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The Effect of Irregular Preliquefaction Loading and Particle Angularity on Postliquefaction Response

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ABSTRACT: Liquefaction of saturated sand is a well-recognized devastating hazard, and it is important to gain insight into the characteristic of liquefied soil, which is a topic that has not yet been comprehensively explored. A better knowledge of the stress-strain behaviour of liquefied soils can improve the engineering assessment of geohazards, such as the induced displacements. In this study, the investigation of liquefied soil is conducted by cyclic loading to induce liquefaction followed by monotonic loading in a triaxial setup. The testing program in this study focuses on determining the effects of two factors on the post-liquefaction soil response: (1) Pre-liquefaction loading history and (2) the sand particle roundness. Three different types of pre-liquefaction harmonic cyclic loading (uniform, taper up and taper down) were applied to reconstituted loose sand specimens to trigger liquefaction followed with monotonic loading. The taper motions are more closely related to the real transient ground motions, which the dominant pulses can be located at either the early or later loading phases. The results show that the transition from a low stiffness to a dilative response depends on the history of pre-liquefaction loading and sand particle roundness.

1 INTRODUCTION

Liquefaction of saturated sand is a well-recognized devastating hazard that has caused catastrophic losses in the past. During a liquefaction event, landslides are often triggered because the shear strength of the soil is significantly reduced due to excess pore pressure generation and decrease of effective stress. Although much research has been devoted in the past few decades to evaluating or improving the soil resistance during undrained loadings, less attention has been given to post-liquefaction soil responses. In fact, it is of equal importance to gain insight into the characteristic of the liquefied soil immediately post-liquefaction and before dissipation of excess pore pressures. In current practice, the shear strength of liquefied soil is usually crudely correlated with indices such as parameters from SPT or CPT, for which conservatism is often built in. There is a general agreement that a flat, low stiffness, portion of the stress-strain plot appears before the beginning of dilation when monotonic loading is applied after triggering liquefaction (Vaid and Thomas 1995; Sivathayalan and Yazdi 2013; Dahl et al. 2014). The low stiffness region ranges from a few to several tens of percent of axial strain (Figure 1).

The change from near zero stiffness to a dilative response is due to particle rearrangement or change of fabric during liquefaction, which was experimentally proven to be a function of density, stress level, sand type (angularity) and fines content (Sitharam et al. 2009; Sivathayalan and Yazdi 2013; Dahl et al. 2014). Variations in the pre-liquefaction loading history should affect the post-liquefaction stress-strain relationship. Sivathayalan and Yazdi (2013) and Dahl et al (2014) characterize the pre-liquefaction effect as induced maximum shear strain, which correlates with the post-liquefaction stress-strain characteristic. However, the pre-liquefaction cyclic loading in these studies is limited to uniform harmonic shear stress cycles, which is a very crude representation of the complex time history of an earthquake ground motion. Liquefying the sand under non-uniform or transient loading prior to post-liquefaction shearing is needed to provide more accurate representations of post-liquefaction strength during an actual seismic event.

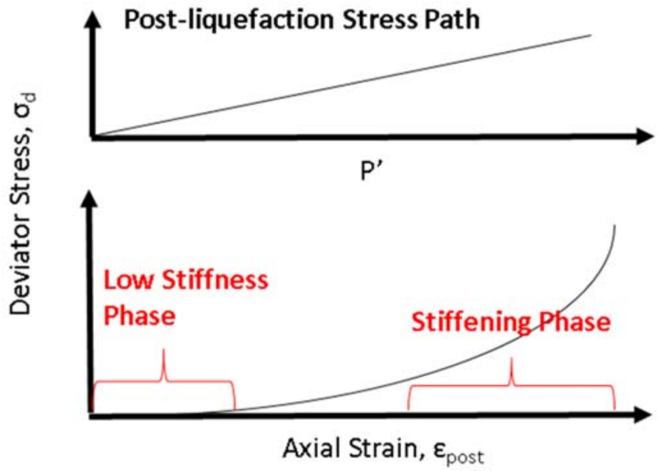

Figure 1: Typical Postliquefaction Stress-Strain Relationship [adapted from Vaid and Thomas (1995)].

