwo.ca*
[2] *Associate Professor, Department of Civil and Environmental Engineering, Western University, ON, Canada, e-mail: asadrek@uwo.ca*

Abstract

The presence of organic fibers can induce a very different cyclic liquefaction behaviour in organic soils and peat deposits, compared to that of granular cohesionless soils. This paper investigates the cyclic shearing response and liquefaction behaviour of undisturbed peat samples, collected from a depth of about 4.0 to 4.5 m at the Port Lands area of Toronto, Ontario, Canada. The peat samples contain high water contents (ranging from 180 to 237%) and organic contents (ranging from about 42 to 60%, including a fiber content of 20 to 30%), which are important factors in the shearing behaviour of peat. The cyclic stress-strain, liquefaction, and post-cyclic behaviours of these samples are examined using stress-controlled cyclic direct simple shear tests. Cylindrical samples are trimmed from large block samples of peat and then subjected to different consolidation vertical stresses and cyclic shear loads in these tests. Undrained shearing is replicated by maintaining a constant-volume condition during cyclic shearing. Because of the laterally confined boundary condition with no initial shear stress, the experimental results are applicable to in-situ level-ground conditions below the phreatic surface where liquefaction can occur. The stress-strain behaviour of Toronto peat shows an accumulation of excess pore pressure with the number of stress cycles. The equivalent excess pore pressure ratios remain essentially below 60%, indicating a cyclic mobility type of behaviour in the peat samples. Despite the relatively low excess pore pressures, the cyclic shear strains accumulate to large values with repeated cycles of loading. Large cyclic shear strains could compromise the performance and serviceability of a structure overlying a peat deposit. The results further indicate a more significant effect of the effective overburden stress on the cyclic liquefaction resistance of Toronto peat compared to those found from cyclic triaxial tests on inorganic cohesionless soils. Post-earthquake settlement behaviour of Toronto peat samples is also presented in terms of post-cyclic volumetric strain. It is found that the post-cyclic volumetric strain increases with increasing the level of cyclic loading, cyclic shear strain, and effective vertical stress. However, the strong relationship between the post-cyclic volumetric strain and shear strain is not unique and depends on the effective overburden pressure.

Keywords: peat, direct simple shear test, liquefaction, cyclic resistance, post-cyclic settlement

1. Introduction

About 18% (1,500,000 km^2) of Canada's land surface is covered by peatlands, which is the highest area of peatland in the world [1]. Peatlands are generally avoided for the construction of roads, buildings, dikes, storage facilities, and other infrastructures because of their high compressibility, creep potential, and void ratio. Therefore, an organic-rich peat material is often removed from a construction site and replaced by a suitable fill material [1–5]. However, some structures or facilities are constructed over peat because of the high cost of removing the existing peat soil, ground improvement, or limited land space. For example, the Sacramento-San Joaquin delta levee system in northern California, which was built on a thick deposit of peat, failed following the Loma Prieta earthquake in 1989 [6, 7]. The main uncertainties in assessing the seismic stability of the levee system were due to limited laboratory and field testing data of the underlying organic peaty soil. The levee experienced seismic instability because the amplification of seismic waves through the peat layer underlying the levee was not considered in the design [8, 9]. The Transportation Safety Board of Canada (2004) [10] also reports two-train derailment accidents in Canada which resulted from foundation instability and large settlement of a peat sublayer. Therefore, it is required to properly assess the stability of geotechnical infrastructure constructed over peat in terms of both static and dynamic loading conditions.

