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Cyclic shear response of Fraser river sand using cyclic ring shear

MUHAMMAD SAFDAR[1], ABOUZAR SADREKARIMI[1], KHALID MAHMOOD[2]
[1]Department of Civil and Environmental Engineering, Western University, London, Ontario, Canada
[2]Sarhad University of Science and Information Technology, Peshawar, Pakistan
Email: safdar.pnu@gmail.com, engkhan2008@gmail.com

Abstract: Cyclic triaxial, direct simple shear, torsional shear, resonant column, and cyclic ring shear apparatuses can also be used for evaluating cyclic shear strength and liquefaction resistance of cohesionless soils. In this study cyclic shear response of Fraser River sand is investigated using constant-volume cyclic ring shear tests. Cyclic shear response of Fraser River sand is evaluated based on several parameters including sample preparation method, vertical stress (σ_v), number of loading cycles to liquefaction (N_L), cyclic stress ratio (CSR), and relative density (D_{rc}). Thirty Fraser River sand specimens are prepared by different sample preparation methods and tested under stress-controlled, constant-volume cyclic ring shear condition. The ring shear specimens are consolidated to vertical stresses of 100, and 200 kPa prior to the application of uniform, sinusoidal, shear stress cycles. The specimens are then subjected to cyclic shear stress ratios (CSR) of 0.08, 0.10, 0.12, 0.15 and 0.20. Cyclic shear strain and vertical stress respectively increase and decrease with increasing the number of loading cycles or when subject to higher CSR. It is found that saturated water-pluviated samples have significantly higher cyclic shearing resistance compare to dry air-pluviated and saturated moist-tamped samples. Compared to cyclic direct simple shear tests, cyclic shearing resistance measured in ring shear experiments is higher due to rigid boundaries of the specimen chamber which impose a perfect plane strain shearing condition.

Keywords: *Cyclic Ring Shear, Cyclic Shear Resistance, Liquefaction, Sample Preparation, Cyclic Shear Strain*

1. Introduction:

In the past 30 years, cyclic shear response and liquefaction resistance of loose to medium-dense cohesionless soils has been among the vital concerns related to the performance of structures located in high seismic zones. Recent evidences of ground failure in cohesionless soils during strong earthquake loading has demonstrated the need for understanding the cyclic shear response of loose to medium-dense sand under cyclic loading. Cyclic liquefaction failure can occur when a cohesionless soil is subjected to cyclic loading in undrained (or constant-volume) shearing. Several researchers [1, 2] have highlighted the fact that earthquake loading can trigger the development of cyclic liquefaction and loss of shear strength of cohesionless soils.

Seed et al., [1] used cyclic triaxial testing with uniform cyclic shear stresses to simulate earthquake loading on soil samples in the laboratory. Seed and his co-workers presented a simplified procedure to evaluate liquefaction potential through stress-controlled testing [1], where the stresses induced by earthquake loads are compared to the cyclic shear strength of soil. Various important parameters influence liquefaction resistance of cohesionless soils such as relative density, cyclic stress ratio, ground motion characteristics and vertical effective stress. These and other parameters have been investigated by various researchers [2, 3, 4].The test results [3] indicate that the danger of liquefaction of saturated sand is determined by the following factors: (1) Void ratio; the higher the void ration the more easily liquefaction will occur. (2) Confining pressure; the lower the confining pressure the more easily liquefaction will occur, and (3) magnitude of cycle stress or strain; the larger the cyclic stress or strain the fewer the number of cycles required to induce liquefaction. Cyclic shear response of Fraser River sand has been studied in detailed in cyclic simple shear [2, 5, 6, 7] and triaxial tests [8, 9, 10].In their [2, 5, 6, 7, 8, 9, 10] work on Fraser River sand, they put great emphasis on sample preparation and a comparison between air-pluviated and water-pluviated soil samples. Fraser River sand samples pluviated through air were more susceptible to liquefaction [2].