In this study, the undrained shear strength of liquefied soils is investigated by performing undrained monotonic shearing on triaxial specimens after inducing liquefaction under cyclic loading in a triaxial setup. The testing program in this study focuses on determining the effects of two factors on the post-liquefaction soil response: (1) Preliquefaction loading history and (2) the sand particle roundness. Three different types of pre-liquefaction harmonic cyclic loading (uniform, taper up and taper down) were applied to reconstituted loose sand specimens to trigger liquefaction followed with monotonic loading. Two types of sand were used: one with well-rounded particles (Ottawa Sand) and one with very angular particles (Blast Sand); the specimens were consolidated to a confining stress of 100kPa, which simulates vertical effective stresses at shallow depths where liquefaction is most probable to occur. The tests were performed under undrained conditions with back pressure saturation to ensure full saturation of all specimens. The taper motions are more closely related to the real transient ground motions, which the dominant pulses can be located at either early or later parts of the loading. The generated data provide valuable insight on post-liquefaction monotonic sand responses.

2 TESTING PROGRAM

Two sands were used in this study: a rounded Ottawa Sand (e_{min} = 0.48, e_{max} = 0.76, Gs = 2.65, C_u = 0.91 and C_c = 1.46) and an angular Blast Sand (e_{min} = 0.43, e_{max} = 0.76, Gs = 2.63, C_u = 1.04 and C_c = 1.71). C_u is the uniformity coefficient; C_c is the coefficient of curvature:

$$C_u = D_{60}/D_{10} \quad (1)$$

$$C_c = (D_{30})^2 / D_{10} * D_{60} \quad (2)$$

where D_{10} is the grain size corresponding to 10% finer, D_{30} corresponding to 30% finer, and D_{60} corresponding to 60% finer. The particle size gradation and soil particle roundness are shown in Figure 2. According to USCS (ASTM D2487), Ottawa sand is classified as SP and homogeneously rounded; Blast sand is SP and heterogeneously angular.

The cyclic triaxial tests (CTX) were performed using a Geotechnical Consulting and Testing System (GCTS) Cyclic Triaxial apparatus (Figure 3). The CTX system uses a closed loop, electro-hydraulically actuated, servo valve that allows for shearing under load or displacement controls. Two linear variable differential transformers (LVDT) were used to measure displacements. One is installed on the vertical actuator to measure the overall displacement, as often employed in traditional triaxial testing. The other LVDT is internally setup on the middle one third of the specimen itself for more accurate strain measurements by eliminating the bias in strain measurements due to the end plates. Moreover, the load cell is installed directly on top of the soil specimen inside the cell chamber. Therefore, the measured data is not subjected to any compliance bias and frictional force that may exist in the ball bearing connection.

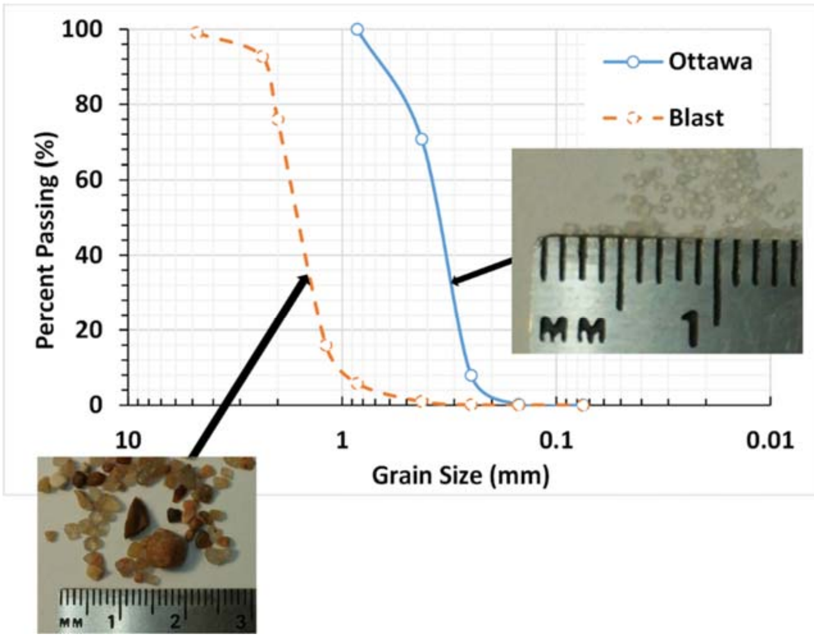

Figure 2: Grain Size Distribution of Ottawa and Blast Sand.