Most studies indicate that peat is highly prone to large settlement, is highly compressible, with low shear strength but high frictional resistance [11–22]. The characteristic of peat under dynamic or cyclic loading (earthquake or vibration) is essential to assess its liquefaction potential, post-cyclic settlement, soil-structure interaction, and ground response analysis. Existing studies on the dynamic characterization of peat include both field testing and laboratory cyclic triaxial, cyclic torsional and simple shear tests on peat from different locations such as the Union Bay in Washington [23], the Queensboro Bridge peat in New York [24], the Mercer Slough peat in Washington [25, 26], Sherman Island peat in California [8, 22, 27, 28], Ojiya City in Japan [29], Sacramento-San Joaquin Delta in California [7], Lake Dian in Kunming [30], Hokkaido peat in Japan, [31], Kayseri peat in Turkey [32], and Greece and Cyprus [33]. However, very few studies have focused on liquefaction potential, cyclic response, and the post-cyclic settlement behaviour of peat or organic soils. In this study, constant-volume (equivalent to undrained test) stress-controlled cyclic direct simple shear (DSS) tests are conducted on undisturbed peat samples collecting from the Port Lands area of Toronto (Ontario, Canada). To carry out the DSS tests, an advanced computer-controlled variable direction dynamic cyclic simple shear system (VDDCSS), manufactured by GDS instruments (UK) is used. The experimental results are compared with the findings of other studies from the literature.

2. Materials and Methods

Undisturbed large blocks of peat were collected from a depth of 4.0 to 4.5 m below the ground surface at Port Lands, which is located near the waterfront area of Toronto city. Test samples were prepared by carefully trimming the block samples with minimum disturbance. The water content of the peat samples varied from 172 to 280%. The dry densities of the samples varied from 3.04 to 4.10 kN/m^3. The optimum moisture content and maximum dry density of the peat samples were also found to be around 85% and 6.22 kN/m^3, determined following the ASTM D698 procedure. The specific gravity of the peat was measured using the ASTM D854 method and was found to vary from 1.90 to 2.0. The organic content and volatile matter content of the peat was determined from the ignition test (ASTM D2974). In this method, about 100 g of oven-dried peat was placed in a muffle furnace at a temperature of 550°C for 6 hrs. The percentage of residue available after 6 hours of heating is the ash content and subsequently subtracting this ash content from 100, the organic content of the peat was found. While the fiber content was determined by soaking about 100g of peat in a 5% sodium hexametaphosphate solution for 15 hours and then washed through a 150 μm sieve. The percentage of the dry mass of the fibrous material left on the sieves is the fiber content of the peat (ASTM D 1997). The fiber content, volatile matter content, and organic content of the Toronto peat were also measured as 20 to 30%, 24 to 54% and 42 to 60%. The organic matter present in the peat was inspected visually and it was found that the peat mainly comprised of pieces of wood, amorphous materials, and partially or fully decomposed roots as shown in Fig. 1. The physical properties of the peat samples used in each DSS test are further summarized in Table 1.

Fig. 1: Photo of a Toronto peat sample

A series of strain-controlled constant-volume (CV) cyclic tests were conducted to observe the cyclic and post-cyclic behaviour of Toronto peat. The peat block collected from the Port Land area was trimmed to prepare cylindrical samples of 70.3 mm in diameter and 25 mm high. The height to diameter ratio of the trimmed samples varied from 2.5 to 2.75. The specimen mold was formed by placing a series of 1.1 mm tick Teflon-coated stainless-steel rings on the bottom platen, held in place by two supporting retainers. A flexible latex membrane, secured by an O-ring to the bottom platen, lined the internal circumference of the steel rings. The latex membrane was then carefully folded over the steel rings so that all the rings were concentrically lined. The trimmed peat specimen was then carefully pushed into the mold. The mold was then mounted on the DSS device and attached with a set of screws. The top platen of the device was centrally aligned with the specimen top by adjusting the bottom platen. A seating load of 5 kPa was subsequently applied to ensure a firm contact between the specimen top and the top-loading platen. The side supporting retainer was then removed, the latex membrane was folded back on the upper platen and secured by an O-ring. The peat specimen was saturated by flushing deaired water through the bottom drainage port to the top drainage port until all the air bubbles disappeared. The saturated samples were then consolidated to three different consolidation vertical stresses (σ'_{vc}) while recording their vertical deformations. Cyclic shearing load was applied by moving the bottom platen relative to the upper platen. A total of 14 samples were sheared at different cyclic stress ratios (CSR) and σ'_{vc}. After the completion of cyclic loading, the peat specimens were reconsolidated to the same σ'_{vc} in order to measure the post-cyclic deformation and vertical strain in Toronto peat samples.