In this study, a comprehensive laboratory research program is carried out to study the cyclic shear response and liquefaction behavior of Fraser River sand using constant-volume cyclic ring shear tests. The effects of specimen preparation method, relative density, vertical stress, and plane-strain boundary conditions are evaluated.

2. Material Tested:

The Fraser River sand used in this research was obtained from a site located at the Fraser River delta in British Columbia, Canada. The specific gravity of sand particles (G_S), maximum (e_{max}), and minimum (e_{min}) void ratios of respectively 2.69, 0.96, and 0.63 were determined following ASTM standard guidelines [11, 12, 13]. The particles of this sand are generally sub-angular to angular based on scanning electron microscopic (SEM) images and they are composed of 55% orthoclase feldspar, 35% quartz, and 10% muscovite based on X-ray diffraction analysis conducted in this study. The grain size distribution and SEM images of the sand particles are shown in Figs. 1 and 2.

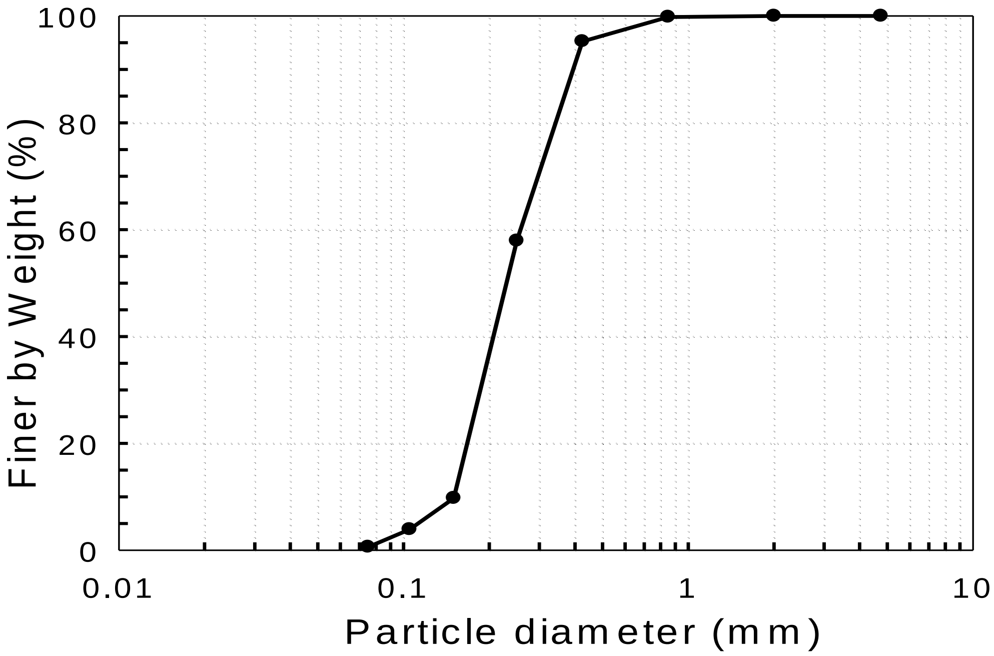

Figure 1: *Average grain size distribution of the Fraser River sand used in this study*