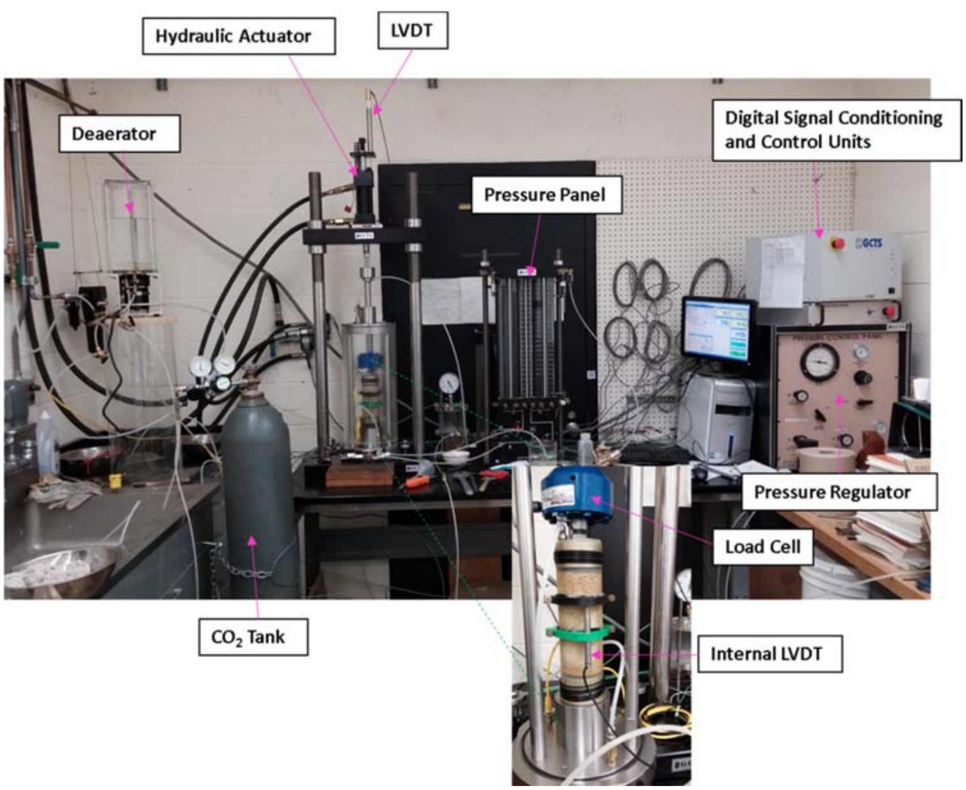

Figure 3: Overall Setup of the GCTS Cyclic Triaxial Apparatus.

For the pre-liquefaction cyclic loadings, in addition to traditional harmonic uniform loading, taper up and taper down sinusoidal motions were also considered to study the effects of the variability of the amplitude in earthquake motions on the post-liquefaction response (Figure 4). Before modelling the complex transient ground motion loadings, it is important to start with relatively simple wave forms, such as the taper up and taper down motions in order to isolate the effects of particular time characteristics of the ground motions. A ground motion is usually composed of one to a few dominating pulses, which can be located at the beginning or later stages of the motion. The taper up motion mimics ground motions that have a major part of the loading towards the end of the ground motion; the taper down motion simulates ground motion for which the higher loading occurs at the beginning. All pre-liquefaction loading were applied at a frequency of 0.2 Hz in order to obtain more accurate and representative measurements of the pore pressure response of the whole specimen (pore pressures were only measured at the base of the specimen). The post-liquefaction shearing was applied at a rate of 0.15%/min while maintaining the undrained conditions.