Table 1- Summary of DSS testing program

Test No.	σ'_{vc} (kPa)	CSR	ω (%)	γ_d (kN/m^3)	e_0 [a]	e_c [a]	Organic content (%)
C1	100	0.100	227	3.16	3.74	2.97	42
C2	100	0.200	190	3.71	3.04	2.61	42
C3	100	0.300	180	4.04	2.72	2.29	60
C4	100	0.325	194	3.84	2.91	2.40	60
C5	100	0.350	172	4.10	2.66	2.15	60
C6	100	0.400	204	3.26	3.60	2.95	42
C7	100	0.500	238	3.04	3.94	3.34	48
C8	200	0.175	223	3.17	3.73	2.53	50
C9	200	0.230	233	3.32	3.52	2.52	42
C10	200	0.250	204	3.55	3.22	2.35	45
C11	200	0.275	197	3.56	3.22	2.19	50
C12	200	0.285	202	3.74	3.02	2.14	42
C13	200	0.300	209	3.52	3.26	2.24	44
C14	200	0.350	228	3.29	3.57	2.51	44

[a] *e_o: initial void ratio; e_c: void ratio after consolidation*

3. Results and Discussions

3.1 Cyclic stress-strain and liquefaction behaviors

In this study, the cyclic stress-strain behavior of Toronto peat is investigated at three different effective vertical stresses (σ'_{vc} = 50, 100, and 200 kPa) and various cyclic stress ratios (CSR). The cyclic load is applied through a stress-controlled constant-volume (CV) cyclic DSS test. Fig. 2 shows typical stress-strain behavior, stress path, changes in shear strain (γ_c) and pore pressure ratio with the number of stress cycles at CSR =0.35 and σ'_{vc} = 200 kPa. The equivalent pore water pressure (Δu) is measured as a reduction in total vertical stress in the cyclic DSS tests of this study. The pore pressure ratio (r_u) is defined as Δu divided by σ'_{vc}. It is observed that the loss of effective stress, i.e., the accumulation of Δu due to the applied cyclic load is not very significant in Toronto peat. For example, r_u does not exceed 0.5 even at a large CSR = 0.35 and higher number of stress cycles, while large cyclic shear strains (γ_c > 8%) are developed. The generation of pore pressure is significant in first few cycles of loading, but then the rate of pore pressure generation significantly drops and the magnitude of Δu stabilizes at higher number of stress cycles. The stress-strain behaviour indicates a cyclic mobility type behavior in the peat samples instead of cyclic liquefaction. Similar cyclic mobility behaviors were also observed at other CSR and σ'_{vc} as shown in Fig. 3 in which r_u remains essentially less than 60% even at large γ_c (of up to 15%). The liquefaction criterion of r_u > 90% [34] therefore does not apply to the peat samples tested in this study. Accordingly, the liquefaction criterion of attaining a double-amplitude shear strain of 7.5% is used to define cyclic liquefaction occurrence for the peat samples in the DSS tests of this study. This criterion is equivalent to a double-amplitude axial strain of 5% in a triaxial test [35–41].