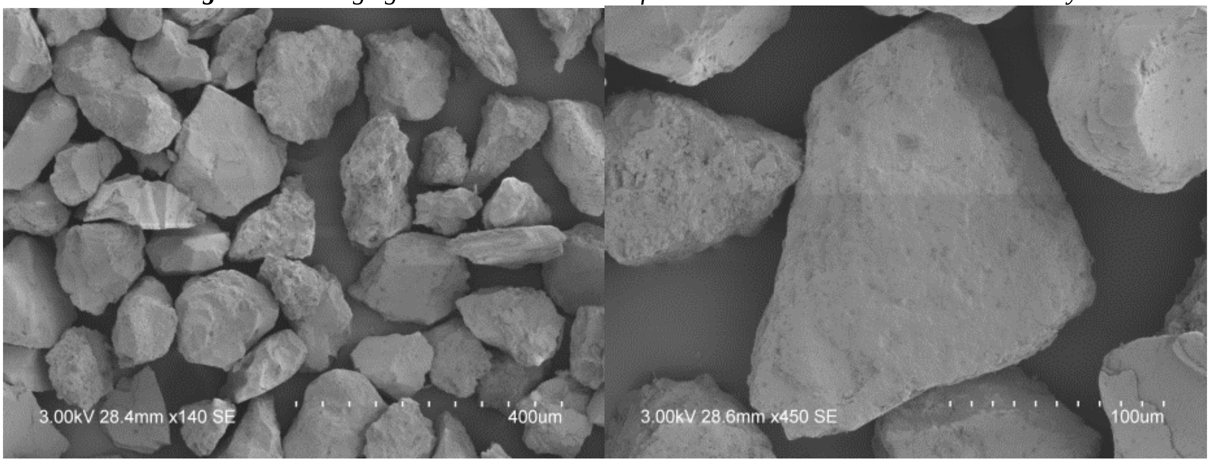

Figure 2*. SEM images of Fraser River sand particles at 140 and 450 magnifications*

3. Experimental Details:

There are a number of methods for reconstituting laboratory sand specimens. These include, dry air pluviation, water pluviation, and moist tamping methods. Dry air-pluviation sample preparation technique closely replicates the particle fabric of Aeolian sands, and water-pluviated samples replicate the particle fabric of fluvial and hydraulic fill sands [8, 14]. Water-pluviation technique is similar to the air-pluviation method in which sand particles are pluviated through de-aired water rather than air, thus ensuring sample saturation. Moist tamping sample preparation technique would replicate the particle fabric of moist-dumped fill sands.

Several researchers [2,14, 15, 16, 17, 18, 19] have studied the effect of specimen preparation techniques on cyclic liquefaction behavior and cyclic resistance of sands. Moist tamping technique has been suggested to result in a collapsible particle structure and therefore more susceptible to liquefaction [2, 17]. Fabric studies and electrical conductivity measurements indicate that the orientation and arrangement of the contacts between sand grains are probably the primary reasons for the observed differences in the cyclic strength of sands [14].Several previous studies [2, 5, 7, 8, 9, 10, 17]have also observed that air-pluviated samples are more susceptible to liquefaction compared to water-pluviated specimens.

The laboratory testing program for this study was designed to analyze the cyclic liquefaction behavior of Fraser River sand specimens prepared by different specimen preparation methods and subject to different cyclic stress ratios (CSR).A cyclic ring shear device (from GCTS, Arizona, USA)was used in the experiments.

The ring shear device accommodates ring-shaped specimens with external and internal diameters of 152.2 mm, and 96.5 mm, respectively and a height of

30 mm. Both stress-controlled and strain-controlled cyclic shearing tests can be conducted with this apparatus. In this study, ten specimens were prepared using each specimen preparation method (i.e. dry air-pluviation, saturated water-pluviation, and saturated moist tamping methods). Dry air-pluviated Fraser River sand samples were pluviated using a funnel and the drop height was used to obtain the desired relative density. In saturated water-pluviation sample preparation method, the sand was pluviated through de-aired water rather than air, in order to obtain saturated samples. In the saturated moist tamping method, the Fraser River sand was thoroughly mixed with 5% water, and then poured and gently tamped in 3 layers (of 10mm height) into the annular ring shear chamber and then subsequently saturated by flushing water.

After specimen preparation, undrained shear was replicated by constant- volume conditions in which a constant specimen height is maintained through a computer-controlled and feedback system. It has been observed that the decrease or increase in applied vertical stress in a constant-volume shear test is essentially equal to the increase or decrease of excess pore water pressure in an equivalent undrained shear test, respectively [20, 21, 22, 23]. As a result of the rigid confining rings of the specimen chamber, the specimen is consolidated under K_o conditions by the application of a vertical stress ($\square_v$) and sheared under plane-strain boundary conditions (compared to axisymmetric boundary conditions in triaxial tests).