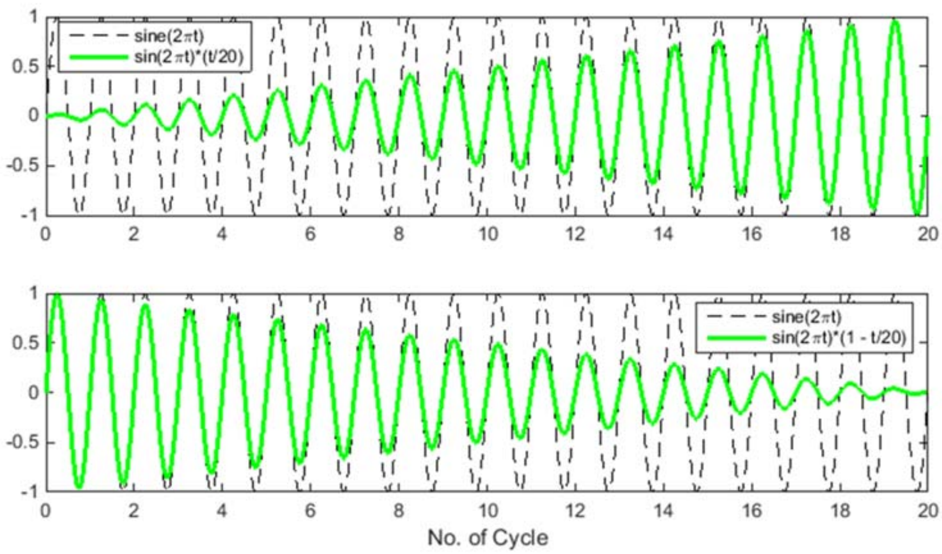

Figure 4: Taper Up (top) and Down (bottom) Loadings compared to uniform loading.

3 SAMPLE PREPARATION

The specimens were reconstituted using the dry pluviation method. To create loose specimens, the dry sand was deposited into a funnel, and the funnel was slowly raised up with almost zero drop height. Therefore, a low energy state was achieved. The specimen was then flushed with CO_2 and de-aired water before applying back pressure saturation while under a seating confining stress of 50 kPa. After a "B-value" of 0.95 or greater was achieved, the specimen was consolidated to 100 kPa (σ'_v). The change in specimen height (through the external LVDT) and correction for membrane penetration (Baldi and Nova 1984) were utilized in calculating the final relative density of the specimen at the end of consolidation. Finally, the specimen was loaded cyclically until liquefaction initiation (stage 1) and followed with monotonic shearing, all while maintaining the undrained condition (stage 2). If the specimen did not liquefy under a defined taper motion, the taper motion was repeated until liquefaction occurred. For this project, initiation of liquefaction is defined when $r_u = 1.0$, or when the excess pore pressures level out at an r_u of at least 0.9.

4 TEST RESULTS AND DISSCUSION

Results of 11 cyclic triaxial test conducted on Ottawa sand and Blast sand are included in this paper. Table 1 summarizes the details of each of the 11 tests. Figures 5 and 6 show typical test results of harmonic and irregular loadings, respectively. The top two rows illustrate the soil responses under pre-liquefaction cyclic loading: deviator stress (σ_d) vs. time, pore pressure ratio (r_u) vs. time, internal axial strain (ε) vs. time, and the stress-strain relationship. The subplots are colour coded so that the time dimension can also be reflected in the stress-strain plot. The respective last rows of Figures 5 and 6 show the post-liquefaction stress-strain response, in which the blue line represents the measurements from external LVDT and the red line is from the internal LVDT.

Table 1: Summary table for the testing program. *The CSR from the taper motions were determined from the largest amplitude (i.e., the first cycle for taper down and last cycle for taper up).

Test #	Sand	CSR	D_r (%)	Motion
1	Ottawa	0.20	60	Sine
2		0.23	54	Sine
3		0.31	65	Sine
4		0.37	61	Sine
5		0.31*	59	Taper Up
6		0.31*	53	Taper Down
7	Blast	0.34	42	Sine
8		0.42	47	Sine
9		0.46	39	Sine
10		0.42*	53	Taper Up
11		0.42*	42	Taper Down

Cyclic resistances of sand can be represented by CSR vs. N_f curves, which are shown in Figure 7. CSR is the cyclic stress ratio, σ_d / (2σ'_v), and N_f is defined as the number of cycle required to achieve r_u = 1.0 or levelling out at a r_u value of 0.9 for this project. Since Blast sand is a very angular sand, compared to Ottawa sand, the frictional force is much stronger when the particles slide against each other and gives a much higher cyclic resistance than the Ottawa sand, even at a slightly looser density range. The lines represent the best fit power function through the data.

Figures 8 and 9 show the stress-strain plots of post-liquefaction monotonic responses. The post-liquefaction responses generally agree with previous findings that there is a low stiffness phase before stiffening occurs under the monotonic loading. Indeed, Figures 8 and 9 illustrate advanced insights that the overall post-liquefaction stress-strain behaviour is highly dependent on the preliquefaction loading history and particle angularity.