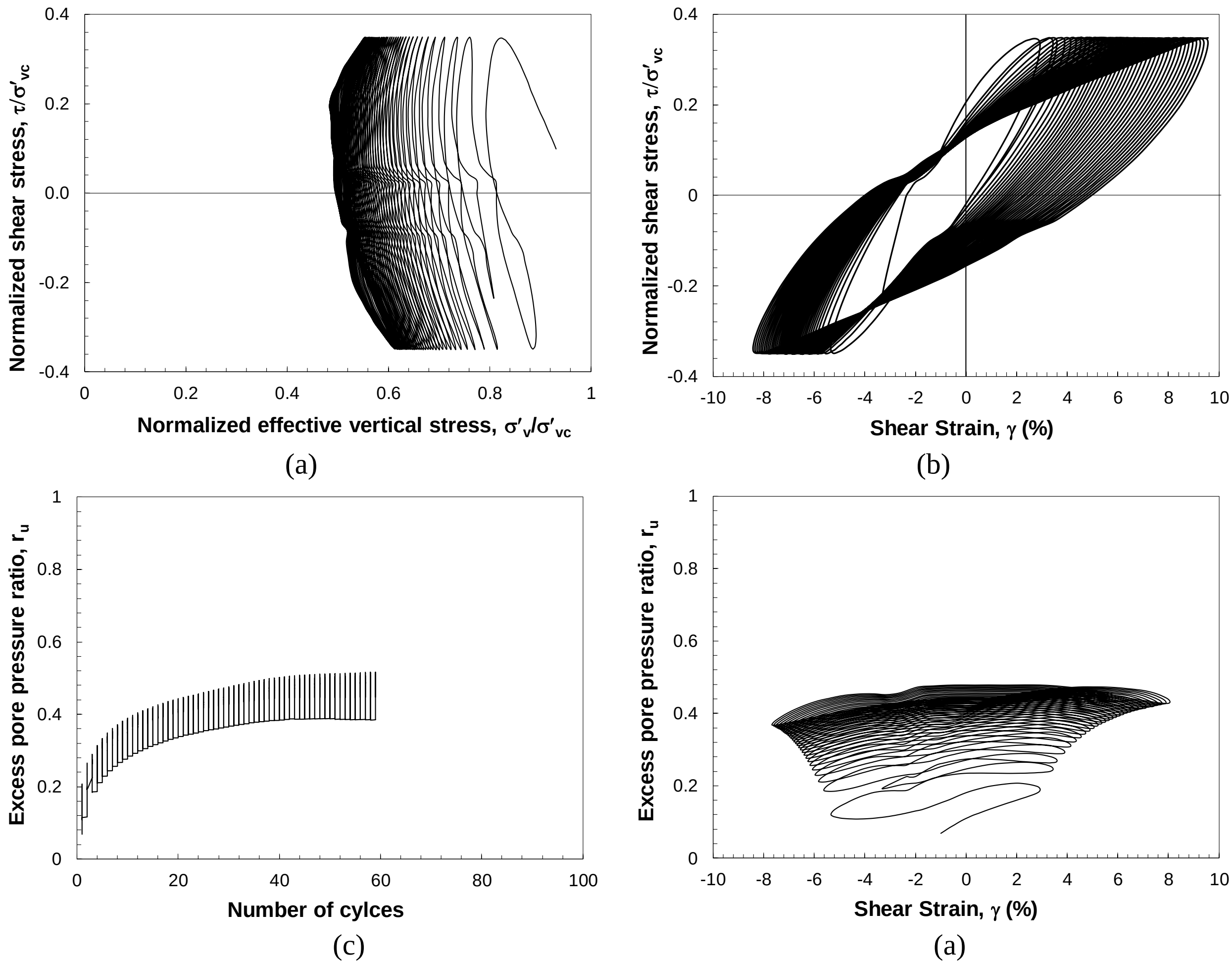

Fig. 2 - Typical results of a cyclic DSS test on Toronto peat at σ'_{vc} =200 kPa: (a) cyclic effective stress path, (b) cyclic shear stress-strain behavior, (c) r_u versus N_c, and (d) r_u versus γ_c

Seed and Idriss (1971) defined the CSR required to reach liquefaction in N_L = 15 cycles as the cyclic resistance ratio corresponding to an earthquake magnitude of 7.5 ($CRR_{7.5}$). The number of cycles required to reach γ_c = 7.5% is plotted against the corresponding CSR for σ'_{vc} = 50, 100, and 200 kPa in Fig. 4. $CRR_{7.5}$ is then estimated from the fitted exponential trendlines at N_L = 15 cycles. Subsequently, $CRR_{7.5}$ = 0.437, 0.373 and 0.273 are found respectively at σ'_{vc} = 50, 100, and 200 kPa. Accordingly, $CRR_{7.5}$ is seen to reduce with increasing σ'_{vc}, i.e., the susceptibility to liquefaction would increase with increasing overburden pressure and the depth of a peat layer.