Cyclic ring shear specimens were consolidated to a vertical stress of σ'_{vc} = 100,and 200 kPa. The amount of vertical compression and thus the volume change of the specimen were carefully measured during the application of the consolidation stress and the specimen void ratio was subsequently calculated at the end of consolidation. Constant-volume cyclic shear tests were performed by subjecting the specimens to different levels of uniform sinusoidal cyclic shear stresses (τ_{cyc}) at a cyclic shearing frequency of 0.1Hz.

The cyclic ring shear machine used in this study was fine-tuned at various cyclic shearing frequencies and it was found that the cyclic shearing frequency of 0.1 Hz gave uniform and much better sinusoidal response. A cyclic shearing frequency of 0.1 Hz has been also used by several other researchers [2, 5, 6, 7, 24, 25, 26, 27] to investigate cyclic shearing and liquefaction behavior. Uniform cyclic shear stress ratios, CSR = τ_{cyc}/σ'_{vc} of 0.08, 0.10, 0.12, 0.15 and 0.20 were applied in the cyclic ring shear tests in this study until a double-amplitude cyclic shear strain,$\gamma_{cyc}$of 7.5% was developed.

Similar to the liquefaction criterion used in cyclic direct simple shear tests, the occurrence of cyclic liquefaction was determined when a double-amplitude cyclic shear strain, γ_{cyc} = 7.5% was reached. This failure criterion is the equivalent of 5% double-amplitude axial strain in cyclic triaxial tests [9, 14, 28].

4. Results and Discussion:

Figs. 2 and 3 show typical cyclic stress-strain and stress path relationships obtained from the ring shear tests performed on Fraser River sand specimens. While all the specimens exhibit gradual increase of shear strain with increasing the number of loading cycles, the amount of vertical stress (σ_v) reduction (corresponding to the generation of excess pore water pressure)increases with the number of cycles.

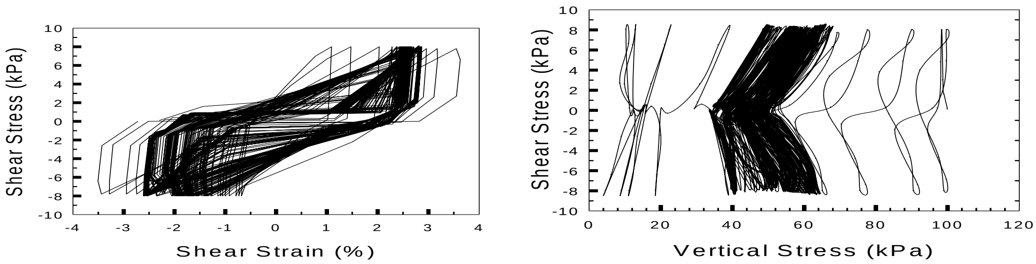

***Figure 3**. Stress-strain and stress-path responses of Fraser River sand inconstant-volume cyclic ring shear test (σ'_{vc} = 100 kPa; CSR = 0.08; D_{rc} = 34%, dry air-pluviated sample)*

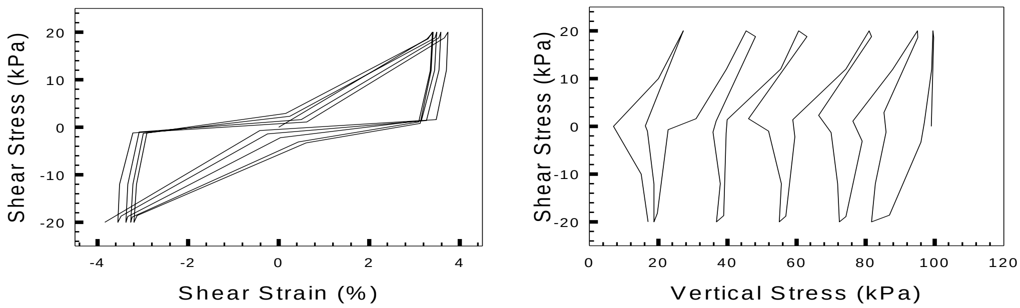

***Figure 4**. Stress-strain and stress-path responses of Fraser River sand inconstant-volume cyclic ring shear test (σ'_{vc} = 100 kPa; CSR = 0.20; D_{rc}= 34%, saturated moist-tamped sample)*

It was the primary interest of this study to examine the cyclic shear resistance of Fraser River sand specimens under different cyclic loadings and sample preparation methods. In order to facilitate this comparison, the number of loading cycles required to reach liquefaction (at γ_{cyc}=7.5%)fora given applied CSR is defined as N_L.Fig.4compares CSR required to reach N_L for each of the specimen preparation methods.