Figure 8 compares the post-liquefaction monotonic responses of Ottawa and Blast sand after uniform undrained loading at different CSR values. The test results indicate the post-liquefaction responses depend on two factors: (1) pre-liquefaction uniform loading CSR and (2) sand particle angularity. For both sand types, it is evident that the higher the pre-liquefaction CSR, the higher the strain needed to initiate dilation. This finding agrees with previous research results on strain control cyclic simple shear (Sivathayalan and Yazdi 2013; Dahl et al. 2014) that the postliquefaction low-stiffness phase range is proportional to the preliquefaction cyclic strain amplitude. Additionally, the homogenously rounded Ottawa sand displays a smooth and typical stress-strain relationship similar to the one presented in Figure 1 (expect SR=0.2), but the heterogeneously angular Blast sand does not exhibit a clear transient phase between the low-stiffness and hardening phases. In general, the liquefied Ottawa sand gives a "brittle" behaviour (sharper increase in the stress-strain plot), but the liquefied Blast sand provides a "ductile" response. It should be noted though that the range of relative densities for the Ottawa sand was higher than that for the Blast sand specimens implying more dilatancy tendency for the Ottawa sand which can be the reason behind the more "brittle" response.

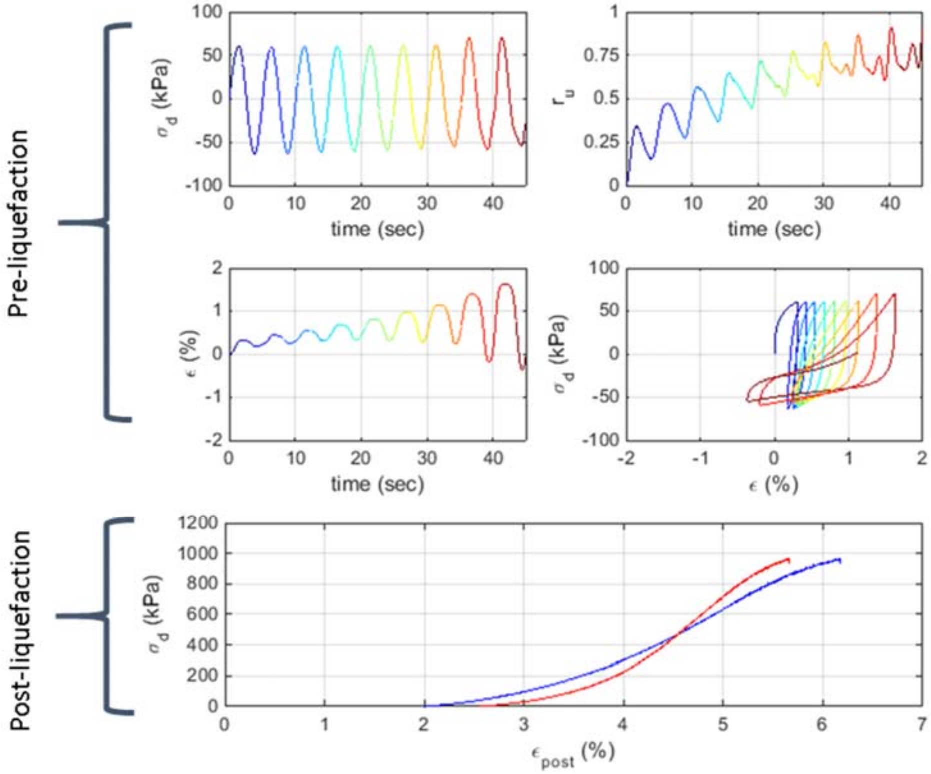

Figure 5: An example of a harmonic loading test result (Ottawa Sand, Test #3).