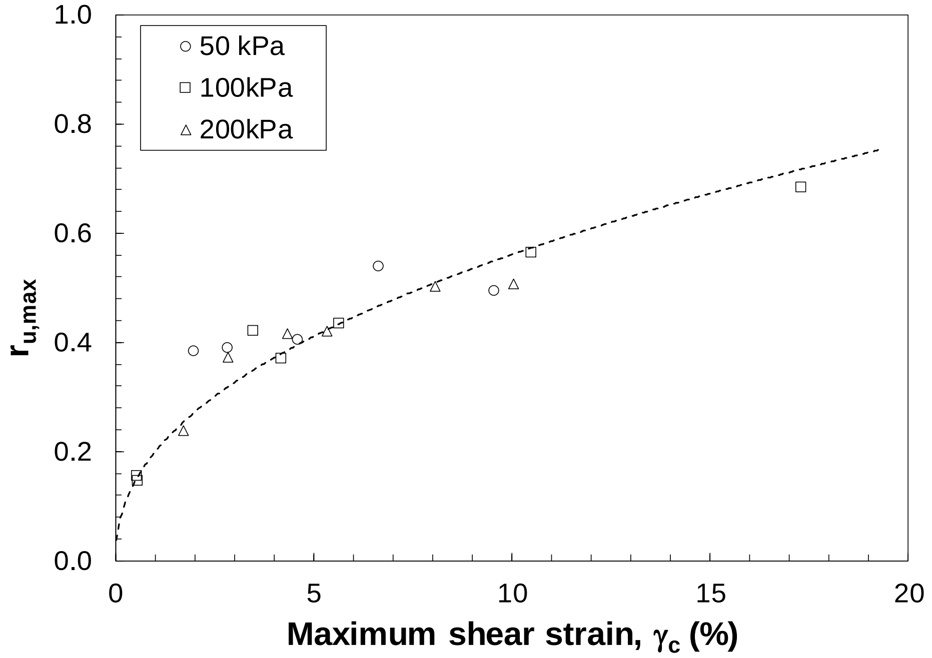

Fig. 3 - Generation of maximum excess pore pressure ($r_{u, max}$) in Toronto peat as a function of γ_c

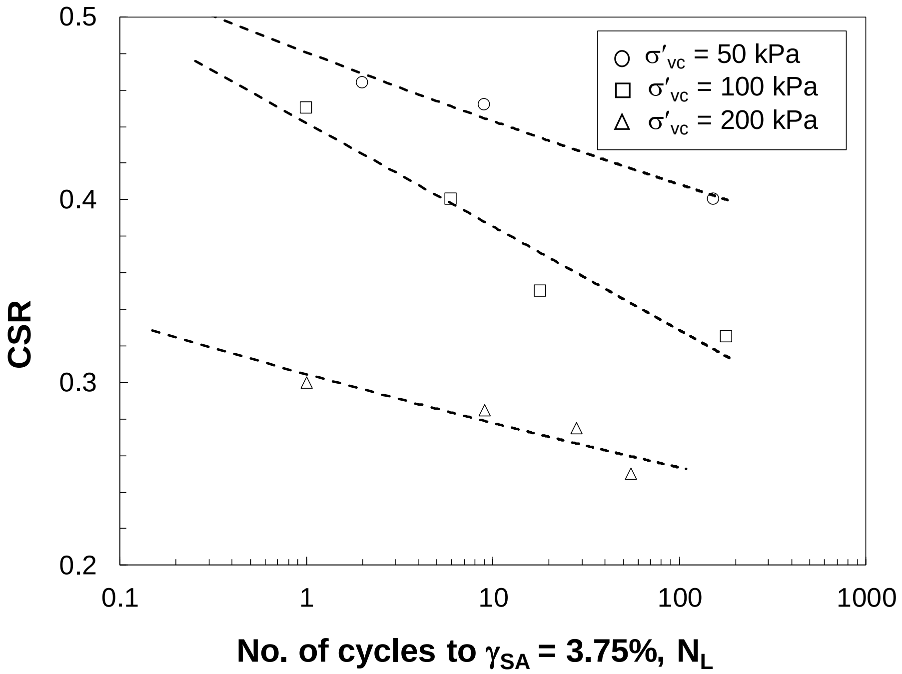

Fig. 4 - Cyclic strength curves of Toronto peat at σ'_{vc} = 50, 100, 200 kPa

3.2 Effect of Overburden Stress on Cyclic Resistance

The change of CRR with σ'_{vc} is commonly expressed by an overburden correction factor (K_σ) and widely used in practice for adjusting CRR to different σ'_{vc} [43, 44]. The K_σ values for Toronto peat are determined by dividing CRR measured at σ'_{vc} = 50, 100, and 200 kPa ($CRR_{\sigma'vc}$) with respect to that at σ'_{vc} = 100 kPa (CRR_1) as shown below:

$$K_\sigma = \frac{CRR_{\sigma'_{vc}}}{CRR_1} \tag{1}$$

The variation of K_σ with (σ'_{vc}/P_a) is illustrated in Fig. 5. The results are also compared with the empirical correlation proposed by Hynes et al. (1998). Their empirical correlation is mainly expressed in terms of an exponent (f), which is a function of site conditions, relative density (D_{rc}), stress history, overburden pressure, and aging. Youd et al. (2001) summarized a report based on the 1996 NCEER and 1998 NCEER/NSF workshops for the evaluation of liquefaction resistance of soils and recommended f = 0.8, 0.7, and 0.6 for relative densities (D_{rc}) of ≤ 40%, 60% and ≥ 80%. It is seen that the values of K_σ obtained for Toronto peat can be fitted with an exponent of f = 0.7, corresponding to D_{rc} = 60% for sands. The sharp reductions of CRR and K_σ with increasing σ'_{vc} for Toronto peat indicate that cyclic liquefaction in the form of excessive shear strain development should be expected in deep peat deposits. This highlights the importance of ground remediation or replacement of peat layers at larger depths or subjected to higher overburden pressures (e.g., under a building foundation, earth/tailings dam).

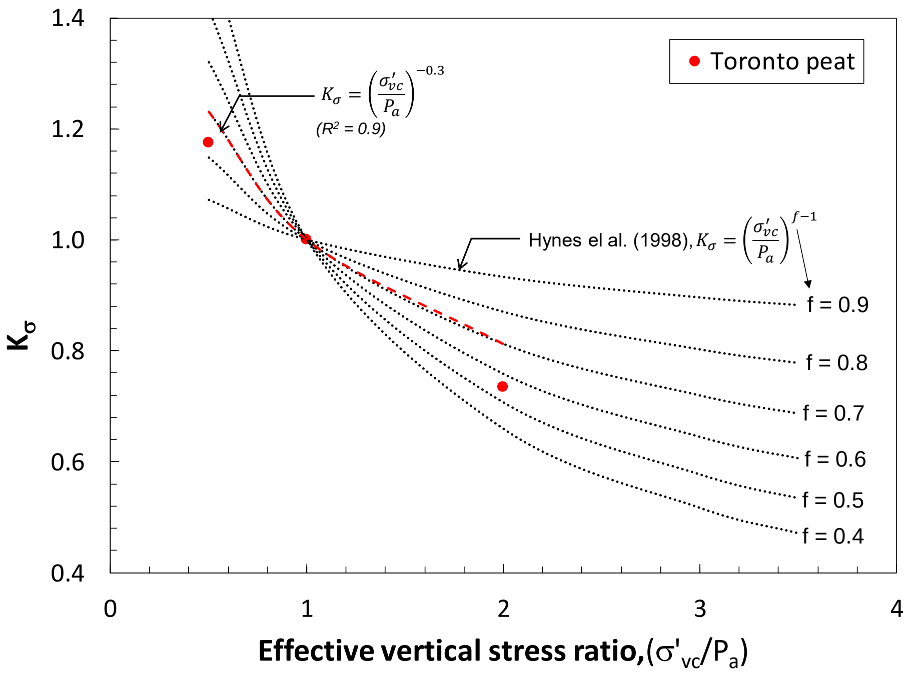

Fig. 5 - Comparison of K_σ factors found for Toronto peat with the empirical relationship developed by Hynes et al. (1998)

3.4 Post-cyclic volumetric strain

In this study, seismic settlement is expressed in terms of post-cyclic reconsolidation vertical strain (ε'_{vol}), which was measured in the DSS tests by reconsolidated the specimens after the end of the cyclic loading. The specimens experienced ε'_{vol} due to primary and secondary compressions of the peat following the dissipation of excess pore water pressure.