Clearly, the Fraser River sand specimens prepared using water-pluviation have a significantly higher cyclic resistance in comparison to those for specimens prepared using dry air-pluviation and saturated moist tamping sample preparation techniques. The results developed from cyclic ring shear tests on dry air-pluviated, saturated water-pluviated and saturated moist-tamped Fraser River sand are also compared with previous research using cyclic direct simple shear tests [2]. It can be seen that cyclic shear resistance from ring shear tests is considerably higher than those from cyclic direct simple shear tests. Several researchers [29, 30] have studied the effect of sample confinement and imperfect boundary conditions on undrained shear strength of soils. The higher resistance observed in cyclic ring shear tests could be associated with rigid boundaries (steel rings) imposing a perfect plane strain condition in ring shear. Whereas, the latex membrane in simple shear tests would allow some deformation and hence imperfect plane strain conditions.

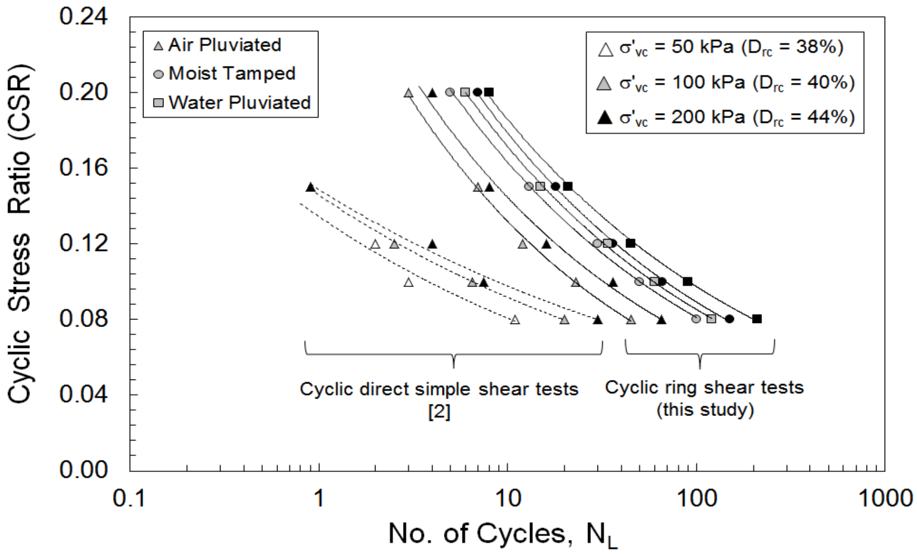

Figure 5. *CSR versus number of cycles required to reach γ_{cyc} = 3.75% from constant-volume cyclic ring shear (this study) and cyclic direct simple shear [2] tests on Fraser River sand specimen*

5. Conclusions:

The cyclic behavior and liquefaction response of Fraser River sand was investigated in this study for samples prepared by different methods, and at different cyclic stress ratios.In all test specimens, higher cyclic stress ratios appear to reduce the cyclic shear strength of Fraser River sand observed in ring shear tests. Fraser River sand specimens prepared using the saturated water-pluviation method exhibited higher cyclic resistances than those prepared using dry air-pluviation and saturated moist tamping techniques. These findings reinforce that sample preparation method can greatly affect the cyclic shear resistance and liquefaction behavior of Fraser River sand. Larger cyclic resistances were also measured in ring shear tests, compared to those from cyclic direct simple shear experiments on similar sand. This is likely associated with the effect of different boundary conditions imposed in these apparatuses.

6. Acknowledgment:

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