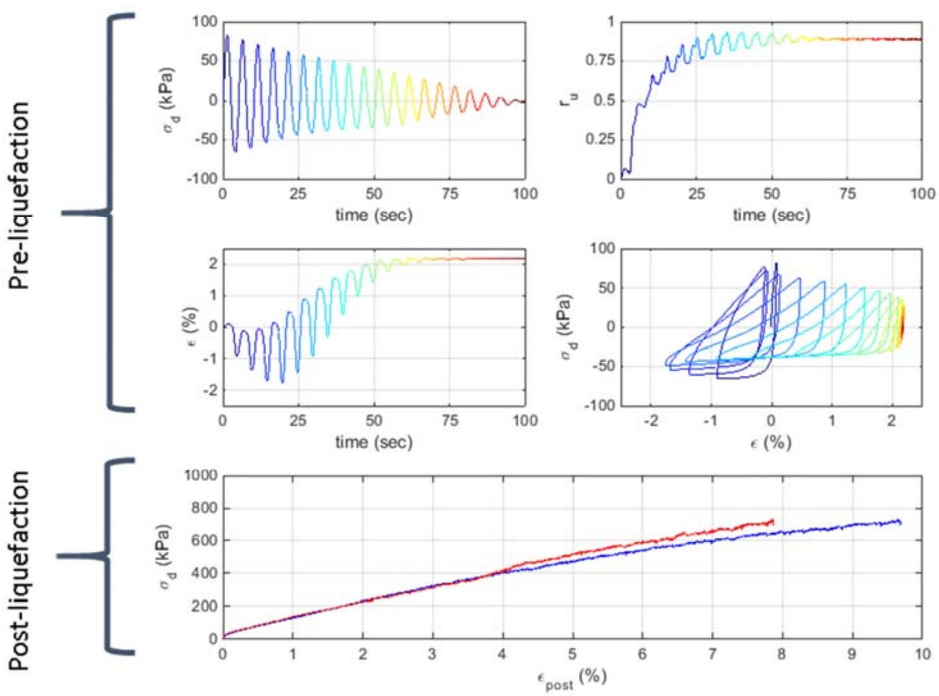

Figure 6: Typical Test result (Blast Sand, Test No #11).

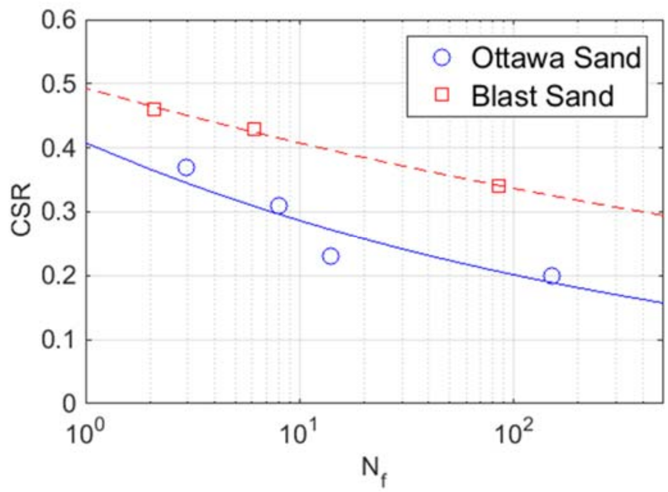

Figure 7: CSR vs. N_f curves.

Figure 9 compares post-liquefaction responses after different patterns of pre-liquefaction cyclic loadings (Harmonic, Taper Up and Taper Down). All the input motions in Figure 9 have equal peak to peak amplitudes; the amplitude of the largest cycle, first cycle in taper down and last cycle in taper up, is the same as the amplitude of uniform cycles of harmonic motion. The post-liquefaction responses after harmonic loading can serve as a baseline, which the current understanding is based on. In both of the tested sand, Ottawa and Blast, the post-liquefaction responses after taper down loadings reveal that the low stiffness phase is absent and the hardening phase picked up immediately once the undrained monotonic started. On the other hand, the post-liquefaction responses after taper up loadings illustrate that the dilation initiation required more axial strain than what is required after harmonic loading. These test results clearly show that the range of the low-stiffness phase is highly dependent on the corresponding pre-liquefaction loading history, and there is an overall consistency in the change in the slope of stiffening phase for both sands (with a clear distinction in the amplitude of strain required to initiate dilation depending on the angularity of the sand).