Typical post-cyclic volumetric strain (ε'_{vol}) versus square root of time plots for Toronto peat are shown in Fig. 6 following cyclic loadings with CSR = 0.175, 0.250 and 0.300 and reconsolidated to σ'_{vc} =200 kPa. It is seen that the peat specimens undergo larger post-cyclic ε'_{vol} when subjected to a higher CSR. The larger applied CSR increases the accumulated pore pressure during the cyclic loading, indicating that a stronger magnitude earthquake can accumulate a larger r_u, resulting in a greater post-earthquake settlement of a peat deposit. Specimens subjected to other overburden pressures also depicted similar trends. Post-cyclic volumetric strains were also higher in specimens subjected to higher σ'_{vc}, which indicates that a peat deposit underlying a heavier structure could experience greater settlement. The continuous increases of ε'_{vol} with time, which show little tendency to slow down, is further consistent with the high secondary compression potential of peat. Similar observations are also made in the literature for inorganic soils such as silt and sands [47–49]. All specimens in this study experienced significantly lower volumetric strains than those induced during the initial consolidation stage (prior to cyclic loading). This can be attributed to the fact that the pre-sheared specimens were denser than the virgin peat samples.

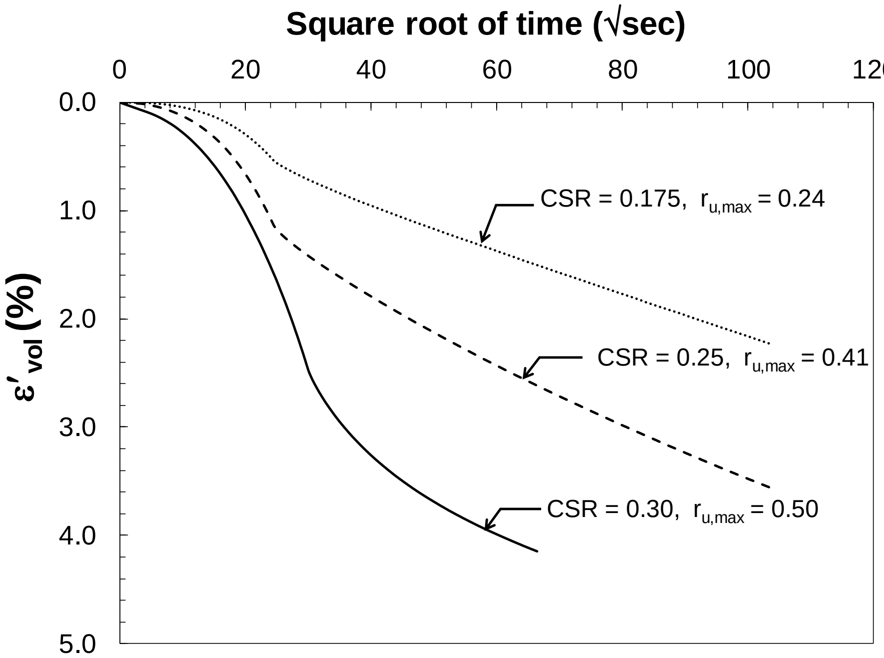

Fig. 6 - Typical post-cyclic volumetric strain (ε'_{vol}) versus square root of time plots for Toronto peat samples

The variation of the reconsolidation ε'_{vol} with the maximum shear strain (γ_{max}) applied during the cyclic loading is shown in Fig. 7. As shown in this figure, ε'_{vol} increases with the accumulated γ_{max} at the end of cyclic loading. Similar observations of increasing ε'_{vol} with increasing γ_{max} are also reported by several other researchers but for inorganic soils [50–53]. For any specific magnitude of γ_{max}, Fig. 7 further shows greater ε'_{vol} accumulation in specimens subjected to higher σ'_{vc}. The ε'_{vol} of Toronto peat are also compared with those measured by Wijewickreme and Sanin (2010) in cyclic DSS tests on normally consolidated Fraser River silt samples at σ'_{vc} = 100 and 200 kPa. Compared to Fraser River silt, Toronto peat samples exhibit greater ε'_{vol} without accumulating as much γ_{max} during cyclic loadings at σ'_{vc} = 100 and 200 kPa.