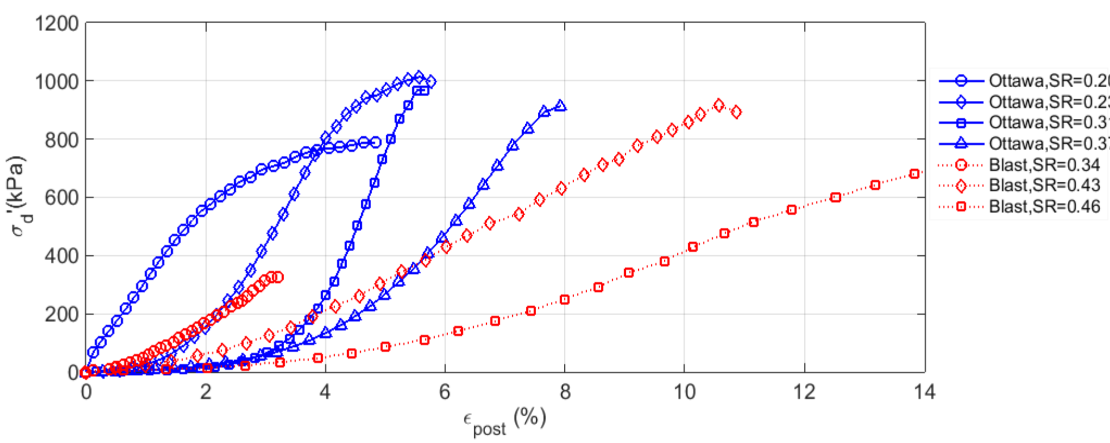

Figure 8: Comparison of post-liquefaction stress-strain curves for different CSR values under harmonic pre-liquefaction loading.

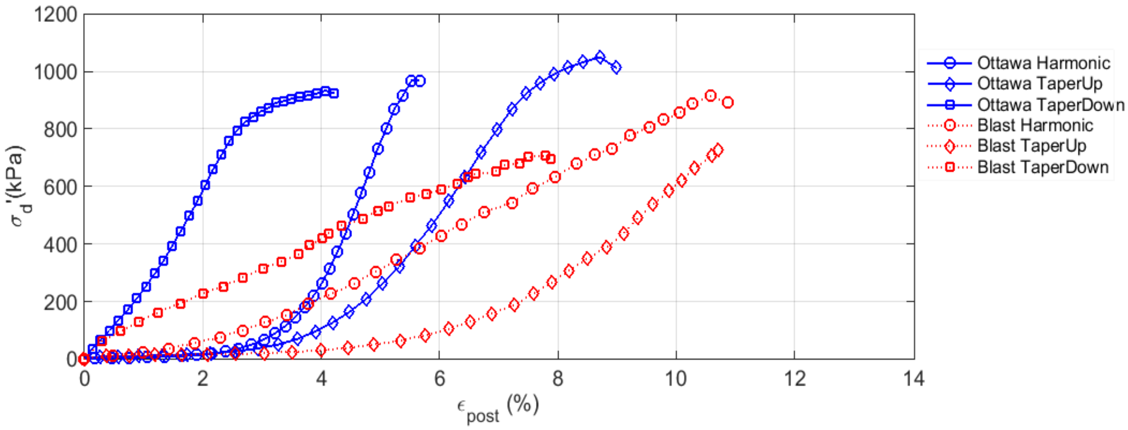

Figure 9: Comparison of post-liquefaction stress-strain curves for different pre-liquefaction loading histories.

5 CONCLUSIONS

This study looked into the effect of irregular pre-liquefaction loading history on the post-liquefaction undrained shear strength of two sands. The sand particle angularity affects the post-liquefaction monotonic behaviour. The homogeneously rounded Ottawa sand samples provides a more "brittle" stress-strain post-liquefaction responses while the heterogeneously angular Blast sand samples provided a more "ductile" stress-strain postliquefaction behaviour. While the conventional way of representing seismic loading is as a series of uniform cycles, taper up or down loading patterns were used in this study as a first step towards understanding the effects of temporal characteristic of earthquake motions on the post-liquefaction strength. The results suggest that using uniform cycles to represent a ground motion that has strong loading at the end can be un-conservative, because the range of low-stiffness phase is higher in post-liquefaction monotonic response after a taper up loading. On the other hand, using uniform cyclic loading to represent a ground motion that has a strong loading at the beginning can be over-conservative, because the stiffening phase picked up right after the soil experienced liquefaction due to a taper down loading. Even though this research is still preliminary, it does offer insight on how irregular pre-liquefaction loading histories affect the post-liquefaction responses. Future studies should involve more complex pre-liquefaction loadings such as actual ground motion records.

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