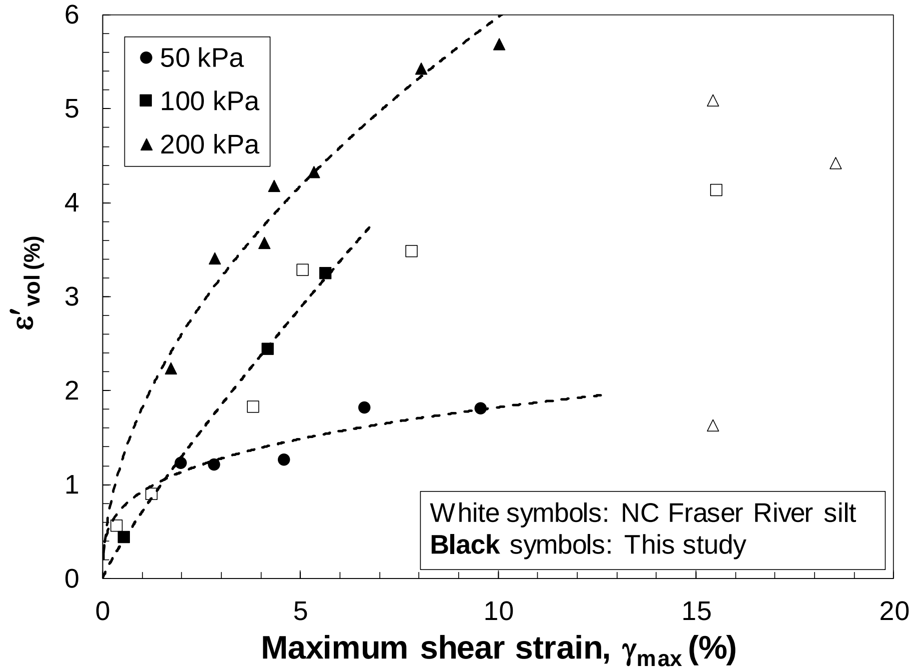

Fig. 7 - Variations of ε'_{vol} with γ_{max} for Toronto Peat (this study) and Fraser River silt [54] in cyclic DSS tests

4. Conclusions

A comprehensive experimental investigation was carried out to observe the cyclic stress-strain behaviour, liquefaction susceptibility, and post-cyclic settlement of Toronto peat by conducting a series of cyclic direct simple shear tests. The peat samples were characterized by water contents of 172 to 280%, specific gravities of 1.9 to 2.0, dry unit weights of 3.04 to 4.10 kN/m^3, fiber contents of 20 to 30%, and organic contents of 42 to 60%. Specimens for simple shear testing were prepared by trimming a large block of peat with minimum disturbance. Cyclic DSS tests were carried out at a constant-volume (CV) condition to observe the undrained cyclic behavior of peat.

The cyclic stress-strain behaviour of peat depicts that the accumulated pore pressure during cyclic loading is limited to less than 60% even with the accumulation of large cyclic shear strains (up to 15 %). The criterion for liquefaction based on the accumulated pore pressure ratio (r_u) > 90% does not occur in peat because of the reinforcing effect of peat fibers. Thus, the definition of liquefaction in terms of accumulated pore pressure would be misleading and fundamentally unsound for peats as their stress-strain pattern is suggestive of a cyclic mobility type behavior. Thus, the cyclic resistance (CRR) of Toronto peat is determined based on the a double-amplitude shear strain of 7.5% in the DSS tests. It is found that the CRR of Toronto peat decreases with increasing effective over burden pressure (σ'_{vc}), indicating that its susceptibility to liquefaction could increase with overburden depth or the construction of a heavy structure on top of a peat layer. The post-liquefaction settlement of Toronto peat is also affected by overburden stress and the accumulated shear strain attained during cyclic loading.

5. Copyrights

6. References

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